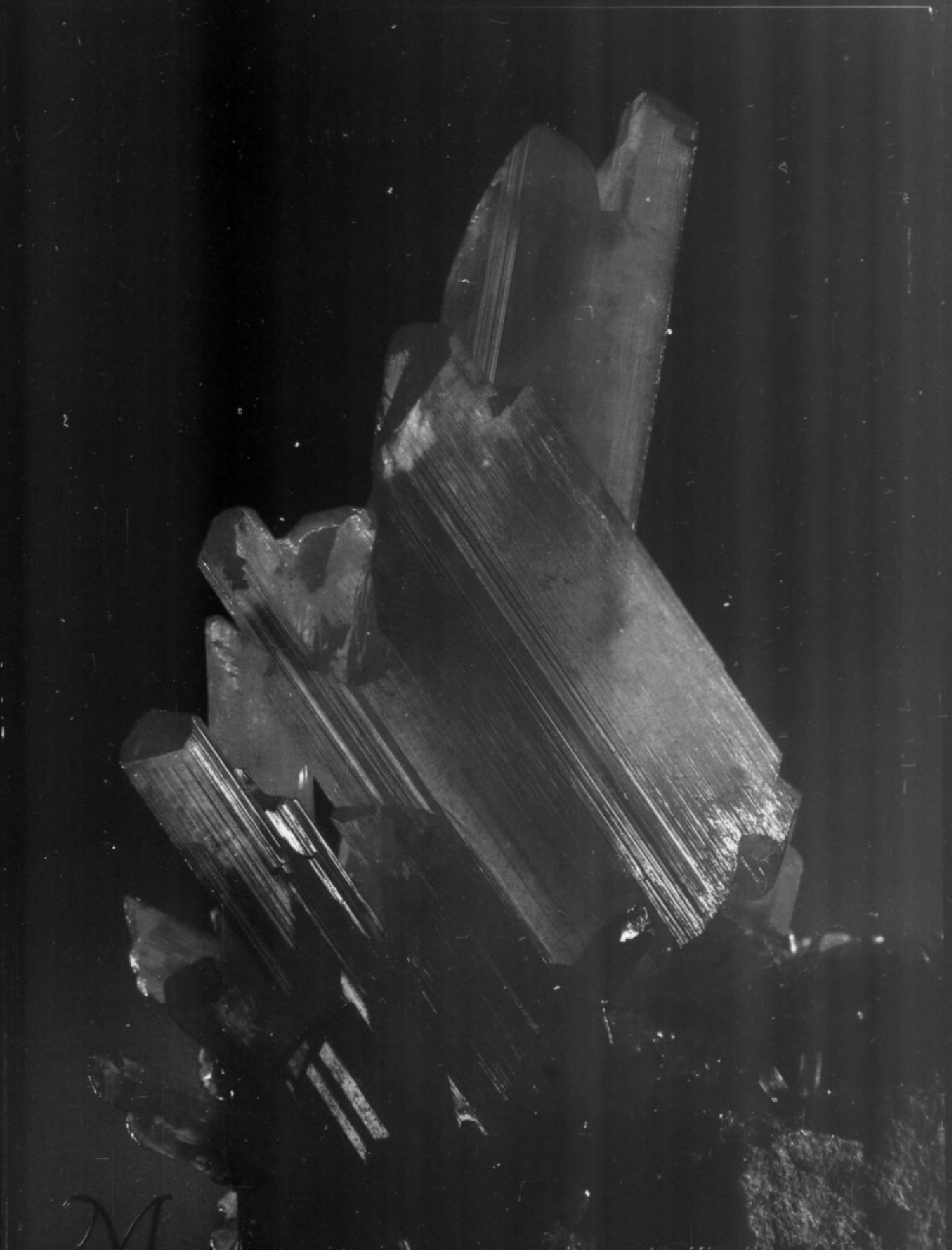

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COVER: CROCOITE crystal group, 5 cm, from Tasmania. Anonymous collection; photo by Harold and Erica Van Pelt.

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INTRODUCTION

Welcome to our largest-ever special issue, at 152 pages, roughly three times our usual allotment of articles and photos. On the occasion of Australia's bicentennial celebration this year, we are commemmorating the mines and minerals of that remarkable country.

Such an issue was first suggested to us by Dr. Howard Worner a few years ago, while he was here visiting the Tucson Show and autographing copies of his book, *Minerals of Broken Hill*, at our show table. Dr. Bill Birch, of the Museum of Victoria, spearheaded the project for us, soliciting articles and photos on our behalf and raising most of the extra funds necessary to produce such a massive edition. Readers may recall, not incidentally, that it was also Bill who compiled the comprehensive and beautifully illustrated article on the gold deposits of Australia in our recent Gold Issue (vol. 18, no. 1).

Of course, many volumes have been written on the mineralogy of Australia; no single issue could hope to be comprehensive. But the topics covered here provide at least an introduction. For those readers with access to back issues, a list of articles on Australian localities previously published in the *Mineralogical Record* is provided. W. E. W.

• • •

Australia!

Australia's mineralogical history really begins with the original inhabitants, the Aborigines, who used and traded appropriate rocks and minerals for a range of purposes, from ceremonial to survival. Following the establishment of European settlements in the late 1700's, it was the discovery of economic minerals which led to the greatest burst of development and prosperity. Copper in South Australia in the 1840's; gold from the 1850's onwards in Victoria and New South Wales and from the 1880's in Western Australia.

The 20th century has been characterized by successive waves of discovery and exploitation. In the 1950's it was bauxite in the Northern Territory and Queensland; in the 1960's, huge deposits—mountains, in fact—of iron ore in Western Australia and islands of manganese in the Northern Territory; in the late 1960's nickel was the boom metal in Western Australia; the early 1970's uranium in the Northern Territory—discovered, if not fully exploited; then gold's turn, once again, in the 1980's. Through the 1900's, four great mines, Broken Hill (silver, lead and zinc); Mt. Lyell (copper); Mt. Morgan (copper and gold) and Mt. Isa (silver, lead and zinc) were the backbone of Australia's metal mining. The country's gemstone resources, based on the precious opal deposits of Coober Pedy, Andamooka and Lightning Ridge and the sapphire fields of the Anakie district in Queensland, were enhanced in the 1980's by the diamond discoveries in the Kimberley Division of Western Australia.

An interest in Australian minerals purely from a collecting viewpoint was slow to develop. For much of our history, collecting was something indulged in only by the major museums and a few knowledgeable individuals (once probably considered eccentric, now seen as farsighted). Attempts to foster the collecting, study and documentation of Australian minerals began with the publishing of *Australian Amateur Mineralogist* in the 1950's, but this foundered on financial rocks after only a few years. The early 1970's saw interest in minerals as a hobby rekindled, when the upsurge in the availability of specimens in the United States and Europe had a "trickle down" effect in Australia. The mid to late 1970's were boom times, for the dealers and the collectors, wealthy and otherwise, who were all caught up in the clamor for exotic pieces. That era has gone, but today the Australian mineral collecting scene has consolidated around a growing number of knowledgeable amateurs who want more than just a superb or interesting collection. They want to know *where*, particularly if it's Australian, *why* and *how*; questions which make the role of the professional mineralogist so important to them.

While Australia is renowned for its mineral deposits, its accomplishments in the science of mineralogy are less spectacular. We have been accused of a "rip it up and sell it off" mentality towards our mineral resources for much of our history; perhaps this may be partly to blame for our very lean contribution to international mineralogical knowledge. There has been no historical period of "classical" studies on Australian minerals, and the country has produced only a handful of eminent mineralogists. With seemingly unlimited resources and great mining operations, it seems a paradox that Australia has contributed only about 85 new mineral species from about 60 type localities. It's not that the minerals aren't there—there's just been no time, or reason, apparently, to investigate and document them thoroughly.

This year, 1988, is Australia's Bicentennial. The official celebrations have their critics, for the perceived financial extravagance and historical misrepresentation of the main events. Yet what is often overlooked is the program of special one-time bicentennial projects of lasting benefit being embarked upon by hundreds of thousands of Australians in thousands of organizations. This special issue of the *Mineralogical Record* is a good example—a celebration of Australian minerals. We hope the articles convey to *Mineralogical Record* readers worldwide some impressions of the romance of their discovery and the richness of their diversity. Above all, we hope they will stimulate a greater concern for the importance of collecting and documenting representative species when they are available.

The chance to guest edit this issue more or less devolved to me and, while it has been quite time-consuming, it has had its own inbuilt reward. Great credit should go to the authors, who have put so much into their contributions. Special mention must be made of Frank Coffa's photography—he has my assurance that I won't be asking him to photograph another mineral for at least another. . . .week. Finally, it is necessary and appropriate to record the generosity of the sponsors, both corporate (led by Australia's largest company, BHP) and individual, without which the size and color content of this issue would not have been achievable. We hope you enjoy it.

Bill Birch
June, 1988

Australian Articles Previously Published

On a spectacular find of crocoite in the Adelaide mines, Dundas, Tasmania (1972) **3**, 111–113. *by A. H. Chapman*

An unusual occurrence of bobierrite at Wodgina, Western Australia (1974) **5**, 265. *by B. Mason & P. J. Dunn*

Famous mineral localities: Broken Hill, Australia (1976) **7**, 25–33. *by B. Mason*

Glendonites, their origins and description (1976) **7**, 60–68. *by B. M. England*

Crocoite and its increasing scarcity (1977) **8**, 24–26. *by K. Lancaster*

The dravite crystal bonanza of Yinnietharra, Western Australia (1977) **8**, 109–110. *by P. J. Bridge, J. L. Daniels & M. W. Pryce*

Zinc phosphates at Reaphook Hill, South Australia (1978) **9**, 20–24. *by C. W. Johnston & R. J. Hill*

Minerals of the Greenbushes tinfield (1978) **9**, 81–84. *by M. Pryce & J. Chester*

Malachite Pseudomorphs from the Sir Dominick mine, Arkaroola, South Australia (1980) **11**, 73–76. *by B. M. England*

Brown's deposit, Northern Territory, Australia (1980) **11**, 287–291. *by D. H. McColl*

First discovery of ruby in Australia (1980) **11**, 371–375. *by D. H. McColl & R. G. Warren*

Crystallized gypsum from the playa lake clays of Lake Gilles (1982) **13**, 187–191. *by B. M. England*

A new stolzite occurrence: Broken Hill, Australia (1983) **14**, 215–216. *by S. K. G. Bywater*

Kornerupine and sapphirine crystals from the Harts Range, Central Australia (1984) **15**, 99–101. *by D. H. McColl & G. Warren*

The libethenite zone, Burra mine, South Australia (1984) **15**, 105–108. *by S. K. G. Bywater*

Sodium-pharmacosiderite, a new analog of pharmacosiderite from Australia, and new occurrences of barium-pharmacosiderite (1985) **16**, 121–124. *by D. R. Peacor & P. J. Dunn*

Famous mineral localities: the Kingsgate mines (1985) **16**, 265–289. *by B. M. England*

Calcioferrite from the Moculta quarry, near Angaston, South Australia (1985) **16**, 477–480. *by W. A. Henderson & V. Peisley*

Natrolite arches from Simmon's Bay, Australia (1986) **17**, 377–379. *by W. A. Henderson & C. M. Garland*

Gold in Australia (1987) **18**, 5–32. *by B. Birch*

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THANKS ALSO . . .

. . . to Gale Thomssen, Promotions Manager of the Mineralogical Record, who is moving on to pursue other interests in local government affairs. Working from her home base in Carson City, Nevada, Gale has represented the Mineralogical Record at professional conferences and mineral shows both in the United States and worldwide.

Gale created the Book Department as a vehicle to promote interest in the study of mineralogy and to provide a service for the magazine's subscribers who wanted a source for books relating to mining and mineralogy. This July the Book Department celebrated its fifth anniversary. From a part-time operation in Gale's garage, the Book Department has become a full-fledged branch of the Mineralogical Record, with a store-front office and three employees who serve a worldwide clientele.

Gale's interest in municipal government was encouraged by her appointment to the Carson City Charter Review Commission. Recently approached by supporters to enter the capital city's mayoral race, Gale decided instead to work with the local Chamber of Commerce in promoting community events. She assures us, however, that she will continue to attend major mineral shows and volunteer for us whenever possible.

Sue Ann Jones, formerly the Book Department's Shipping Manager, will replace Gale as Promotions Manager. She will work with Marilee Chirila, Book Department Manager, in running the Carson City office.

Thank you, Gale, for your dedication and enthusiasm. You will be missed.

Marilee Chirila

EARLY AUSTRALIAN MINERALOGY

●

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INTRODUCTION

Australia, the island continent with a land area almost exactly the same as the continental U.S., is richly endowed with economic minerals. The country is the largest world producer of bauxite, alumina and mineral sands (rutile, zircon, ilmenite and monazite) and the largest exporter of iron ore and coal. It is among the top three producers of gold, lead, zinc, silver, nickel, manganese, precious opals, sapphires and diamonds and is a significant producer of nephrite jade. It has major resources of these minerals and gems and also of uranium and phosphates. Recent exploration indicates a considerable potential for production of platinum and other specialist metals such as gallium and the whole spectrum of the rare earths.

An understanding of the richness of Australia's mineral resources was not possessed by the early settlers, nor indeed did English officaldom give a high priority to minerals and mines in their plans to establish Australia as a new colony in the late 18th century. The initial object was to found a penal settlement to which convicts, hitherto transported to North America, could be sent. (The United States of America was no longer a British colony, having won its independence only a few years before the first settlement took place at Sydney Cove, Port Jackson, in New South Wales on January 26, 1788.)

Captain James Cook, the famous English explorer, had reconnoitered the east coast of Australia in 1770 and taken possession of the country in the name of the British Crown. Cook had with him on the voyage a wealthy young naturalist, Joseph Banks, who was to become famous for his patronage of Australian botany. He did little for Australian mineralogy.

Bank's choice of Botany Bay, the abode of the plants that had excited him in 1770 when he landed there with Cook, as the place for the first British settlement proved quite unsuitable. It lacked fresh water and soil suitable for growing vegetables and cereals. Forced to look elsewhere, the founding governor, Arthur Phillip (1738–1814) happened upon the nearby Port Jackson, named but not examined by Cook. That port was to become the famous and beautiful harbor around which the present city of Sydney has grown.

Governor Phillip had no experts to advise him on the suitability of the soils and the rocks on which the infant penal settlement was established, but steps were taken to forward to Sir Joseph Banks specimens of some clay and "stone" taken out of a "slate" quarry which the Governor thought contained some metal. The stone was heard of no more; it was undoubtedly a shale for there is no slate near Sydney and the "metal" was probably pyrite or marcasite. Banks thought the "metal" was not worth attention but he did arrange for the clay to be analyzed by the potter-chemist, Josiah Wedgwood (1730–1795).

Wedgwood found that aqueous dilution of hydrochloric acid in which the clay had been digested yielded an insoluble precipitate. No such precipitate occurred with similar treatment of common china clay, so Wedgwood claimed discovery of a new elementary "earth" which he named "Sydney Earth" or "Sydneia" after its source. However, the validity of the so-called sydneia was cut short when other chemists, using other portions of the same Sydney clay, failed to confirm Wedgwood's observations. One of us (Vallance, 1975) has suggested that the precipitate arose from contamination of Wedgwood's hydrochloric acid with bismuth.

During its brief *floruit*, sydneia gained wide notice in the scientific literature. It even raised the thought of mineral nature in Australia having novelty to match those of the plants and animals. Yet, strangely, the thought does not seem to have prompted activity. Other mineralogical specimens sent by Governor Phillip to London disappeared without a trace. Progressively it became apparent that the area about the settlement held no particular mineral riches. Interesting discoveries had to wait until more of the country was examined by people able to make informed observations. Not surprisingly, the lead, such as it was, came from exploring expeditions that happened to call on New Holland, as the country was often named in those days.

In 1791, George Vancouver (1757–1798) examined a chalky substance which, after tests with acids and blowpipe as well as optical examination, was deemed to resemble the "earth" described by Cronstedt in his *Essay Towards a System of Mineralogy* (1788) (Vallance, 1986). This undoubtedly was earthy gypsum.

French expeditions, staffed with a wider spectrum of scientists than the English explorers, discovered in Van Diemen's Land (now called Tasmania) "bronze red" hematite as well as red ochre and "tripoli," the latter probably being a clay.

Coal was discovered in New South Wales during the 1790's, as were "iron stone" (goethite-hematite) and salt (halite); indeed it was reported in 1798 that an immense cliff of salt existed in the interior of the colony. It turned out to be only incrustations of halite on sandstone.

Governor Hunter, Phillip's successor, encouraged exploration and the search for mineral wealth. Two young naval men deserve mention: Matthew Flinders (1774–1814) and George Bass (1771–1803). It was Bass who tested black sands from the beaches of islands in what became known as Bass Strait; he is credited with finding arsenopyrite and cassiterite in those sands. Sands from the east coast of Australia yielded to the Irish chemist and mineralogist Richard Chenevix (1774–1830) evidence of the iron-titanium oxide "menachanite" (ilmenite), then considered a rare mineral.

Among the many contributions to geographical knowledge made by Flinders during his circumnavigation of Australia 1801–03, was the discovery of the "red cliffs" on the west side of Cape York in northeastern Queensland. Over a century and a half later those red cliffs were found by a geologist Arthur Evans to be one of the largest and richest bauxite deposits in the world; the location is now known as Weipa. Flinders, or rather his naturalist, Robert Brown (1773–1858), actually reported pisolitic "iron ore" from the seabed near Weipa.

Colloform pyrolusite was discovered by Brown at Melville Bay in the Northern Territory in 1803, when Flinders called there (Vallance and Moore, 1982), but once again more than a century and a half elapsed before those rich deposits were commercially exploited.

BEGINNINGS OF OFFICIAL MINERALOGY

In February of 1803 the first mineralogist officially to be appointed by the British Crown was designated for service in the infant colony of New South Wales. A. W. H. Humphrey (1782?–1829) was indeed more of a prospector than a professional mineralogist but his appointment did at least mark a distinct shift in British decision-making, and, incidentally, owed nothing to Banks.

One of the authors (Vallance, 1981) has examined the background to Humphrey's appointment. An English gentleman, C. F. Greville (1749–1809), had pressed the British government to take an interest in minerals and as he was a noted collector (the Greville Collection passed by purchase to the British Museum after his death) it could be that he (Greville) hoped that Humphrey would become the source of interesting and valuable specimens from the strange southern island continent. If that be the motive, there is no evidence that Humphrey succeeded in fulfilling Greville's hopes. Nevertheless, he did at least help stimulate some interest in searching for minerals.

Bass's friend William Paterson (1755–1810), for instance, in charge of the settlement at Port Dalrymple in Tasmania, ordered his men to search for minerals to send to Sydney for Humphrey to examine. The *Sydney Gazette* for 24 November 1805 was able to report that "A variety of rare and apparently valuable minerals has been received, amongst which is the pure asbestos combined with a ponderous ore, which is found in great abundance." But it appears that Humphrey himself had little success in his searches. He resigned in 1812 and became a magistrate.

The then governor, Lachlan Macquarie (1762–1824), sought a "scientific mineralogist" to replace Humphrey but London was in no hurry to respond. Macquarie was no longer governor when John Busby (1765–1857) reached Sydney in 1824 to begin duty as "Civil Engineer and Mineral Surveyor," *not* as His Majesty's Mineralogist, the high-sounding office Humphrey had held. As it turned out, Busby was kept far busier securing Sydney's water supply than prospecting for minerals.

A convict, John Hutchinson (died 1820), transported for forgery, appears to have conducted chemical test on clays for earthenware, and copperas made from pyrites. The latter came from the coals of the Hunter Valley some 120 km north of Sydney. Hutchinson was probably the first in Australia to use sulfide minerals as raw materials. Another pioneering experimenter was James King (1800–1857) who, among other things, tested local glass sands and established a pottery.

It might be thought that the establishment in Sydney in 1827 of a colonial natural history museum (since 1834 the Australian Museum) would have enlarged local interest in minerals by affording colonists access to a reference collection and, in turn, attracting donated specimens. In fact, the first printed catalog, issued in 1837, lists few minerals of any sort and only one Australian specimen.

Although early opportunity for mineralogy was lost, it is appropriate here to mention later developments. The Australian Museum employed no one to work on its minerals until 1859, when, briefly, it had the services of J. R. Gygax (1809–1859), a Swiss with medical training who also had had extensive experience with minerals (Vallance, 1986). Not until 1881 did the museum admit that its mineral collection, by that time an extensive one, deserved a curator. French-born Felix Ratte (1845–1890) was appointed to the post (Chalmers, 1979) and he followed the practice which was to be adopted for many years in the other museums in Australia of relying on the acquisition of already identified material, much of it foreign. None can be said to have fostered mineralogical studies before the emergence of the Industrial and Technological Museum in Melbourne in 1870. It is of interest that Melbourne itself did not exist when the museum in Sydney was founded.

With little help from the Australian Museum, colonial interest in minerals began to prosper from the 1830's. Collections began to be put together and shipped overseas. One of the first to receive careful examination was that which came into the possession of the American Francis Alger (1807–1863). Alger's pioneering work on Australian minerals and the valuable exchanges which took place from 1840 on between James Dwight Dana (1813–1895) and the Reverend W. B. Clarke (1798–1878) are dealt with in the following article by Robert Middleton.

NOTABLE PIONEER MINERALOGISTS

The 1830's saw the arrival in Australia of two highly individual characters who were keen students of mineralogy. Jan Lhotsky (1795–1866), a Pole, and the German Johann Menge (1788–1852) each brought aspects of continental European mineralogical training and knowledge. Dr. Lhotsky's ancestry was Bohemian but he had studied in Prague, Vienna, Berlin, Paris and Jena. Among his many professors were A. J. M. Brochant de Villiers (1772–1840) in the Paris École des Mines and C. F. C. Mohs (1773–1839) in Vienna. Lhotsky ascribed much of his knowledge of mineralogy to Mohs (Vallance, 1977). Both Brochant and Mohs had studied under A. G. Werner (1749–1817) at the famous Bergakademie in Freiberg and so Lhotsky can be said to have brought to Australia a thorough grounding in the Wernerian school of thought.

Lhotsky reached Sydney in 1832 as a political exile hoping to prosper as a traveling collector of natural history material. He had already to his credit a paper on the hydrous iron phosphate mineral cacoxenite (Vallance, 1977) in a respected European journal. In the Colony of New South Wales Lhotsky was soon to establish a reputation not only as a collector and dealer in minerals but as an editor-publisher. His essay "Mineralogy of Australia" (*New South Wales Magazine* **1** (1), August 1833) was the first of its kind and certainly demonstrated his breadth of experience (Vallance, 1977). Unfortunately, he received little support and moved to Hobart in Tasmania in 1836 and then in 1838 returned to London, still hoping to advance the knowledge of the natural world but still treated as a radical and an exile.

Johann Menge, like Lhotsky, was both an idealist and an enthusiast, perhaps more eccentric but certainly more practical. At the age of 17 Menge had begun assisting K. C. von Leonhard in the latter's mineral dealing business in Hanau. After Leonhard was appointed Professor

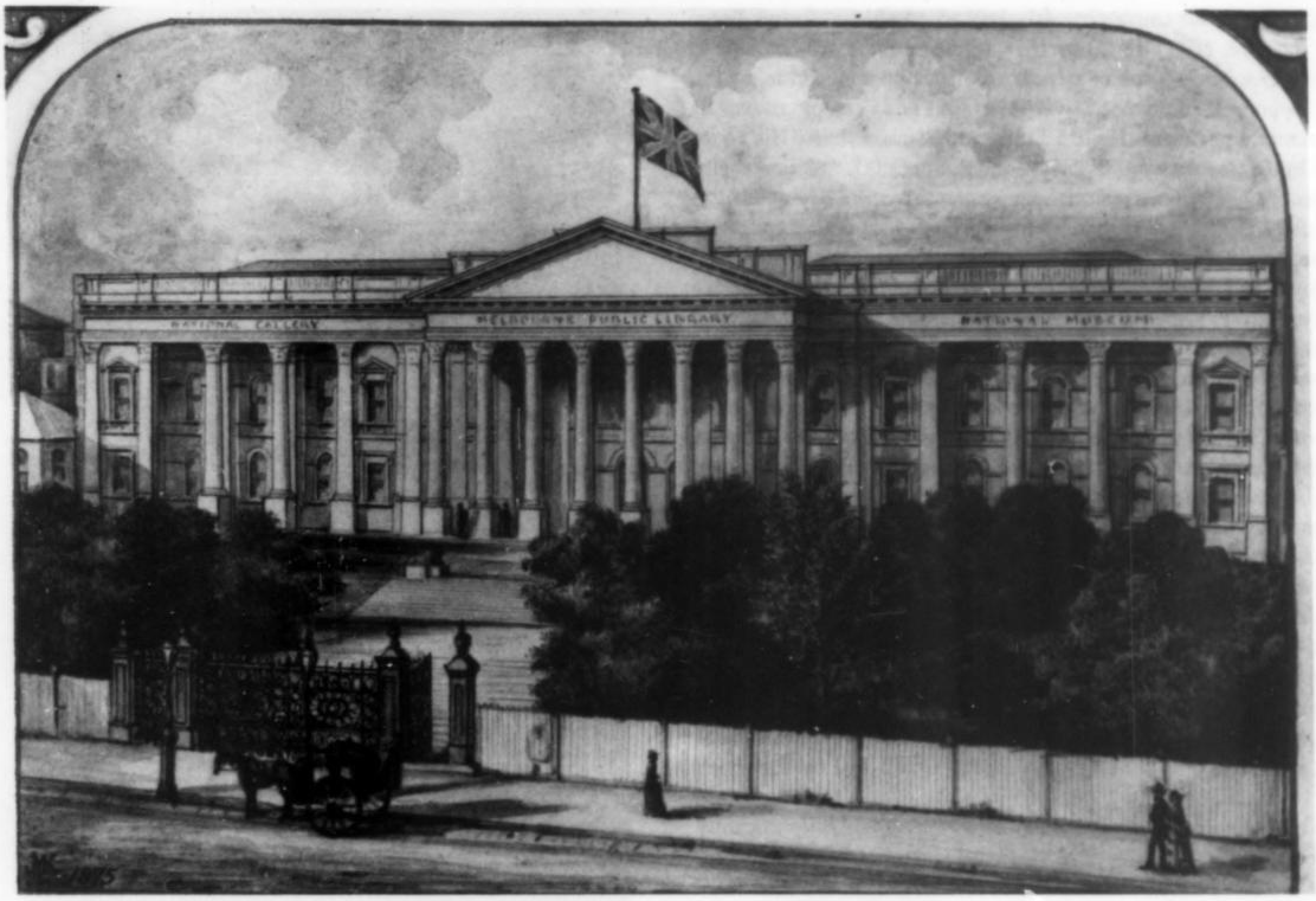


***Figure 1*. The Industrial and Technological Museum in Melbourne, founded in 1870, was housed in this building, along with the Melbourne Public Library and National Gallery.**

of Mineralogy at Heidelberg in 1817, Menge ran the business for a time. He then adopted the life of a traveling collector, first in Iceland (1819) and later in the Ural Mountains. His grasp of mineralogy can be judged from the published accounts of his travels (Vallance, 1975), and an uncommon monograph issued at Hanau (Menge, 1819).

The pioneer of Uralian mineralogy moved to London in 1830 as a dealer in minerals and a teacher of languages. In 1836 he was appointed "Mine and Quarry Agent and Geologist" to the South Australian Company before the formal establishment of the colony of South Australia. Menge arrived in January, 1837, being among the first German settlers in a state later noted for its German heritage and two years before the arrival of his famous comtemporary in New South Wales, the Reverend W. B. Clarke (Cooper *et al.*, 1986).

Menge's position with the South Australian Company was terminated a little over 12 months after he had been appointed, but he remained in South Australia to follow the style he plainly preferred, that of a solitary prospector. By 1840 a list of minerals he had found in the colony had appeared in an Adelaide newspaper. There and in later lists, published and unpublished (South Australian Archives), one finds idiosyncratic names like "gawlerite" (a red mineral) and "sturtite" along with other familiar and recognizable species. Whatever Menge's "sturtite" may have been, it certainly was not the same as the mineral from Broken Hill given that name in 1930.

Menge was not surprised when lead ore was found near Adelaide in 1841, or when copper was found in rich deposits somewhat further north in South Australia in 1843–1845. (Robert Middleton's article mentions the famous oxidized copper deposits of Kapunda, Burra Burra, Wallaroo and Moonta, and the magnificent specimens which came out of those mines.)

Menge had from 1838 been predicting that valuable mineral deposits would be found in South Australia and urged colonists to search for metallic mineral ores. Menge's catalogs of South Australian minerals provided a basis for subsequent compilations in the second half of the 19th century. An eight-page pamphlet he published in Adelaide in the early 1840's lists more than 500 minerals and rocks and was intended for the local market (Cooper, 1986).

By the late forties, South Australia, the youngest of the Australian colonies, had by far the most highly developed metalliferous mining industry, lead and copper mainly, but also gold. No one denied the inspirer of colonial metal mining his Australian soubriquet, "Menge the Mineralogist" (Cawthorne, 1859).

The first monograph on geology and mineralogy was published in Australia in 1846. The author, Thomas Burr (1813?–1866), was then Deputy Surveyor-General of South Australia. The first chemical data on the famous South Australian atacamites were supplied by the British chemist Andrew Ure (1778–1857).

Overseas interest in Australian minerals had certainly been rekindled, and far more productively than in the days of sydneia.

THE GOLDEN LEGACY: AUSTRALIAN MINERAL SCIENCE.

From 1851, gold transformed Australian society and nowhere more plainly than in Melbourne, a quiet provincial town that soon had to serve as capital of the country's richest colony, Victoria. The richness of both alluvial and quartz reef gold in southeastern Australia was well described by Dr. Bill Birch in the *Mineralogical Record*'s Gold Issue of last year (Birch, 1987). What Birch did not discuss was the impact of the wealth and population explosion on the growth of tertiary education in Australia. In Sydney a university was in process of creation before the gold rushes; teaching began there in 1852. The University of Melbourne came into existence a year or two later.

Neither university appointed a teacher of mineralogy in the formative years but the University of Sydney accepted a gift from Edward Deas-Thomson (1800–1879) in 1854 to create three scholarships in the natural sciences, one of which was for mineralogy. Melbourne was to appoint Fredrick McCoy (1817–1899), a paleontologist, as its first scientific professor. He had little interest in minerals. His counterpart in the University of Sydney, John Smith (1825–1885), a chemist, was not much more concerned with the subject. They nodded to mineralogy in their courses and practically left it at that.

Significantly, however, McCoy became active in Melbourne's new Natural History Museum and in the well-organized Geological Survey of Victoria, established ahead of the comparable body in the colony of New South Wales. Minerals were acquired for the museums in both of the rapidly growing cities but there was no initiation of mineralogical research. That strikingly matched the example of the two colonies' motherland; Britain was mineralogically backward by comparison with continental Europe. There was then no contemporary British work on Australian minerals to approach the quality of the researches published in Europe by such as A. L. O. L. Des Cloizeaux (1817–1897) on quartz, J. F. C. Klein (1842–1907) on atacamite, Albrecht Schrauf (1837–1897) on azurite and brochantite and V. L. von Zepharovich (1830–1890) also on atacamite. Even Australian samples of malachite, chabazite and other minerals in the British Museum were brought to the attention of the mineralogical world through the work of the Austrian, Viktor von Lang (1833–1921).

Scientific interest in the copper minerals of South Australia continued in Europe and the U.S., and it was established by such men as G. H. B. Kerl (1824–1905) in Germany and A. B. Northcote (1831–1869) in London that Australian gold nuggets were significantly different in composition from Californian gold (Kerl, 1853; Northcote, 1853). Gemstones from the auriferous drifts received attention from G. M. Stephen (1812–1894) and Rev J. I. Bleasdale (1822–1884) (Stephen, 1854; and Bleasdale, 1861–1866).

Other minerals came to light in the Victorian alluvial deposits, among them cassiterite and crystals and dendrites of gold, and a magenta-colored corundum which Stephen called "barklyite" (Stephen, 1862) after the Victorian governor of the time. Incidentally, many of the gold dendrites were thought to be man-made. The German-born artist and naturalist L. P. H. Becker (1808–1861) claimed to validate the existence of native zinc in the basalts near Melbourne.

Becker (1857), in his paper on zinc, made a significant acknowledgment to a Mr. George Ulrich, then on the staff of the Mining Commission of Victoria. This G. H. F. Ulrich (1830–1900) had graduated in 1851 from the famous Bergakadamie in Clausthal in Germany and arrived in Victoria in 1853. To his mastery of mineral science he added three year's experience as a digger on the goldfields before he took up a position with the Mining Commission under Professor McCoy. Although assigned to field-mapping work, Ulrich quickly demonstrated his particular skills and interest in his paper describing the uncommon minerals pharmacosiderite and scorodite from the quartz reefs at Tarrengower, Victoria (Ulrich, 1857).

When in 1862, the Geological Survey added a chemist to its staff, Ulrich took the opportunity to promote the study of specimens collected by field parties. C. S. Wood (1837–1864), the first chemist, had little chance to make an impact; he was already ailing when appointed. Ulrich had to await the arrival of his successor, J. C. Newbery (1843–1895), a graduate of Harvard University, but like Wood, also trained in the new Royal College of Science in London, the establishment of which marked a change in British attitudes to technical education.

Ulrich not only had the good fortune to have a colleague of the competence of Newbery but a valued mentor in the person of Alfred Richard Cecil Selwyn (1824–1902), director of the first Geological Survey of Victoria.

Figure 2. **George H. F. Ulrich.**

In a joint essay (Selwyn and Ulrich, 1866), Ulrich offered a descriptive list of Victorian minerals, mostly of his own determination. Three years later came an announcement that, for mineral science in Australia, retains great significance. It was the first record from Australia of a mineral species new to science and still recognized as valid today. The novelty of the material which Ulrich called *maldonite*, after its source locality, had been established in Melbourne and its formula Au_2Bi fixed from Newbery's analyses. However, what should have been a year of rejoicing turned out otherwise. Economic uncertainty had succeeded golden prosperity in Victoria. To save money and also perhaps to satisfy the ego and jealousy of the then Secretary for Mines, R. B. Smyth (1830–1889), the government dismissed Selwyn's excellent team and the Geological Survey was disbanded (Coulsell, 1985).

Fortunately for mineralogy, as well as for Ulrich and Newbery, a new opportunity appeared in Melbourne. At the end of 1869, the government agreed to reorganize its public museums. The mineral, mining and agricultural collections of what had become McCoy's museum were transferred to a new Industrial and Technological Museum. There at last minerals would be in skilled hands. In 1870, Newbery became scientific superintendent of the new museum and Ulrich in effect his curator of minerals. The fruitful collaboration of these two continued until 1878 when Ulrich left to accept the professorship of mining in the University of Otago in New Zealand.

Ulrich's curatorship in Melbourne began with a notable work (Ulrich, 1870) that supplied further detail on maldonite as well as many new data on ore minerals, on zeolites, on struvite found in Skipton Cave near Ballarat (famous gold mining town, now city) and two minerals which Ulrich named "selwynite" and "talcosite," thinking them new species. The last two were subsequently shown to be mixtures but the study of struvite deserves further comment. Besides analyses made by Newbery's assistant, E. F. Pittman (1849–1932), Ulrich presented a list of crystal angle measurements which was probably the first goniometry carried out and published in Australia.

Figure 3. **Cosmo Newbery.**

Ulrich and Newbery continued their study of the Skipton guano; they had as able collaborators a young chemist from Scotland, R. W. E. MacIvor (1856?–1917), and Ulrich's mineralogist friend in Bonn, Germany, J. J. G. vom Rath (1830–1888). This collaborative work led to the identification of six rare hydrous phosphates; four of them were new to science. Rath published the names *hannayite* and *newberyite* on the basis of research in Melbourne and Bonn; *dittmarite* and *schertelite* are due to MacIvor. The other two were struvite and brushite. Incidentally, two more hydrous phosphates from the Skipton Cave have been identified in the last decade; they are *taranakite* (Pilkington and Segnit, 1980) and *sasaite*, (Coulsell, 1987).

Ulrich was an inspirer of mineralogists and chemists as well as a distinguished contributor to mineralogy. With the mastery he brought from Germany, Ulrich must be regarded as the founder of scientific mineralogy in Australia and he made Melbourne the founding center.

When Ulrich moved to the professorship at Dunedin the pace and quality of mineralogical research in Melbourne subsided. His successor at the Industrial and Technological Museum was the Australian-born O. R. Rule (1835–1926) who, though an energetic collector, made no particular impact on science (Cousell, 1980). A young man fresh from Ulrich's classes in Dunedin followed Rule but he, R. H. Walcott (1870–1936), soon found himself enmeshed in museum politics that led to the mineral collection returning to the older natural history museum (now part of the Museum of Victoria).

Walcott had few opportunities to demonstrate his scientific abilities in his early Melbourne years but Ulrich's influence was not completely extinguished. During the 1870's mining schools had sprung up in the gold fields of Ballarat (1870) and Bendigo (1873) and these, and others founded later in the century, became the places where much of the basic mineralogy taught in the colony of Victoria was offered. From men like chemist A. M. Smith (1844–1926) and geologist F. M. Krause (1841–1918) Victorian students learned much practical mineralogy.

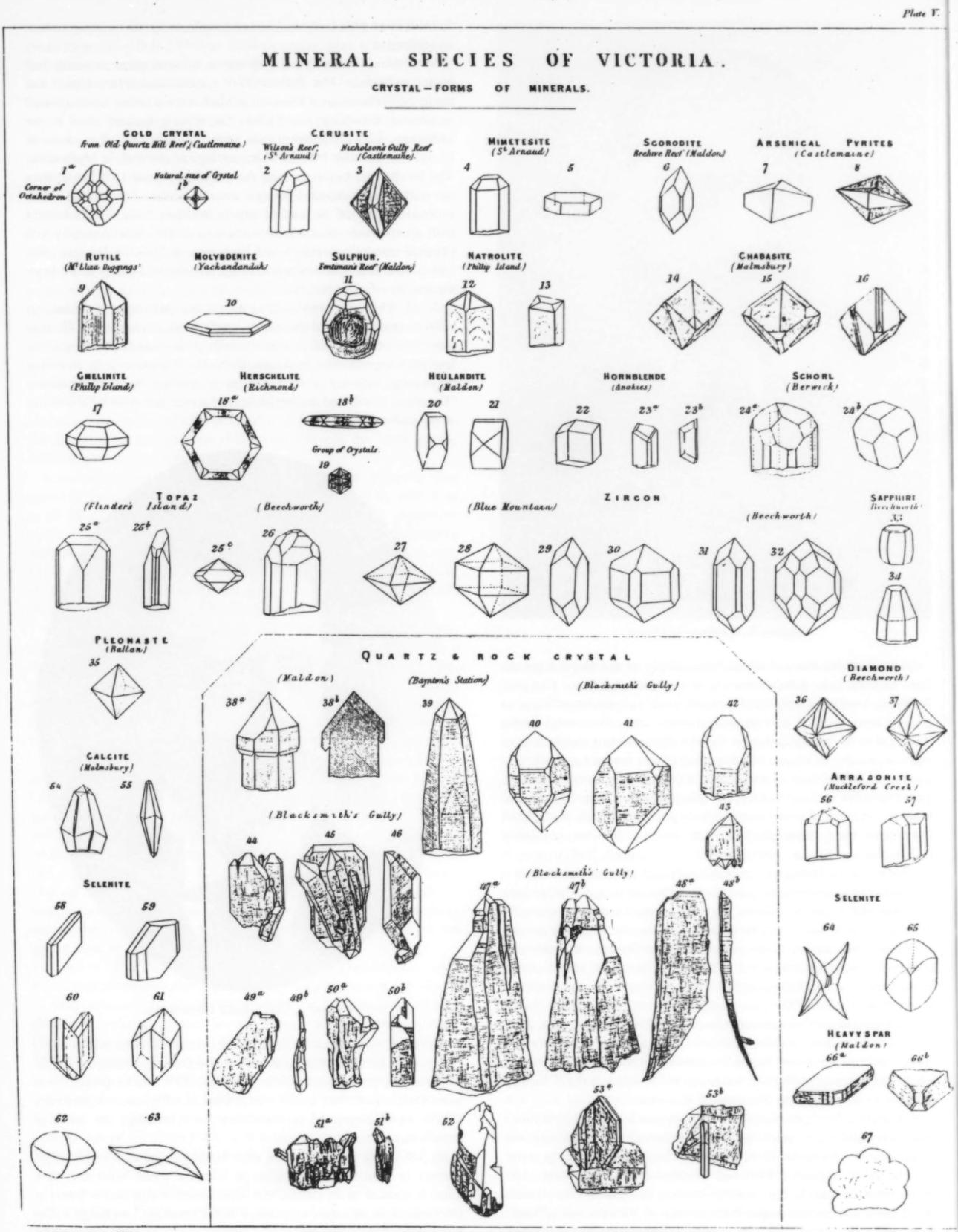
Meanwhile, leadership in Australia mineralogical research had passed to Sydney. The shift involved a contrast in styles. Ulrich had made the Technological Museum in Melbourne a center for excellence in general mineralogy; in Sydney the science became fixed in the university. Ulrich's collaboration with Newbery and other chemists brought an enviable breadth to mineralogical research in Melbourne. The results that began coming from Sydney about 1870 were from the start more focused. Sydney's mineral science reflected the educational origins of its leading exponents; they were British-trained with an emphasis on chemistry and less of the crystallography and physical mineralogy which had been part of Ulrich's German education. The distinction of mineralogy in colonial Sydney arose from the quality of its chemists.

A. M. Thomson (1841–1871) joined the University of Sydney in 1866 to teach practical chemistry, geology and mineralogy. He was soon promoted to a full professorship in geology and mineralogy, the first such appointment in Australia. Sadly, his career was short but his legacy included several papers, a practical book on minerals (Thomson, 1869) and the beginnings of a rock and mineral collection at the university.

Figure 4. **Archibald Liversidge.**

Thomson was succeeded in 1872 by Archibald Liversidge (1847–1927). Both had been trained in the London college (Branagan, 1973). Liversidge's professorship from 1874 to 1882 was in geology and mineralogy; from 1882 until his retirement in 1907 it was in chemistry though he also retained responsibility for mineralogy for many of those years.

By 1888, one hundred years after the beginning of European settlement in Australia, the colony of Victoria could boast five new mineral species to its credit; but New South Wales had a work of information on minerals unmatched in the country. Liversidge's *The Minerals of New South Wales* was already in its third edition by 1888



G.H.F. Ulrich. Del. 1870

Figure 5. **Crystal sketches published by Ulrich in 1870.**

R Shepherd lith

Figure 6. **Beautiful group of gold crystals illustrated in Liversidge's *Minerals of New South Wales* (1888), said to be in the Edinburgh Museum.**

(Liversidge, 1888). It earned acclaim in Europe and America as well as in Australia.

Liversidge's achievements went far beyond that of an assiduous investigator. His position and influence enabled him to promote his favored science elsewhere in Sydney. He had a hand in the establishment of the Geological Survey of New South Wales and of a government mining museum that lost its collection by fire in 1882 but started anew. Later, with the appointment of the London-trained G. W. Card (1865–1943) in 1882, the museum in collaboration with geological survey chemists gained much respect for mineralogical research.

For Liversidge, however, his closest ties outside the university remained with the Australian Museum which, like Thomson before him, he served as a trustee. In that influential position he was able to arrange the appointment of a full-time curator of minerals, the already-mentioned Felix Ratte (1845–1890). That Ratte (1885) could list a collection more than doubled in size in twelve years reflected well on an active curator and a no less active trustee. Ratte, however, found little time for research and apparently found the pressures of life too much to bear, and committed suicide after only nine years in office. He was succeeded by Thomas Cooksey (1864–1945), a chemist trained in England and Germany. Cooksey turned to other fields in 1899 and left little of moment as his legacy in mineralogy.

Charles Anderson (1876–1944) from Edinburgh joined the museum in 1901 and initiated research that was to bring much credit on both himself and the Australian Museum. Anderson's expertise in crystallography and physical as well as chemical mineralogy was something hitherto rare among British graduates settling in Australia.

The wealth of mineral species, several new to science, coming out of Broken Hill in far western New South Wales added a great stimulus to mineralogy not only in Australia but overseas as well. That is another story which has been well documented in a host of papers and a book, *Minerals of Broken Hill,* produced by Australian Mining and Smelting Ltd. to commemorate the centenary of the discovery of the great silver-lead-zinc orebody in 1883 (Worner and Mitchell, 1983).

CONCLUSION

After a slow and faltering beginning, Australian mineralogy could count some notable achievements by the end of the 19th century. The thirteen valid new mineral species yielded in colonial times, 1788–1900, are listed on Table 1.

Table 1. **Mineral species first found in Australia, 1788–1900 (from Vallance, 1986).**

Name	Formula	Colony	Author(s)	Year
Maldonite	Au_2Bi	Victoria	Ulrich	1869
Hannayite	$(NH_4)_2Mg_3H_4(PO_4)_4 \cdot 8H_2O$	Victoria	Rath (Ulrich/MacIvor)	1878/9
Newberyite	$MgHPO_4 \cdot 3H_2O$	Victoria	Rath(Ulrich/MacIvor)	1879
Dittmarite	$(NH_4)MgPO_4 \cdot H_2O$	Victoria	MacIvor	1887
Schertelite	$(NH_4)_2MgH_2(PO_4)_2 \cdot 4H_2O$	Victoria	(MacIvor)	1906
syn: schertalite (MacIvor, 1902), muellerite (MacIvor, 1887)				
Marshite	CuI	New South Wales	Liversidge/March	1892
Dundasite	$PbAl_2(CO_3)_2(OH)_4 \cdot H_2O$	Tasmania	Petterd	1892
Stibiotantalite	$SbTaO_4$	Western Australia	Goyder	1893
Willyamite	(Co,Ni)SbS	New South Wales	Pittman	1893
Heazlewoodite	Ni_3S_2	Tasmania	Petterd	1896
Raspite	$PbWO_4$	New South Wales	Hlawatsch	1897
Miersite	(Ag,Cu)I	New South Wales	Spencer	1898
Sulvanite	Cu_3VS_4	South Australia	Goyder	1900

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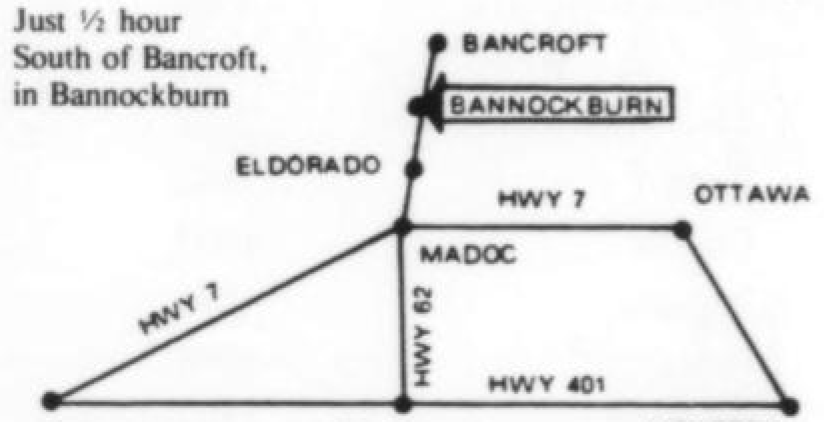

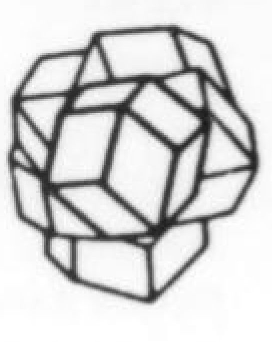

EARLY AMERICAN INTEREST
in
AUSTRALIAN MINERALS

●

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To early explorers and naturalists, Australia was like an enormous living museum inhabited by wondrous plants and animals that challenged the imagination. It was a vast treasure house that provided an incredibly rich field for discovery, and it almost seemed that everyone who stepped ashore there in the early years immediately found something new and curious in the realm of flora and fauna. But what of its minerals? Surely a land so richly blessed by nature would produce an abundance of minerals as well.

Today, writing two hundred years after the founding of the first European colony there, we know that Australia truly is a land of interesting minerals. But the mineralogical treasures of the remote continent were not to be revealed as quickly nor as easily as the biological. Mineral discoveries were scanty in the early years of the Australian colonies. And in America, a still-young country very much concerned with discovering its *own* minerals, information about the minerals of Australia arrived slowly and sporadically. The development of American knowledge of Australian mineralogy, and the addition of Australian specimens to American collections, was a slow process, one which could not even be hastened by the visit to that far-away land by a young man destined to become America's most eminent mineralogist.

First Specimens

Exactly when the first specimens of Australian minerals found their way to America remains an interesting though, as yet, unanswered question for the historian of mineralogy. Perhaps the answer lies in an early mineral catalog (Anonymous, 1829) now in the possession of Richard Hauck, which suggests that a collection containing specimens of "blue and colorless topaz" from "New Holland"[1] was being offered for sale in America as early as 1829, forty-one years after the 11 ships of the First Fleet had landed at Sydney Cove, signaling the beginnings of European settlement in Australia.

While it would be impossible to say with any degree of certainty whether these topazes were in fact the first specimens to reach America from Australia, there is no doubt that the occurrence of topaz was among the earliest information which the pioneering generation of American mineralogists had about the little-known continent. As early as 1814, readers of *The American Mineralogical Journal*, America's first periodical devoted exclusively to mineralogy and geology, would have known that topaz occurred in Australia through Robert Jameson's paper "On the topaz of Scotland," which was reprinted from the *Memoirs of the Wernerian Natural History Society* of Edinburgh. In reviewing the few topaz localities known throughout the world at the time, Jameson mentioned specimens he had acquired from "Hawkesbury River in New Holland" and "Cape Barren Island in Basses Straits"[2] (Jameson, 1814). By the time the first American topazes were found about 12 years later, the noted Yale scientist Benjamin Silliman was sufficiently familiar with the occurrence of topaz in Australia to be able to say of the newly discovered American specimens: ". . . more generally this topaz is nearly or quite colorless, like the topazes of New Holland . . ." (Silliman, 1826).

Further information on the existence of topaz in the southern continent arrived in America in 1827, this time in a remarkable paper published in Silliman's *American Journal of Science*. Having appeared earlier in the *Transactions of the Royal Society of Edinburgh*, it was written by the distinguished Scottish physicist Sir David Brewster,

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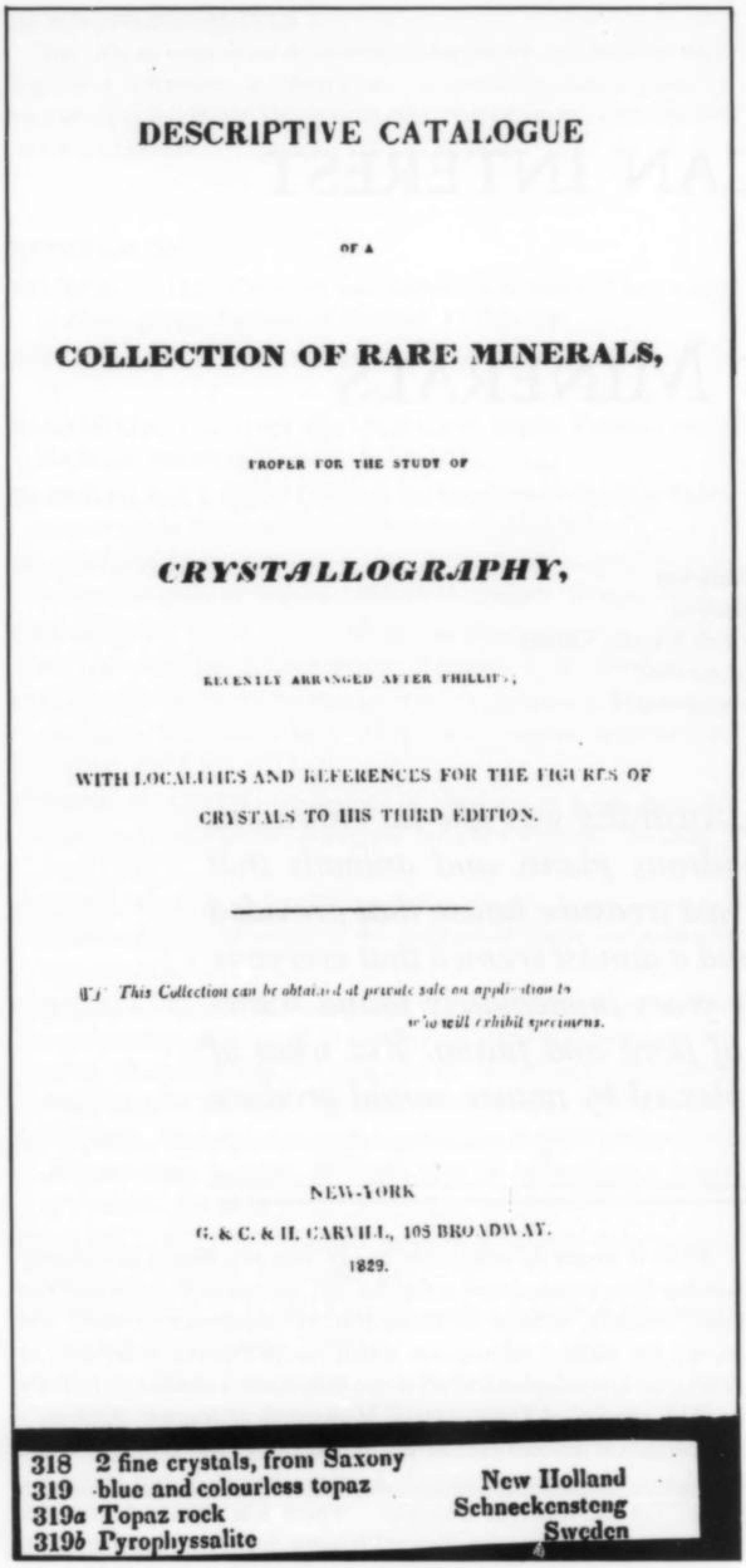
[1] New Holland was an early name for Australia.

[2] Bass Strait separates Tasmania from mainland Australia.



DESCRIPTIVE CATALOGUE

OF A

COLLECTION OF RARE MINERALS,

PROPER FOR THE STUDY OF

CRYSTALLOGRAPHY,

RECENTLY ARRANGED AFTER PHILLIPS;

WITH LOCALITIES AND REFERENCES FOR THE FIGURES OF
CRYSTALS TO HIS THIRD EDITION.

☞ *This Collection can be obtained at private sale on application to*
who will exhibit specimens.

NEW-YORK
G. & C. & H. CARVILL, 108 BROADWAY.
1829.

318	2 fine crystals, from Saxony	
319	blue and colourless topaz	New Holland
319a	Topaz rock	Schneckensteng
319b	Pyrophyssalite	Sweden

***Figure 1.* This little-known catalog describes a collection containing some of the earliest Australian specimens to reach America. Richard Hauck collection.**

and was entitled "On the existence of two new fluids in the cavities of minerals, which are immiscible, and possess remarkable physical properties" (Brewster, 1827). Brewster had been conducting some of the earliest scientific studies on the nature of fluid inclusions in minerals (Smith, 1953), and specimens of New Holland topaz had contributed much to his pioneering efforts. With his superb drawings of various inclusions, his paper must have captured the attention of many American readers.

Aside from topaz, however, news of other discoveries was slow to arrive. Thus, it is not surprising that little information on Australian occurrences was to be found in the first generation of important mineralogical works produced in America. Parker Cleaveland's *Elementary Treatise on Mineralogy and Geology* (1822) listed no Australian localities among its species descriptions. The 1835 edition of Charles Upham Shepard's *Treatise on Mineralogy* included only topaz, and when the first edition of James Dwight Dana's *System of Mineralogy* appeared in 1837, it listed only coal. By 1838, a year in which residents of Sydney celebrated the 50th anniversary of the founding of the first European settlement in Australia, a resident of America seeking specimens, or simply information about the minerals of the vast southern continent, would have found little reward for his efforts. However, two young Americans, one destined for lasting fame, the other largely to be forgotten, were about to turn their attention, if only briefly, to Australia, thus adding the first strictly American contributions to the knowledge of the continent which would in years to come produce so much to excite the mineral enthusiast.

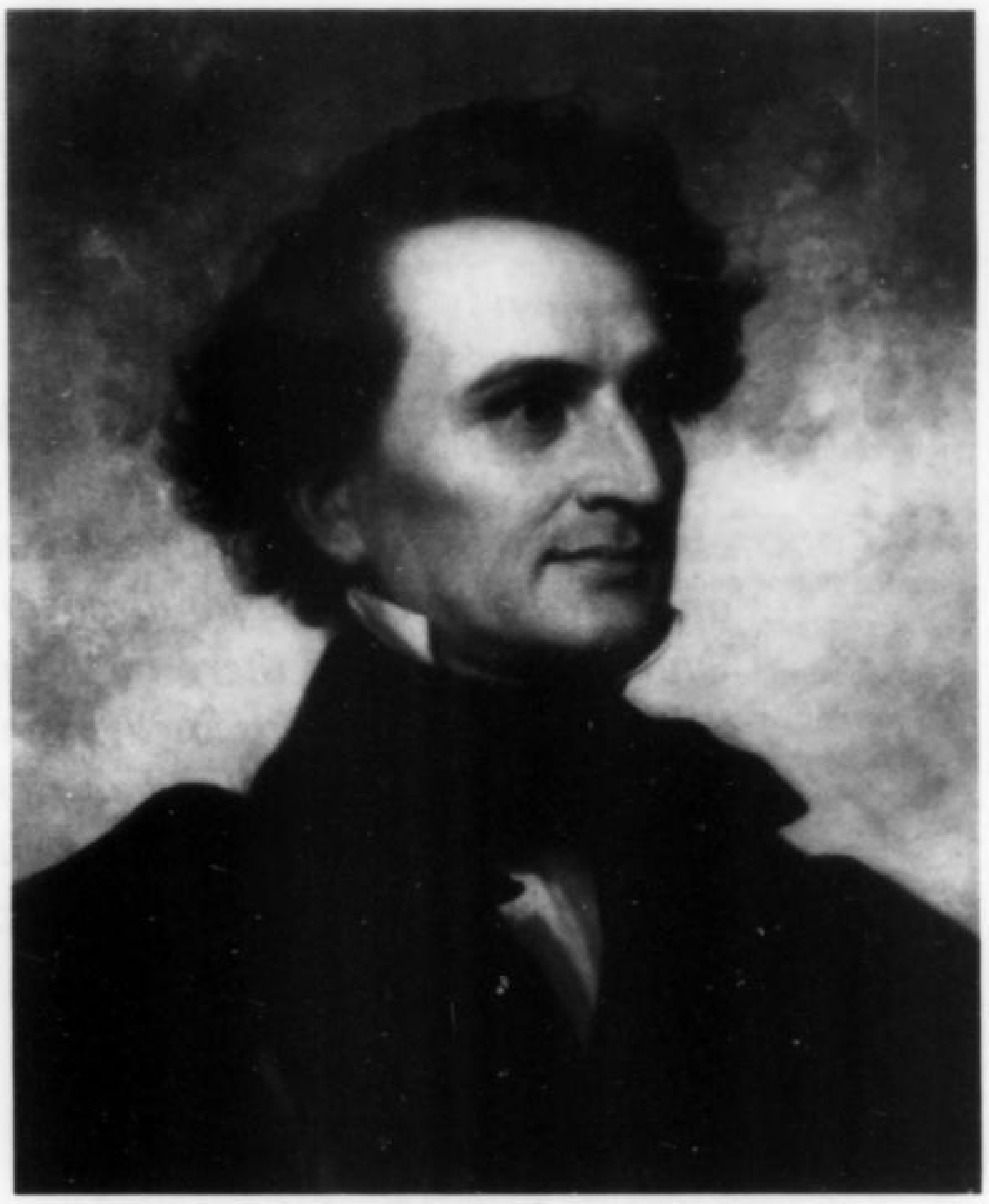


***Figure 2.* James Dwight Dana (1813–1895), from a painting by Daniel Huntington. Courtesy Yale University Art Gallery; bequest of Edward Salisbury Dana, B.A. 1870.**

The Arrival of Dana

The American sailing ships *Vincennes* and *Peacock* had been at sea for well over a year by the time they arrived at Sydney Cove in the British colony of New South Wales on the evening of November 29, 1839. They were part of the small fleet of ships which comprised the U.S. Exploring Expedition of 1838–1842, under the command of Lt. Charles Wilkes. Having departed Norfolk, Virginia, in August of 1838, the fleet was into the second year of a four-year voyage during which they would sail more than 87,000 miles. Before returning to New York harbor in June, 1842, they would chart hundreds of little-known Pacific islands, map over 800 miles of the coast of the Oregon territory in America's northwest, and explore more than 1500 miles of the coast of Antarctica, thus confirming the existence of that continent. The need to properly house the thousands of scientific specimens collected during the voyage would eventually contribute to the

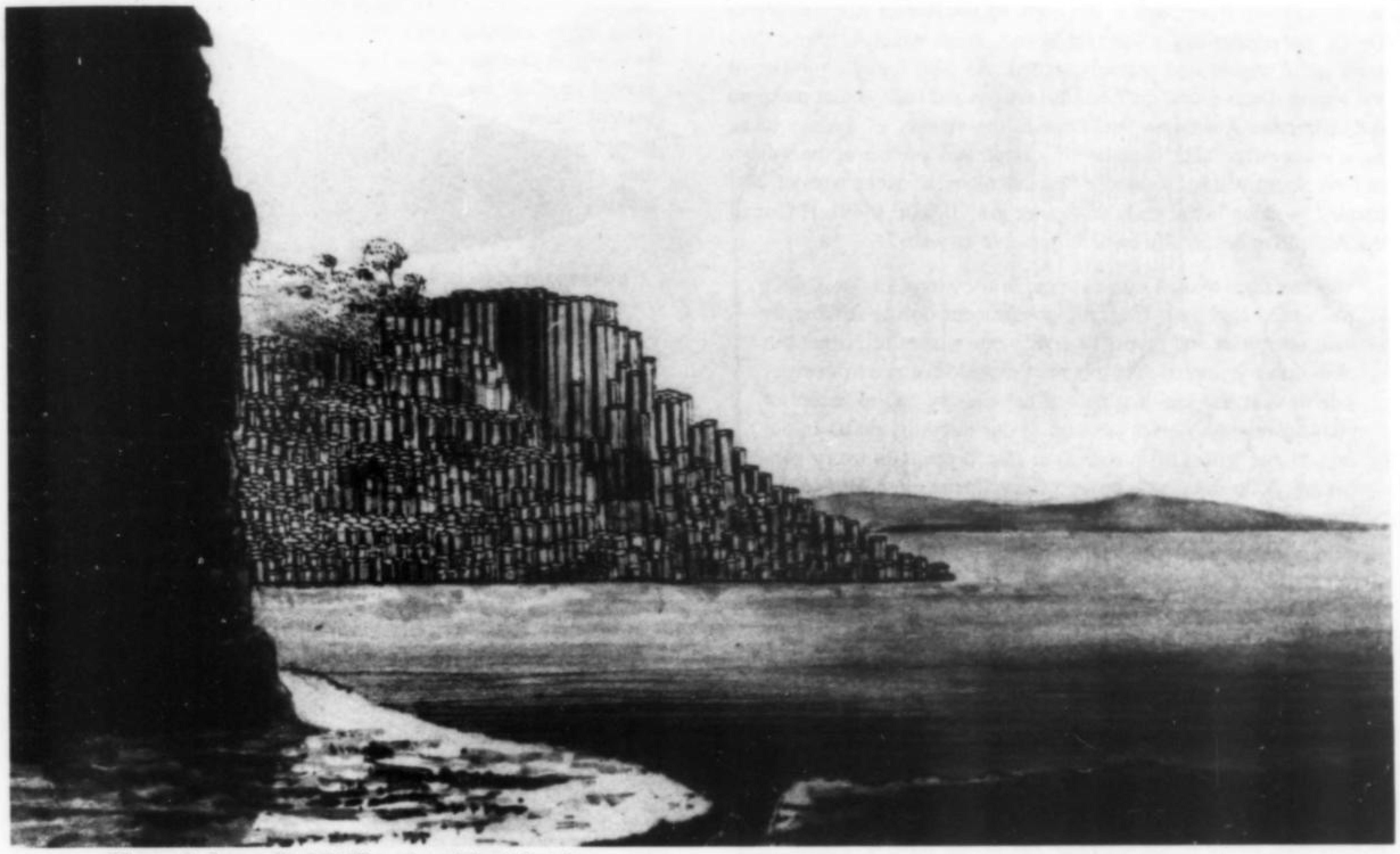
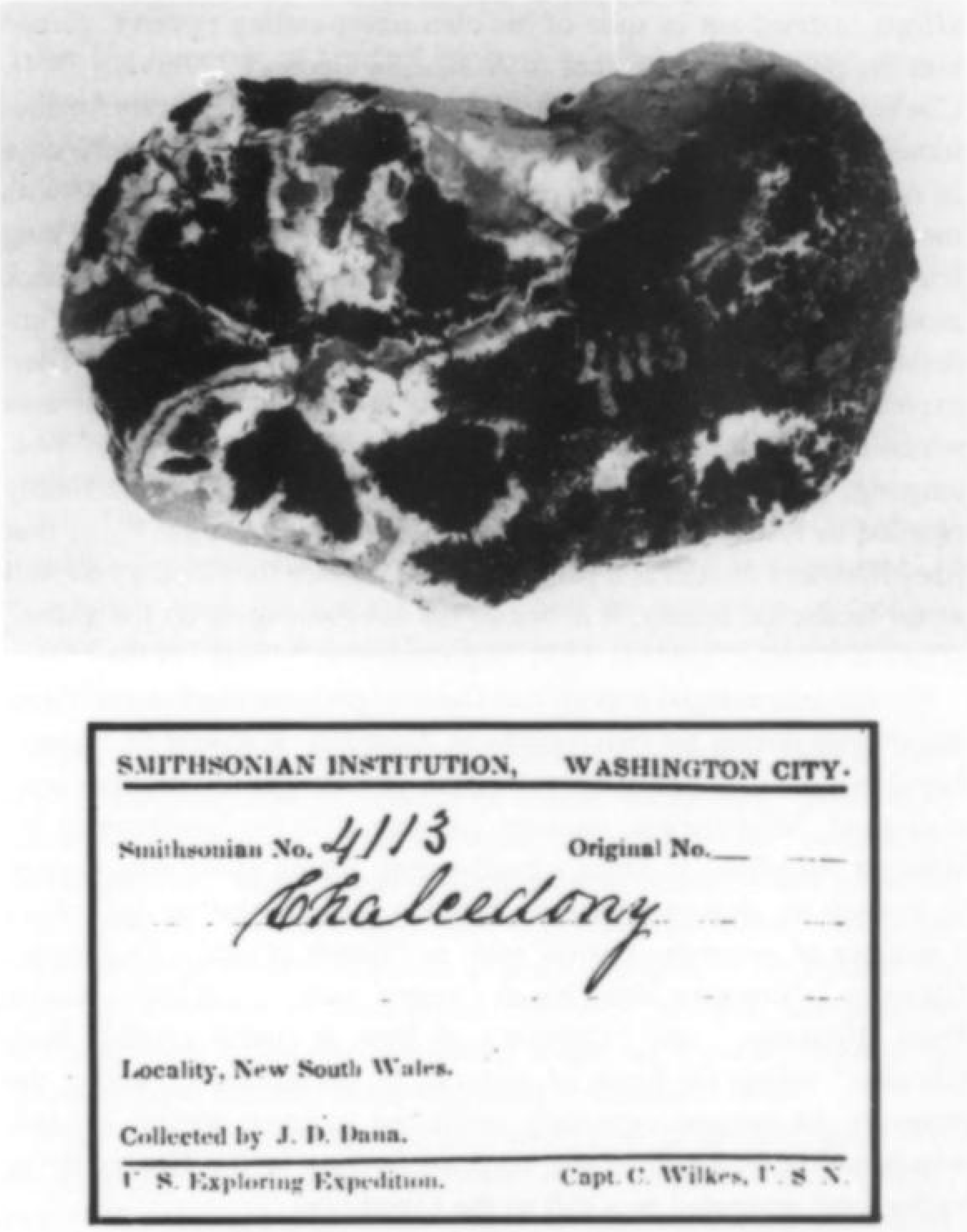


***Figure 3.* James Dwight Dana's original sketch of basalt columns near Kiama, in the Illawarra district of New South Wales. Courtesy Sterling Memorial Library, Yale University.**

rise of the Smithsonian Institution as America's National Museum. Although little known today,[3] the Expedition was one of the great events in the history of American science, due largely to the collecting, research and subsequent publications of the nine civilian scientists and artists who accompanied the full complement of naval officers and crewmen. Among the scientific corps was a young man who would become a legendary figure in the history of American mineralogy. His name was James Dwight Dana.

Dana was only 26 years old when he stepped ashore at Sydney on the morning of November 30, 1839; however, his scientific reputation was already established. After graduating from Yale University six years earlier, he had spent 16 months at sea as a teacher of mathematics to midshipmen in the U.S. Navy, and while cruising in the Mediterranean region he had climbed Mount Vesuvius, a vivid description of which he published in the *American Journal of Science* (Dana, 1835) as his first contribution to the scientific literature. By 1837, at the age of only 24, he had published the first edition of his *System of Mineralogy*, which was highly acclaimed not only in America but in Europe as well. Now, as geologist to the heralded Exploring Expedition, he was in the midst of the great adventure of his youth, a four-year voyage of exploration and discovery which would give him a competence in natural history comparable to that of Charles Darwin (who benefitted immeasurably from his travels on the *Beagle*) (Stanton, 1971).

Dana and most of the other expedition scientists remained in New South Wales for two months while the majority of the fleet sailed away to the south in search of Antarctica. Dana devoted his time to geology—examining outcrops, collecting specimens and preparing sketches and maps. His travels took him to the south of Sydney through the Illawarra district and Kangaroo Valley to Mount Coolangatta on



SMITHSONIAN INSTITUTION, WASHINGTON CITY.

Smithsonian No. 4113 Original No.

Chalcedony

Locality, New South Wales.

Collected by J. D. Dana.

U. S. Exploring Expedition. Capt. C. Wilkes, U. S. N.

***Figure 4.* Specimen collected by James Dwight Dana in New South Wales while with the U.S. Exploring Expedition. National Museum of Natural History collection; photo by Vic Krantz.**

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[3] See Viola and Margolis (1985) for the full story of this fascinating event.

the Shoalhaven River, and to the north up the Hunter River valley as far as the present-day village of Scone, areas which in those days were quite remote and sparsely settled. As with today's traveler to the region, Dana found the beautiful ranges and valleys that make up the distinctive Australian landscape in the vicinity of Sydney to be most impressive. "The great depth, extent, and number of the valleys of New South Wales," he wrote "are calculated to excite wonder, and perplex us much in the study of their origin" (Dana, 1849). He found the Australian hospitality to be impressive as well:

> We have been treated with extreme courtesy and kindness since we landed here, all, from the government down, striving by their attentions and favors to gratify our wishes or further our objects in our several departments. Invitations come from every side to visit this and that part of the country and to accept of their hospitality; horses are sent to our doors to aid us in our excursions; letters of introduction forced on us to every gentleman along our way—boxes of specimens often offered us. Indeed, we have found open doors and open hearts everywhere. (Dana to E. C. Herrick, dated 28 January 1840, Maitland, New South Wales, quoted in Gilman, 1899)

Among those residents of the Sydney area who took a special interest in the arrival of the American expedition was the Rev. William Branwhite Clarke (1798–1878), who himself had only recently arrived in the colony. While preparing for the clergy at Cambridge University in his native England, he had been privileged to study geology with the renowned Adam Sedgwick, among the most influential of British geologists. Clarke became the first professionally trained geologist to settle permanently in Australia, and for nearly 40 years he would be an important figure in the scientific life of the country, contributing much to the early knowledge of Australian geology. His diligent efforts, carried out in spite of his own never-ending poverty, earned him the popular title "Father of Australian Geology" (Jervis, 1944). Clarke's diary, now preserved in Sydney's Mitchell Library, meticulously records many of the events in his life during his early days in Australia, including his meeting and subsequent explorations with the young American visitor James Dana, who became his life-long friend. The diary contains a fine account of their travels on horseback around the New South Wales countryside as they attempted to understand the mysteries of the geology of the strange new land. Their exploration of the Illawarra district, a spectacularly beautiful area which lies to the south of Sydney near the modern-day city of Wollongong, is especially well-recorded. It is an area that Dana fondly recalled in later years in his correspondence with Clarke: ". . . that [the] Illawarra district is a perfect gem of a place for Geology as well as for landscape beauty; it is one of the loveliest spots on the globe" (Dana to Clarke, Sept. 1, 1851, reproduced in Moyal, 1976).

For the mineralogist hoping that Dana might have made some major discoveries during his two months in Australia, it should be remembered that his interests there were more broadly geological than mineralogical. Nevertheless, catalogs (preserved in the Smithsonian Institution Archives) in Dana's handwriting listing specimens packed in Sydney for shipment back to America indicate that he did collect a number of minerals. Entries such as "quartz crystal—Keelhogue, Illawarra," "compact black basalt covered with . . . stilbite—Kiama Point, Illawarra," and "carbonate of lime in coarse crystals from Glendon" reflect the kinds of minerals he encountered. Among the minerals, he became especially interested in some curious crystals which had been found to the north of Sydney in the Hunter River valley, and presented as a gift to the expedition.

> Various specimens of remarkable prismatic forms of lime were presented to us by Mrs. Robert Scott of Glendon . . . Some of the crystals are twenty inches long; three or four inches is the average size. They have a rhombic form, and taper towards each extremity, the two ends curving slightly in opposite directions. Stars of four and six rays, and also globular masses, bristled on all sides with the ends of prisms, are common among them. They have a very rough, brownish exterior, like a fragment of sandstone; and within, instead of the regular cleavage structure of a proper crystal, the texture is crystalline granular. (Dana, 1849)

***Figure 5.* Glendonite from Scott's Flat, near Glendon, New South Wales. Los Angeles County Museum collection, gift of Brian England; photo by the author.**

Dana was referring to the interesting pseudomorphs which eventually came to be known as "glendonites" (see England, 1976, for a review). Little-known today among mineral collectors, these intriguing crystals are now thought to be calcite pseudomorphs after ikaite ($CaCO_3{\cdot}6H_2O$), a rare mineral which forms only at temperatures less than about 5°C (Shearman and Smith, 1985). Almost 150 years after Dana studied them, glendonites are now attracting renewed scientific interest because of their potential use as indicators of paleo-environment, since their presence in a sedimentary rock is indicative of very cold temperatures at the time of formation. Strangely, even though Dana's attention was obviously drawn to these curious crystals, he seems to have largely forgotten them in later years; in the subsequent editions of his *System of Mineralogy* their occurrence in Australia was not mentioned.

Dana later wrote of his explorations in Australia: "As the time spent in these investigations was short—about two months—we can gratify but partially, in a geologic point of view, the curiosity which so strange a land may well excite . . ." (Dana, 1849). Yet, in a short time he had accomplished much. The results of his investigations, including his description of the glendonites, was published as "Geological Observations on New South Wales," a major chapter in his massive report (now exceedingly rare!) on the *Geology* of the Exploring Expedition (Dana, 1849). His work formed one of the most important early contributions to the knowledge of Australian geology, and while he had found little that would excite today's mineral enthusiast, his description of the curious glendonites did constitute one of the earliest contributions by an American to Australian mineralogy.

In the years to come, generations of Dana's students, as well as the countless readers of his many textbooks and scientific papers, would share in the rich harvest of knowledge which he gained in Australia and the other distant lands visited during the four years of the expedition. Though he never returned to Australia, he maintained a correspondence with the Rev. Clarke, their letters frequently recalling their enjoyable travels together. Years later, in 1882, the Royal Society of New South Wales awarded Dana its Clarke Medal (named in honor of the Rev. Clarke) "in recognition of his eminent work as a naturalist, and especially in reference to his geological and other labors in Australia, when with the United States Exploring Expedition round the world in 1839."

Francis Alger

Within a few months of Dana's departure from Australia, another young mineralogist was describing a collection of Australian specimens recently brought to America.

In the annals of science, Francis Alger (1807–1863) remains an appealing though little-known figure. He was a member of the early generation of workers whose efforts led to the rise and progress of mineralogy in America. Unlike Dana, however, he has been largely neglected by historians. While a full review of Alger's career is beyond the scope of this article,[4] a summary is presented here for the benefit of those unfamiliar with this nearly forgotten figure. We begin with the words of his long-time friend, Dr. C. T. Jackson, who describes the origins of Alger's mineralogical interests.

> Francis in youth was not studious, and had only a common school education. His taste for study commenced in 1824, when his attention was first drawn to the science of Mineralogy. . . . In 1826, his father made a trip to Nova Scotia for the purpose of creating a furnace for smelting iron ores at Clements, on the Annapolis basin. He took Francis with him, and there the young mineralogist began his field labors by collecting such minerals as occur in the iron ores of Digby Neck and in the trap rocks of Grenville. He brought home a small collection of zeolites, amethyst, quartz, and agates, of which he published a list in the *Boston Journal of Philosophy and the Arts*." (Jackson, 1866)

The specimens collected by the 19-year-old Alger were perhaps the first minerals from Nova Scotia to be brought to the United States. He made several subsequent trips there along with his friend Jackson, their efforts resulting in the collecting of a number of fine specimens which were freely distributed to collections in America and abroad. Their published works on Nova Scotia mineralogy and geology, together with their active distribution of specimens from there, served to bring to light a significant amount of new information on the mineral occurrences of an area about which little had been previously known. As we shall see, Alger's efforts would have a similar effect with regard to Australia.

In later years, Alger would become very interested in the mines of the Franklin, New Jersey, area, would become part-owner of some of the mining properties there (Palache, 1935), and would be instrumental in disseminating to the scientific community specimens and information about the rare and unique mineral occurrences of that now-famous locality. His long-time interest in the minerals of America's New England region would lead him to a legendary association with the enormous beryl crystals found at Beryl Hill near Grafton, New Hampshire. "Finding that he could not extract and bring home to his cabinet a large beryl of five tons weight . . . he purchased the hill, had the crystal uncovered of rock, and considered it as in his cabinet and one of his specimens" (Jackson, 1866). Alger produced a dozen or so scientific papers on mineralogical subjects during his career, some of which, such as his classic "Crystallized gold from California" (Alger, 1850), still make excellent reading today. His most important published work, however, was the preparation of a fifth edition of William Phillips's *Elementary Treatise on Mineralogy* (Alger, 1844). In its earlier editions this work had been extremely popular abroad, and Alger decided to adapt it to the needs of American students by the addition of extensive information pertinent to American minerals. The resulting work was enlarged by nearly 300 pages, and while Alger had intended it for schools and for beginners to the subject, it became widely accepted by professionals as well because of its wealth of information on American localities.

Much more could be written about Alger's activities, but it is his contribution to our knowledge of Australian minerals which is of interest here.

On the evening of June 4, 1840 (Dana was in the Fiji Islands on that day, still with the Exploring Expedition), Alger was reading a paper entitled "Notice of minerals from New Holland" to members of the Boston Society of Natural History, one of the early scientific societies organized for the promotion of natural history in America.

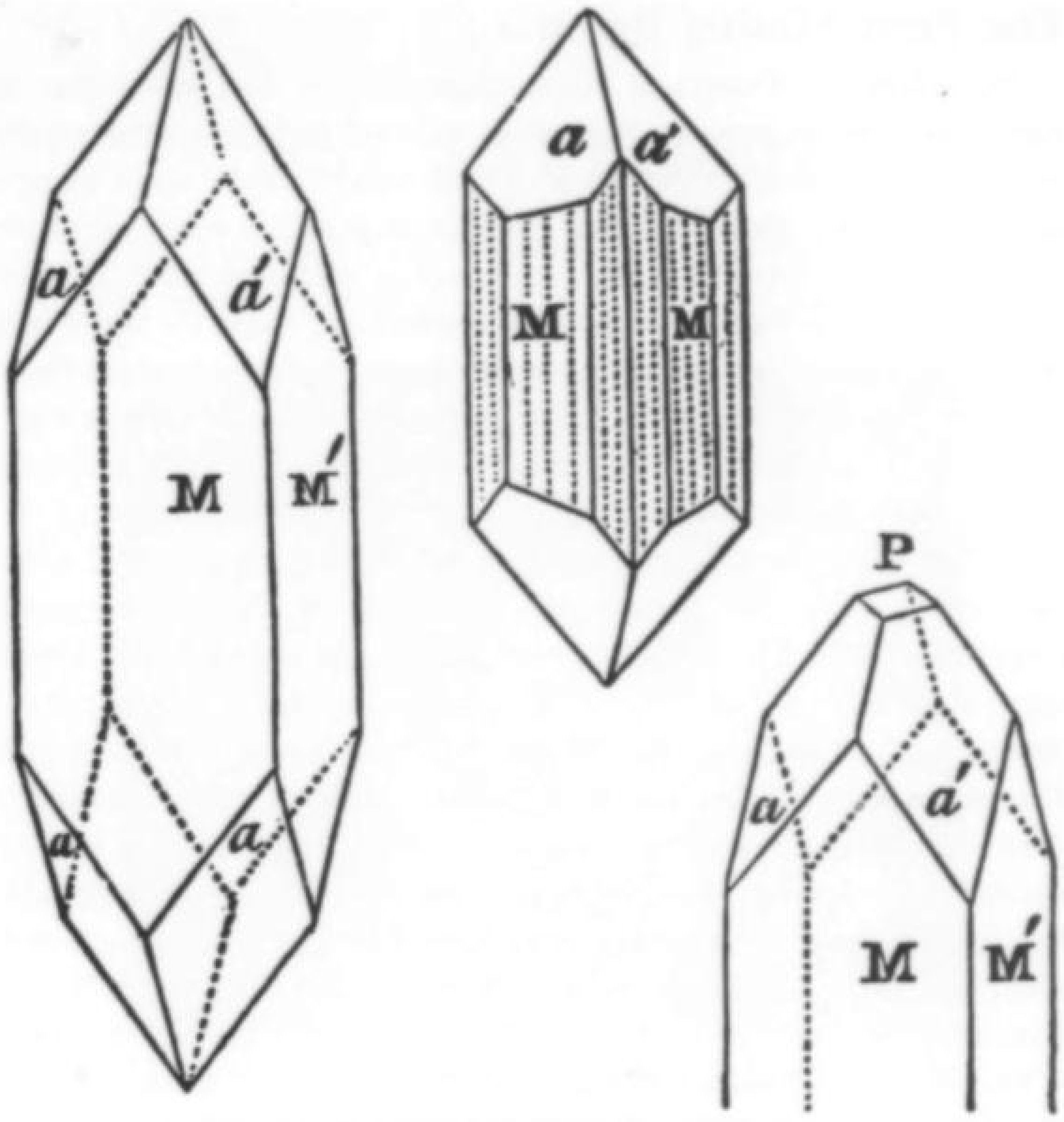

***Figure 6.* Apophyllite crystals from Australia, as illustrated in Francis Alger's "Notice of Minerals from New Holland."**

> For the minerals of which I propose to offer a brief notice on the present occasion, I am indebted to John Eldridge, Esq., of Yarmouth, Mass., who very liberally permitted me to select them from a collection purchased by him several years since, while on a visit to Calcutta, to which city they had recently been brought, as "curiosities," by a person from the coast of New Holland. Their exact locality it is not in the power of Mr. Eldridge to give me; a circumstance to be regretted, as the information would give additional interest to the specimens, by directing future discoverers to the spot where others of still greater interest might probably be met with . . .
> . . . They are, I believe, the first and only collection of minerals which has been brought to this country from New Holland; and certainly their uncommon beauty, and the perfection of their crystalline forms, demand for them some public record. (Alger, 1840)

Alger proceeded to describe specimens of apophyllite, stilbite, heulandite, natrolite, various crystals of quartz, along with "green chalcedony and heliotrope," "ribbon agate and moss agate," cacholong, "chlorophoeite," and an unidentified mineral which he felt might be a new species, all associated with amygdaloidal basalt. Using the scanty information on Australian geology available in America at the time, he attempted to determine, with little success, the possible localities from which the specimens might have come. Sources in Tasmania have recently been suggested (Vallance, 1986).

Alger said of Australia: "Less is known of its mineralogical productions than of any other department of its natural history" (Alger, 1840). Yet through this single paper he had succeeded in making known, just as he had done with Nova Scotia, some of the earliest information to arrive in America regarding the minerals of an area about which little had been known. With their fine crystal drawings, his were among the earliest detailed descriptions of Australian minerals to be produced (Vallance, 1986).

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[4] A separate article on the life of Alger is in preparation by this author.

The First Mining Boom

The efforts of Dana and Alger represent the first generation of American contributions to Australian mineralogy. Given the wealth of information which exists today, their results might seem meager and insignificant. However, their work came at a time when very little in the way of interesting mineral discoveries had been made in Australia. The simple fact was that the overwhelming majority of the map of "New Holland" was utterly blank. Perhaps 5% of the vast continent had been explored, and of that area only a fraction had been settled. And much of the area that had been settled, particularly that around Sydney, was dominated by relatively young sedimentary rocks, virtually barren for the mineralogist. Out on the desert plains 600 miles west of Sydney lay the "broken stony hills" (Sturt, 1849) where many years in the future Charles Rasp, a boundary rider on the Mount Gipps sheep station, would discover what was to become Australia's most famous mineral locality. But the site we know today as Broken Hill was, at the time of Dana's visit to Sydney, well within the enormous blank that filled most of the map of Australia. Isolated and unseen (except by the Aborigines), it was separated from the nearest settlement both by the desert in the midst of which it lay, and by distance, that uniquely Australian characteristic which had such a strong influence in molding the country's history (see Blainey, 1983). The development of the mineral deposits for which Australia is justly famous today would have to await further exploration and the subsequent spread of settlement to new areas more geologically favorable for the discovery of valuable mineral deposits. It wouldn't be very long, however, before that happened.

It was only a year after Dana departed Australia that events near Adelaide in the newly settled colony of South Australia, a thousand miles by sea from Sydney, would signal a change in the situation. That part of the continent had been blessed with rich ore deposits, many of which lay close to the sea near areas which were to be quickly settled, and among the early settlers in the new colony were Cornish miners who knew enough about minerals to recognize important ores when they saw them. It is not surprising then that minerals were discovered in South Australia not long after that colony was founded. Australia's distinguished historian Geoffrey Blainey, whose superb work *The Rush That Never Ended* is essential reading for anyone interested in the history of Australian mining, describes that first discovery:

> In Adelaide at the start of 1841 the people who sat on the shaded sides of their houses on summer evenings may have seen smoke rising to the east. On a steep hill only four miles from Adelaide smoke from burning grass signaled the birth of Australian metal mining. Two Cornish miners, "persons in the humbler walks of life," found a lode of rich galena jutting above dry grass, and set fire to the grasses to expose the hidden outcrops. (Blainey, 1978)

Such was the origin of the Wheal Gawler, Australia's first metal-producing mine. Within a few years, the discovery of rich copper ore at Kapunda, 40 miles to the north of Adelaide, resulted in the opening of Australia's first copper mine in 1844. By June of 1845, a little more than five years after Dana had visited Australia, a shepherd named Streair walked into Adelaide with impressive specimens of copper ore from an isolated site in the wilderness a hundred miles to the north, a location that would become well-known in the mineralogical world as the site of the Burra Burra mine, perhaps Australia's first great specimen-producing locality.

The fame of South Australia's rich and valuable mines spread quickly throughout Australia, stimulating resident interest in the search for minerals, and leading to the discovery of deposits in other parts of the country. With the 1851 discovery of gold near Bathurst, New South Wales, across the Blue Mountains from Sydney, the great period in the development of Australia's mineral wealth had begun. In the years to come, specimens from remote places like Burra Burra and Wallaroo would find their way into the finest collections throughout the world and would form the basis for an increasing number of published scientific studies. Surely no one could ever again say of Australia, as had the Polish explorer/geologist Paul Edmund de Strzelecki, who arrived in New South Wales in the same year as Dana: "the scarcity of simple minerals was such as might have discouraged the most ardent and persevering mineralogist who ever devoted himself to the science" (Strzelecki, 1845).

***Figure 7.* An early Australian specimen in the collection of the Academy of Natural Sciences of Philadelphia. Photo by the author.**

It seems, however, that specimens from Australia's new-found mines were slow to arrive in America. The Academy of Natural Sciences of Philadelphia, founded in 1812, had been perhaps the most active American institution in developing a mineral collection. But a catalog compiled in 1868 indicates that only 14 Australian specimens were in the collection by that time, with those being limited to asbestos, opal, semi-opal, wood opal, pyrite, "micaceous iron" (hematite), and malachite. Other prominent collections, such as those at Harvard and Yale Universities, also record the addition of early Australian specimens as discoveries were made. But it wasn't until the great period of collection building began in America that museums and private collections saw the addition of the kind of extraordinary specimens for which we know Australia so well today.

Dealers and Collectors

The latter third of the 19th century was a period of rapid growth in the popularization of mineralogy in America. It was a time which saw the birth of the first organizations for mineral enthusiasts, with the New York Mineralogical Club being founded in 1886, and the Philadelphia Mineralogical Society following in 1892. Early journals for mineral collectors also appeared, such as the *Exchanger's Monthly* in 1885 (subsequently changed to *Mineralogist's Monthly*), followed by *Goldthwaite's Monthly* in 1892, with both of these publications merging into the *Mineral Collector* in 1894. More importantly, however, it was the beginning of a remarkable period which saw the development of the most important private mineral collections ever assembled in America. A number of collections as notable for size as for their quality were assembled, each of which could have filled a museum. While specimens in earlier generations of American collections had been largely utilitarian in nature, these collections were notable for their emphasis on aesthetics.

Perhaps the earliest of the group was William S. Vaux (1811–1882) of Philadelphia, who had acquired an interest in minerals early in life. By the time of his death in 1882, his collection numbered some 6000 specimens and was the finest in America. It was donated to the Academy of Natural Sciences of Philadelphia, the institution with which Vaux had long maintained a close association. With the addition of Vaux's collection, the Academy acquired a number of additional Australian specimens, but his collection was clearly not as rich in Australian minerals as those collections assembled later, considering that such notable localities as Broken Hill were not found until after his death.

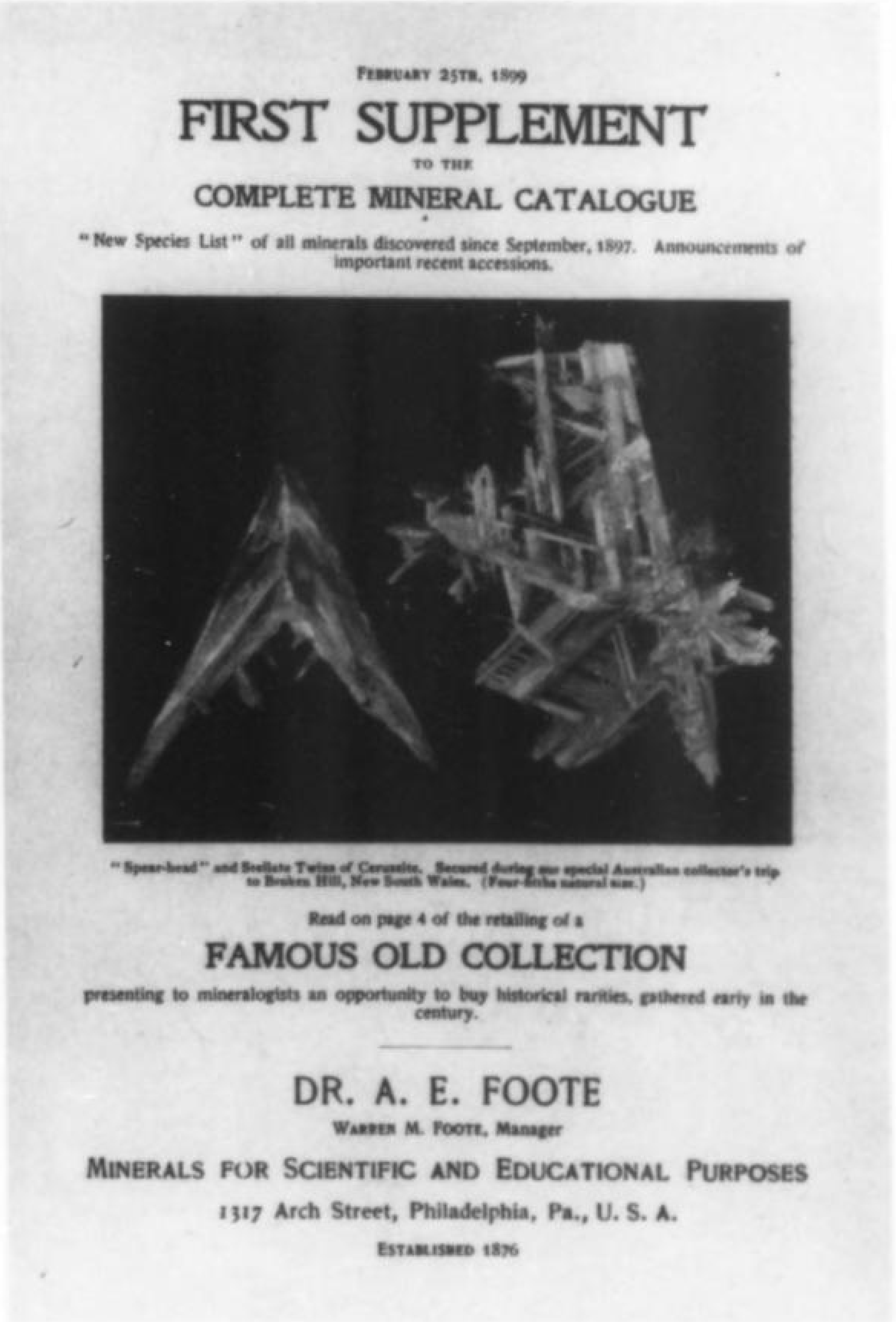
In later years, the tradition would be carried on by such individuals as W. W. Jefferis (1820–1906), also from Philadelphia, who assembled a collection containing 12,000 specimens later acquired by the Carnegie Institute in Pittsburgh. Another Philadelphian, Clarence Bement (1843–1923), also amassed 12,000 specimens, surpassing both Vaux and Jefferis (and virtually everyone else!) in quality. As we will see later, his collection, subsequently acquired by the American Museum of Natural History, was especially rich in Australian minerals. Among the other prominent collectors were Frederick Canfield, Jr. (1849–1926), whose 9000 specimens, along with the 16,000 specimens of Washington Roebling (1837–1926), were acquired by the Smithsonian Institution in a single year. Harvard University was the recipient of the 6000 specimens which comprised the collection of A. F. Holden (1867–1913), and Bryn Mawr College received the 10,000 specimens assembled by George Vaux, Jr. (1863–1927). The rise of this group of wealthy collectors (and there were others not mentioned above), willing to spare neither expense nor effort in obtaining the finest specimens available, was a major factor contributing to the arrival in America of many extraordinary specimens from Australia and the rest of the world.

This period also saw the appearance of a new generation of specimen dealers to supply the needs of the increasing numbers of collectors. Individuals like Henry Ward and George English are still well known today for their role in distributing fine specimens to museums and private collectors. It was another figure, however, who would emerge from the 1876 Centennial Exposition in Philadelphia to play perhaps the leading role in bringing fine Australian specimens to America.

Dr. Albert E. Foote (1846–1895) had become interested in minerals at an early age. He received an M.D. degree from the University of Michigan but remained an ardent collector of not only minerals but other natural history specimens as well. A former employee, Charles Toothaker, wrote:

> He came to the Centennial Exposition in Philadelphia in 1876 and made a handsome exhibit of splendid minerals. He rented a cheap building on North Forty-Fourth Street just outside the Exposition grounds and stored there a lot of material for which there was no room in his exhibit. Visitors, especially teachers of chemistry and mineralogy, saw his display and wanted to purchase specimens. He took them to his little shop outside the Fair Grounds and soon, to his surprise, he found himself running a business . . . He stayed in Philadelphia and I went to work for him in July, 1890. By that time he was known to all the great mineralogical museums of the world and to all the important private collectors. I became acquainted with his customers—Clarence S. Bement, George Vaux, Jr., W. W. Jefferis, Colonel Washington A. Roebling and others . . . . (Toothaker, 1951)

In assessing the impact of Foote's activities, the legendary George F. Kunz wrote: "In the twenty-eight or thirty years of his collecting, he has placed in the cabinets of the world several millions of specimens, besides many thousands of small cabinets in which the specimens were sold as low as one hundred for a dollar. The impulse given and the facilities afforded both to beginners and to advanced collectors by this vast amount of distribution are beyond calculation in their influence on the development of this branch of study" (Kunz, 1895).


February 25th, 1899

FIRST SUPPLEMENT

TO THE

COMPLETE MINERAL CATALOGUE

"New Species List" of all minerals discovered since September, 1897. Announcements of important recent accessions.

"Spear-head" and Stellate Twins of Cerussite. Secured during our special Australian collector's trip to Broken Hill, New South Wales. (Four-fifths natural size.)

Read on page 4 of the retailing of a

FAMOUS OLD COLLECTION

presenting to mineralogists an opportunity to buy historical rarities, gathered early in the century.

DR. A. E. FOOTE

Warren M. Foote, Manager

Minerals for Scientific and Educational Purposes

1317 Arch Street, Philadelphia, Pa., U. S. A.

Established 1876

***Figure 8.* Cover illustration from one of the many catalogs issued by the Foote Mineral Company. Richard Hauck collection.**

Although Foote died in 1895, the business he had begun was carried on for several years by his son, Warren M. Foote. The various editions of the Foote catalogs, which still make excellent reading for even today's mineral enthusiast, tell us that by 1897 the company had retained the services of "an Australian mineralogist[5] who is collecting as our exclusive agent. He has not only a scientific appreciation of minerals, but likewise the collector's instinct, which knows and gets a good specimen. Localities are visited expressly in our interest; collections are purchased, and everything, including the very best, is at once shipped to us." The company could soon boast that they were "not only the first to place a large choice of these minerals before American and European museums, but we have from season to season, for eight years, augmented our stock with the results of oft-repeated trips to the principal localities. In one instance more than a year was spent at one mine. The combined stocks of all other dealers do not approach our series of Australian minerals." The catalogs tell of remarkable stolzite, raspite, cerussite, anglesite, embolite, azurite, pyromorphite, etc., from Broken Hill; malachite and atacamite from South Australia; opal from White Cliffs in New South Wales and the Bulla Creek district in Queensland; vivianite from the Falls of the Wannon River in Victoria; stibiotantalite from Western Australia; chabazite, phillipsite, gmelinite, mesolite, analcime, etc., from Victoria; axinite from the Roseberry district, Tasmania; calaverite from Kalgoorlie; and on and on . . . .

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[5] The identity of Foote's Australian collector remains a mystery.

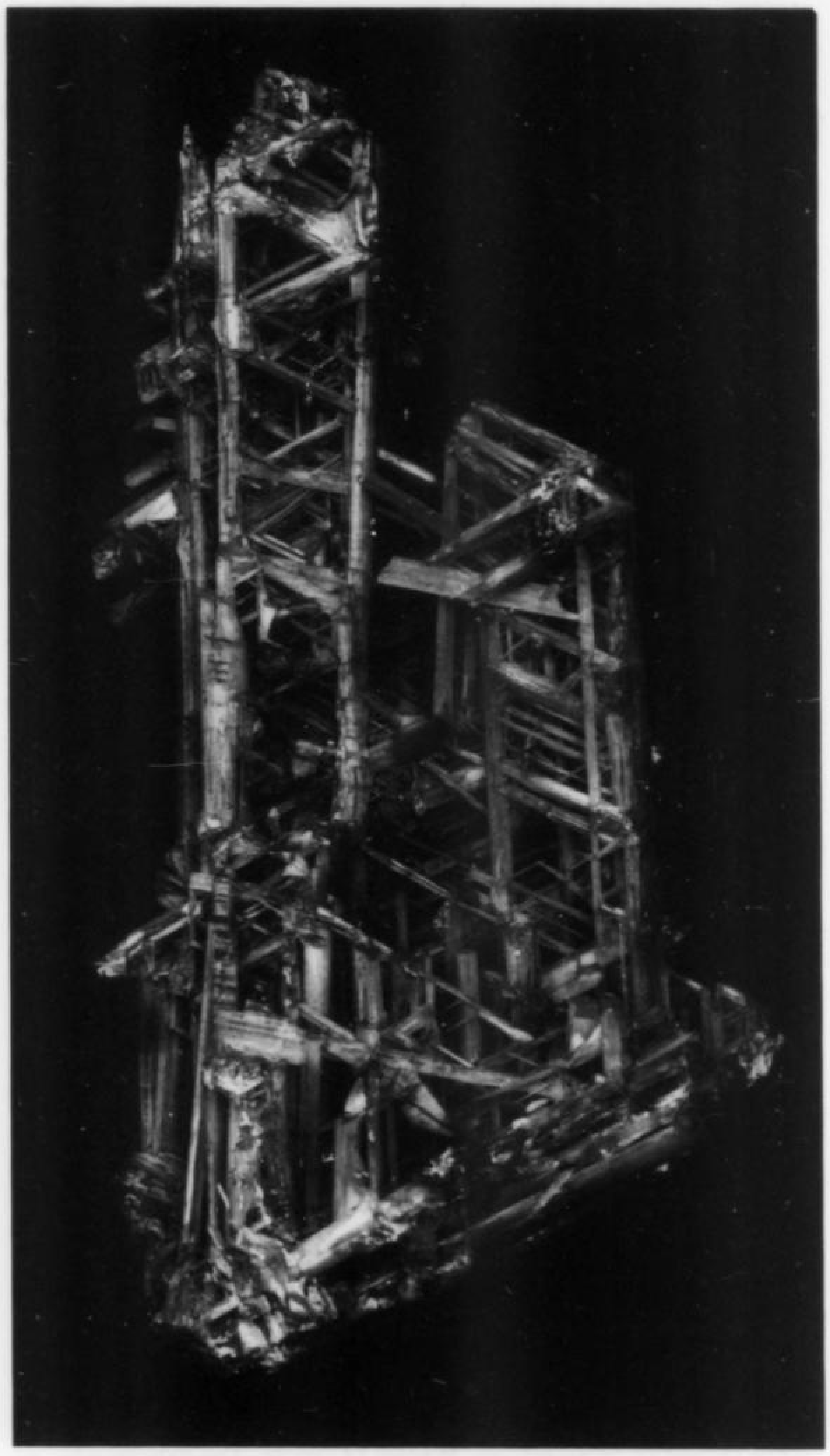


Figure 9. **Superb cerussite from Broken Hill, acquired by Clarence Bement from Foote Mineral Company in 1899 and now in the collection of the American Museum of Natural History. AMNH photo.**

Efforts to obtain crocoite specimens at the famed Adelaide mine near Dundas, Tasmania, are described in this excerpt from an undated Foote catalog issued around 1899:

> The discovery of new forms of this wonderful mineral is the result of over a year's work of our collector, in which the old Siberian specimens were totally outclassed. The various Tasmanian mines yielding the chromate of lead have been abandoned for some years and offered no hope of specimens in the future, the water in the levels having ruined all the specimens in the porous rock. The surface indications at the Adelaide appeared to warrant operations, and a tunnel was driven into the hill above. After much expensive labor a number of fine, rich colored crystals on dark gangue were found, and a good supply of pure massive Crocoite saved. Further on, however, in a clayey deposit, our collector was fortunate to strike a patch of loose prisms 3 to 9 cm long, superbly terminated, and of a most gorgeous translucent to transparent scarlet-red. The planes are exceptionally brilliant, and the angles of ideal sharpness and perfection . . . . Only a few perfect crystals were saved as compared with the number of broken, but otherwise choice crystals. Following this great strike, several months of fruitless and expensive tunneling forced an abandonment of the work, at a depth of 232 feet, closing the most extensive mining ever done solely for scientific mineral specimens.

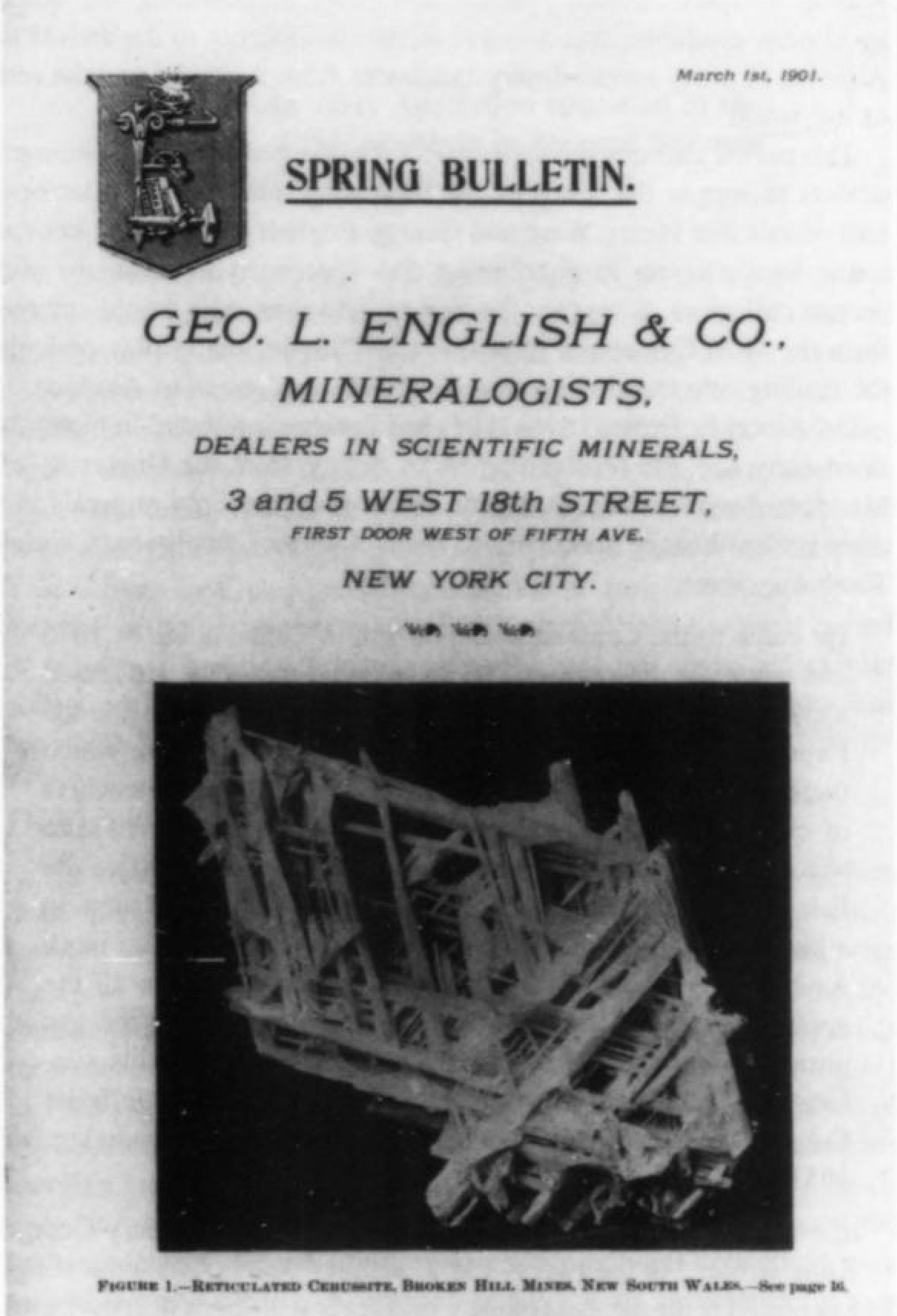
The *First Supplement to the Complete Mineral Catalog*, issued by the Company in 1899, tells of extensive offerings of Broken Hill minerals:

> The numerous shafts sunk have proved a veritable treasure ground for science. However, the distance from the large cities and the attitude of the operating companies have discouraged collectors, and few good specimens have been saved . . . The present consignment of 1100 pounds, resulting from the five weeks' trip of our collector, contains far superior specimens to those sold by us a year ago, as well as additional varieties. Little collecting could be done, and no purchasable specimens were left behind.

And of the cerussites from Broken Hill it was said:

> Never has this beautiful mineral been seen in more magnificent crystallizations than these . . . here indeed is one of nature's permanent beauties . . . .

Among the major American collectors of the day, it appears that Clarence Bement, the wealthy Philadelphia businessman, benefitted



March 1st, 1901.

SPRING BULLETIN.

GEO. L. ENGLISH & CO.,
MINERALOGISTS.
DEALERS IN SCIENTIFIC MINERALS,
3 and 5 WEST 18th STREET,
FIRST DOOR WEST OF FIFTH AVE.
NEW YORK CITY.

FIGURE 1.—RETICULATED CERUSSITE, BROKEN HILL MINES, NEW SOUTH WALES.—See page 16.

Figure 10. **Cover illustration featuring Broken Hill specimens offered by George English. Richard Hauck collection.**

the most from Foote's offerings of fine Australian specimens. By 1900, Bement's collection numbered some 12,000 specimens and was perhaps the finest in America. It contained extensive suites of Australian minerals, including crocoites and various Broken Hill specimens of extraordinary quality, virtually all obtained from Foote. Bement's collection was acquired by J. Pierpont Morgan in 1900, and he in turn presented it as a gift to the American Museum of Natural History.

Bement wasn't the only American collector who was acquiring the best that Australia had to offer. Like Bement, Washington A. Roebling had acquired a taste for mineralogy early in life. He pursued the subject until his death, at which time his collection contained 16,000 specimens. Trained as a civil engineer, he had joined his father in building many of the early suspension bridges in North America. When his father was killed during the early construction of the Brooklyn Bridge, Roebling took over the job. But he was stricken with the "bends" as a result of spending long periods working in the high pressure of the caissons and was forced to give up active supervision of the job. It was to his minerals that Roebling turned for relief from the suffering caused by the poorly understood ailment (Phillips, 1927).

In assembling his extraordinary collection Roebling corresponded widely with prominent scientists, collectors, and dealers throughout the world. At some point near the end of the 1800's, he became acquainted with a notable figure in the history of the Broken Hill area. George Smith, nicknamed "Specimen Smith" for his diligence in acquiring specimens (Worner and Mitchell, 1982; Smith, 1987), had been submanager, and later, manager of the Australian Broken Hill Consols Mine from 1890 to 1898. He was responsible for the preservation of a large quantity of fine Broken Hill specimens, some of which found their way into Roebling's collection, later acquired by the Smithsonian Institution. Many of Smith's handwritten labels, preserved along with the specimens, can be seen today in the Smithsonian's collection.

Figure 11. **Type specimen of willyamite from Broken Hill. Acquired by W. A. Roebling from George Smith, National Museum of Natural History collection; photo by the author.**

Researchers

With the increasing availability of interesting discoveries from Australian localities during the latter part of the 19th century, it is not surprising that more and more Australian minerals became the subject of scientific studies, some of which were conducted by Americans whose efforts would add to the pioneering contributions of James Dwight Dana and Francis Alger years earlier.

Among the earliest of the new generation of American contributions was the work of Edward Salisbury Dana, who was carrying on the mineralogical tradition established by his distinguished father. After graduating from Yale University in 1870, the younger Dana had traveled to Europe for several years to study the latest methods in crystallography. While in Vienna during the winter of 1873–74, he was fortunate in being able to examine a suite of extraordinary atacamite crystals which had been discovered in the copper mines of Wallaroo, South Australia. The published results of his extensive goniometric measurements on these crystals, in which he confirmed the orthorhombic nature of the mineral (Dana, 1874), were among the earliest of his many contributions to mineralogy. The crystals which he studied are still housed today in the collections of the Natural History Museum in Vienna (Dr. G. Niedermayr, personal communication).

An Australian specimen which had been exhibited at the Centennial Exposition held in Philadelphia in 1876 attracted the attention of Edwin Goldsmith, a long-time participant in the affairs of the Academy of Natural Sciences. "In the Academy's collection," wrote Goldsmith, "I noticed a mineral without a name but having on its label the words 'Victoria, Australia.' On inquiry, I received the information from the curator in charge that said specimen had been presented by the Australian Centennial Commission" (Goldsmith, 1878). The great Centennial Exposition had been an important event mineralogically, not only because it marked the emergence of the now-legendary Dr. Foote, but because visitors were able to view extensive exhibits of minerals sent by various foreign governments. Victoria, Tasmania, New South Wales, and South Australia were among those foreign exhibitors, and their displays (mostly ores) certainly served to better inform Americans of the mineralogical wealth of Australia. The collections of several American institutions definitely benefitted—both the Philadelphia Academy of Natural Sciences and the Smithsonian Institution received large portions of these exhibits as donations. It was one of those donated specimens, a reddish yellow alteration product of stibnite, which formed the basis for Goldsmith's study. Goldsmith named the mineral "stibianite," a name which has since been abandoned.

Figure 12. **Embolite from Broken Hill, collected by George Smith, August 7, 1897, and later acquired by W. A. Roebling. National Museum of Natural History collection; photo by the author.**

Another Philadelphian, Dr. F. A. Genth, who was widely known for his skills as an analytical chemist, contributed an interesting study

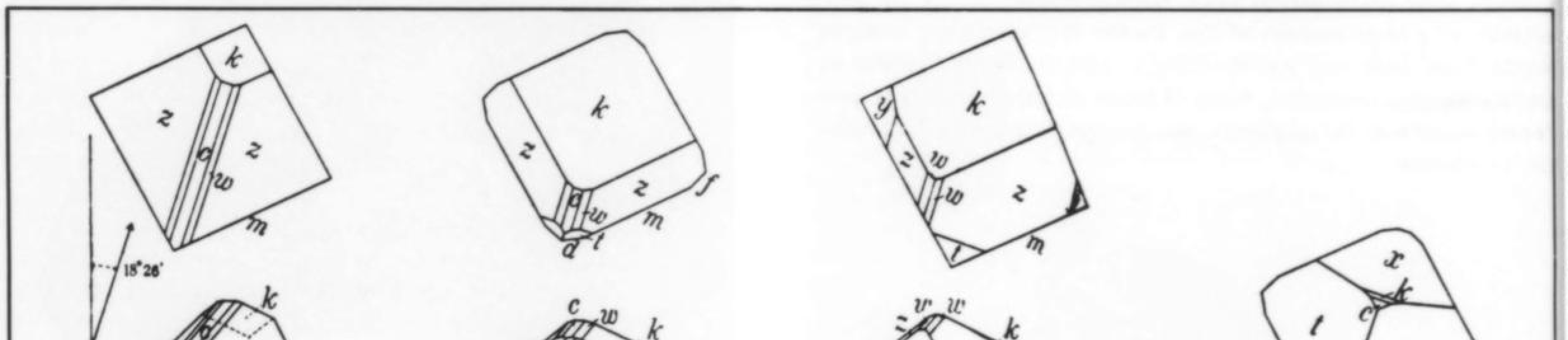
Bottle 1 measured Crystals
" 2 Crystals for Study.
MINERALOGICAL CABINET.
Nº 85620
Crocoite
Lead Chromate
Forms (001) (010) (110) (120) (210)
(011) (012) (021) $(\bar{1}01)$ (111) $(\bar{1}\bar{1}1)$ (530)
Loc. Tasmania (310)?
C. P.

Figure 13. **Tiny crystals used by Charles Palache in his study of crocoite from Tasmania. Harvard University Mineralogical Museum collection; photo by the author.**

on native tin associated with platinum, iridosmine, gold, corundum and other minerals from localities near Oban, New South Wales (Genth, 1886).

William P. Blake, for many years Professor of Geology at the University of Arizona, was the author of an excellent paper entitled "The various forms in which gold occurs in nature" (Blake, 1885). Like many other works written by earlier generations, it continues to make interesting reading today. Blake's short description of crystal-

Figure 14. **Tasmanian crocoite crystals as drawn by R. G. Van Name.**



lized gold from Australia, while based largely on information previously published by the noted Australian mineralogist Archibald Liversidge, is deserving of mention because it provided one of the earliest notices in an American publication of Australian gold crystals.

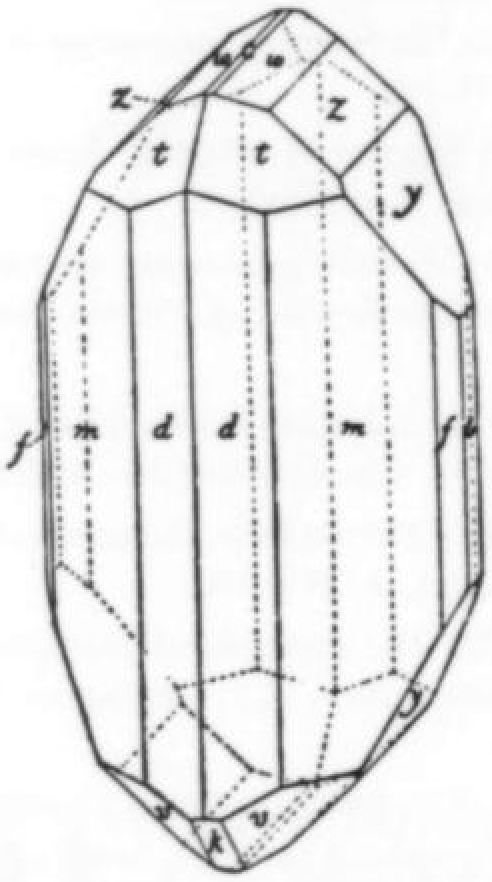


Figure 15. **Crocoite from Tasmania as illustrated in Palache.**

The beautiful Tasmanian crocoite which had already attracted the attention of American collectors had, by 1896, become a subject of scientific interest as well. The noted Harvard mineralogist Charles Palache, who achieved lasting fame for his classic studies on crystal morphology, published in the pages of the *American Journal of Science* (Palache, 1896) a description of the complex crystals. "Through the kindness of Mr. Stephen A. Douglas of San Francisco," wrote Palache, "the writer came into possession some time since of specimens of crocoite from Tasmania representing, so far as his information extends, a new or undescribed locality for this mineral. . . . The mineral occurs in a silver-bearing lead deposit known as the Adelaide mine on Mt. Dundas, west coast of Tasmania. . . . It is said to occur in considerable abundance, a statement bourne out by the appearance of these specimens and the many others in Mr. Douglas's possession" (Palache, 1896). Palache had arrived at Harvard in late December, 1895 (Frondel, 1956), and his study of Tasmanian crocoite, completed in January of 1896, was among the earliest of his many studies on crystal morphology to be carried out there. Today, the tiny crocoite crystals used in his goniometric studies can still be seen in the collection of Harvard's Mineralogical Museum.

Additional studies on the morphology of Australian crocoite were conducted by R. G. Van Name, of Yale University, using specimens acquired for the Yale collection from the Foote Mineral Company. Van Name undoubtedly expressed the feelings of many other mineral enthusiasts of the day when he wrote: "These Tasmanian crystals of crocoite with their superb color, high luster and remarkably perfect crystallization, are most beautiful natural objects, scarcely surpassed by crystals of any other known mineral" (Van Name, 1902).

With the minerals of Broken Hill attracting the attention of mineralogists around the world, it is not surprising that they formed the basis for studies in America. A. J. Moses, long associated with the School of Mines at Columbia University, and an authority on mercury minerals, studied "mercuric oxide" from Broken Hill supplied by the New York mineral dealer Roy Hopping (Moses, 1901). Remarkably complex crystals of azurite from Broken Hill were used by Samuel L. Penfield to illustrate two landmark papers on the methods of crystal drawing (Penfield, 1902, 1905). Edward H. Kraus and C. W. Cook used specimens supplied by the Foote Mineral Company for their study of iodyrite from Broken Hill (Kraus and Cook, 1909), carried out in the Mineralogical Laboratory of the University of Michigan. Specimens from Broken Hill were also used by Oliver Bowles, of the University of Minnesota, in his study of the crystallography of pyromorphite (Bowles, 1911).

Conclusions

By the early years of the 20th century, superb specimens of Australian minerals had found their way into the finest public and private collections in America, and into the hands of some of the most notable mineralogists of the day. Some measure of the growth of American knowledge of Australian minerals through the years can be gained from an examination of information on Australian localities given in the subsequent editions of Dana's *System of Mineralogy*. As stated earlier, the first edition (1837) had mentioned only coal. The second edition (1844), completed only two years after Dana's return from the Exploring Expedition, added only wood opal (but nothing about the glendonites!). By the third edition (1850), alunogen, galena, chalcopyrite, cuprite and apophyllite were added. The fourth edition (1853) added gold, diamond, corundum, atacamite, beryl, chrysocolla and pharmacosiderite, for a total of 14 species. The list had expanded to 23 by the fifth edition, published in 1868. When the sixth edition appeared in 1892, the list had more than doubled, to 58 species (for comparison, the seventh edition, published in 1944 and 1951, included 152 species, excluding the silicates). Certainly the state of knowledge had progressed much since that day in 1839 when young Dana stepped ashore in a land which had so little knowledge of its own geography, much less its minerals.

Acknowledgments

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The Mineral Collection of
THE AUSTRALIAN MUSEUM

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Developed through the guidance of informed and long-serving curators, the Australian Museum mineral collection is a balanced blend of specimens from Australia and worldwide occurrences. Classics and recent finds are interspersed with rough and cut gem materials. Holdings range from the highest quality display specimens, appreciated by mineral collectors and the public at large, to extensive comparative material stored for the demands of research.

THE EARLY EXPANSION

The Australian Museum, founded in 1829 in Sydney, houses the oldest and largest public collection of minerals in Australia. The 45,000 specimens are a balance of Australian and worldwide material. They are the fruits of the labors of small but dedicated staffs of mineralogists, who also curated rock and meteorite collections among other diverse tasks. The early minerals were supervised by curators responsible for the whole of the museum's collections (among them were the Reverend W. B. Clarke, the "Father of Australian Geology," and Gerhard Krefft, a zoologist), or by trustees (such as A. M. Thomson and Archibald Liversidge, professors of geology in the University of Sydney).

The first person with any mineralogical knowledge to work at the museum was J. R. Gygax, appointed in 1859. The first curatorial mineralogist, Felix Ratte, was appointed in 1881, by which time an extensive collection already existed, and it was he who started the first mineral register. Ratte, together with Dr. Thomas Cooksey, cataloged 15,000 minerals, rocks and meteorites between 1887 and 1901. Fine collections of European and American minerals were purchased from dealers such as Ward and Howell, Foote, Gregory, Sturtz, Kranz, Bertrand, Schuchardt and Stadtmuller. Some of these outstanding specimens remain on display: lead and zinc minerals from the classic Scottish localities of Leadhills and Wanlockhead; fluorite from Cumberland and Derbyshire in England; diamonds from South Africa; gold and tellurides of gold and silver from Transylvania, Romania. An exchange with a Glasgow museum brought minerals found in railway excavations: prehnite from Barrhead and the rare cadmium sulfide mineral, greenockite, from Bishopton. Another exchange with the Noumea Museum furnished nickel minerals from New Caledonia.

Australian and New South Wales minerals were acquired for the collection in greater numbers toward the end of the 19th century. In 1895, the Broken Hill Proprietary Company donated the first of many splendid secondary minerals from the oxidized zone of the orebody, particularly cerussite, anglesite, pyromorphite and iodargyrite. Exciting minerals came from western Tasmania: lead minerals such as galena, cerussite and crocoite from the Zeehan-Dundas fields and cassiterite from Mt. Bischoff, then the world's largest tin mine. Many minerals of economic importance were cataloged from Australian mining fields of the time. Valuable specimens of calaverite and other gold tellurides came from Kalgoorlie, Western Australia. Native gold came in from new fields nearby like Lucknow in New South Wales, or far-distant, like Darwin in the Northern Territory. Three hundred economic minerals were presented by the Queensland Government Geologist, including gold from the rich Croydon and Charters Towers fields, cassiterite from Herberton and Stanthorpe and cinnabar from Kilkivan. The Australian Museum became a major repository for samples of the nation's mineral wealth. This was acknowledged by the museum authorities, who agreed to purchase a collection from D. A. Porter in 1901, consisting of about 1200 minerals from the productive New England area of New South Wales, including specimens of cassiterite, wolframite, molybdenite, bismuth, fluorite, topaz and zircon.

THE RESEARCH ROLE

Seventy-five years after its inception, the mineral collection began to take on a new research role with the appointment of Charles Anderson, a University of Edinburgh graduate. Anderson expanded crystallographic studies and chemical analyses of Australian minerals; his 22 published papers include studies of cerussite and azurite. This research was apparently undertaken at the expense of acquisitions, as only 7500 specimens were gained in his 20 years in the Mineral

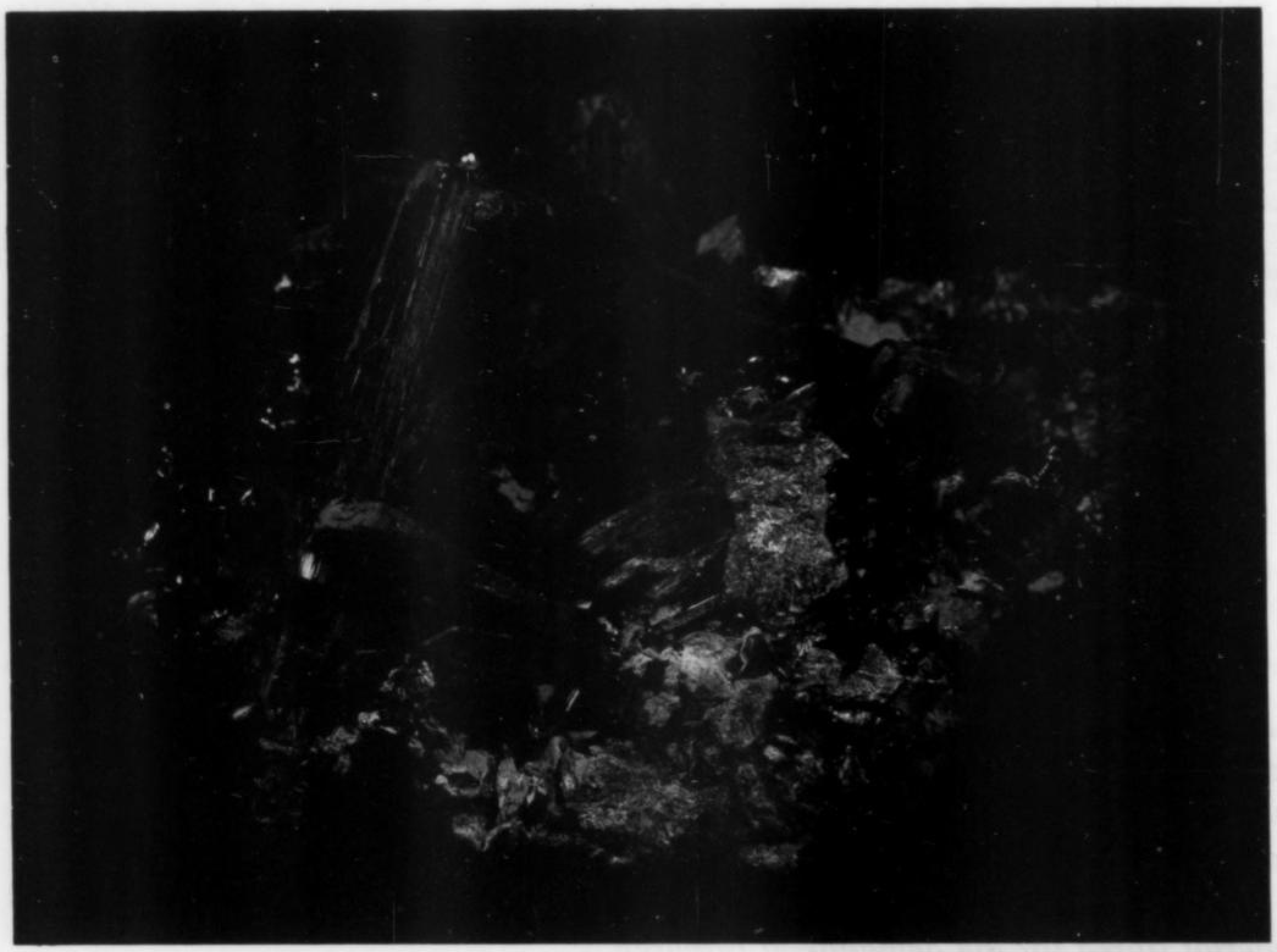

Figure 1. **Azurite with malachite replacement, from the Girofla mine, Mungana, Queensland; 12 cm across; photo by Steinwood Studios.**

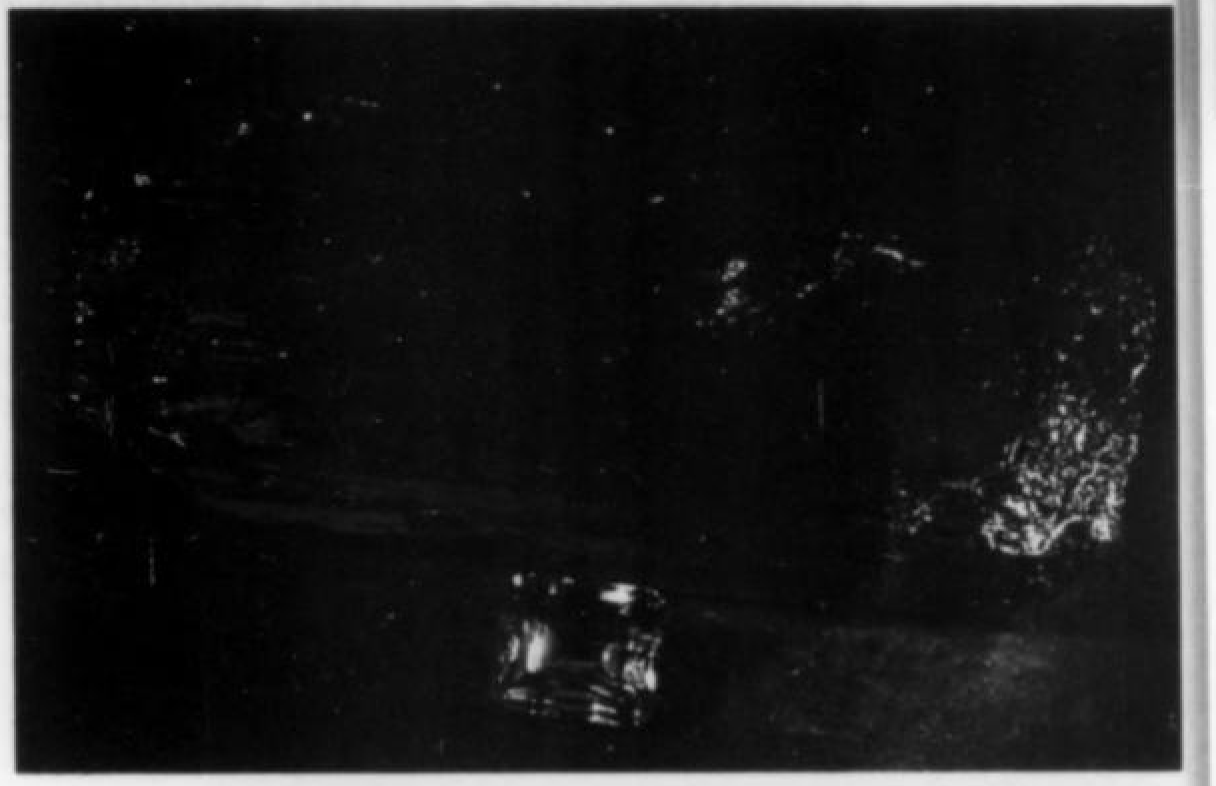

Figure 2. **Aquamarine crystal (9 cm) and cut stone (11.53 ct) from Mt. Surprise, Queensland; photo by R. Weber.**

Department. One highlight was the 1907 purchase from George Smith of a collection of 1500 mineral specimens from Broken Hill, New England, and other New South Wales localities. Smith was at various times manager of the English and Australian Copper Mining Company, the Australian Broken Hill Consols Mine and the Chillagoe Mines in Queensland before he became an inspector with the New South Wales Department of Mines. The advantages he took of the opportunities to collect fine specimens from mining centers, and his discerning eye for a fine piece, earned him the nickname "Specimen Smith." So fine was his eye for significant specimens that his pieces were rarely, if ever, exchanged from the museum collection. One unique piece is a specimen of chrysocolla replacing azurite and malachite from Mungana, Queensland. A year later an unrelated purchase bought another superb specimen from this area—malachite replacing azurite.

THE FIELD FORAYS

Charles Anderson became director of the museum in 1921 and moved his research interests into vertebrate palaeontology. Custody of the mineral collection passed to Thomas Hodge-Smith, who maintained the balance of curation and research, but widened the scope of field collections. His trips included collecting at zeolite, calcite and garnet localities in northern New South Wales, and at Broken Hill, but his major effort was an expedition to the Harts Range, in remote central Australia, in 1930. Here shortage of fresh provisions caused the party to suffer from scurvy, but they returned with many fine minerals from the pegmatites and metamorphic rocks.

Many minerals from Hodge-Smith's trips remain on display and, apart from this research material, the excess stocks helped later in making substantial exchanges. Some of the museum's most spectacular, large specimens were negotiated from Ward's Natural Science Establishment, including descloizite and germanite from Southwest Africa (now Namibia); franckeite, teallite and other rare sulfides from Bolivia; vanadinite from Morocco; and two polished slabs of Australian minerals picked up by a Ward's agent—stichtite in serpentinite

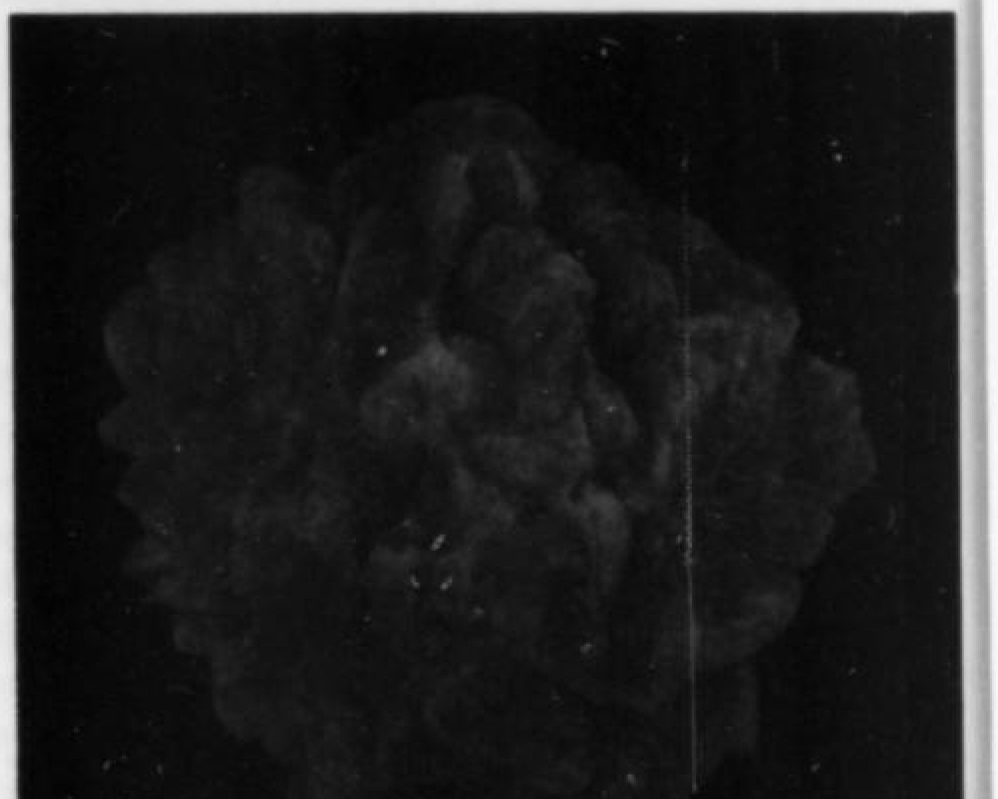

Figure 3. **Opal replacing glauberite crystals (opal "pineapple") from White Cliffs, N.S.W; 9 cm across; photo by R. Weber.**

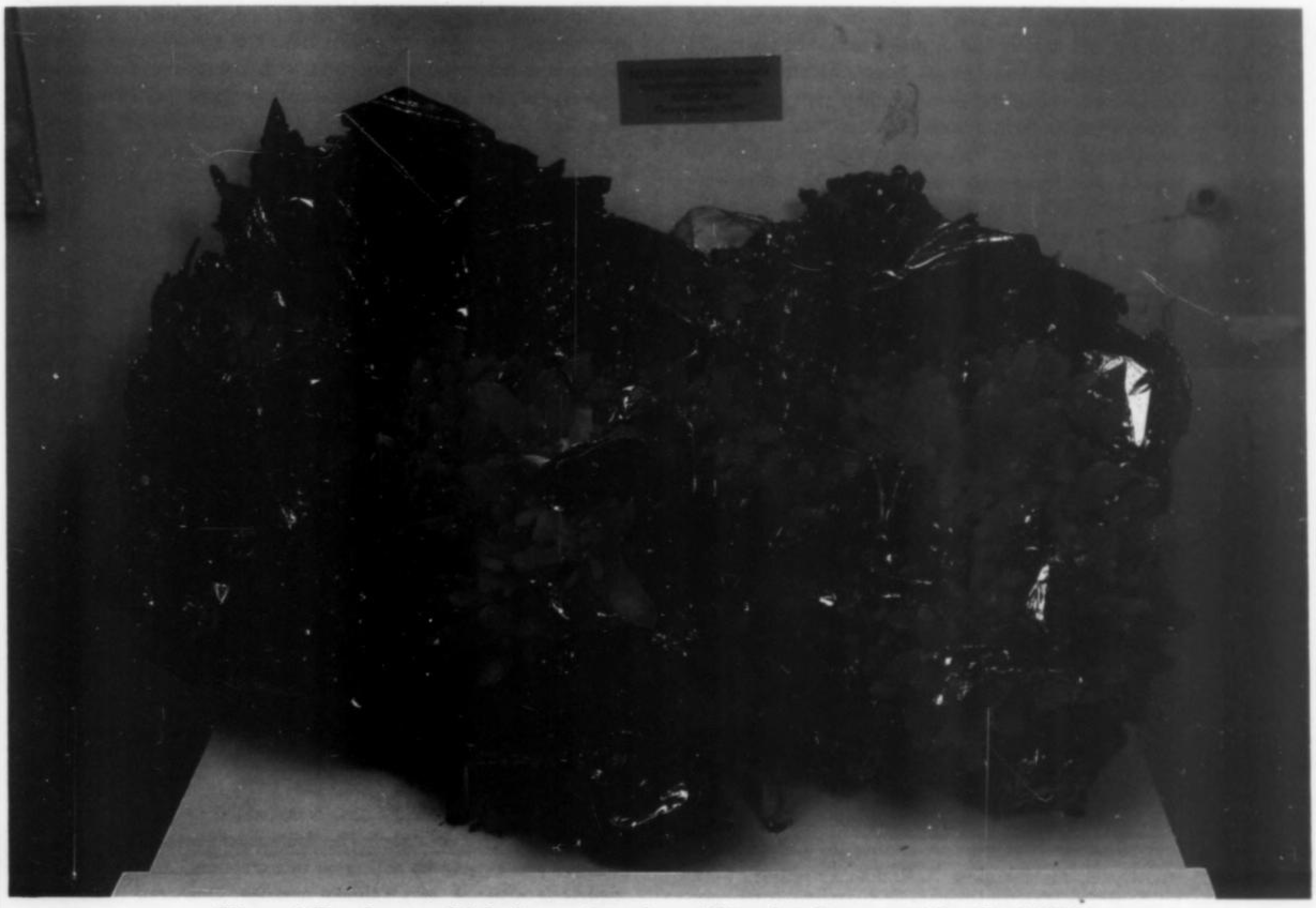

Figure 4. **Very large molybdenite specimen from Allies mine, Deepwater, New South Wales.**

from Dundas, Tasmania, and banded jasper from Marble Bar, Western Australia.

The most important purchase in 1927 was 1700 of the most choice specimens still possessed by George Smith. His Australian material was notable for rare silver minerals from the A. B. H. Consols mine, Broken Hill, and New England minerals. He also had fine overseas specimens, having exchanged with collectors such as Colonel Washington A. Roebling in the U.S. Other important purchases were 500 specimens forming the second of the D. A. Porter collections, registered in 1929 and rich in New England minerals, and the R. Eustice collection of 300 select specimens, mostly from the early copper mines of South Australia, but also containing outstanding Broken Hill specimens. Some 800 small but perfect crystals of largely foreign minerals were presented by Professor Liversidge. The finest single bequest, made to the Museum in 1933, was the official collection of the Block 14 Proprietary mine at Broken Hill, which held some of the best cerussite, pyromorphite and other rare secondary minerals such as stolzite and silver halides ever put together from this orebody. A statuesque reticulated cerussite later came to represent this species in Peter Bancroft's 1973 book, *The World's Finest Minerals and Crystals*. The family of a prominent mining man, W. H. Yates, also presented his collection of 300 specimens of molybdenite and bismuth minerals from little-known Australian localities.

THE EXHIBITS

Hodge-Smith's reign saw the reorganization of the display minerals into a series of handsome, vertical "florentine"-style cabinets, a great improvement on the older cases. The Mineral Gallery was the first gallery in the museum to be artificially lit. One of the world's exceptional display pieces in the gallery shows large molybdenite blades on quartz from Deepwater, New South Wales, obtained in 1944.

On the death of Hodge-Smith in 1945, his position passed to R. O. Chalmers, who had joined the museum in 1929 and had asssisted Hodge-Smith in many of his enterprises in mineral acquisition and research. At this time the museum began a rewarding association with Maurice Mawby at the Zinc Corporation mine, through exchanges for many of the new finds coming out of Broken Hill, such as sturtite, pyrosmalite, inesite and apophyllite.

A GREATER SYNTHESIS

The mineral collections continued to flourish under the versatile guidance of Oliver Chalmers, who in particular took a great interest in gemological aspects and studies of meteorites and tektites. His 42 years of service, until his retirement in 1971, culminated in the publication of two books drawing on the mineral collections: *Australian Rocks, Minerals and Gemstones* in 1967 and *The Observer's Book of Rocks and Minerals of Australia* in 1979. He analyzed many minerals in the collection and collected on many field trips, assisted by John Lovering, who later became Professor of Geology at Melbourne University, and Judy James who contributed much to the growth and care of the collections. Chalmers kept up a close association with Arthur Combe, a dedicated mineral collector from Sydney who worked at mines throughout Australia and with overseas geological surveys; Combe left his splendid collection to the museum in 1949.

THE MODERN MINERAL SHOW

In the last 15 years, the collections have expanded under the joint curatorship and management of F. Lin Sutherland, Joan Henley, and associates Oliver Chalmers and Albert Chapman. Recognizing the need for new material, Sutherland arranged for the museum to receive an annual grant from the Museum Trust to buy fine specimens from visiting and local mineral dealers and at major mineral shows such as the Tucson Show in Arizona. Some pieces, bought with the guidance of Albert Chapman, are among the finest of their type—wulfenite from New Mexico; calcite on fluorite from Elmwood, Tennessee; and chalcopyrite and arsenopyrite from Panasqueira, Portugal to mention only a few. Australian gold specimens weighing up to 32 ounces were bought to fill a gap in the collection. Collecting trips around Australia added significant suites from the Pilbara and eastern goldfields, Western Australia; the Harts Range in Central Australia; Flinders Ranges and Olary area, South Australia; the Rum Jungle and Alligator River regions, Northern Territory; and the Broken Hill district, New South Wales. Collecting in Tasmania, paricularly at zeolite localities, was undertaken jointly with the National Science Museum of Japan. Research has concentrated on exotic high-pressure minerals found in Australian volcanic rocks; minerals of the earth's lower crust and mantle have been added to the collections.

A new Mineral Gallery was opened in 1986. The cream of the collection is shown in an informative context, leading into a safari-style exhibit of Australian mineral localities. An innovation introduced by Joan Henley was the Museum Mineral Sales, which have helped to raise funds for the purchase of quality display specimens. Initially, only excess materials from the collections were sold, but the sales proved so popular with the public that they have been continued with minerals purchased directly from, or sold on commission for, dealers.

THE GEM GAINS

One highlight of the museum's collection is the gem material. Since Anderson's time, the mineralogists have kept an ongoing interest in gem minerals and their informed approach has led to the acquisition of a broad range of cut and uncut material. The collection has benefitted from the discovery of gem materials in new mining areas of Australia as they occurred. Opals, the foremost Australian gemstone, were entered in the museum's register in 1854, from South Australia, and in 1873 from the new fields in southwest Queensland. Superb precious opal replacements of fossil molluscs and radiating glauberite crystal groups (so-called opal "pineapples") were purchased from a pioneer on the White Cliffs field in New South Wales. This is the only locality for opal "pineapples" and fewer than 200 have been found. In the 1930's Percy Marks, a prominent Sydney jeweller, made a handsome donation of over 50 fine specimens of precious opal. More recently, the museum purchased large spectacular halves of a banded precious opal seam called "painted lady" from Andamooka, South Australia, to supplement fine cabochons from the Lightning Ridge, Coober Pedy and Andamooka fields. A new taxation incentive scheme encouraged additional donations, such as an exquisite suite of cut "boulder" opals from Quilpie, Queensland, and a precious opal replacement of a large fossil pelecypod from Coober Pedy.

Sapphire is one of Australia's prominent gemstones, and the museum has recently acquired a set of 38 round brilliant cut stones from the New England area, illustrating the range of colors found there: vivid blue through green to gold and orange. The Anakie field in Queensland is represented by two exceptional stones—a golden sapphire of 12 carats, and a cushion-cut green-brown color-change stone of 34 carats. Also from New England are cut green beryls and a golden beryl crystal. Aquamarines include a fine crystal and a cut stone from Mt. Surprise, Queensland. Emeralds from Poona and Menzies in Western Australia include spectacular crystals set in black mica schist. Eastern Australian diamonds in the collection come mostly from the main fields around Copeton and Airly Mountain in New South Wales, but because these stones are unusually "hard," most remain uncut. A recent acquisition is a 5-carat brilliant-cut stone from the large, newly opened diamond pipe at Argyle, Western Australia.

The best Australian topaz crystals in the collection come from Oban, New South Wales, and are exceptionally large and clear, varying in color from colorless to light blue and brown. Colorless topaz, the so called "Killiecrankie diamond" from Flinders Island in Tasmania, is represented by a crystal in granite and a brilliant-cut stone. Australian quartz is abundant in the collection, with fine specimens of amethyst, rock crystal, smoky quartz, citrine and cairngorm from the New England area. The largest cut stone is a 188-carat colorless quartz from Oban. A range of cut garnets and zircons includes orange hessonite from the Harts Range and sherry-colored zircon from the Strangways Range, central Australia.

Other more specialized cut stones include golden labradorite from the Hogarth Ranges, New South Wales; rich green peridot from Cheviot Hills, Queensland; deep blue tourmaline from Kangaroo Island, South Australia and iolite from the Harts Range.

For comparison and contrast with Australian stones, the museum has a comprehensive suite of gemstones from other countries. There is a variety of African diamond crystals, some of unusual habit, and a perfect, 3-carat octahedral crystal in kimberlite from the Mir pipe, Siberia. A fine-quality emerald crystal in matrix from Colombia, South America, contrasts with an unusual trapiche emerald cabochon. There are some striking sapphires, the largest being a 60-carat, native-cut blue stone from India. A range of large and beautiful stones comes from Brazil—a magnificent, 179-carat, cut kunzite; colorful beryls among which is an impressive 69-carat morganite; quartz ranging from deeply colored amethyst to colorless crystals filled with rutile inclusions; also topaz, golden chrysoberyl and euclase. Among the rarer stones are an 11-carat rhodochrosite from South Africa, a 20-carat trap-cut diaspore from Turkey; an 18-carat sphalerite from Santander, Spain; and a sinhalite from Sri Lanka.

FUTURE GROWTH

Australia's bicentennial marks 200 years of increasing awareness of the continent's mineralogical composition in relation to mineral resources of other countries. The Australian Museum's charter is to preserve and expand its collection of exceptional and representative Australian material, as a national heritage. One need is for greater acquisition of some of the finest Australian gems and precious metals, such as precious opal, sapphire, diamonds, collector gem species and gold. This expensive exercise will require the assistance of outside benefactors and the use of tax incentives. Other future aims are to acquire good Australian private collections as they become available, to computerize the mineral collection to make information more easily accessible to researchers, and to expose minerals in the collection to a wider public through well illustrated and informative publications.

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Minerals of

WESTERN TASMANIA

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Western Tasmania is one of Australia's most important base-metal mining regions. Commencing with the discovery of tin at Mt. Bischoff in 1873, the region has subsequently become a major producer of gold, osmium, iridium, tin, silver, lead, zinc, copper and iron. A diversity of mineral species has been produced from the numerous mines and scattered prospects throughout the region. Many of these are of significant mineralogical interest and several are world famous.

HISTORY

Western Tasmania's geographical location and topography create a bleak and inhospitable region, which hindered exploration and development. Its 40° south latitude results in exposure to the westerly winds known as the "roaring forties" which blow uninterrupted from the southern tip of Africa. Their uplift over the mountainous coastal terrain results in heavy rain during the winter months. This climate, with the resultant prolific growth of vegetation, rugged terrain and raging rivers, offered little encouragement for early colonists.

The first European settlement in Western Tasmania was a penal colony, established on Sarah Island in Macquarie Harbour in 1822. It was selected because of its geographical isolation; as escape on foot was considered impossible.

The region remained relatively unexplored until government parties were formed to search for mineral resources in the late 1850's, in an attempt to halt the mass population exodus to the goldfields of Victoria and New South Wales. Binks (1980) details the exploits of these parties and their work in cutting access tracks into the region. This early exploration, however, did not identify any significant mineral resources.

It was the discovery by James "Philosopher" Smith, a lone prospector and experienced bushman, of lode tin south of the Arthur River in 1871 that was the catalyst for mining in the region. Smith's discovery subsequently developed into the Mt. Bischoff tin mine at Waratah, which became the richest tin mine in the world during the 1880's.

News of Smith's discovery inspired other prospectors to fan out into the south and west and find numerous mineral prospects and extensive deposits: The Heemskirk tin field in 1876; the gold and osmiridium alluvial deposits of the Pieman tributaries in 1879; the rich Zeehan-Dundas silver-lead deposits in 1882; the Iron Blow gold discovery that became the Mt. Lyell copper mine in 1883; the Renison tin mine in 1890; and the Mt. Reid mineral field (Rosebery-Williamsford) in 1894.

Major mines were established and towns built for the mining population, the more important being Queenstown (Mt. Lyell mine), Zeehan (Zeehan-Dundas silver-lead mines), Rosebery (Renison/Mt. Reid mineral field), Tullah (Mt. Farrell) and Waratah (Mt. Bischoff). Seaport settlements grew at Remine (Trial Harbour) and Strahan on the West Coast, and Burnie in the north, for the transport of goods and people to and from the mining fields. An extensive network of narrow-gauge railways provided the communication links from these settlements to the mines. These continued to operate into the 1960's, with the first road access to the north coast being opened as recently as 1962. Rae (1983) provides an excellent insight into this facet of mining operations. Current access into much of the region is by vehicular tracks along the abandoned railroad beds.

A revival of mining during the 1960's resulted in the reopening of the Mt. Cleveland tin mine at Luina and the commencement of mining of the iron ore deposits at Savage River. Recent exploration has resulted in the location and mining of silver-lead-zinc deposits at Que River in 1980 and the discovery of the Hellyer silver-lead orebody, which began production in 1986.

GEOLOGY

Collins (1985) has described the regional geology of Western Tasmania as consisting of rocks ranging in age from late Precambrian to early Devonian, occurring in zones between and within Precambrian regions.

The largest Precambrian region, the Tyennan region, bounds the area to the east and consists of sedimentary rocks that were deformed and metamorphosed during the Frenchman Orogeny (about 800 million years ago). The Rocky Cape region forms the western boundary and consists of comparatively unmetamorphosed sedimentary sequences which were extensively folded during the Penquin Orogeny (about 725 m.y. ago). These two regions acted as structural blocks during

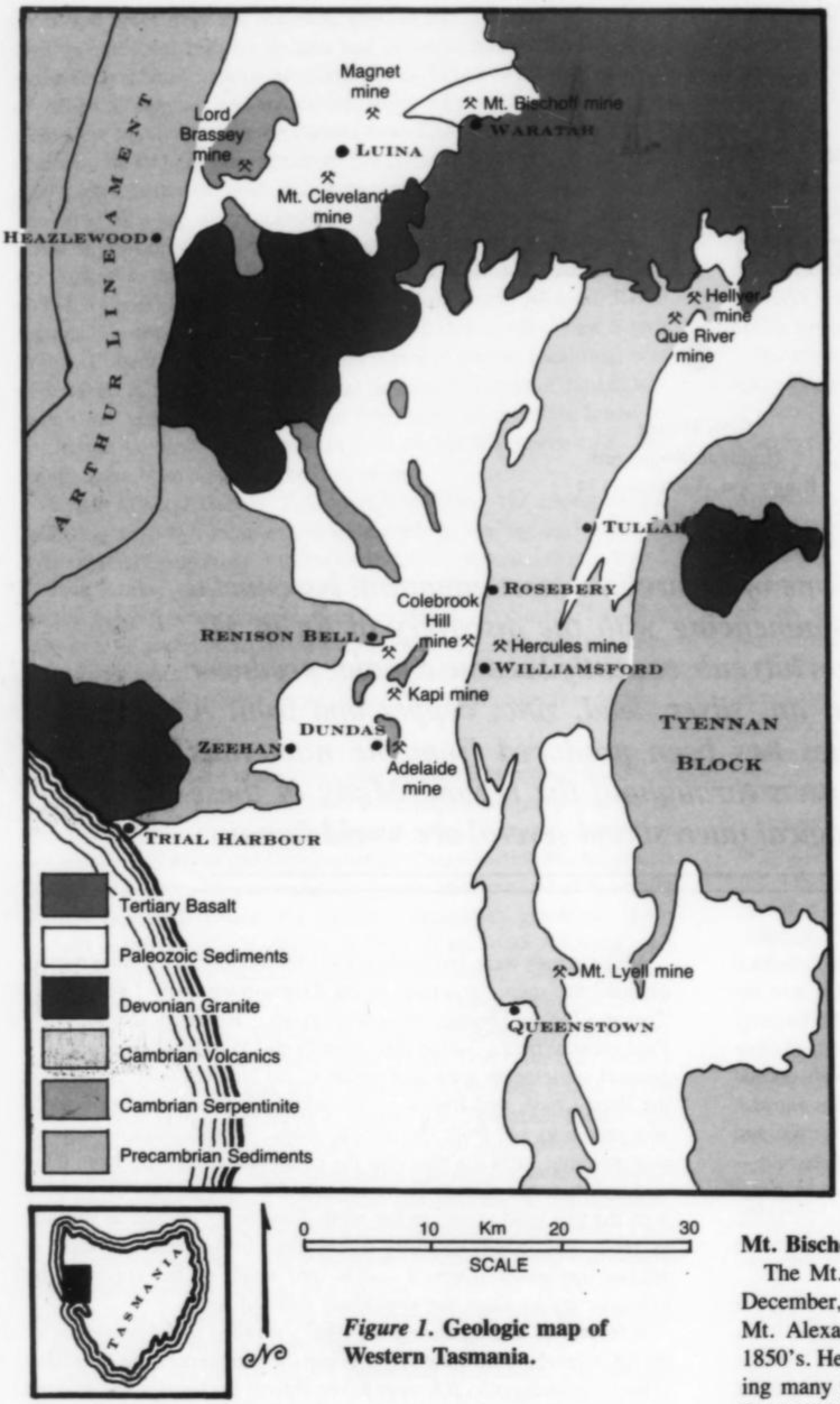


Figure 1. **Geologic map of Western Tasmania.**

later periods of deposition and intrusion, strongly controlling the regional geological setting. Transecting the Rocky Cape region is a belt of metamorphic rocks known as the Arthur Lineament. These consist of extensive dolomite and magnesite units and at the Savage River, siliceous lenses of pyrite and magnetite, which are currently being mined for the magnetite.

The main late Precambrian and Cambrian troughs have developed between the Rocky Cape and Tyennan regions. The basal sequences consist of shallow marine sediments, dominated by siliceous sandstone and siltstone which locally contain thick beds of dolomite. They are conformably overlain by deeper marine mudstones and graywacke turbidites, locally containing interbedded limestones. During a later compressional phase, large ultramafic masses were emplaced along steep thrusts cutting into the sediments and are the source of nickel sulfides, chromite and osmiridium.

The intrusion of the Mt. Reid volcanics, consisting of a central belt of rhyolitic and andesitic lavas, ash flows and other pyroclastics together with intrusive rocks, occurred during the middle Cambrian. They are flanked on the western side by marine sediments and water-lain tuffs. This belt is host to several major volcanogenic massive sulfide deposits which occur as stratiform lenses containing Zn, Pb and Cu with Ag and Au. They are confined to the central belt extending from Elliot Bay in the south to Que River in the north, a distance of 150 km. In the southern end, near Queenstown, the deposits are copper-rich, being dominated by the large disseminated pyrite and chalcopyrite orebody at Mt. Lyell. In the north, the deposits are dominantly sub-aqueous, exhalative, stratiform massive sulfides enriched in Zn and Pb, as typified by the Que River deposit.

The Ordovician period was dominated by the deposition of shallow marine limestones in the warm seas that inundated much of Western Tasmania. They occasionally contain stratabound disseminated and veined base-metal sulfides representing a minor metallogenic epoch.

Extensive deformation occurred during the middle Devonian, correlating to the Tabberabberan Orogeny of eastern Australia. The geanticlines of the Cambrian period remained as relatively complete blocks, with folding and faulting being constrained to areas between the converging blocks. During the late Devonian, several granitic intrusions were emplaced at relatively shallow depths in the folded rocks. These contain minor tin-tungsten mineralization, mined on a small scale at Mt. Heemskirk.

The region was largely unaffected by the extensive emplacement of dolerite in the central and eastern part of the state during the Jurassic. The basaltic lava flows which occurred in the northwest during the Tertiary period extend south to Waratah.

THE MINES

Brief description is given below of the more significant mines; the reader is referred to other publications such as Pink (1982) and Bisset (1962) for further information.

Mt. Bischoff mine, Waratah

The Mt. Bischoff tin deposit was discovered by James Smith in December, 1871. Smith was a Tasmanian who spent two years in the Mt. Alexander goldfields in Victoria during the gold rushes of the 1850's. He returned to Tasmania and became a lone prospector, spending many years searching for minerals in the Northwest. McIntosh Reid (1923) described the area as follows:

> The region he selected for exploration is extremely rugged, and is dissected by numerous fast-flowing streams. The mountains are heavily clothed with forest, and progress over them is impeded by a thick undergrowth of bauera and horizontal scrub. Into this dismal region Smith forced his way, and carried on his self-appointed task with extraordinary fortitude, returning to his base only when exhausted by fatigue and hunger.

The geographical isolation made the establishment of mining difficult for Smith, but in 1873 he persuaded several Launceston businessmen to form the Mount Bischoff Tin Mining Company. The company was initiated with 12,000 shares of $10, however, over $200,000 was expended before the first dividends were paid in 1878. A major cost was the building of a wooden railed, horse-drawn tramway between the mine and Burnie, a distance of 77 km, which took

Figure 2. **The Mt. Bischoff mine ca. 1890. Photo Latrobe collection, State Library of Victoria.**

Figure 3. **The Mt. Lyell mine, Queenstown, in 1902. Photo Latrobe collection, State Library of Victoria.**

3 years (Godfrey, 1984). The company subsequently produced more than 57,000 tonnes of metallic tin from the deposit during its operational life up to 1942.

Mt. Cleveland mine, Luina

The Mt. Cleveland orebody was discovered by Whyte River gold prospectors in 1898, who believed that the gossanous outcrop was a silver-lead lode. In 1908, the small Cleveland Tin Mining Company was formed to mine the deposit. They achieved little success, as the oxidized zone was shallow and the sulfide ore was found to have high tin content which was difficult to recover. The company ceased operations in 1914 and the mine was leased out. Following a sharp drop in the price of tin in 1917, the mine was found to be uneconomic and was abandoned.

Interest was shown in the deposit by Aberfoyle Tin N. L. in 1960, with a drilling program establishing significant ore reserves. The company constructed more than 60 new houses at the old Whyte River townsite of Luina in 1968 and mining operations were resumed. It became Australia's second largest tin producer (after Renison), with an annual production of 1500 tonnes of tin and 500 tonnes of copper. The imposition of quotas by the International Tin Commission, together with the declining grade of ore, resulted in the closure of the mine in 1986. The recent mining operations produced a range of mineral species, including excellent specimens of calcite, fluorite and vivianite.

Magnet mine, Waratah

The Magnet was a moderate-size silver-lead mine, situated 8 km west of Waratah. The deposit was found in 1891, and the Magnet Silver Mining Company was formed in 1894 to commence large-scale mining. Operations continued until 1940, when the mine was closed and the plant and township sold. During this time the mine produced 227 tonnes of silver and 37,000 tonnes of lead from 620,000 tonnes of ore. As was typical of many of the mines in the region, the Magnet relied solely on a narrow-gauge railway for communications, with the people, their food and furniture being railed in from Waratah and the ore concentrates railed out. A small, isolated settlement was established along the adjacent creek valley to service the mine and the close-knit independent community (Godfrey, 1984).

The Magnet is known to mineral collectors for its diversity of mineral species. Petterd (1896) records such minerals as anglesite, crocoite, phoenicochroite, chalcophanite, cerussite, dolomite, "embolite," matlockite, mimetite, silver, pharmacosiderite, phosgenite, proustite, pyrargyrite, pyromorphite, rhodochrosite, smithsonite, symplesite and vanadinite from the locality, with many of these species being collected in recent times by eager micromineral collectors. The locality is, however, best known for its yellow cerussite.

Lord Brassey mine, Heazlewood

This was a small mine that was worked for nickel ore in the late 1890's. It is located in a serpentinite outcrop, locally known as Nickel Hill. Mining operations consist of a shaft and drives. The nickel-iron sulfide ore (principally heazlewoodite and magnetite) occurs in veins up to 5 cm thick along shear planes, and also finely disseminated in the serpentinite. Zaratite is relatively abundant as coatings along the shears and joint planes, closely associated with heazlewoodite. Hellyerite is relatively rare, apparently restricted to a single joint plane within a small section of the mine.

Adelaide mine, Dundas

This mine was one of many small silver-lead producers which operated in the Zeehan-Dundas area during the period 1890 to 1915. The orebody is adjacent to the contact of an ultrabasic intrusion that has been completely serpentized. It consists of a large gossanous outcrop and oxidized zone extending to a depth of over 75 m. Mining operations extended to a depth of 100 m, with a recorded 6000 tonnes of ore having been mined for a return of 1500 tonnes of lead and 45,000 kg of silver. Much of the ore was from the oxidized zone, which was mined for flux for the Zeehan smelters and which undoubtedly contained many spectacular crocoite specimens. The mine has produced a wide range of mineral species and is the premier locality for crocoite. Other minerals recorded from this mine include dundasite, for which it is the type locality, cerussite, gibbsite, massicot, phosgenite, pyromorphite and vauquelinite. Since 1960, the Adelaide has been intermittently mined for crocoite specimens and is currently held under claim by Frank Mihajlowitz.

Mt. Lyell mine, Queenstown

Whereas Mt. Bischoff was the catalyst for the mining development of Western Tasmania, the Mt. Lyell mine has been the predominant mineral producer. The mine has had an intriguing history, ranging from the austere and methodical smelting developments under Robert Sticht, to the extravagances of James Crotty (Blainey, 1954).

The deposit was found in 1883 by prospectors, who had followed gold along the King River and found specks of gold at the "Iron Blow," a large ironstone outcrop. Initial attempts at mining the outcrop for gold were disappointing, and it was not until ore samples were analyzed in 1891 that copper was determined to be the major mineral. The Mt. Lyell Mining Company was formed in January of 1892 to commence copper mining operations. This company, later registered as the Mt. Lyell Mining and Railway Co. Ltd., has continually mined the orebody to the present day. Production from the mine is recorded at 1.6 million tonnes of copper, 700 tonnes of silver and 36 tonnes of gold from 93 million tonnes of ore. The deposit consists of massive disseminated chalcopyrite-bornite; no significant mineral specimens have been found in the mine.

MINERALS

The region, with its considerable and diverse mineral wealth, has produced a wide range of mineral species. The following review covers the more notable mineral occurrences. The reader is referred to other publications, such as the excellent *Catalogue of the Minerals of Tasmania* (anonymous, 1969) for further reading.

Anglesite $PbSO_4$

Excellent specimens of anglesite were found in the Comet-Maestries mine in the 1890's. Petterd (1893) describes them as being "large and beautifully developed, occurring in masses of considerable size, sometimes containing massicot at the interstices and as a base."

Transparent to white tabular crystals up to 6 cm tall were collected during mining operations.

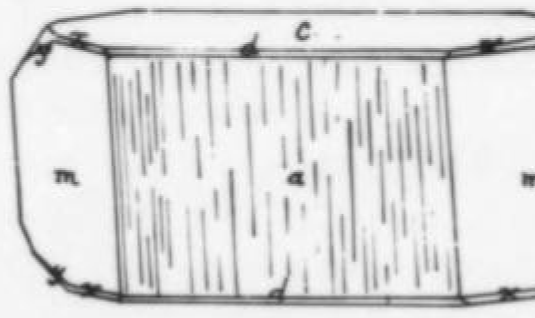


Figure 4. **Anglesite from the Maestries mine.**

Fine anglesite specimens, consisting of flat tabular crystals up to 1 cm across on a galena-gossan base, also occur at the Magnet mine.

Barite $BaSO_4$

Nice specimens of transparent yellow barite crystals came from the Rosebery mine in the 1970's. The crystals are up to 2 cm long on plates up to 20 cm across.

Calcite $CaCO_3$

Calcite is a relatively common gangue mineral in many of the mines. Fine crystallized specimens have occasionally been found; probably the best specimens in recent times have come from the Renison mine. These consist of interpenetrant rhombohedral crystals, exhibiting a saddle-shaped form. Individual, clear to white crystals up to 5 cm across are common. Crystal plates up to 20 cm across from this locality exist in several collections.

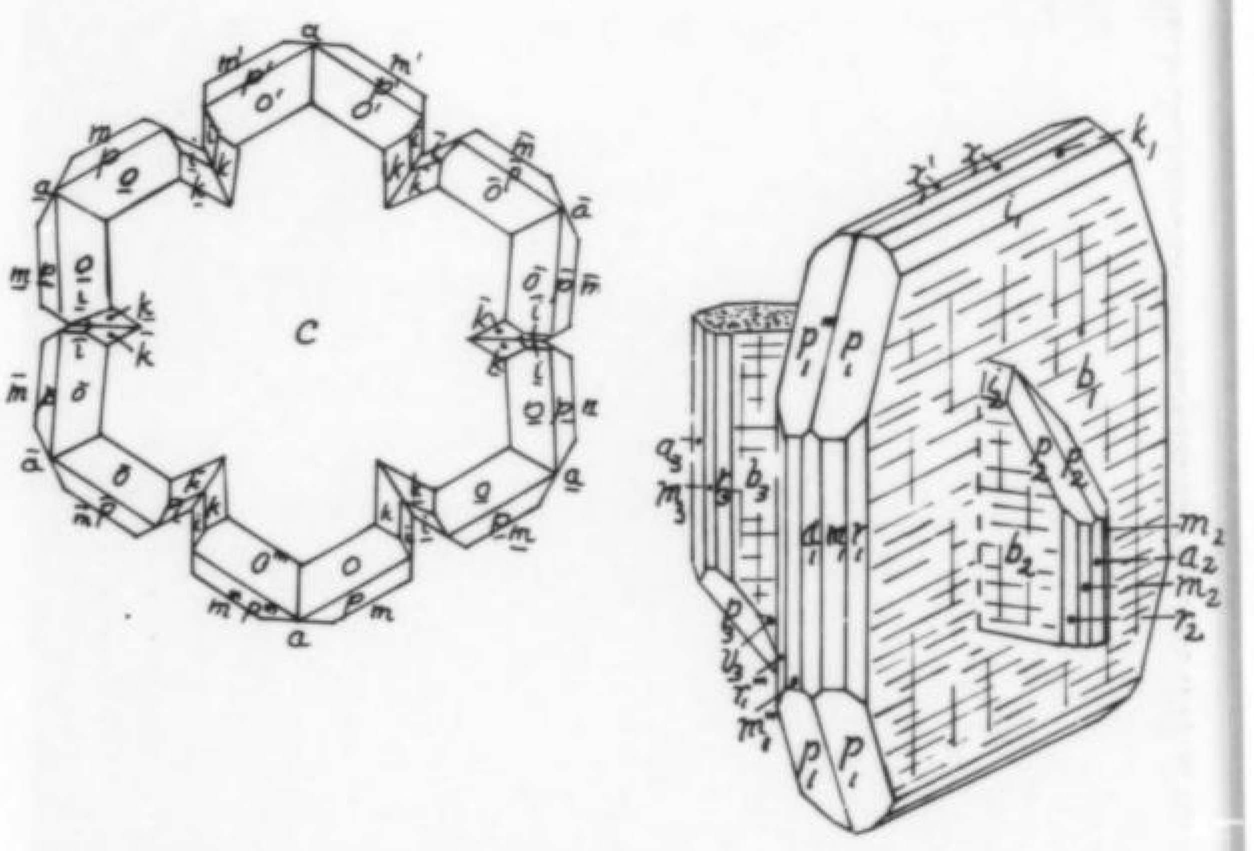


Figure 5. **Cerussite crystals: (left) Magnet mine, (right) Comet mine.**

Cerussite $PbCO_3$

Spectacular specimens of white reticulated crystal masses have been found in the Comet mine at Dundas, which closely rival crocoite in specimen quality. Excellent specimens, mined during the 1890's, reside in the West Coast Pioneers' Memorial Museum in Zeehan.

Also notable is the yellow, so-called "chrome" cerussite from this region. Petterd (1902) first records this type from the Adelaide mines in Dundas, with a chemical analysis identifying a small chromium content. It was subsequently reported by Petterd (1903) from the Magnet mine as "occurring in fractures and vugs in the gossan zone . . . the color is canary-yellow . . . it is a most attractive mineral and soon arrests attention." These two localities have produced spectacular mineral specimens of a slightly different form.

The Magnet locality produced individual bright yellow crystals and crystal groups of flat tabular pseudo-hexagonal form, exhibiting the characteristic cyclic twinning of cerussite. The individual crystals reach up to 1 cm across and are scattered on a brown to black matrix of iron and manganese oxides which enhances their appearance.

The habit from the Adelaide mine, while also showing cyclic twinning, generally consists of groups of more blocky crystals of a characteristic "cog-wheel" appearance. They are a pale yellow color, much lighter than from the Magnet. The Adelaide specimens consist of masses of crystal groups to 1 cm on plates up to 20 cm across and are particularly prized in collections.

Recent analyses cast doubt that the yellow color is due to chromium (Birch, personal communication).

Crocoite $PbCrO_4$

Crocoite is certainly the most notable mineral species found in Western Tasmania. It is one of the most spectacular minerals, with Tasmanian specimens representing the best of the species found worldwide. It has been found in most of the Dundas mines, also at the Kapi at Northeast Dundas, as well as several mines at Heazlewood.

Petterd (1893) records the first Tasmanian occurrence at the Heazlewood Silver-Lead mine in 1890. Crocoite was found at the Adelaide mine at Dundas in 1891 and became a principal ore there, with (unfortunately) large quantities being mined for flux for the Zeehan smelters in the 1890's. However several magnificent specimens from this period survived and now reside in the collection of the West Coast Pioneers Memorial Museum in Zeehan.

In recent years several of the Dundas mines have been reopened by local miners to produce specimen material for the collector market. Frank Mihajlowitz, a Zeehan miner, produced many spectacular specimens from the Adelaide mine during the 1970's (Kovac, 1978). Andersen (1985) describes a pocket found in 1970 as measuring 2 by 2.5 m, with approximately 2000 specimens ranging between 2 cm and 45 cm across being recovered. More recently, Mike Phelan at the Red Lead mine has been the sole producer of specimens for the collector market.

The more notable Adelaide mine specimens consist of crystalline masses up to 45 cm across, with slender individual crystals up to 15 cm long. The crocoite typically occurs as bright red, slender, straw-like individual crystals and reticulated masses in a "limonite" gossan matrix.

The Kapi mine at Northeast Dundas has also produced some attractive specimens with yellow cerussite crystals perched on top of the crocoite. The crocoite crystals from this locality generally occur as fibrous crystalline masses on the surfaces of joint planes in the oxidized zone.

Dundasite $PbAl_2(CO_3)_2(OH)_4 \cdot H_2O$

The Adelaide mine at Dundas is the type locality for dundasite. It was first recorded as a new mineral species by Petterd (1893), who accurately described it as "composed of small spherical aggregates, usually closely matted together. Under the lens these bunches show an extremely fine radiating structure. The color internally is silky milk-white with a velvety outer crust of a dusty yellow-brown. The surface often has numerous adherent crystals of crocoite which [do] not rarely penetrate the mass."

Dundasite has been found in most of the Dundas mines, as well as the Kapi (Northeast Dundas) and the Hercules mine (Williamsford). The Adelaide has produced the best specimens; Andersen (1985) records one occurrence as yielding 150 specimens ranging in size from 2 cm to 40 cm across.

Liggins (1982) also describes a form of dundasite from the Comet mine consisting of pale blue spherules up to 5 mm across, overgrowing crocoite crystals.

Ferro-axinite $Ca_2Fe^{+2}Al_2BSi_4O_{15}(OH)$

The Colebrook Hill locality near Rosebery has produced attractive specimens of the iron-rich member of the axinite group. The host rock consists of massive veins of ferro-axinite and actinolite, with bands of sulfide ores, predominantly of pyrrhotite, chalcopyrite and arsenopyrite. Calcite and quartz are gangue minerals with datolite and danburite also recorded. The ferro-axinite is a deep brownish violet color and is often coarsely crystallized. Fine specimens are often obtained when etched from the calcite, yielding vugs up to 10 cm across lined with individual wedge-shaped crystals to 4 cm.

Fluorite CaF_2

The best Australian fluorites have come from the Mt. Cleveland tin mine at Luina. Specimens first became available to collectors in the early 1980's. The fluorite color ranges from translucent pale green through white to colorless, forming as individual cubes up to 10 cm across. Choice specimens consisting of quartz crystals up to 10 cm long combined with fluorite cubes have also been found. The quartz is often coated with groups of dolomite crystals. Pale blue to mauve, transparent fluorite crystals up to 4 cm have been found at the Hercules mine at Williamsford and at the Renison tin mine.

Gibbsite $Al(OH)_3$

Gibbsite is a common mineral in the Dundas mines. It occurs as white to cream crusts on gossan and as a coating on crocoite crystals. In recent years, chemical methods for removing it without harm to the underlying crocoite have been developed.

Heazlewoodite Ni_3S_2

The Lord Brassey mine at Heazlewood is the type locality for this mineral. It was first identified and described by Petterd (1896) as a sulfide of nickel and iron related to pentlandite, occurring in narrow bands in serpentine. However, the mineral was not fully analyzed at that time and it was considered a variety of pentlandite until Peacock (1947) established it as a separate mineral species. Heazlewoodite occurs as massive light yellow-bronze veins and blebs, associated with magnetite in serpentinite.

Hellyerite $NiCO_3$

Hellyerite was identified as a new mineral by Willams *et al.* (1959) from samples collected at the Lord Brassey mine at Heazlewood. It occurs as thin, pale blue coatings, associated with zaratite, on shear planes in serpentinite. It was named after Henry Hellyer, who was the Van Diemen's Land Company's surveyor in the 1820's. Binks (1980) describes the many journeys Hellyer made into the then-unexplored and inhospitable northwestern region of Tasmania. He was the first European to visit and describe the country around Waratah and Heazlewood.

Iridosmine (Os,Ir)

White metallic grains were found by alluvial miners when gold panning on the tributaries of the Pieman River, west of Waratah, during the 1890's. The metal was identified as an osmium-iridium mineral which became locally known as osmiridium. The presence of iridosmine in the gold reduced its value, as there was little use for it at that time.

The use of osmium as a hardening agent increased demand and hence its price and led to a boom in iridosmine mining in the 1920's. Substantial quantities were obtained from alluvial deposits along many of the creeks west of Waratah, with large nuggets, up to 120 grams, being recorded. The source of the iridosmine was traced to blebs in the serpentinite of Bald Hill at Heazlewood. Attempts were made to mine the deposit, but it was proved to be uneconomic.

Mawsonite $Cu_6^{+1}Fe_2^{+3}Sn^{+4}S_8$

Microscopic analysis of bornite ore specimens from Mt. Lyell and Tingha (in N.S.W.) by Markham and Lawrence (1965) identified a

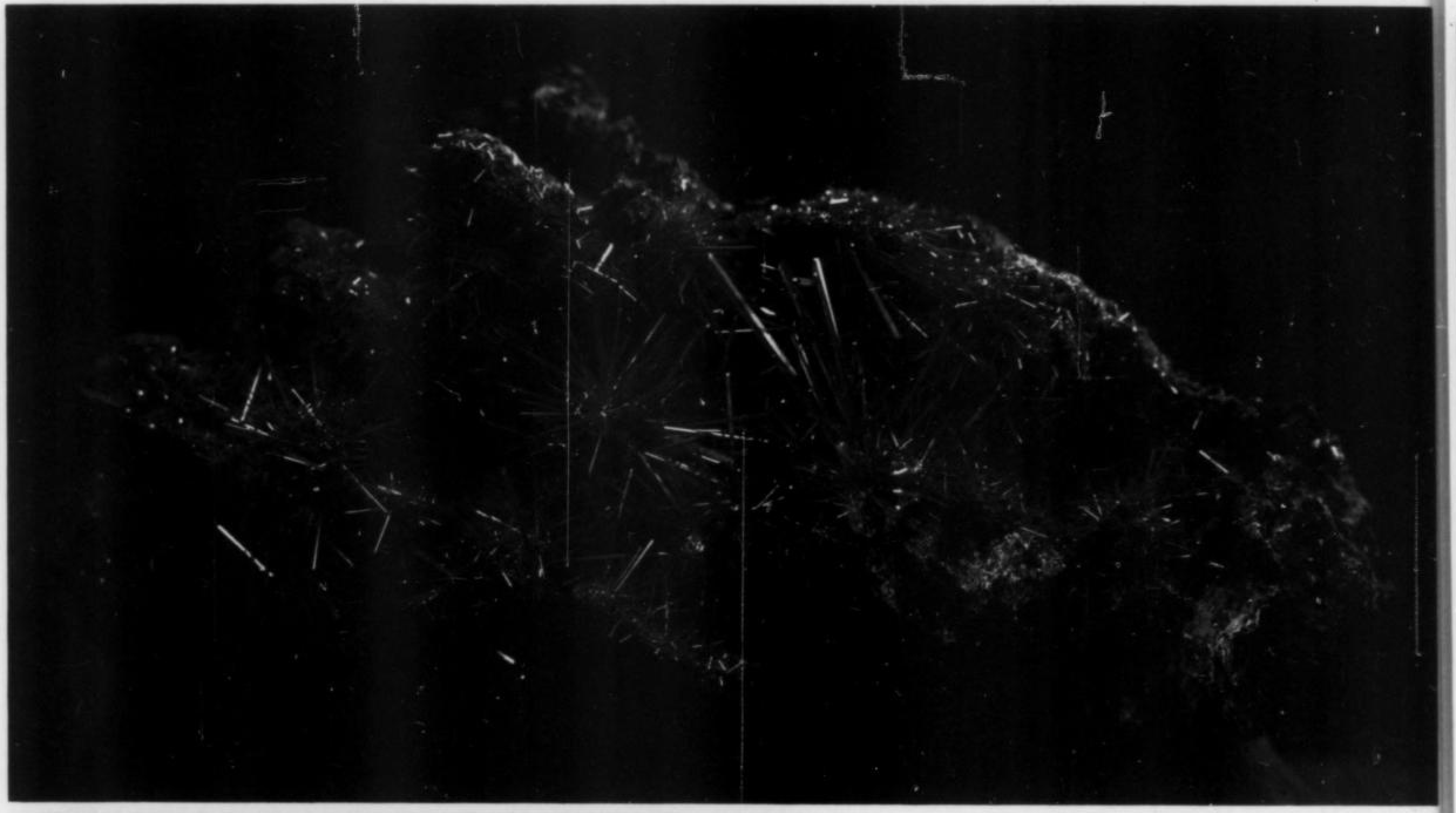
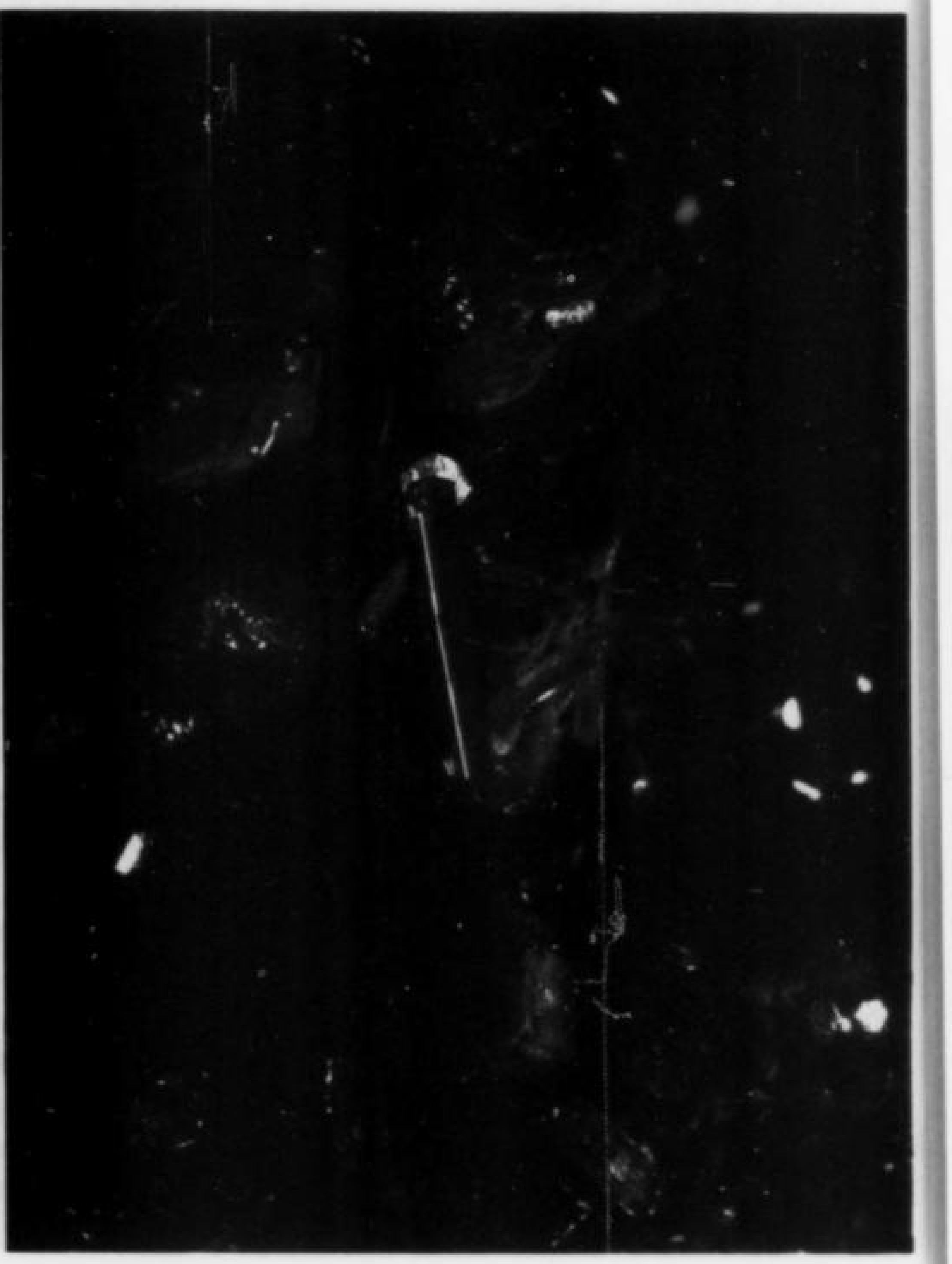


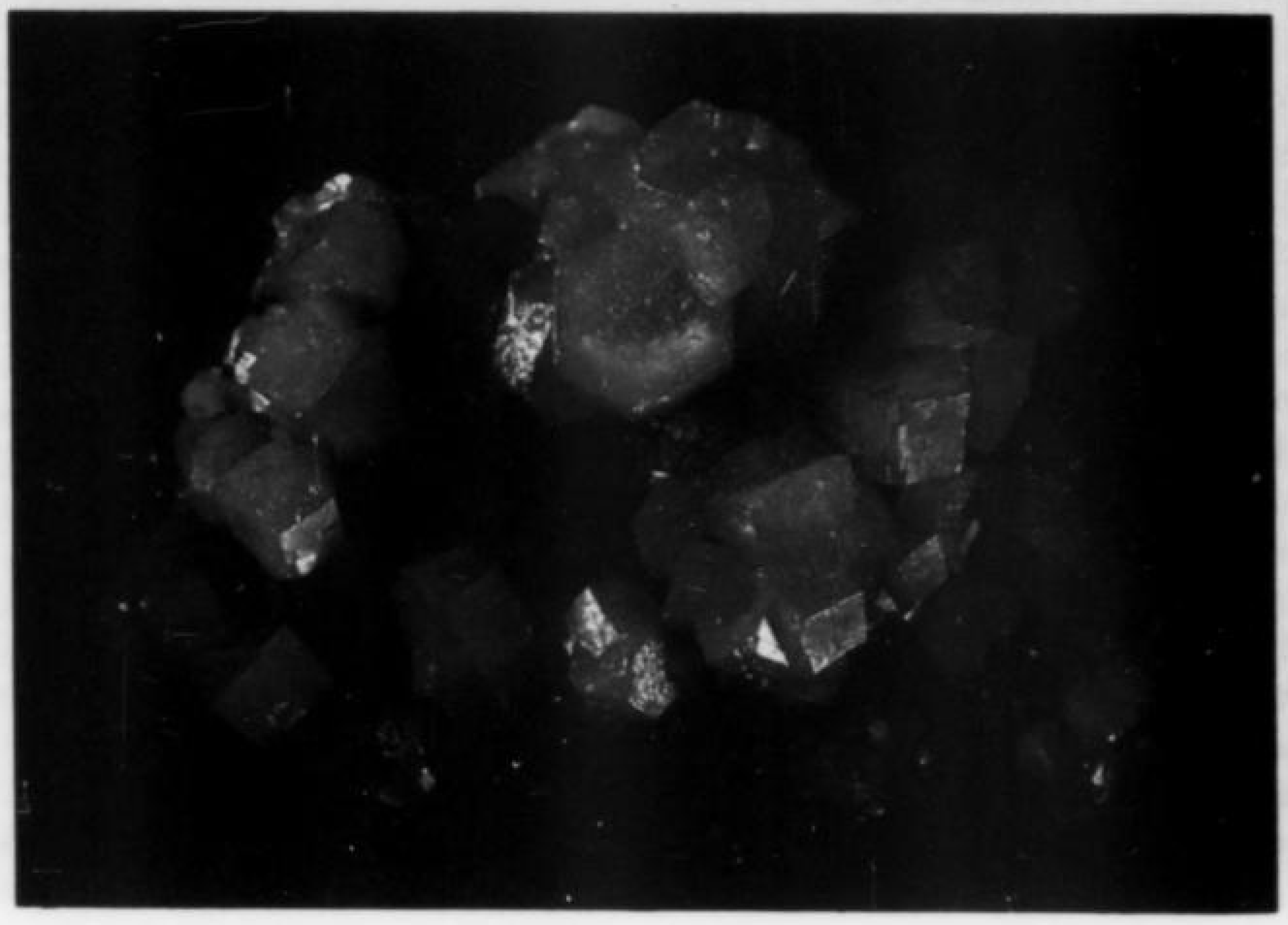
Figure 6. Above Crocoite, Adelaide mine. B. Shelton collection; photo by Latrobe Studios.

Figure 7. (Left) Crocoite group, 4 cm, Red Lead mine. B. Shelton collection; photo by Frank Coffa.

Figure 8. (Lower Left) Pyromorphite group, 3 cm, Sylvester mine. B. Shelton collection; F. Coffa photo.

Figure 9. (Below) Pyromorphite and crocoite crystals to 3 mm, Kosminski mine. Museum of Victoria collection; photo by F. Coffa.





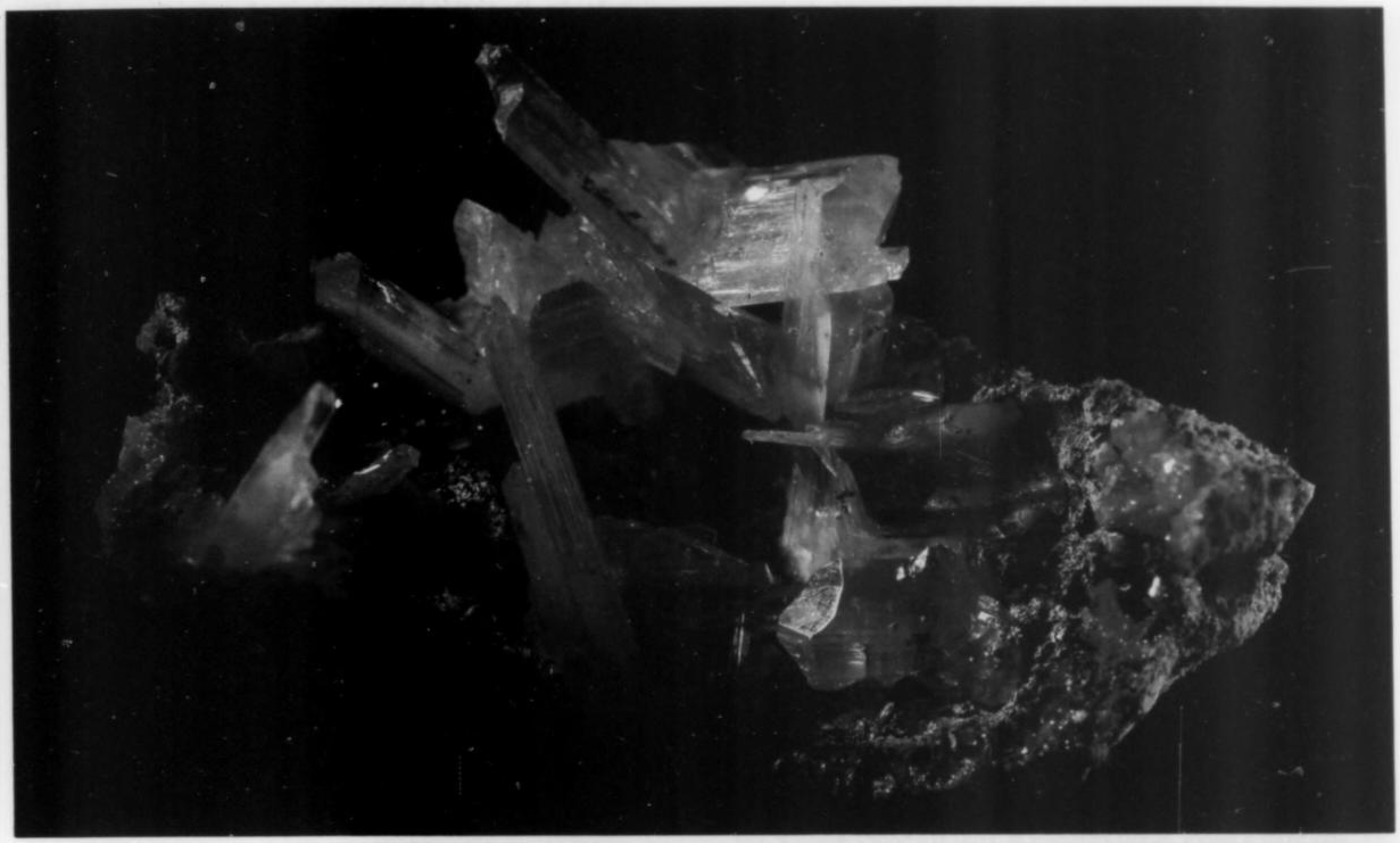
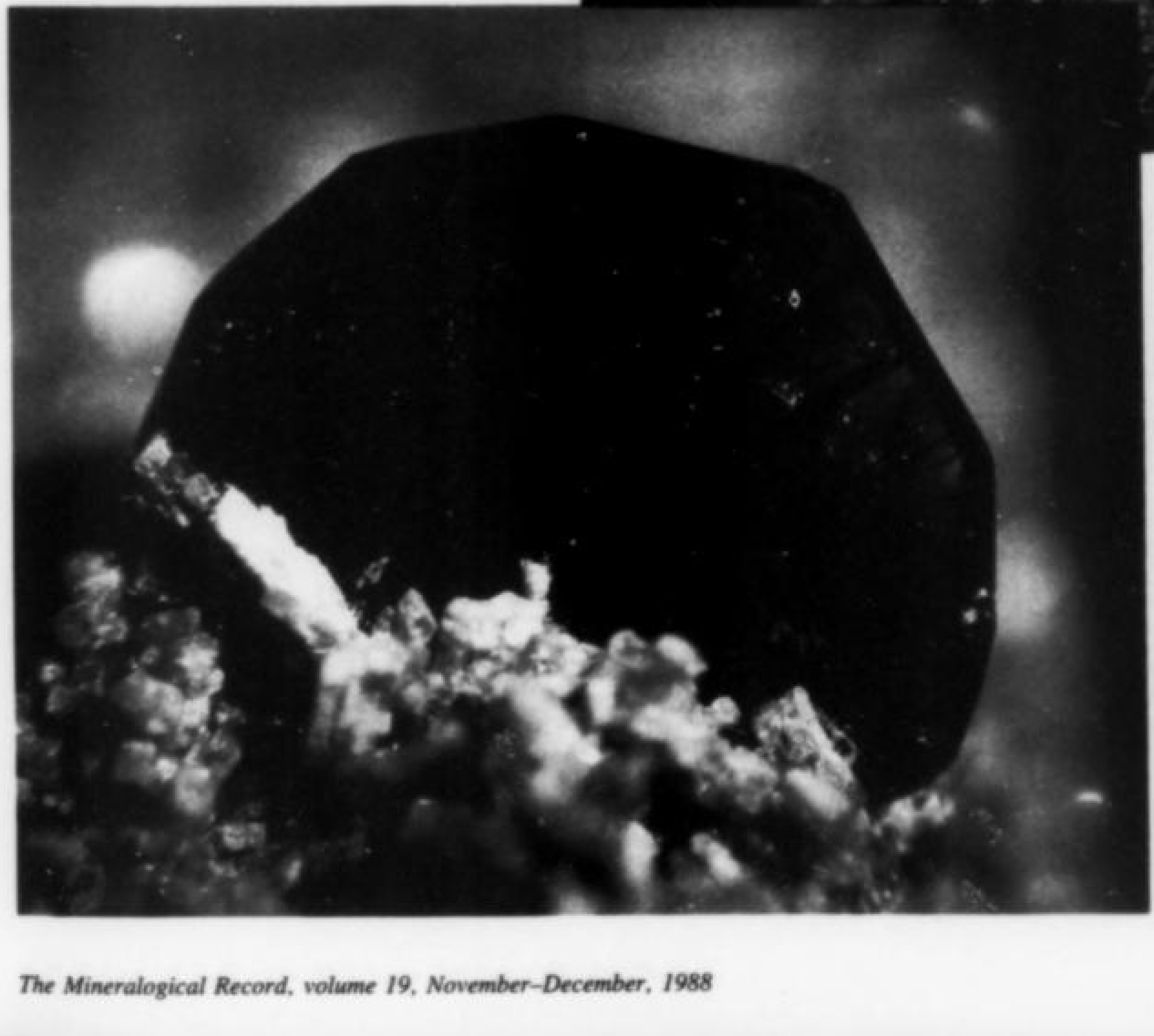


Figure 10. (Above) **Cerussite group, 4 cm, Kapi mine. B. Shelton collection; photo by F. Coffa.**

Figure 11. (Right) **Cerussite with crocoite, 6 cm, Dundas. Museum of Victoria collection; photo by J. Haupt.**

Figure 12. **Rhodochrosite with quartz, 2.5 cm, Hercules mine. M. Newnham collection; photo by J. Haupt.**

Figure 13 (Below) **Ferro-axinite crystal, 3 mm, Colebrook Hill. J. Haupt coll. and photo.**



new mineral which they named after the distinguished Australian geologist and Antarctic explorer, Sir Douglas Mawson. Mawsonite is one of several minerals previously described as "orange bornite" but which had not been characterized. Mawsonite occurs as small, irregular, orange-colored inclusions up to 1 mm across, in bornite.

Philipbornite $PbAl_3(AsO_4)_2(OH)_5 \cdot H_2O$

This mineral was described as a new mineral species by Walenta, Zwiener and Dunn (1982), from a Dundas-area mine (probably the Red Lead). It occurs as grayish green earthy crusts, associated with crocoite.

Pyromorphite $Pb_5(PO_4)_3Cl$

Pyromorphite has been recorded from many of the mines in the region. Interesting specimens have come from the Adelaide and Kosminsky mines at Dundas, where it occurs as pale yellow-green, hexagonal crystals up to 5 mm long, occasionally associated with crocoite. The Sylvester mine at Zeehan has also produced attractive pyromorphite specimens consisting of deep olive-green crystals up to 5 mm long in both fibrous and hexagonal forms. Pseudomorphs of hinsdalite after pyromorphite have also been found at this locality (Birch, 1977).

Rhodochrosite $MnCO_3$

Attractive specimens of pink rhodochrosite in rhombohedral crystals to 1 cm have come from the Hercules mine at Williamsford.

Shandite $Pb_2Ni_3S_2$

Shandite was first identified as a new mineral species by Ramdohr in 1949. It was found as small grains in polished sections of nickel ore, and from a minor nickel prospect at Trial Harbour (Peacock and McAndrew, 1950).

Stichtite $Mg_6Cr_2(CO_3)(OH)_{16} \cdot H_2O$

Stichtite was first found in Tasmania in 1891, but was referred to as kämmererite until 1910 when it was analyzed and described by Petterd as a new mineral species (Twelvetrees, 1914). It was named after Robert Sticht, the then General Manager of the Mt. Lyell Mining and Railway Company. The type locality is Stichtite Hill, above the Adelaide mine, at Dundas.

It is a chromian serpentine and forms as lilac-colored formless masses with serpentinite. It has been reported from several other localities in the region, the most notable being Tunnel Hill near Renison Bell. Here Lancaster (1977a) describes a 10 cm wide seam that was mined to produce the fine specimens that are seen in collections today.

Vivianite $Fe_3^{+2}(PO_4)_2 \cdot 8H_2O$

Little has been recorded of the vivianite occurrence at the Mt. Cleveland tin mine at Luina. Magnificent specimens of long slender crystals and crystal groups, up to 12 cm long, on quartz have come from this mine. The crystals are heavily striated parallel to their length and are a characteristic deep blue-green color.

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VOLCANIC ZEOLITES AND ASSOCIATED MINERALS

from New South Wales

●

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Extrusive volcanism has formed a significant part of the geological history of New South Wales since the Carboniferous period, and extensive outcrops of volcanic rocks are widespread throughout the eastern part of the state. Many of these outcrops contain vesicles lined with zeolites and associated secondary minerals, giving enormous potential for field collecting.

INTRODUCTION

New South Wales, like much of eastern Australia, has had a long history of episodic volcanism since the Carboniferous period. This volcanism arose from both active plate margin events and more stable intraplate events associated with the break-up of the Gondwanan supercontinent in stages (Veevers, 1984). Basaltic volcanism became increasingly dominant, as the Australian plate evolved through rifting and sea-floor spreading along its margins (Sutherland, 1985). This left a legacy of highly suitable host rocks and processes for the development of secondary mineral associations. The distribution of zeolite-bearing volcanic rocks in New South Wales is shown in Figure 1.

Some of the volcanic sites that have yielded noteworthy zeolitic occurrences, either for well crystallized species or the rarer zeolites, are described. A geochronological framework is adopted in describing the suites, because the older sequences are more varied in rock types. This would affect the initial chemistry of solutions involved in secondary deposition and would encompass low-grade metamorphic alteration resulting from tectonic events.

The New South Wales zeolites show many similarities to those described from basaltic areas in southeastern Australia, with some exceptions. There is little development of zeolites in aquagene volcanics (pillow lavas, hyaloclastite tuffs and breccias and flow foot breccias), a feature of Tasmanian basalts, where such zeolite suites are associated with hydrated calcium silicates such as tacharanite (Sutherland, 1976, 1980). Younger basaltic volcanics (less than 10 m.y.) are also absent, whereas in western and central Victoria they have yielded some classic localities for zeolites (Hollis, 1979; Vince, 1980). Phillipsite, a relatively rare zeolite in New South Wales, is often present in both the younger and some of the older basalts from Victoria (Birch *et al.*, 1979; Coulsell, 1980), and Tasmania. Some rare zeolites that were first identified in New South Wales suites (ferrierite: England and Ostwald, 1978; levyne: England and Ostwald, 1979), were described in Victoria and Tasmania shortly afterwards (Birch and Morvell, 1978; Birch, 1979; Andersen, 1984). Other rare zeolites found in the Victorian-Tasmanian basalts (gmelinite, gonnardite: Tasmania Department of Mines, 1970; Birch, 1976) have been recently identified in New South Wales (this paper). Gmelinite (equivalent to Victorian "herschelite") was described from Inverell, New South Wales, by Liversidge (1888), but his analysis conformed to that of chabazite.

An extensive source of zeolites in Tasmania, the Jurassic dolerites (chabazite, stilbite, scolecite, laumontite), has no equivalent in mainland Australia where zeolites in doleritic intrusions of similar age are rather limited (Sutherland, 1977). Zeolites are recorded from scattered

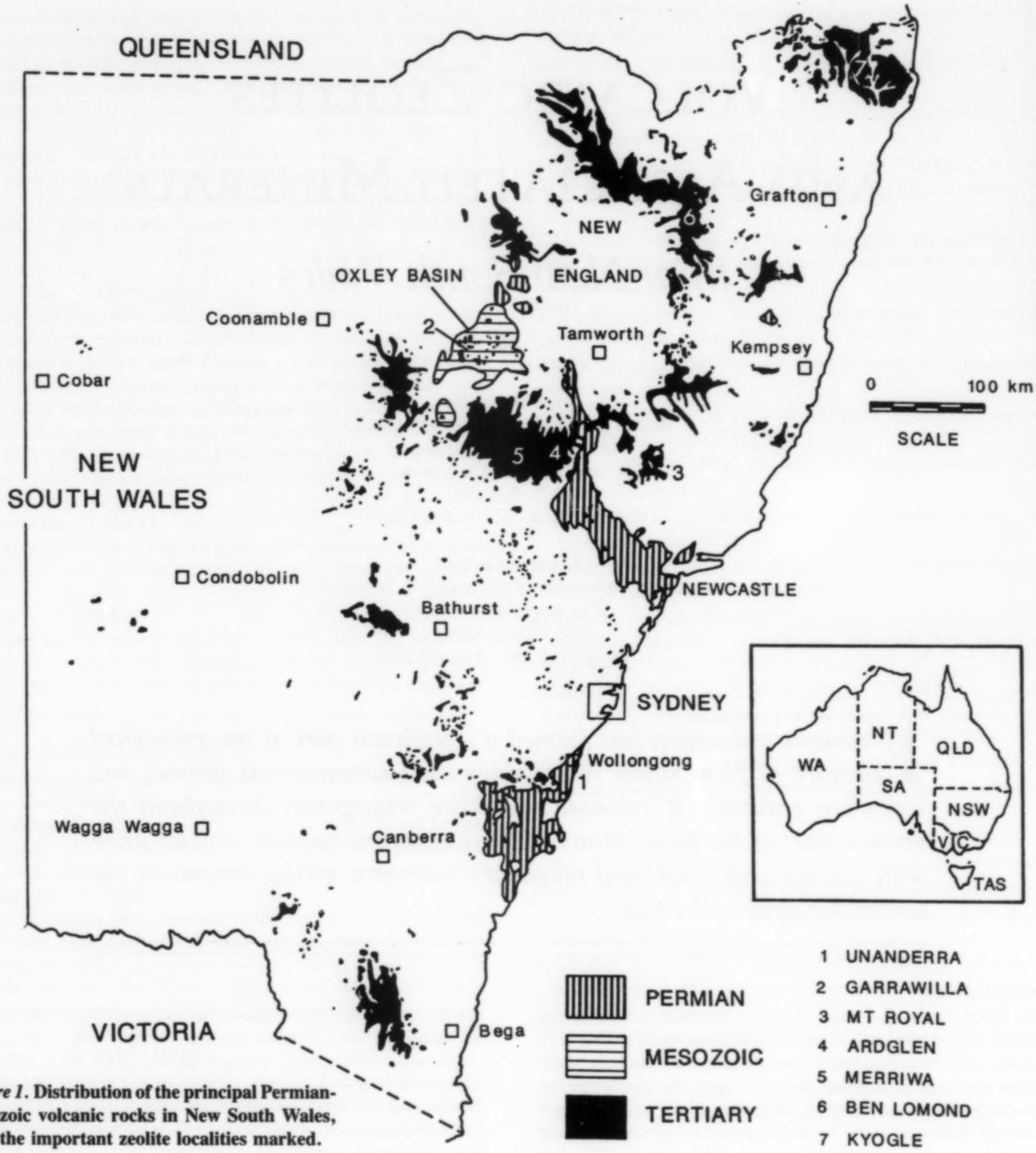


***Figure 1.* Distribution of the principal Permian-Cenozoic volcanic rocks in New South Wales, with the important zeolite localities marked.**

localities in Permian to Cenozoic volcanics in Queensland (Dunstan, 1913), but lack of published detailed studies makes comparisons with suites from southeastern Australia difficult. Barium zeolites are scarce in southeastern Australia, but harmotome and barian phillipsite are known from vesicles in garnet pyroxenite xenoliths from a Quaternary volcanic breccia near Proston, Queensland (Sutherland, unpublished data). Zeolites in Cretaceous volcanic rocks have been scarcely studied in New South Wales. The state lacks widespread development of these rocks, as compared with voluminous volcaniclastic sediments found in the Otway Basin, Victoria, where plagioclase-heulandite-clinoptilolite assemblages pass down into an albite-laumontite assemblage at burial depths exceeding 1200–1500 m in the 3-km-thick Cretaceous sequence (Duddy, 1980).

The study of zeolites in eastern Australia has generally followed research developments elsewhere. However, work on phacolite varieties of chabazite from Melbourne, Victoria, played an important part in unraveling the mineralogical status of herschelite (Vince, 1980). A study of natrolite arches from Flinders, Victoria, is novel for suggesting whisker growth (Henderson and Garland, 1986). Work on the Tasmanian zeolite suites revealed some associated minerals previously considered much more limited in natural abundance (tacharanite: Sutherland, 1976; vaterite: Matsubara *et al.*, 1981). Among descriptions of New South Wales zeolites there are the excellent early crystallographic studies by the mineralogists at the Australian Museum (Anderson, 1907; Hodge-Smith, 1924, 1929). Some experiments on solubility of basalt were used to demonstrate an extraneous cold-water

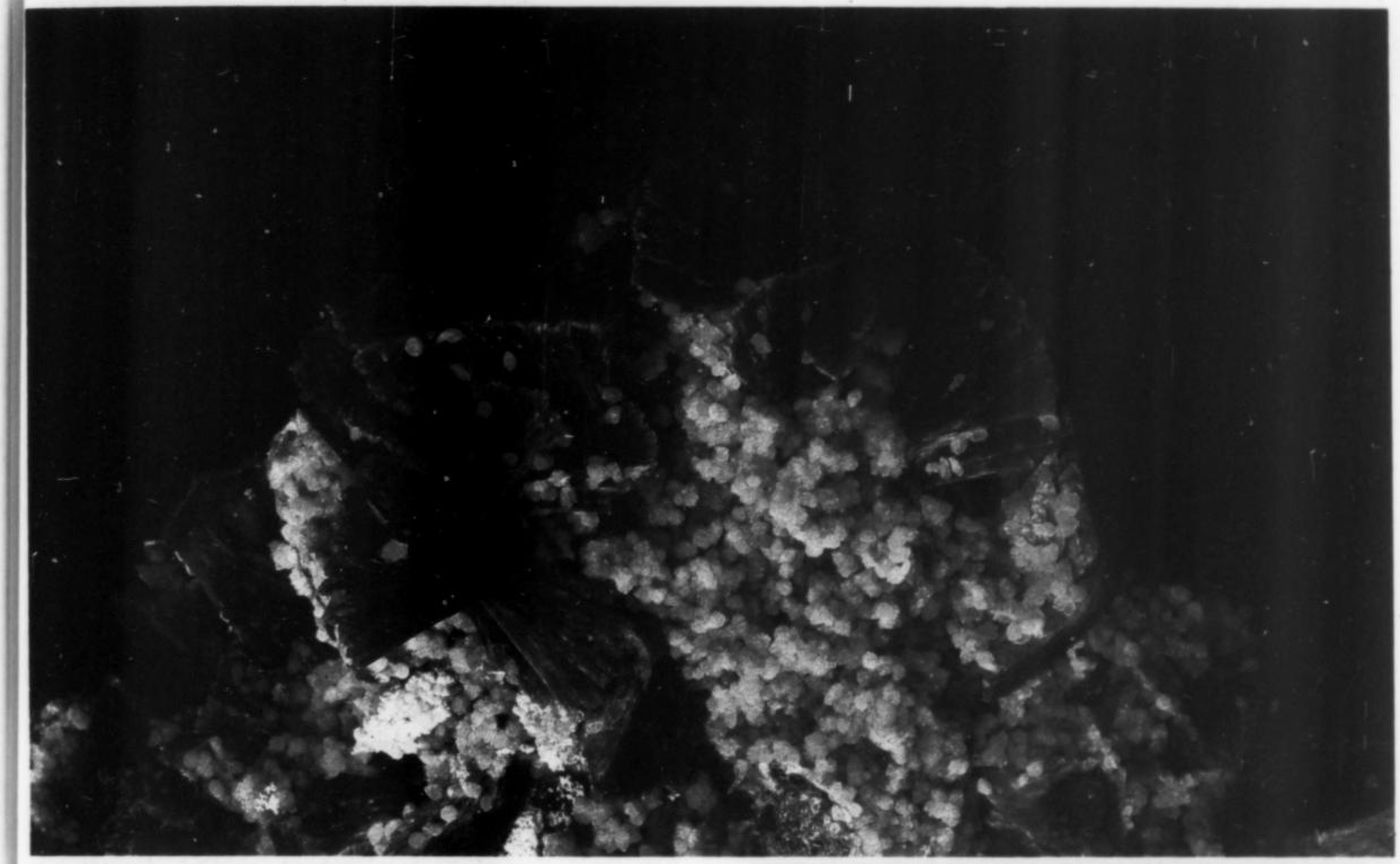
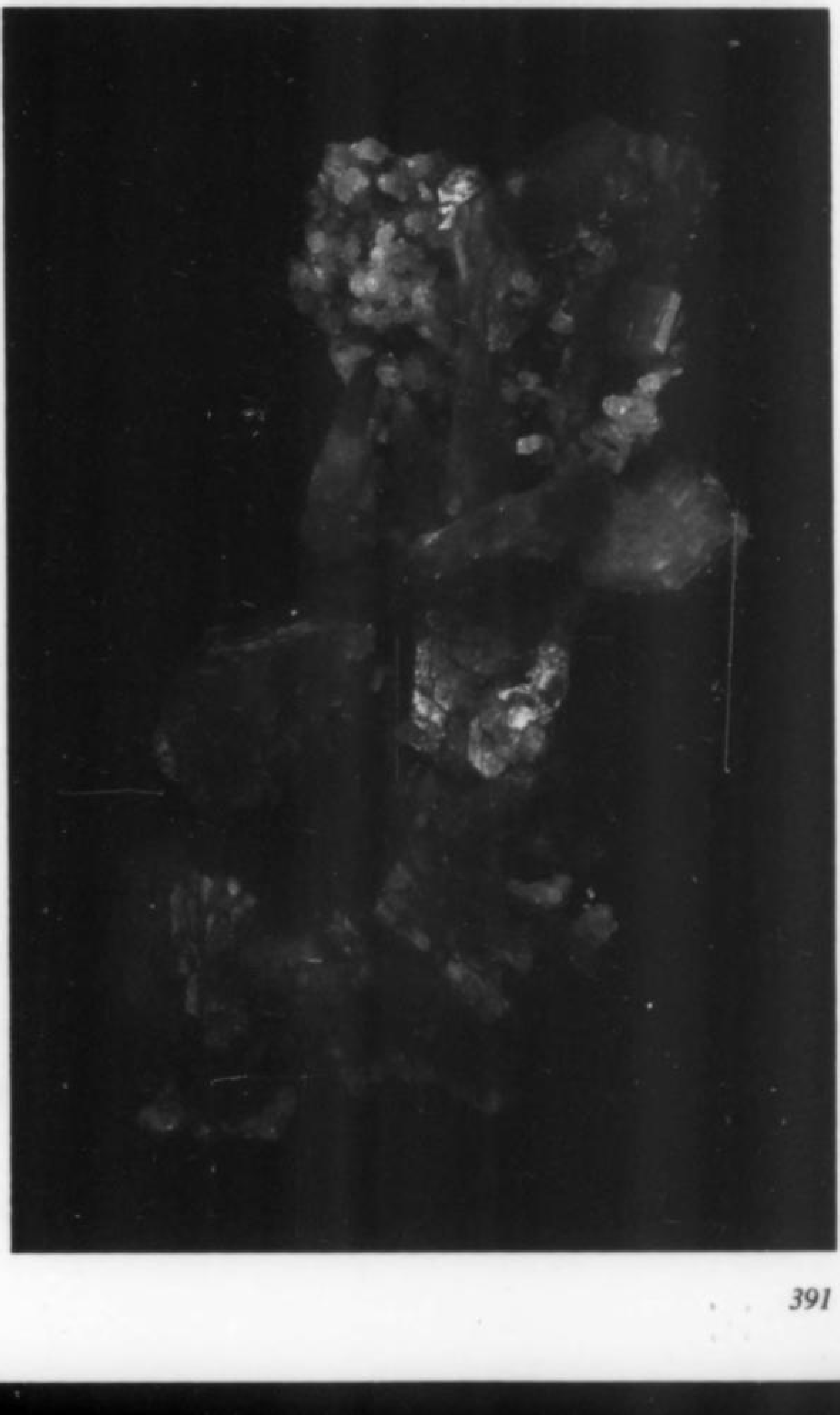


Figure 2. **Fans of orange heulandite associated with later white drusy quartz from the Garrawilla volcanics. Specimen as pictured is 12 cm across. Janet and Brian Head specimen. Photograph by Brian M. England.**

Figure 3. **Slightly divergent groups of pale peach-pink stellerite crystals from the Garrawilla volcanics associated with minor spherulitic white quartz. Specimen is 15 cm in length. Brian M. England specimen (M77.4.7) and photograph.**



deposition of zeolites in the Barrington area, including heulandite as an atypical low-temperature type (Nashar and Basden, 1965).

Australian zeolites were mentioned in a Dutch account in 1840, but were unlocalized (Liversidge, 1888). Stilbite was one of the first minerals of an "uneconomic" nature from New South Wales to arouse scientific interest, following its reported occurrence by Stutchbury in 1853 (Chalmers, 1934). Since then some 18 zeolite species have been described from New South Wales. Not included in this paper are zeolites in the more altered pre-Permian volcanic sequences, such as the clinoptilolite which is common in the Carboniferous tuffs of the Hunter Valley.

ZEOLITES IN PERMIAN VOLCANICS

Secondary minerals in early Permian volcanic sequences have been studied along the Hunter-Mooki thrust fault system, stretching 250 km from Newcastle into the New England area (Nashar and Purvis, 1971). These volcanics include lavas, breccias and froth flows, with olivine basalts predominating over more silica-saturated basalts, andesites and, locally, trachyandesites. Some horizons in these rocks are highly altered. Zeolites identified in the secondary assemblages include mordenite, heulandite, stilbite, laumontite, analcime, mesolite, scolecite, thomsonite and natrolite. Quartz, calcite, prehnite, epidote, pumpellyite, datolite and titanite are accompanying species, together with chlorite, iron/titanium oxides, pyrite, montmorillonite and celadonite.

Three partially overlapping zeolite assemblages have been recognized:

(1) Quartz, mordenite, stilbite and/or heulandite, analcime, mesolite, laumontite, scolecite and thomsonite.

(2) Laumontite, prehnite, analcime and thomsonite.

(3) Laumontite, mesolite, prehnite and thomsonite

Local developments of natrolite-mesolite may represent equivalents of the analcime-thomsonite assemblages and, similarly, stilbite-scolecite assemblages may replace laumontite assemblages. The widespread occurrence of both laumontite and stilbite and an absence of laumontite-quartz assemblages suggest zeolitic alteration at temperatures close to the upper limit of stilbite stability (195–200°C), although the prevalence of prehnite and absence of stilbite in some areas suggest locally higher temperatures. The rocks are affected by regional tectonism (Roberts and Engel, 1987), complicating resolution of deuteric and metamorphic alterations.

Comparatively little crystallographic and chemical data are available on the zeolites themselves. Scolecite from Werris Creek, associated with heulandite and stilbite in decomposed andesite, was analyzed by Anderson (1907) and the heulandite was given the forms *b*{010}, *m*{110}, *x*{021}, *t*{201}, *u*{$\bar{1}$11} and *s*{$\bar{2}$01}.

Several zeolite localities are recorded in late Permian volcanic rocks in the southern Sydney Basin (Chalmers, 1967). These occur within members of a potassium-rich basalt (latite), basaltic andesite and andesite volcanic series (Carr, 1985), in which heulandite, laumontite, stilbite, prehnite, calcite, analcime, natrolite, chabazite and some rare zeolites are recorded. The assemblage has been considered deuteric in origin, rather than resulting from much later infillings. However, in a detailed study, Raam (1968) examined the zeolite assemblages in both the altered submarine volcanics and the enclosing 165-m-thick sequence of conglomerates, sandstones and siltstones in the Kiama area. He found albite, calcite, chlorite, clay minerals and laumontite to be common authigenic minerals in the sediments whereas prehnite, pumpellyite, epidote and titanite were additional minerals in the volcanics. Thus the laumontite is not solely deuteric and low-grade "burial" metamorphism alone could not account for the assemblage, as the rocks have lain at depths of less than 1000 m. The rocks were not subjected to the early Permian folding of the Sydney Basin, so that zeolitization probably resulted from later thermal events and may be related to a high heat flow (up to 200°C) during late Cretaceous rifting of the Tasman margin at around 90 m.y. (Embleton *et al.*, 1985).

Of those localities which have provided specimens for the collector, only the occurrence at Unanderra has been studied in detail.

Unanderra

A quarry in Permian latite 3.5 km south of Unanderra, on the South Coast of New South Wales, has provided outstanding specimens of the rare magnesian zeolite ferrierite in association with calcite, laumontite and heulandite. The quarry was operated by the Wollongong City Council as a source of roadbase during construction of the F6 Southern Freeway and ceased operation on completion of that project. It has since been used as a garbage disposal site. Specimens were also collected from a large cutting on the Freeway adjacent to the quarry. The occurrence has been described in detail by England and Ostwald (1978) and it is from this paper that much of the following description has been drawn.

The ferrierite and associated minerals were found in large, isolated vesicles in the Dapto latite member of the Permian Shoalhaven Group, outcropping between Dapto and Unanderra and partially overlain by Permian sediments of the Pheasant's Nest Formation (Bowman, 1970). The latite exposed in the quarry was distinctly porphyritic in texture, with plagioclase (labradorite) crystals to 1 cm long.

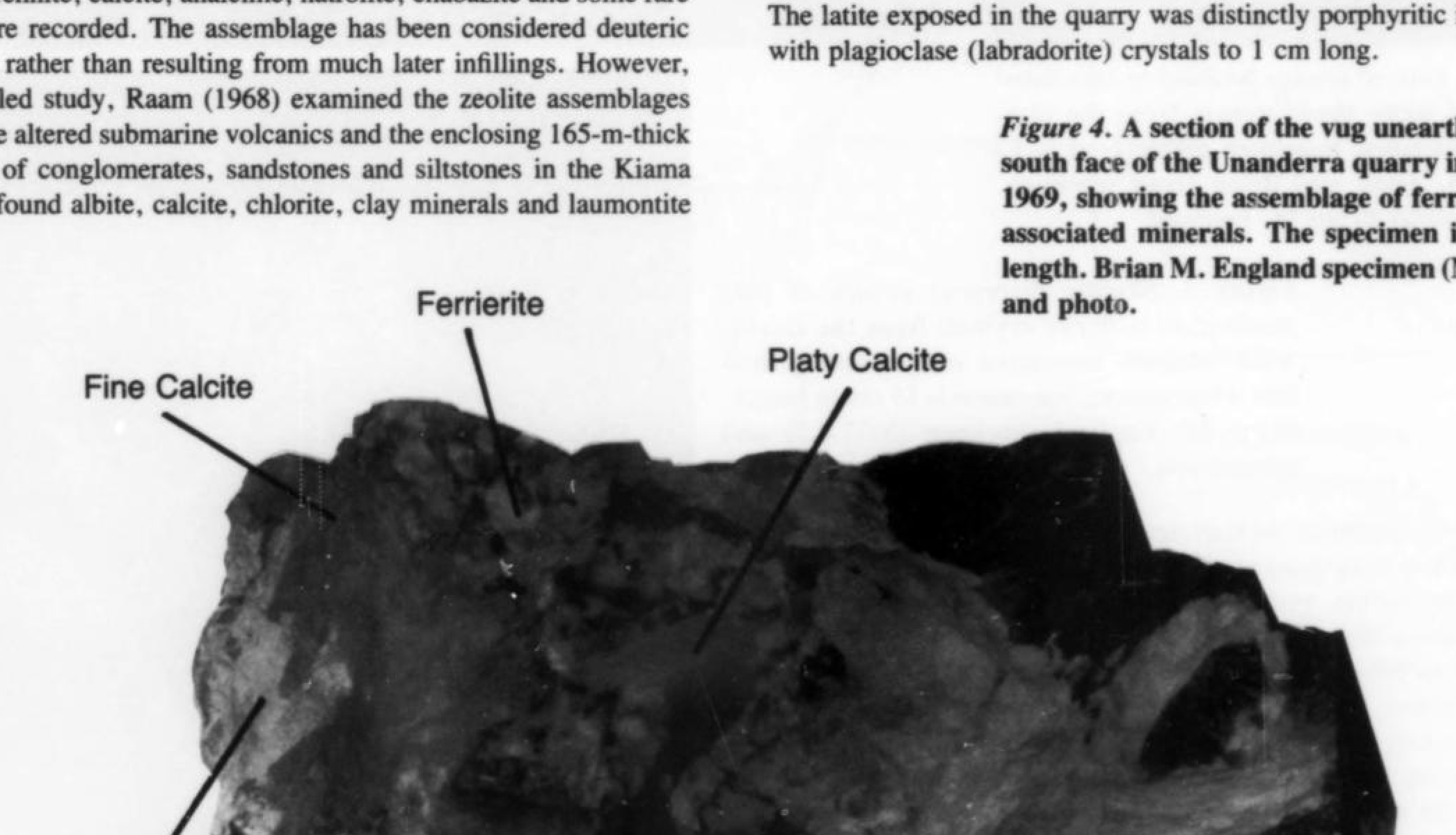
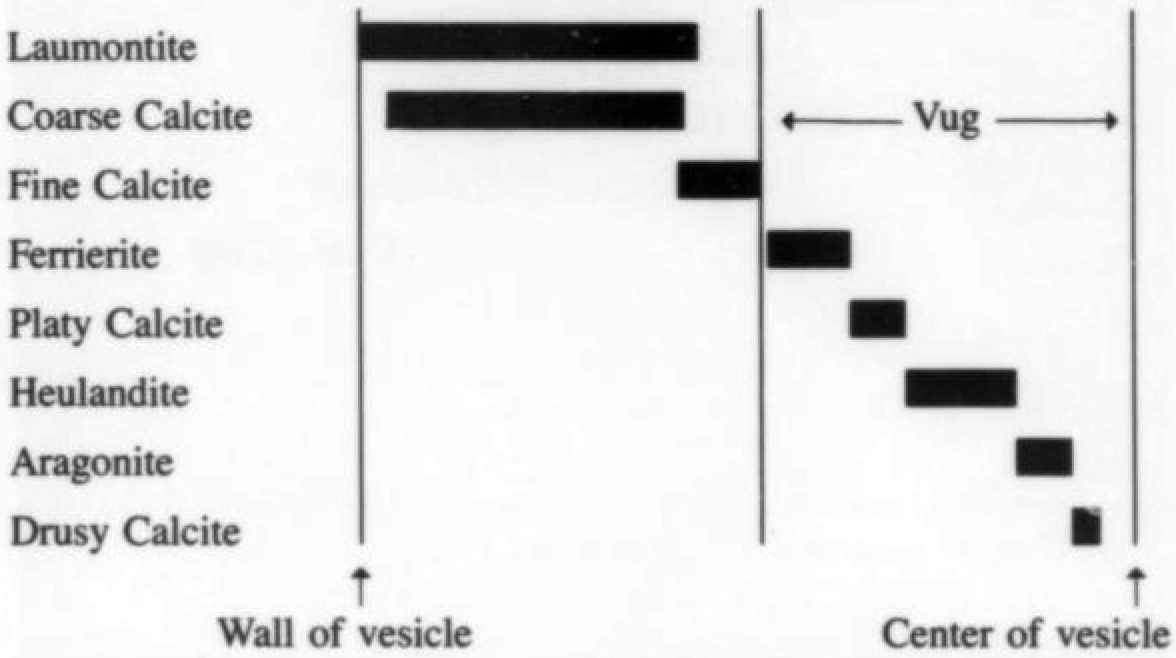


***Figure 4.* A section of the vug unearthed in the south face of the Unanderra quarry in October 1969, showing the assemblage of ferrierite and associated minerals. The specimen is 7 cm in length. Brian M. England specimen (M69.10.2) and photo.**

The finest specimens were located in October 1969 by one of the authors (B.M.E.) in the company of Barry Cole (Epping, Sydney), shortly after the closure of the quarry. At that time the locality represented the first occurence of ferrierite in the Southern Hemisphere and the fourth in the world.

An observed paragenetic sequence of the secondary minerals found at Unanderra, based on the close examination of the limited number of specimens preserved in the collection of one of the authors (B.M.E.) and Barry Cole, is presented in Table 1.

Table 1. **Paragenetic sequence of zeolites and associated secondary minerals in the Dapto latite.**



Aragonite $CaCO_3$

Divergent sprays of colorless, prismatic aragonite crystals up to 2 cm long were occasionally found associated with earlier heulandite in vesicles.

Calcite $CaCO_3$

Calcite was the most abundant of the secondary minerals at Unanderra, to the extent that it almost entirely filled many of the larger vesicles. The most notable occurrence was one very large vesicle in the south face of the quarry occupied by coarsely crystalline fawn-colored and brown calcite, with cleavage faces reaching 30 cm. Specimens from this vesicle are strongly fluorescent in longwave ultraviolet light, the fawn calcite showing bright yellow fluorescence and the brown a patchy orange, revealing growth zoning not otherwise visible. It was a cavity in the center of this vesicle which provided the finest ferrierite/heulandite specimens. Other large vesicles were found to contain unusual, coarsely reticulated sheets of calcite composed of small colorless to white rhombohedra of the form $r\{10\bar{1}1\}$.

In cavities within the larger vesicles, calcite occasionally occurred as colorless crystals of the form $r\{10\bar{1}1\}$ up to 1 cm in diameter, but was more common as platy white crystals rarely more than 0.1 mm thick and up to 3 cm across, arranged in scattered subparallel groups on ferrierite/heulandite. Crystals with this habit were also found filling many of the smaller vesicles, in which the coarse, cleavable calcite was totally absent.

Ferrierite $(Na,K)_2MgAl_3Si_{15}O_{36}(OH)\cdot 9H_2O$

Vesicles in the Dapto latite have provided some of the finest specimens of ferrierite ever found. The best were found lining an irregular cavity approximately 30 cm in diameter near the center of a mass of coarsely crystalline fawn-colored and brown calcite. Part of this cavity, showing the ferrierite and associated minerals, is pictured in Figure 4.

The ferrierite occurred as bladed, white, acicular crystals arranged in divergent to hemispherical groups averaging 2.5 mm in diameter deposited directly on lightly iron-stained and roughly surfaced "nailhead" calcite crystals forming the wall of the cavity. The only associated minerals are well formed, colorless crystals of heulandite and the unusual platy calcite described above. Unanderra ferrierite typically shows the orthorhombic pinacoids *a*{100} and *b*{010} terminated by *c*{001} and *d*{101}.

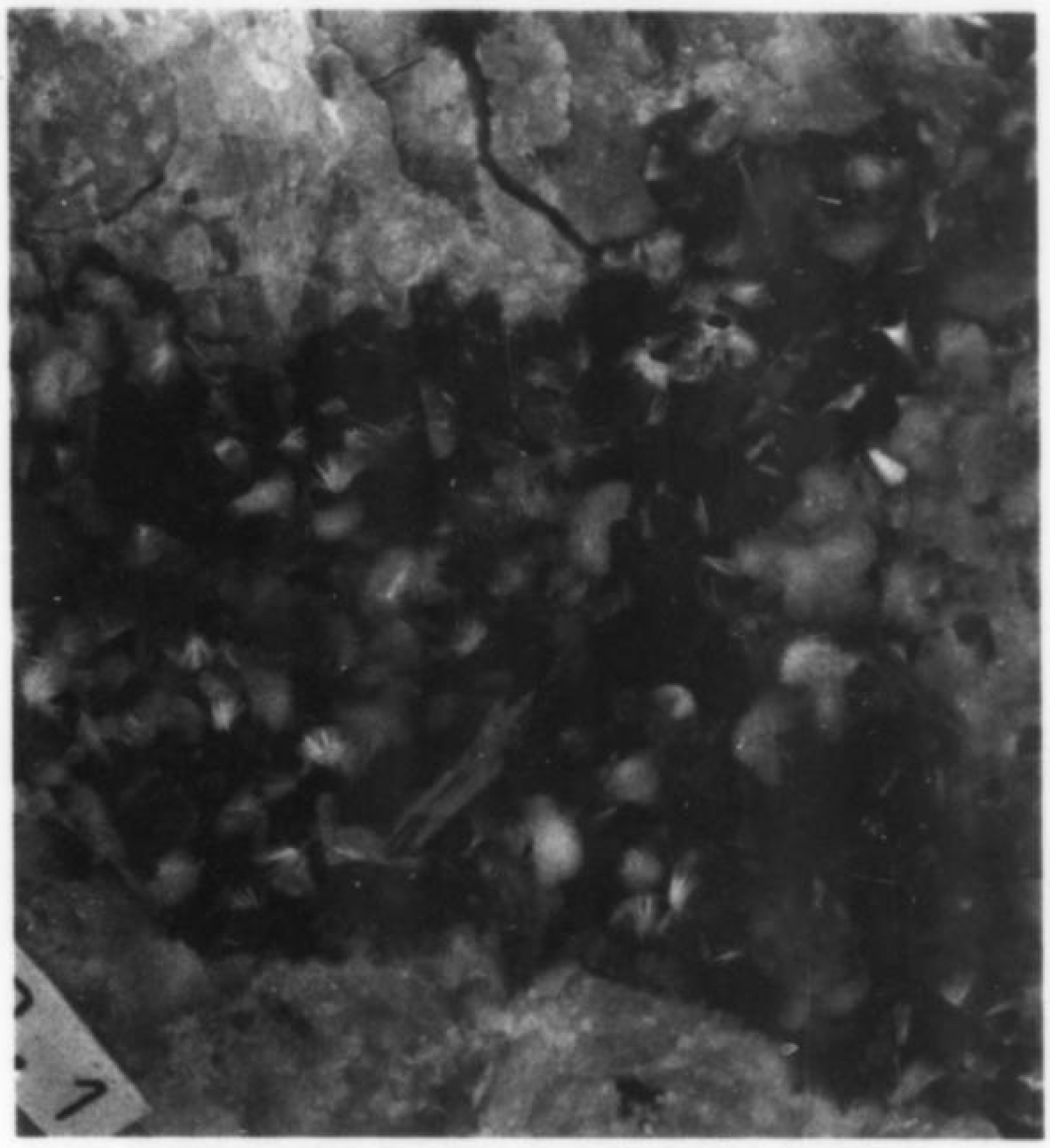


Figure 5. **Radiating groups of white bladed ferrierite crystals to 2 mm, with prismatic colorless heulandite and minor platy white calcite in a cavity in massive fine grained calcite rimmed by laumontite from Unanderra. Brian M. England specimen and photograph.**

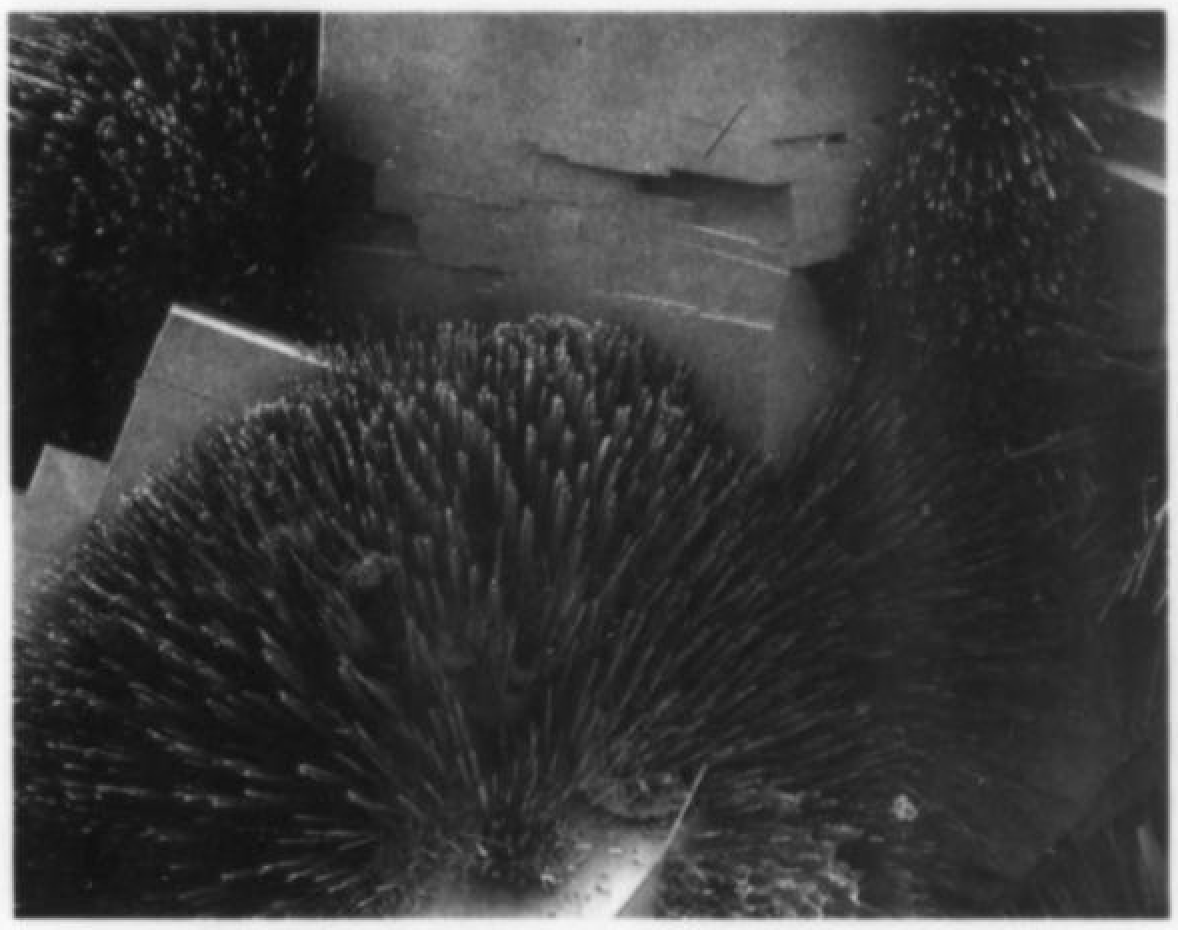


Figure 6. **Radiating to spherical groups of ferrierite crystals from Unanderra, associated with well formed transparent crystals of heulandite. Field of view is 2.5 mm in length. Scanning electron micrograph by Brian M. England.**

Wavelength-dispersive electron probe microanalysis of Unanderra ferrierite showed unusually high SrO and significantly lower K_2O and Na_2O compared to other analyzed ferrierites (England and Ostwald, 1978).

In some ferrierite/heulandite-lined cavities the ferrierite was subsequently preferentially coated by drusy calcite in etched crystals having the form $r\{10\bar{1}1\}$, giving the ferrierite the appearance of compact, radiating, spherical groups.

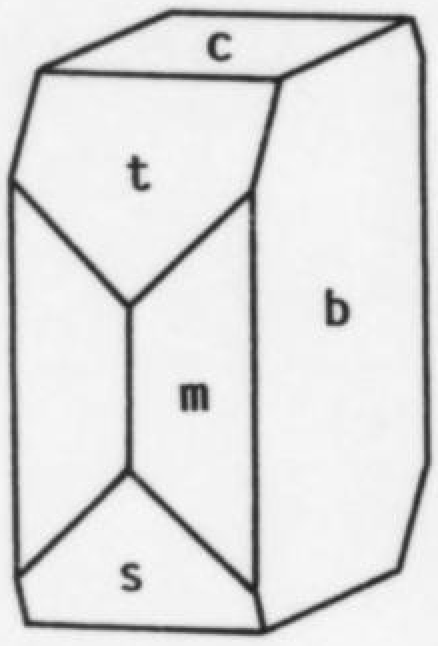


Figure 7. **Drawing of a typical heulandite crystal from the Dapto latite at Unanderra, showing the forms $c\{001\}$, $t\{101\}$, $m\{110\}$, $s\{10\bar{1}\}$ and $b\{010\}$. Drawing by Brian M. England from specimens in the Brian M. England collection.**

Heulandite $(Na,Ca)_{2-3}Al_3(Al,Si)_2Si_{13}O_{36}\cdot 12H_2O$

Heulandite was most commonly found as vesicle linings associated with later aragonite. It was also found with ferrierite and platy calcite lining irregular cavities in massive calcite bodies occupying the larger vesicles. It occurs as prismatic, colorless crystals up to 5 mm long consisting of the forms $c\{001\}$, $t\{101\}$, $m\{110\}$, $s\{10\bar{1}\}$ and $b\{010\}$, thickly encrusting vesicle walls or scattered over the calcite cavity linings, partially enveloping any earlier ferrierite or platy calcite. Occasionally, small glassy heulandite crystals were seen to be supported and often completely penetrated by groups of divergent ferrierite blades.

Laumontite $CaAl_2Si_4O_{12}\cdot 4H_2O$

Laumontite was the first of the secondary minerals to form and occurred as large idiomorphic prismatic crystals up to 5 cm long, invariably enclosed by later fawn-colored and/or brown calcite. Much of the laumontite dehydrated rapidly on exposure to powdery "leonhardite" and its abundance in the vesicle linings made the preservation of ferrierite/heulandite specimens very difficult. As a result, many of the fine specimens collected from this occurrence have since disintegrated despite repeated and varied attempts to arrest this process.

ZEOLITES IN MESOZOIC VOLCANICS

Some exceptional specimens of stellerite and heulandite have been recovered from the volcanics within the Oxley Basin in northern New South Wales. Pyroclastic deposits and flows, which range from olivine basalts to trachytes in composition, occurring within the sedimentary sequence have been intruded by domes of trachyte and phonolite. This activity dates from the Triassic to Jurassic periods (206–149 m.y.; Dalhunty and McDougall, 1966; Bean, 1974; Ewart *et al.*, 1985; Dalhunty, 1986). The main pockets of zeolitization lie within the Jurassic Garrawilla volcanics in the Garrawilla area near Coonabarrabran, where some 90 localities have been collected from and described (Chalmers, 1934; Head, 1979).

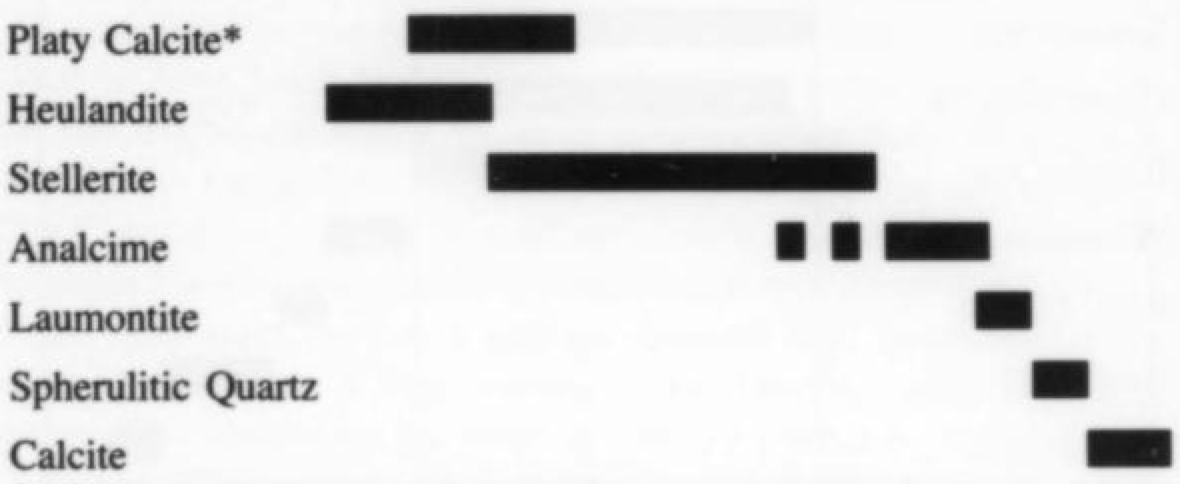
Garrawilla

Zeolites show at all levels in the valleys of Garrawilla and Mitchells Creeks, within two extensive flow units lying between impervious Mesozoic sandstones. Most of the deposits occur in the underlying unit, which acts as a local aquifer, and are concentrated in three separate levels in bands up to 30 m thick. The minerals are found in vesicles, cavities and as irregular vein-like masses. The best specimens have come from completely sealed vugs in solid rock, where the crystals are clean, unaltered and show good color but are difficult to excavate without damage (Head, 1979). Some of the species suggest deposition from deuteric or thermal waters, perhaps related to hot spring activity during waning episodes of volcanism.

Many of the finest specimens ever found are displayed in Janet and Brian Head's private mineral museum "Crystal Kingdom" at Coonabarrabran, which was specially set up to feature the local minerals. Other fine specimens may be seen in Warren Somerville's "Gallery of Minerals," located in Orange, New South Wales, and in the Albert Chapman collection (Sydney). It is from these and the collection of one of the authors (B.M.E.) that most of the following data have been obtained.

An observed paragenetic sequence is shown in Table 2.

Table 2. **Paragenetic sequence of zeolites and associated secondary minerals in the Garrawilla volcanics.**



*Removed by groundwater dissolution

Analcime $NaAlSi_2O_6\cdot H_2O$

Glassy to milky white trapezohedral crystals of analcime from 1 to 5 cm in diameter occur lining vesicles up to 12 cm across at all levels in the volcanic sequence. Crystals are often found alone in vesicles, but associated minerals may include heulandite, stilbite, laumontite, calcite and rarely natrolite.

Calcite $CaCO_3$

Calcite is common in the Garrawilla area, especially on the high levels of the Mitchells Creek valley, and was the last of the vesicle minerals to crystallize. Although it is most common as white to colorless, coarsely crystalline vesicle fillings, especially at higher levels in the volcanic sequence, several occurrences of crystallized calcite have been found at lower levels.

Of particular note is an apparently localized abundance of pseudo-octahedral crystals from a few mm to 2 cm across scattered on stellerite. These crystals appear to be a combination of $c\{0001\}$ and one of the rhombohedron forms. Gray scalenohedral crystals up to 7 cm in length have been found on crusts of crystallized laumontite and one vesicle contained sceptered crystals consisting of highly modified rhombohedra perched on the terminations of scalenohedrons in parallel position.

Heulandite $(Na,Ca)_{2-3}Al_3(Al,Si)_2Si_{13}O_{36}\cdot 12H_2O$

Although heulandite is found at all levels in the sequence, it is far less common than stellerite and only rarely do crystals exceed 2 cm in length.

In habit, heulandite from the Garrawilla volcanics closely resembles the better-known specimens from the Deccan traprocks of India. Typically, crystals are composite in nature, comprising several tabular individuals in near parallel growth. Divergence on (010) is common, occasionally producing spectacular fan-shaped groups up to 10 cm across. The major forms present are $t\{101\}$, $s\{10\bar{1}\}$ and $b\{010\}$, with minor $m\{110\}$ and occasional small $x\{011\}$ and $z\{054\}$ faces. The form $c\{001\}$ is only rarely observed, giving crystals a distinctive rhombic outline on (010). Crystals are usually very lustrous and color varies from colorless through salmon-pink, orange and red to deep burgundy.

Heulandite is commonly found in association with stellerite and/or drusy quartz, but only rarely occurs with analcime. Unlike stellerite, heulandite has not been found associated with laumontite.

Figure 8. Bright orange crystals of heulandite to 6 cm from the valley of Garrawilla Creek. Specimen is 11 x 14 cm. Brian M. England specimen (M85.6.8) and photograph.

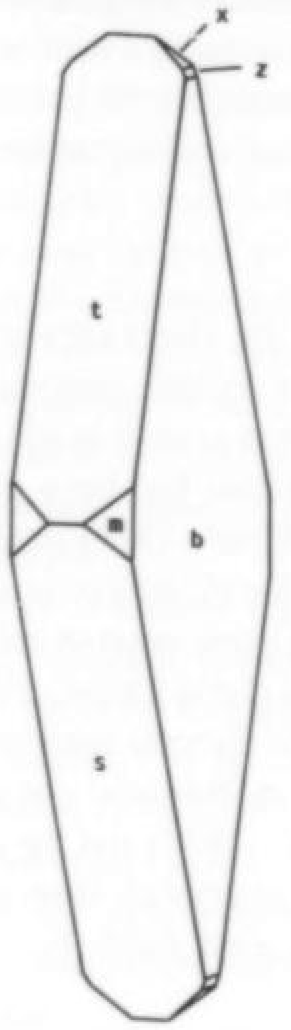


Figure 9. Forms shown by heulandite from the Garrawilla volcanics. Drawing by Brian M. England from specimens in the Janet and Brian Head collection.

Laumontite $CaAl_2Si_4O_{12}\cdot 4H_2O$

Prismatic crystals of laumontite up to 3 cm long, showing the forms *m*{110} and *c*{001}, are found at all levels in the sequence. The crystals most commonly occur as scattered radial clusters on stellerite, but have also been found associated with drusy and spherulitic quartz and analcime. Occasional vesicles have been found lined with continuous crusts of crystallized laumontite associated with later scalenohedral calcite.

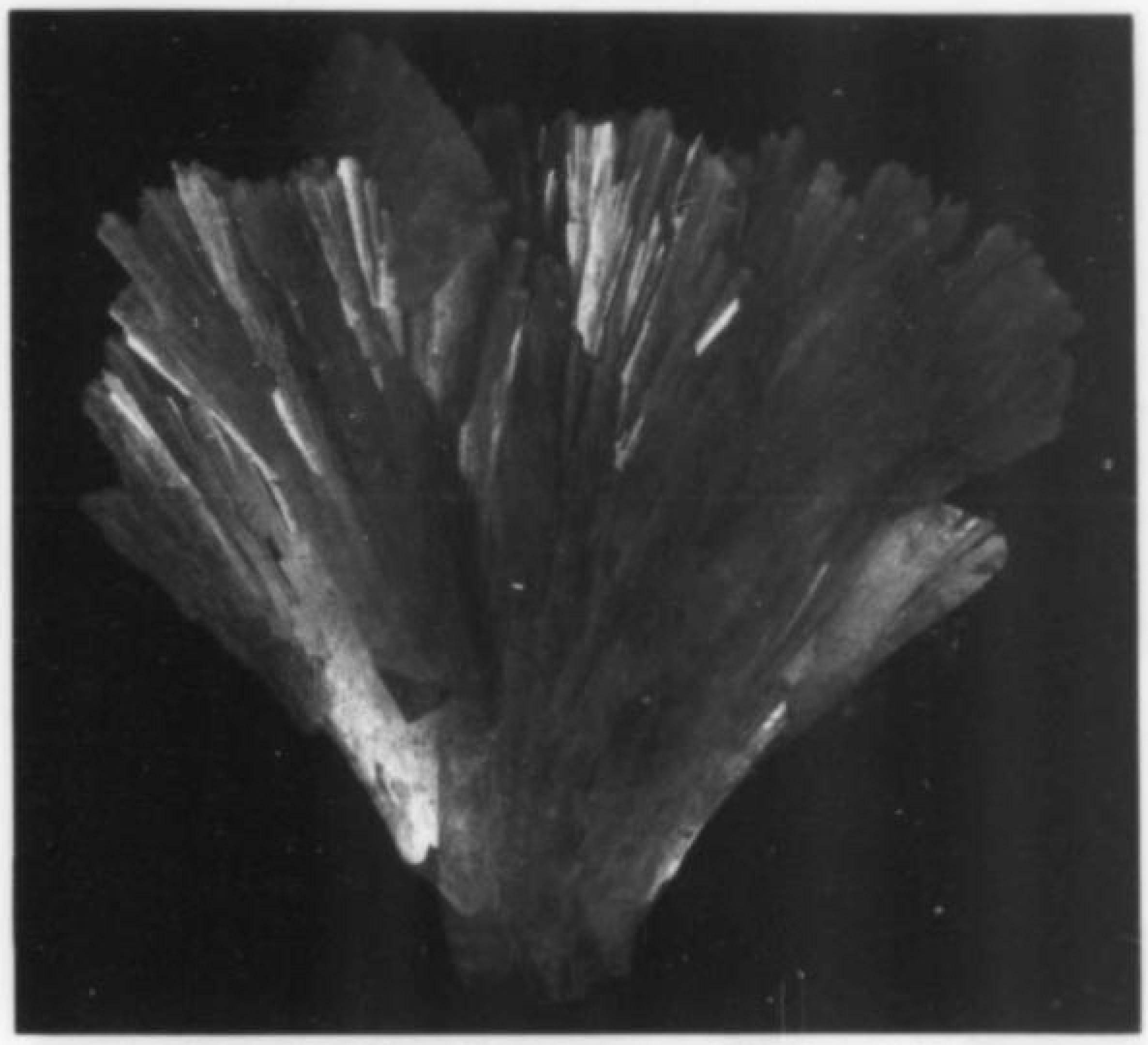


Figure 10. Fan-shaped group of brick-red heulandite crystals 5 cm across from the Garrawilla volcanics. Janet and Brian Head specimen. Photograph by Brian M. England.

Figure 11. Pale peach-pink crystals of stellerite on brown fan-like groups of heulandite from the valley of Garrawilla Creek. Specimen is 11 cm in longest dimension. Brian M. England specimen (M75.1.1) and photograph.

Natrolite $Na_2Al_2Si_3O_{10}\cdot 2H_2O$

Natrolite is rare. Acicular crystals up to 2 cm in length have been collected from analcime-lined vesicles.

Prehnite $Ca_2Al_2Si_3O_{10}(OH)_2$

The main prehnite occurrence is located 13 km northeast of the zeolite deposits. Small-scale mining of the deposit has yielded spectacular specimens of gray, green, lemon-yellow and golden prehnite in both botryoidal and stalactitic habits, with individual stalactites reaching 9 cm.

Figure 12. **Stalactitic green prehnite from the Garrawilla volcanics. The specimen is 10 cm in length. Janet and Brian Head specimen. Photograph by Brian M. England.**

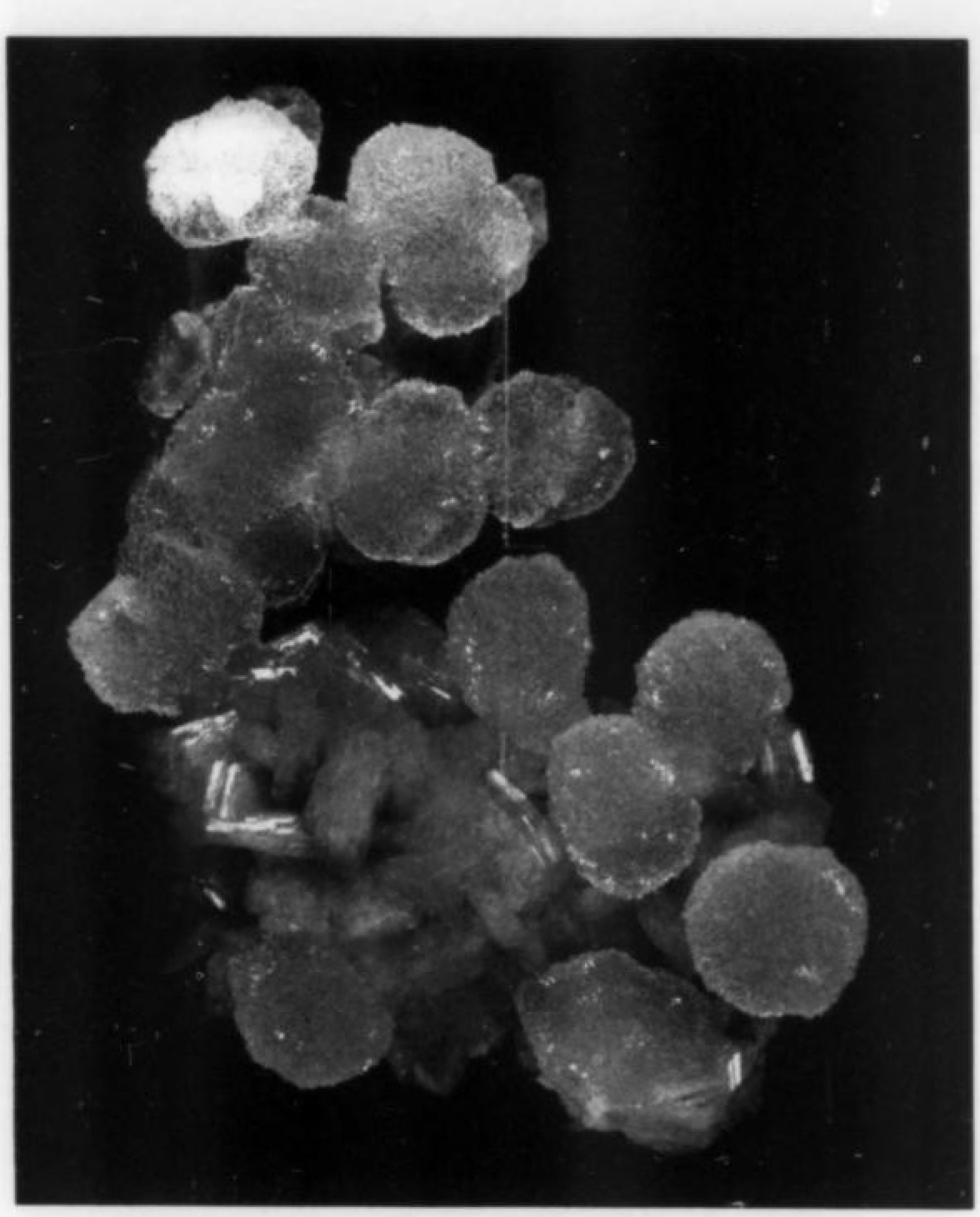


Figure 13. **Colorless quartz spherulites with pale pink stellerite from the Garrawilla area. Specimen is 6 cm tall and from the Janet and Brian Head collection. Photograph by Brian M. England.**

Quartz SiO_2

Quartz is common at all levels within the Garrawilla volcanics, but is most common toward the middle of the sequence in the valley of Mitchells Creek. It typically forms distinct spherulites composed of compact radiating columnar crystals in which only the terminating $r\{10\bar{1}1\}$ faces are visible. These spherulites form continuous encrustations, or occur as individuals up to 2 cm in diameter scattered over stellerite. Occasional sheaf-like groups of doubly terminated crystals to 3 mm have been found on stellerite. Although blue, pink, yellow, green, gray and black specimens have been collected, the quartz spherulites in the Garrawilla area are most commonly white or colorless.

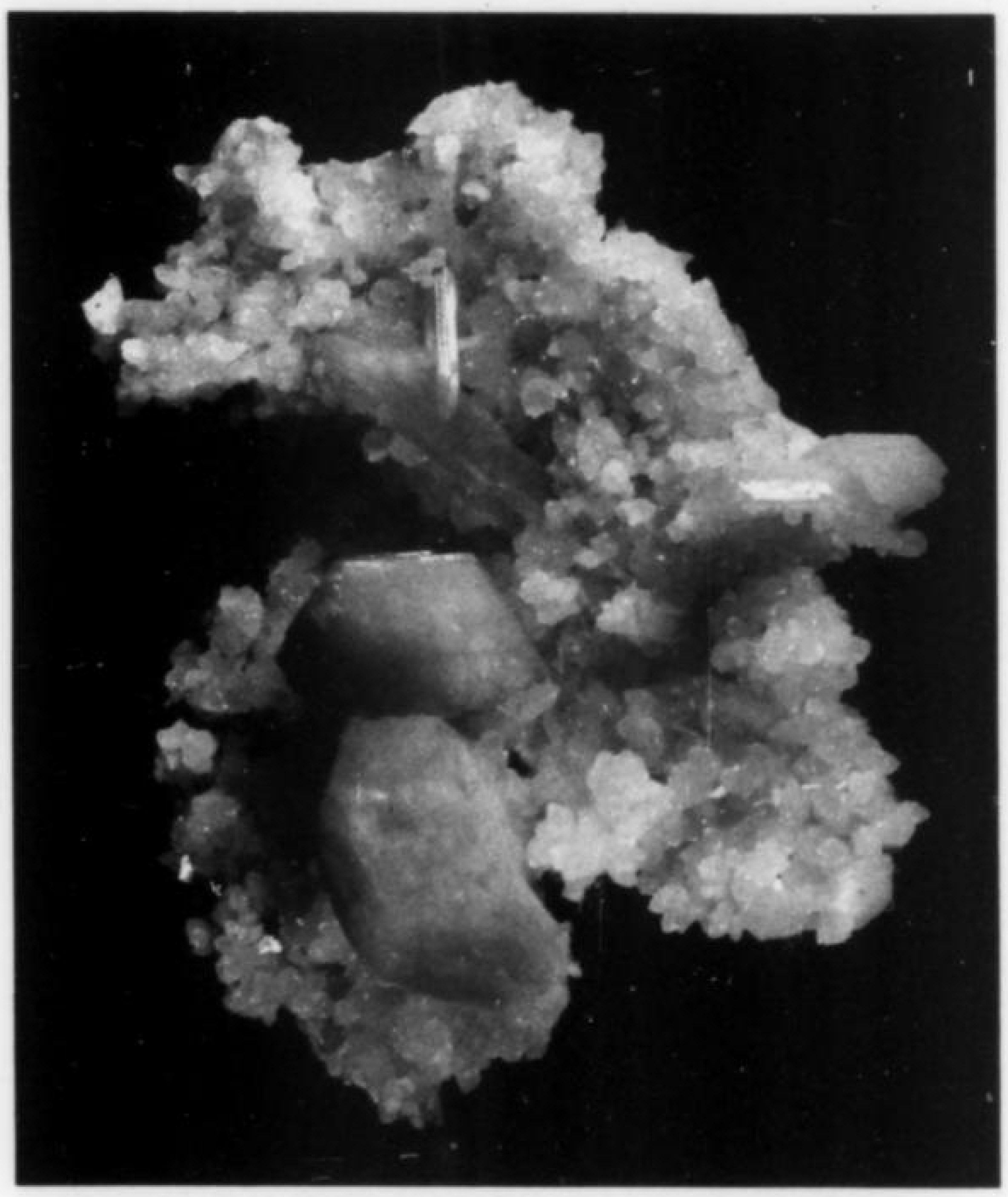


Figure 14. **Pale peach-pink groups of stellerite on white spherulitic quartz from the Garrawilla volcanics. Specimen is 10 x 12 cm. Brian M. England specimen (M85.6.7) and photograph.**

Saponite $(Ca/2,Na)_{0.3}(Mg,Fe^{+2})_3(Si,Al)_4O_{10}(OH)_2{\cdot}4H_2O$

Saponite was identified as greenish gray massive material associated with brownish red crystalline chabazite in vesicles in a drill core from the Garrawilla volcanics at Springfield (Slansky, 1981). It is likely that the tough clay-like material often found coating stellerite and heulandite crystals is also saponite.

Stellerite $CaAl_2Si_7O_{18}{\cdot}7H_2O$

Stellerite is the most common zeolite in the Garrawilla volcanics and is found at all levels in the sequence in crystals ranging from 1 to 12 cm in length. Color varies from pale peach-pink to bright orange. The crystals closely resemble stilbite and indeed had been identified as such by both museums and collectors (Head, 1979) until recent research revealed their true identity. Their identification as stellerite was based on crystal structure determination using neutron diffraction (Miller and Taylor, 1985), chemical analysis (Fredrickson, 1985), X-ray powder diffraction (XRD) and differential thermal analysis (DTA) (Slansky, 1981). Although there is no gap in chemical composition between stilbite and stellerite (Passaglia *et al.*, 1978) and the dividing line is somewhat arbitrary, the composition of crystals from the Garrawilla volcanics falls well within the stellerite field (E. Slansky, personal communication).

To verify their identification, specimens figured in this paper and several from the collection of Janet and Brian Head (Coonabarrabran) were checked by energy-dispersive X-ray microanalysis (EDS) and XRD. No sodium was found in these specimens (within EDS detection limits), and the diagnostic 240 and $20\bar{4}$ reflections for stilbite (Slansky, 1985) were absent in X-ray diffractograms. Hence there is little doubt that the majority of specimens in collections are indeed stellerite. (A short note on the stilbite/stellerite problem is being prepared for *The Australian Mineralogist*.)

The crystals are distinctly tabular in habit, consisting of *b*{010}, *a*{100} and *r*{111} with occasional small *c*{001} terminations. Isolated single crystals are rare; the most common habit is parallel to subparallel, slightly divergent groups on matrix. Individual crystals faces are nearly always clearly discernible, unlike those in the typical wheatsheaf stilbite groups.

Stellerite is commonly associated with heulandite, laumontite, analcime, spherulitic quartz and calcite, with up to four of these coexisting on individual specimens.

ZEOLITES IN TERTIARY VOLCANICS

Tertiary basalts, dated at between 10 and 75 m.y., are widespread in New South Wales, and some of the larger volcanic complexes also include trachytes and rhyolites (Wellman and McDougall, 1974). One of the older basalt shields dated around 53 m.y. forms the Mount Royal Range and Barrington Tops. Here amygdaloidal lavas in the eastern sequence were studied by Nashar and Davies (1960). The secondary minerals fill vesicles singly or in various combinations and show a paragenetic sequence of manganite, interlayered montmorillonite/illite, chabazite, natrolite, second generation manganite, chalcedony and clay. Chabazite crystals up to 5 mm across have been found, varying from simple rhombohedrons to combinations of rhombohedrons with other forms. Natrolite occurs as acicular crystals less than 5 mm long, sometimes in radiating groups and very rarely enmeshed in chabazite as doubly terminated fibers. These secondary assemblages were considered as cold-solution deposits derived by weathering of the basalts, rather than deuteric reactions (Nashar and Basden, 1965).

A very extensive region of zeolite-bearing olivine basalts forms the Liverpool Ranges in the northern Hunter Valley. These ranges are the amalgamation of two large shield volcanoes of different ages (Schön, 1985), an older eastern edifice 38–41 m.y. old and a younger western center 32–35 m.y. old. One of the best zeolite occurrences is exposed in the Ardglen quarry, located within the older volcanic sequence. Here the assemblage is typified by sodic species, including natrolite, analcime and gmelinite. The zeolitization may have accompanied the growth of the volcano, as an apparent neck transecting the basalts was exposed in the quarry on a visit by one of the authors (F.L.S.) in September 1978. This observation is supported by an occurrence of sedimentary analcime found in laminated beds of volcanic ash, which oozed up into an overlying basalt flow exposed in a railway quarry at Murrurundi near Ardglen (Nashar, 1978). The Ardglen suite contrasts with an unusual assemblage containing more calcic and potassic zeolites in the Merriwa-Cassilis area, which falls geographically close to the younger part of the Liverpool Range basalts. However, the host basalt is strongly altered and its precise relationships are uncertain.

Another extensive region of basalts with many developments of zeolites, including the outstanding Ben Lomond occurrence, extends through the New England region. Though overlapping the Liverpool Range volcanics in age, these basalts range into younger series (dates fall between 19–41 m.y.; Wellman and McDougall, 1974; Ollier, 1982; F. L. Sutherland and J. D. Hollis, unpublished data). Similar altered lavas on the southwest side of this volcanic shield are overlain by a 35 m.y. basalt flow, suggesting that zeolites are best developed in the older flows.

The largest single volcanic complex in New South Wales is the Tweed Shield in the northeastern part of the state. These volcanics, which extend into the adjacent state of Queensland, consist of basalts interbedded with and intruded by trachytes and rhyolites. They erupted around a central core, now forming Mt. Warning, in the early Miocene (21–24 m.y.; Wellman and McDougall, 1974; Ewart, 1982). A zeolite occurrence at Mt. Lyon, 21 km north of Kyogle, is stratigraphically located in a silica-saturated basalt overlying rhyolite (N. C. Stevens, unpublished data). The principal zeolite is coarsely crystalline rhombohedral white chabazite in which columnar cavities are rimmed by chalk-white thomsonite. Gonnardite in groups of radiating needles forms rosettes. This occurrence differs from widespread occurrences in the adjacent Main Range basalts of Queensland, where abundant chabazite is accompanied by mesolite or scolecite.

Ardglen

The Ardglen quarry, operated since around the turn of the century by the New South Wales State Rail Authority (Way and Works Branch) for roadmaking and rail ballast, lies on the western side of the Great Northern Railway just north of Ardglen Railway Station. Ardglen is a small settlement on the eastern edge of the Liverpool Range, 240 km north-northwest of Sydney.

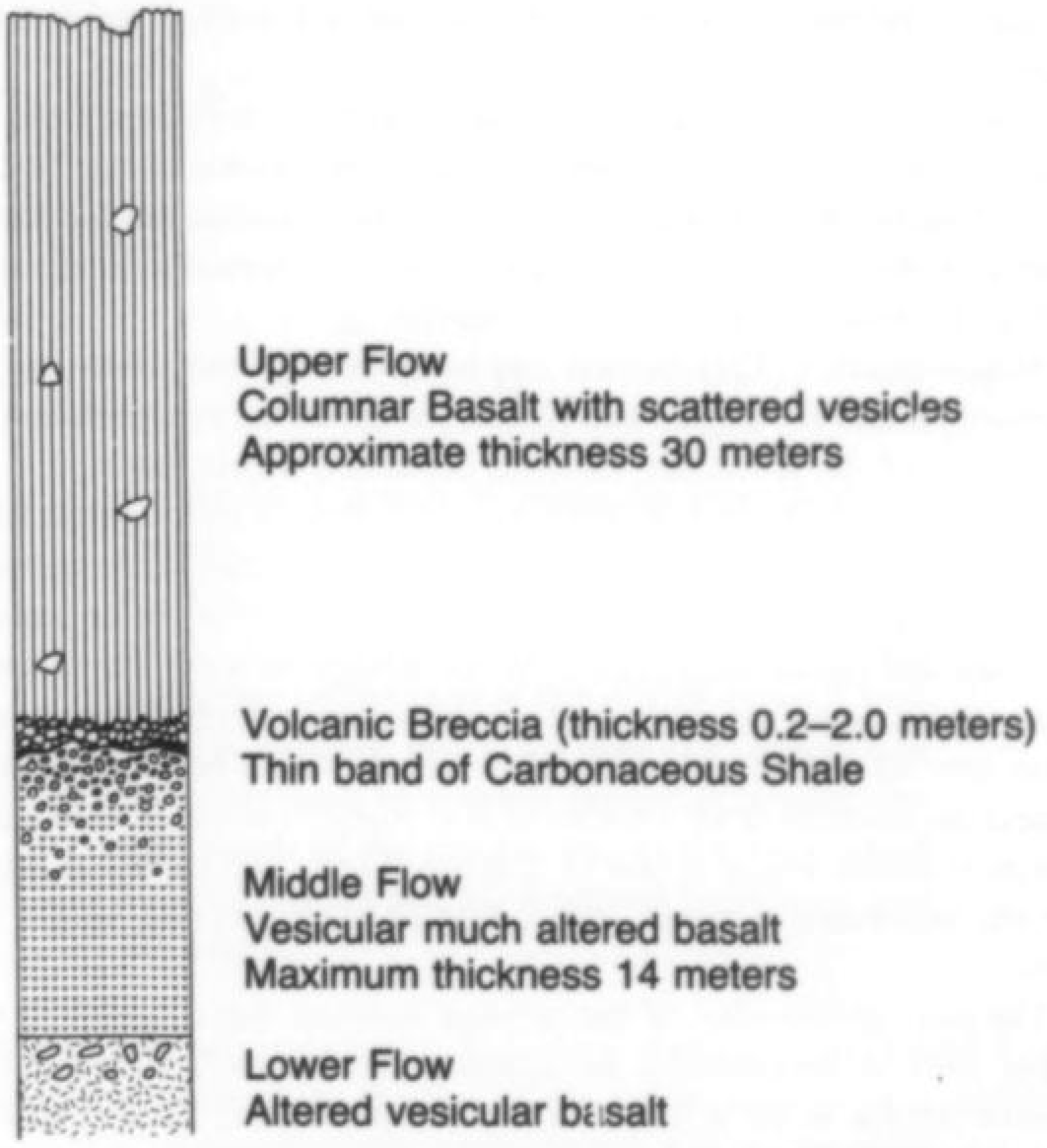


***Figure 15.* Vertical section through the basalt flows at Ardglen, New South Wales. Redrawn from Hodge-Smith (1924).**

At least three distinct flows have been recognized at Ardglen. Columnar jointing is well developed in the upper flow, with individual columns of dense unweathered basalt varying from 0.5 to 2 m in diameter. The columns are invariably separated by a light colored alteration selvage consisting mainly of calcite and natrolite from a few mm to a maximum of 10 cm in thickness, the thicker areas containing an abundance of soft yellow clay. The central portion of this selvage often contains fissure-like shrinkage vugs lined with short acicular crystals of natrolite and, very rarely, calcite (Hodge-Smith, 1924). Scattered throughout the dense basalt are large vesicles up to a meter or more across, lined with comparatively large crystals of natrolite and very occasionally apophyllite. The thickness of the upper flow is impossible to ascertain due to the removal of its upper part by erosion. The lower boundary is marked by an irregular band of very coarse volcanic breccia.

The contact between the breccia and the upper flow is very irregular but quite distinct. The breccia itself consists of very coarse fragments of basalt and shale up to 15 cm in diameter and has been intruded by the upper flow in places. Irregularly shaped vugs conforming to the shape of the interstices between the fragments are occasionally partially filled with a horizontally layered chert-like material, which appears to be a mixture of calcite and analcime (Hodge-Smith, 1924). These vugs contain a greater variety of secondary minerals than the vesicles in the basalt flows, including gmelinite, analcime, natrolite, prehnite, aragonite and calcite.

The junction between the breccia and the middle flow is also irregular and is delineated in places by a thin band of carbonaceous shale, suggesting that the middle flow had undergone considerable weathering and erosion and had probably even supported a luxuriant vegetation prior to the deposition of the breccia (Hodge-Smith, 1924).

The middle flow consists of an upper vesicular basalt and a lower more dense basalt, which presumably represent two distinct phases of a single flow. Both are extensively decomposed. Although analcime, natrolite, calcite and rare chabazite are present, no significant specimens have been collected, due mainly to the small size of the vesicles. Where closely spaced vesicles have been completely filled by secondary minerals, the light colored weathered basalt has a distinct spotted appearance known to the quarrymen and local residents as "native cat."

The lower flow crops out in the bed of a creek downslope from the quarry floor. The basalt is very similar in appearance to the "native cat" of the middle flow and is similarly altered. Natrolite and analcime, both as white to colorless, well formed crystals, appear to be the only secondary minerals present in the vesicles.

Hodge-Smith (1924) carried out extensive investigations on the Tertiary basalts at Ardglen and placed the following interpretation on the origin of the secondary minerals contained within them.

The most significant feature of the upper flow is its unaltered fresh nature. The scattered vesicles that are present are lined with relatively large crystals of natrolite and rarely apophyllite, while the crystals of natrolite and calcite associated with the selvage between the columns of unaltered basalt are small. If the natrolite and calcite of the selvage were derived from magmatic waters then it would be reasonable to expect the natrolite-lined vesicles to also contain calcite. The fact that calcite is absent would appear to indicate at least two modes of origin for the secondary minerals, depending on their location within the flow.

The pale yellow clay of the selvage between the columns in the upper flow is undoubtedly decomposed basalt produced by in-situ weathering due to the action of downward percolating surface waters. Hence the natrolite and calcite associated with the selvage material may be assumed to have had a similar origin. Analcime, which generally forms at a higher temperature than natrolite, is never found in the selvage material, even though this extends right down to the breccia at the base of the upper flow. The large vesicles in the upper flow show no indications of groundwater access and hence the natrolite lining these vesicles probably crystallized contemporaneously with the cooling of the basalt.

The absence of analcime from the upper flow and its abundance in the underlying breccia may be explained in terms of the temperature gradient of the cooling basalt, with natrolite formed at relatively low temperatures in vesicles in the upper part of the flow and analcime at higher temperatures in vugs in the breccia. The superimposed natrolite and calcite in these vugs appears to have been deposited at a later stage from downward-percolating mineralized surface waters.

Hodge-Smith concluded that the natrolite and apophyllite in the vesicles of the upper flow and the analcime from the breccia crystallized contemporaneously with cooling of the basalt and were essentially derived from the same magmatic waters. On the other hand, the natrolite and calcite of the selvage and breccia resulted from the weathering of the basalt and were precipitated from downward-moving surface waters.

The problem of the genesis of zeolites in the middle flow is much more complex and it has been impossible to determine to what extent the middle flow has been affected by magmatic waters accompanying the upper flow or by downward-percolating surface waters containing material in solution derived from it.

An observed paragenetic sequence of secondary minerals at Ardglen, based on the close examination of several hundred specimens in the Brian M. England, George Dale, Gary Farnham and Australian Museum collections, is presented in Table 3. Most of these specimens appear to have been collected from the breccia zone. It is remarkable that, while zeolites are abundant at Ardglen, the range of species is comparatively limited.

***Table 3*. Observed paragenetic sequence of zeolites and associated secondary minerals at Ardglen, New South Wales.**

Analcime $NaAlSi_2O_6 \cdot H_2O$

Analcime is the most abundant of the zeolite species found at Ardglen, even considering its absence from the upper flow. It is common as crusts of trapezohedral crystals, rarely reaching more than 5 mm in diameter, either deposited directly on basalt or on a thin chlorite selvage. Occasional vugs contain stalactites of chlorite up to several cm long on which colorless analcime has crystallized. Such is the clarity of the crystals in most specimens that the color and hence the nature of the substrate is readily apparent. Unusual greenish gray druses of analcime, preserved from the early days of quarrying, owe their color at least in part to an underlying selvage of pale green chlorite.

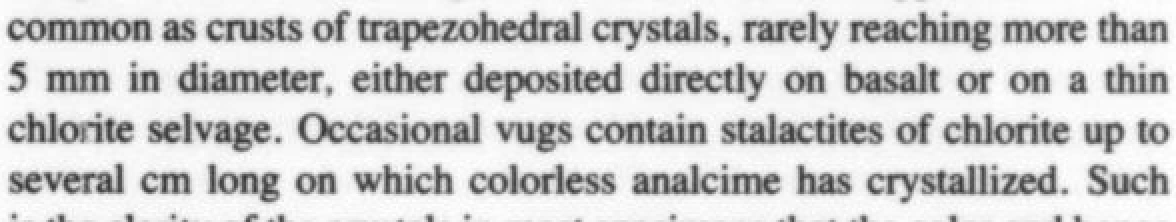


***Figure 16*. Stalactitic chlorite coated with colorless trapezohedral analcime from Ardglen. The specimen is 23 cm across. Australian Museum specimen D19974. Photograph by John Fields, Australian Museum.**

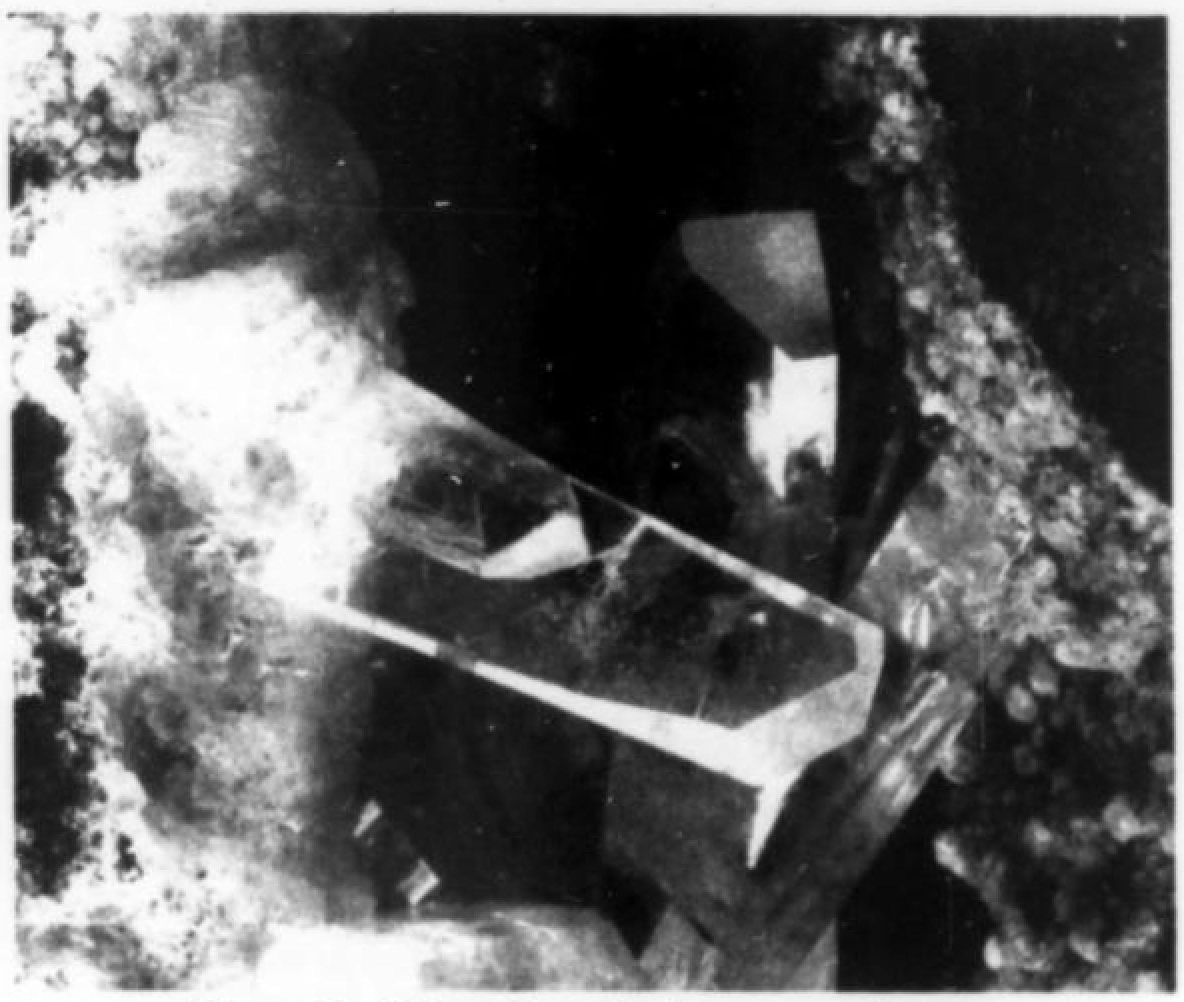


Figure 17. **Prismatic colorless aragonite crystals on a matrix of calcite and analcime from Ardglen. Main crystal is 1.5 cm in length. Brian M. England specimen (M85.6.6) and photograph.**

Aragonite $CaCO_3$

Spectacular specimens of water-clear, lustrous, prismatic crystals up to 4 cm long have been found recently in vugs within the breccia zone, associated with weathered analcime and late-stage globular white calcite. The crystals consist of the forms $m\{110\}$ and $b\{010\}$ terminated by various combinations of $p\{111\}$, $k\{011\}$, $i\{021\}$ and $r\{041\}$. Simple contact twins on (110) are rare. Symmetrical distortion of $m\{110\}$ has given most of the crystals a distinct bladed habit. The aragonite shows a very pale pinkish white fluorescence under both longwave and shortwave ultraviolet light and a distinct but very pale yellow phosphorescence.

Calcite $CaCO_3$

Calcite is common in cavities in both the lava flows and the breccia and occurs in a variety of habits and associations. The most spectacular specimens have amber-colored crystals of the form $M\{40\bar{4}1\}$ reaching 2.5 cm in length associated with natrolite "puffballs" on analcime.

Natrolite crystals are commonly thickly sprinkled with minute, colorless calcite rhombohedra, a combination which provides superb micromounts.

Distinct scalenohedral crystals are rare, although vesicles lined with pale yellow columnar crystals (on which no definite forms are recognizable) to 1 cm in length are relatively common. Specimens of natrolite and analcime with white to pale yellow overgrowths of globular calcite, in which the forms present are difficult to recognize, are abundant. Many of these specimens show a pale pink fluorescence under both longwave and shortwave ultraviolet light due to the presence of trace quantities of manganese replacing calcium.

Unfortunately, the majority of calcite specimens from Ardglen show varying degrees of etching due to subsequent groundwater movement through the cavities.

Chabazite $CaAl_2Si_4O_{12}\cdot 6H_2O$

Chabazite is rare at Ardglen and the only crystals observed have been those of the multiply twinned pseudohexagonal "phacolite" variety. Crystals are white in color, reach 6 mm in diameter and are usually found deposited on natrolite (as in Australian Museum specimen D19984).

Gmelinite $(Na_2,Ca)Al_2Si_4O_{12}\cdot 6H_2O$

Gmelinite is relatively uncommon at Ardglen, but is conspicuous when present because of its pale to deep pink color and bright luster. It appears to have been the first of the zeolite species to crystallize.

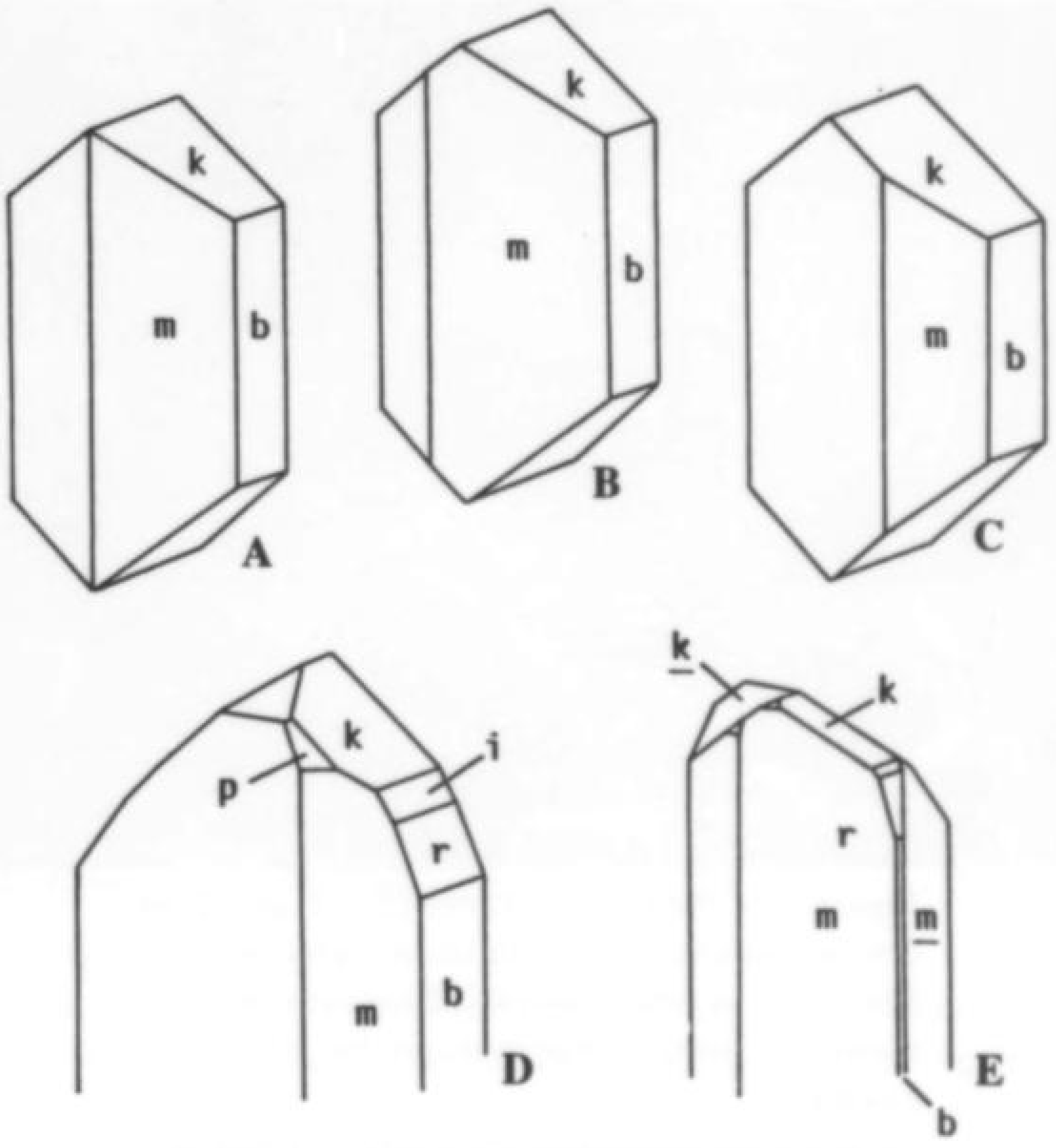


Figure 18. **Crystals of aragonite from Ardglen showing observed combinations of the forms $m\{110\}$, $b\{010\}$, $p\{111\}$, $k\{011\}$, $i\{021\}$ and $r\{041\}$. Crystals B, C and D show symmetrical distortion (offsetting) of the $m\{110\}$ faces. Crystal E is twinned on (110); note the presence of the prominent re-entrant groove extending the full length of the crystal due to the very small $b\{010\}$ faces. Brian M. England specimens and drawings.**

Crystals, although rarely more than 3 mm in diameter, are well formed and consist of $r\{10\bar{1}1\}$, $p\{01\bar{1}1\}$ and $m\{10\bar{1}0\}$. The habit of Ardglen gmelinite closely resembles that of gmelinite/chabazite intergrowths from Flinders, Victoria (Birch, 1976), although preliminary X-ray powder diffraction (XRD) studies suggest that such intergrowths are not a feature of Ardglen gmelinite.

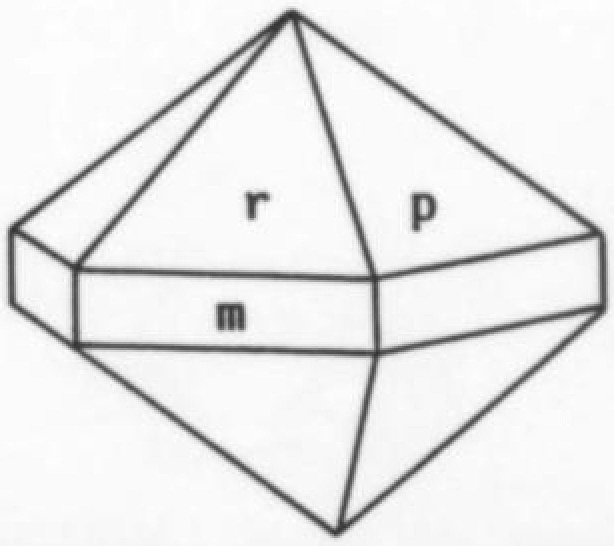


Figure 19. **Drawing of a typical gmelinite crystal from Ardglen $r\{10\bar{1}1\}$, $p\{01\bar{1}1\}$ and $m\{10\bar{1}0\}$. Redrawn from Birch (1976).**

Gmelinite is usually found alone in vugs as a thin crust of microcrystals or as spheroidal to stellate intergrowths scattered among small, colorless, trapezohedral crystals of analcime. Crusts of crystallized gmelinite have also been observed partially coating natrolite.

Gyrolite $Ca_2Si_3O_7(OH)_2\cdot H_2O$

Specimens in the Australian Museum collection (notably D46359)

Figure 20. **Stellate intergrowths of gmelinite crystals on analcime from the Ardglen quarry. The larger crystal group is 2.5 mm in diameter. Scanning electron micrograph by Brian M. England.**

show pearly white spherulites of thin platy crystals to 2 mm in diameter supported and often penetrated by prismatic natrolite.

Hydroxyapophyllite $KCa_4Si_8O_{20}(OH,F)\cdot 8H_2O$

Apophyllite crystals analyzed for fluorine by a newly developed pyrohydrolysis method (Doolan, 1987) gave values of around 112 ppm. Hence the crystals are very close to the hydroxyapophyllite end-member in composition.

Figure 21. **Tabular colorless crystals of hydroxyapophyllite associated with prismatic natrolite from the Ardglen quarry. Specimen is 9.5 cm in length. Australian Museum specimen D41783. Photograph by John Fields, Australian Museum.**

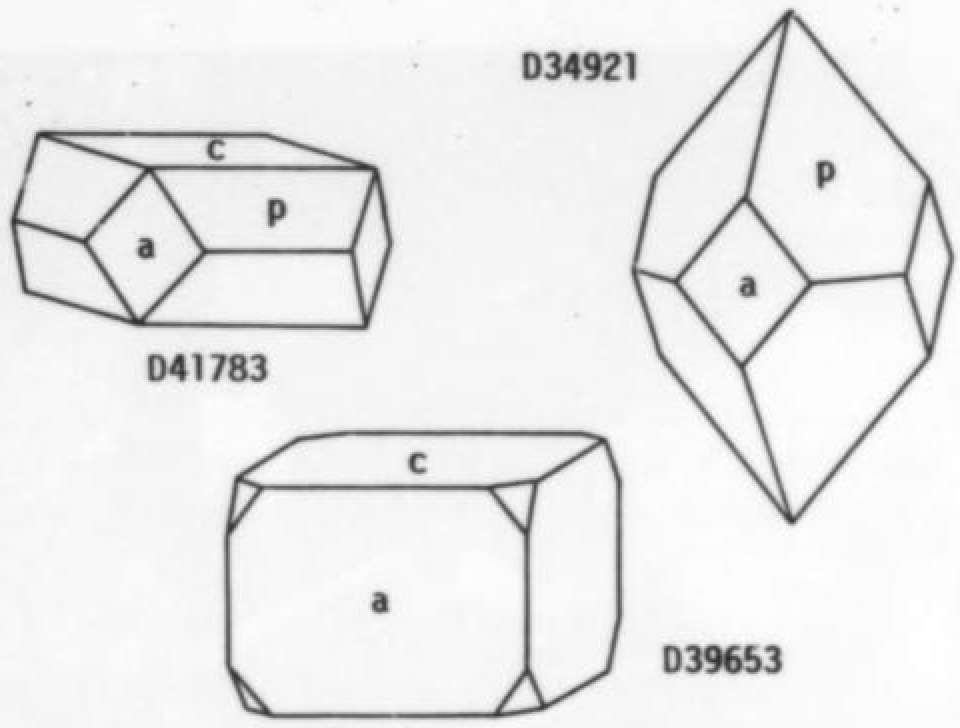


Figure 22. **Hydroxyapophyllite crystals from the Ardglen quarry showing the forms *c*{001}, *a*{100} and *p*{111}. Drawings by Brian M. England from specimens in the Australian Museum collection.**

Hydroxyapophyllite is relatively common and is always associated with earlier natrolite, often suspended among the natrolite crystals and penetrated by them. Crystals are either opaque white or colorless, reach 2.5 cm in diameter and comprise the forms *a*{100}, *c*{001} and *p*{111}.

Figure 23. **White prismatic crystals of natrolite coating basalt fragment 15 cm across from the Ardglen quarry. Australian Museum specimen D21276. Photograph by John Fields, Australian Museum.**

Natrolite $Na_2Al_2Si_3O_{10}\cdot 2H_2O$

Natrolite is the most spectacular of the Ardglen zeolites and many hundreds of fine specimens have been produced since the quarry first opened. It is most common as crusts of closely spaced, radiating, acicular to prismatic, colorless crystals completely lining vesicles. Outstanding specimens exceeding half a meter across have been collected. Individual crystals vary from a few mm to over 4 cm in length and consist of the forms *a*{100}, *b*{010} and *m*{110} terminated by *p*{111}, with the *m* faces predominating.

Where analcime is present as a cavity lining, natrolite commonly forms radiating sprays of acicular to columnar crystals up to 1 cm in length scattered over the analcime surface. This association, with the irregular nature of many of the cavities containing inward-projecting

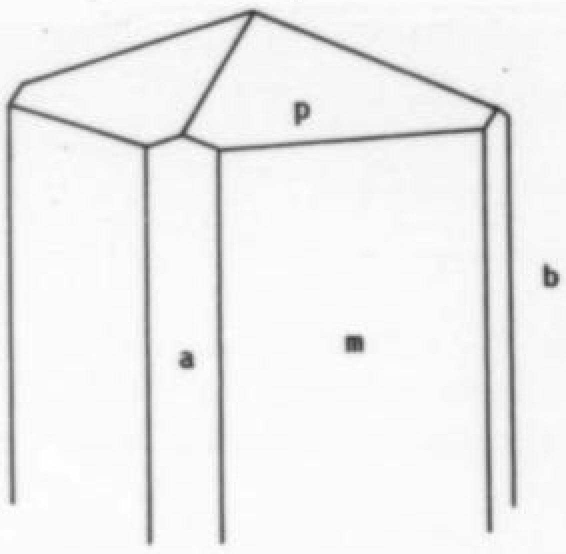


Figure 24. **Typical natrolite crystal from Ardglen showing the forms *a*{100}, *b*{010}, *m*{110} and *p*{111}. Redrawn from Hodge-Smith (1924).**

stalactites and mounds of basalt and/or chlorite, offers ample opportunity for the collection of miniature, thumbnail and micromount specimens of outstanding aesthetic quality. More rarely observed are "puffballs" of white acicular crystals perched on pinnacles of drusy analcime and associated with late-stage pale amber-colored calcite rhombohedra.

An unusual occurrence, restricted to the breccia zone, is the presence of crusts of short acicular natrolite crystals lining anastomosing dehydration fissures in a bedded sandy mixture of carbonate, analcime and natrolite formed at the base of the vugs between basalt fragments. Specimens of this type reaching 30 cm across have been collected.

Prehnite $Ca_2Al_2Si_3O_{10}(OH)_2$

A single specimen in the Australian Museum collection (D21440) consists of a pale green reniform crust of prehnite on natrolite.

Todorokite $(Mn^{+2},Ca)Mn_4^{+7}\cdot H_2O$

Although not observed during this present study, todorokite has been found as froth-like coatings of felted microcrystals with brassy color and distinct metallic sheen on manganocalcite in small vesicles in the altered basalt (Lawrence *et al.*, 1968). The todorokite is regarded as a product of deuteric alteration of the basalt, with manganiferous titanian augite being the probable source.

Merriwa

Several localities in the Merriwa-Cassilis area of the Hunter Valley have provided interesting suites of zeolites and associated secondary minerals. The most notable of these was exposed in 1968 during reconstruction of a section of the Merriwa-to-Cassilis road at Willy Wally Gully, 29 km north-northwest of Merriwa. The locality represents the first recorded occurrence of both levyne and offretite in Australia.

The host basalt is strongly altered in outcrop, with abundant nontronite as vesicle and fissure fillings. Vesicles are abundant and vary from a few mm to a maximum of 12 cm in diameter; most are lined with zeolites.

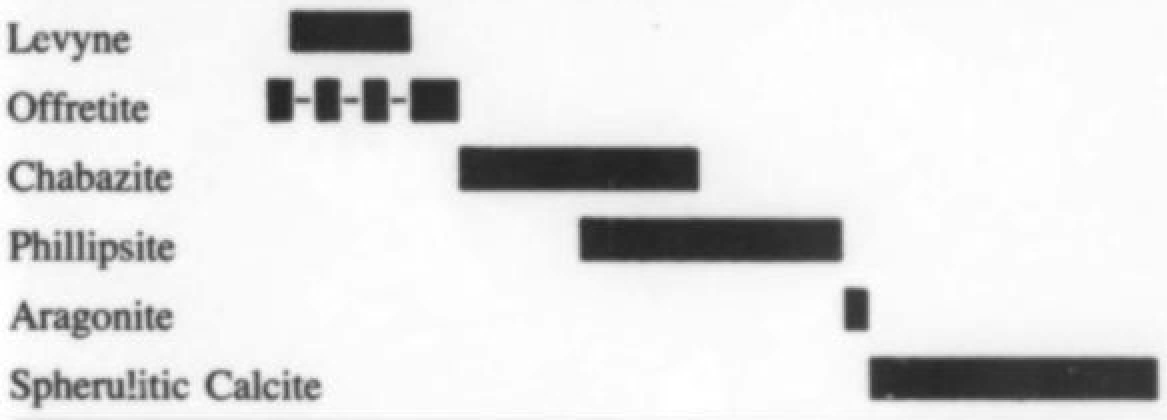
While the occurrence of calcite is ubiquitous throughout the vesicle zone, rarely are more than two zeolite species directly associated in any one vesicle. The following direct associations were noted:

Offretite
Levyne–Offretite
Levyne–Offretite–Chabazite
Chabazite–Phillipsite
Chabazite (phacolite)–Natrolite

The similarity in structural formulae for levyne and chabazite suggests that levyne crystallization was favored by locally higher concentrations of sodium and potassium. However, why levyne formed in some vesicles while others contain chabazite, with the sodium and potassium present absorbed by almost simultaneous phillipsite crystallization, remains a mystery. The proximity of both associations precludes temperature gradient as the cause.

The paragenetic sequence of zeolites and associated minerals at Willy Wally Gully is shown in Table 4. These data were compiled from examination of specimens in the Brian M. England collection and relationships observed *in situ* at the locality.

Table 4. **Observed paragenetic sequence of zeolites and associated secondary minerals at Willy Wally Gully, Merriwa, New South Wales.**



Aragonite $CaCO_3$

Only one specimen of aragonite has been recovered from Willy Wally Gully. It is a single spray of colorless prismatic crystals 8 mm across associated with chabazite and phillipsite.

Calcite $CaCO_3$

Calcite is widespread throughout the vesicular zone as white spherulitic forms up to 1 cm across produced by repeated splitting of the crystals along the rhombohedral cleavage directions due to sectorial enrichment in $MgCO_3$. The more magnesium absorbed in the calcite structure, the greater is this splitting effect until eventully the corners of the rhombohedron curl alternately up and down toward the *c*-axis forming an almost complete sphere (England, 1984).

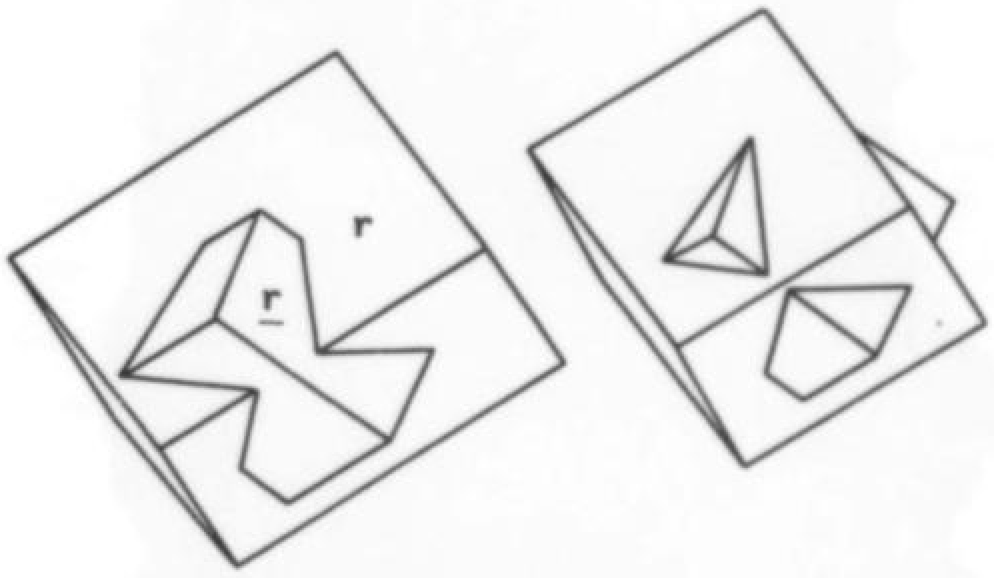


Figure 25. **Typical habits of Willy Wally Gully chabazite showing unequal interpenetrant twins having the form *r*{10$\bar{1}$1}. Drawings by Brian M. England.**

Chabazite $CaAl_2Si_4O_{12}\cdot 6H_2O$

Chabazite is the most abundant of the zeolite minerals at Willy Wally Gully. It commonly occurs alone in vesicles but can also be associated with levyne/offretite, phillipsite, natrolite, aragonite and calcite, although only very rarely is chabazite associated with more than one other zeolite species in the same vesicle. Crystals are usually colorless, smooth-faced, reach 1 cm in diameter and consist of the form *r*{10$\bar{1}$1}. Unequal interpenetrant twins, with the *c*-axis as the twin axis, are common.

Erionite $(Ca,Na_2,K_2)_4(Al_8Si_{28})O_{72}\cdot 27H_2O$

Detailed scanning electron microscopy (SEM)/energy dispersive X-ray microanalysis (EDS) of the vesicle minerals from Willy Wally Gully revealed a single isolated occurrence of erionite as radiating groups of subparallel prismatic crystals to 0.05 mm in length on nontronite vesicle lining. The crystals have the forms *m*{10$\bar{1}$0} and *c*{0001} and closely resemble those from Malpais Hill, Arizona (Thomsen, 1983). Erionite was not found in association with any

Figure 26. **Erionite crystals on nontronite vesicle lining from Willy Wally Gully, near Merriwa. Field of view is 0.2 mm across. Scanning electron micrograph by Brian M. England.**

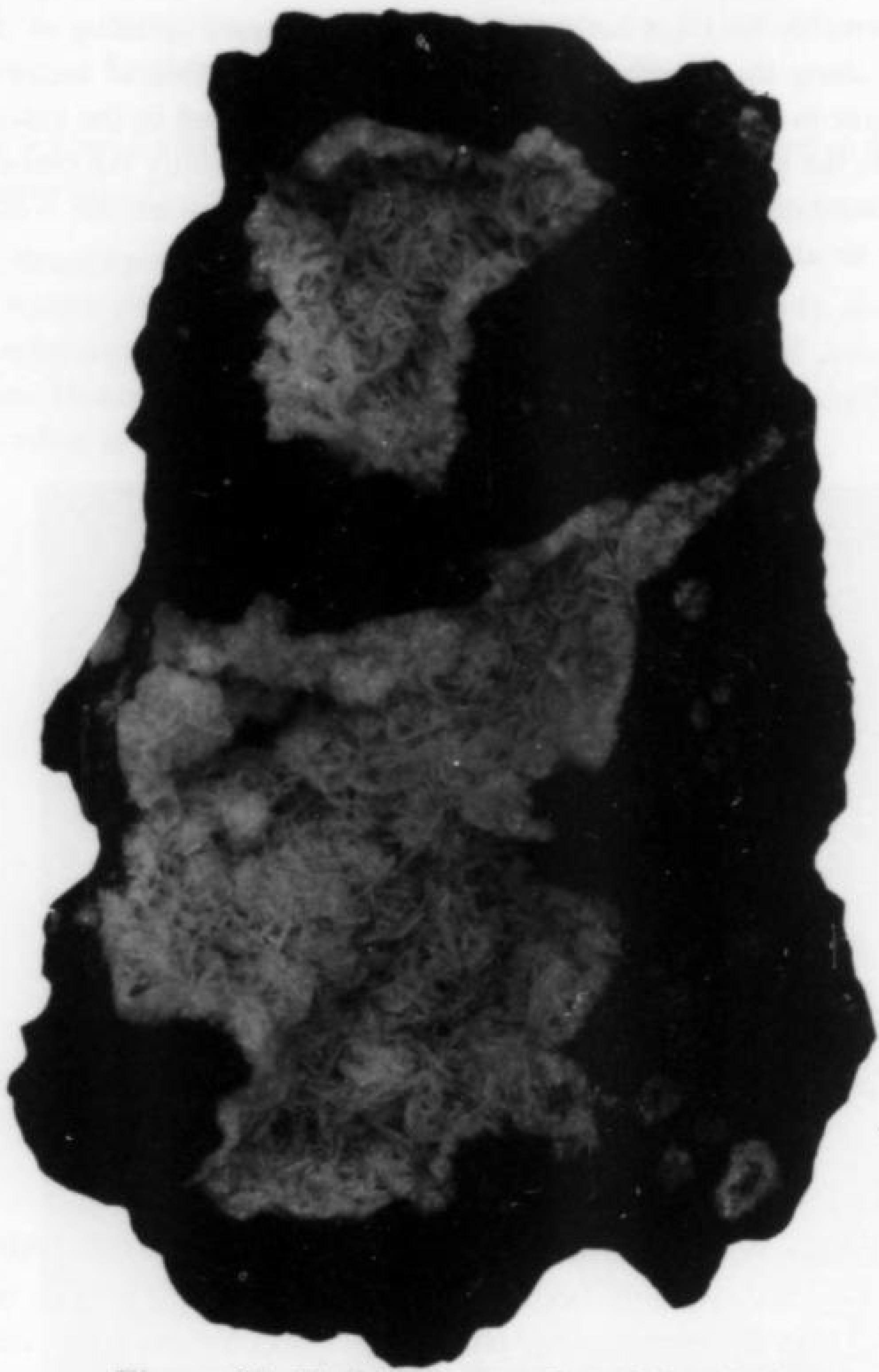


Figure 27. **Vesicles in weathered basalt from Willy Wally Gully lined with platy crystals of levyne-offretite. Specimen is 7 cm in length. Brian M. England specimen (M68.7.1) and photograph.**

other zeolite species and hence its position in the paragenesis is unknown.

Levyne $(Ca,Na_2,K_2)Al_2Si_4O_{12}\cdot 6H_2O$

Levyne occurs as thin platy crystals to a maximum diameter of 5 mm, thickly encrusting the walls of vesicles and accompanied by overgrowths of fibrous offretite. Crystals show the forms $c\{001\}$, $r\{11\bar{2}1\}$ and $s\{\overline{22}41\}$ and are tabular on $c\{0001\}$.

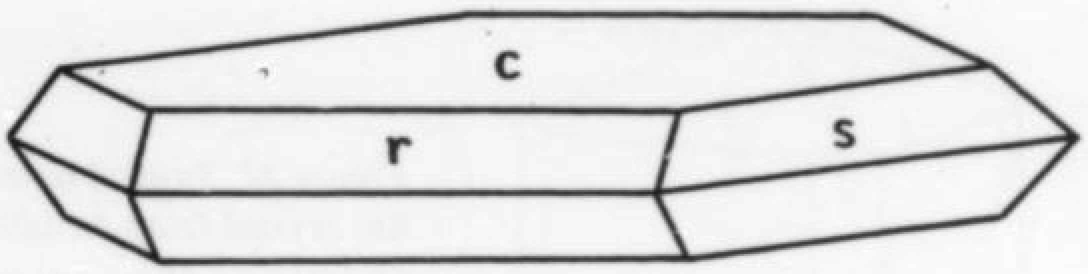


Figure 28. **Drawing of a typical levyne crystal from Willy Wally Gully showing the forms $c\{0001\}$, $r\{11\bar{2}1\}$ and $s\{\overline{22}41\}$. Redrawn from Goldschmidt (1918).**

Although characteristically found alone in vesicles, rare specimens showing levyne/offretite intergrowths directly associated with later chabazite have been found.

Electron probe microanalysis of selected crystals showed the presence of high calcium (11.4 weight % CaO) but only minor sodium and potassium (1.8 weight % Na_2O and 0.42 weight % K_2O respectively), giving a (Na + K)/Ca ratio of only 0.19 (England and Ostwald, 1979). Hence the levyne from Willy Wally Gully is considerably richer in calcium than that of Beech Creek, Oregon (Sheppard *et al.*, 1974) and Clunes, Victoria (Birch, 1979).

Figure 29. **Transversely broken section of a levyne crystal from Willy Wally Gully showing the fibrous overgrowth of offretite on the $c\{0001\}$ faces. Field of view is 0.07 mm across. Scanning electron micrograph by Brian M. England.**

Natrolite $Na_2Al_2Si_3O_{10}\cdot 2H_2O$

A small roadside quarry a few hundred meters to the east of Willy Wally Gully has strongly weathered basalt containing vesicles lined with natrolite associated with chabazite ("phacolite" variety) and powdery white calcite. Here the natrolite occurs as tufts of radiating white prismatic crystals to 5 mm in length. However, since the natrolite is not directly associated with the Willy Wally Gully zeolite suite, but occurs somewhat above it stratigraphically, it has not been included in the paragenesis shown in Table 4.

Offretite $(K_2,Ca)_5Al_{10}Si_{26}O_{72}\cdot 30H_2O$

The offretite at Willy Wally Gully is characteristically intimately associated with levyne as fibrous intergrowths on the $c\{0001\}$ faces, resulting in the ubiquitous pearly luster of the levyne crystals. Offretite development tends to be greater toward the center of the $c\{0001\}$ faces, reaching a maximum thickness of 0.06 mm. Occasionally levyne/offretite intergrowths are associated with free-standing elongate sheaves of fibrous offretite, which occasionally appear to penetrate and hence pre-date the levyne crystals. Several distinct generations of levyne/offretite development are evident.

Offretite also occurs alone in vesicles, apparently unassociated with levyne, as elongate sheaves of subparallel fibers to 0.5 mm in length resembling miniature shaving brushes, on a matrix of spheroidal nontronite. The growth origin for many of these sheaves appears to be represented by a central, dense, roughly tabular core, which may be levyne in part, aligned at right angles to the length of the sheaves.

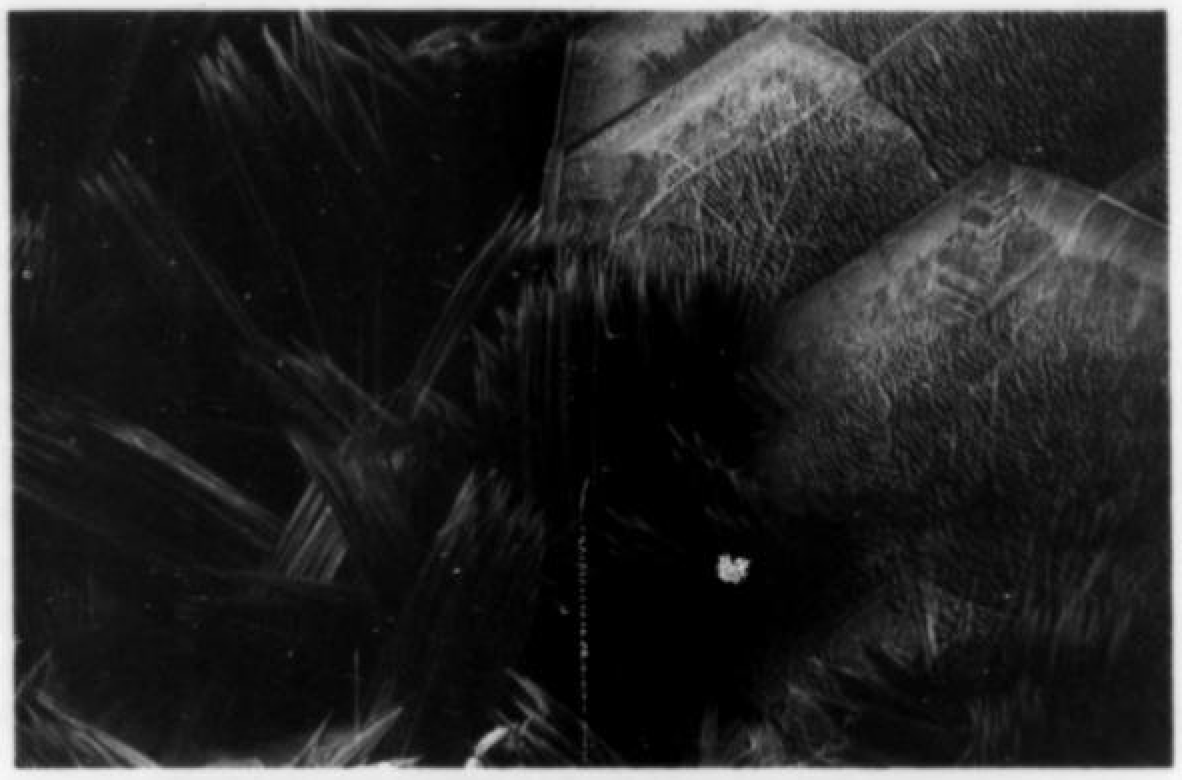


Figure 30. **Offretite growing epitaxially on the *c*{0001} faces of levyne crystals and as separate sheaves of fibrous crystals from Willy Wally Gully. Field of view is 0.6 mm in longest dimension. Scanning electron micrograph by Brian M. England.**

Figure 31. **Radiating group of offretite crystals penetrating a levyne crystal coated with epitaxial offretite from Willy Wally Gully. Field of view is 0.2 mm in maximum dimension. Scanning electron micrograph by Brian M. England.**

Figure 32. **Offretite with nontronite spheroids from Willy Wally Gully. Field of view is 0.8 mm high. Scanning electron micrograph by Brian M. England.**

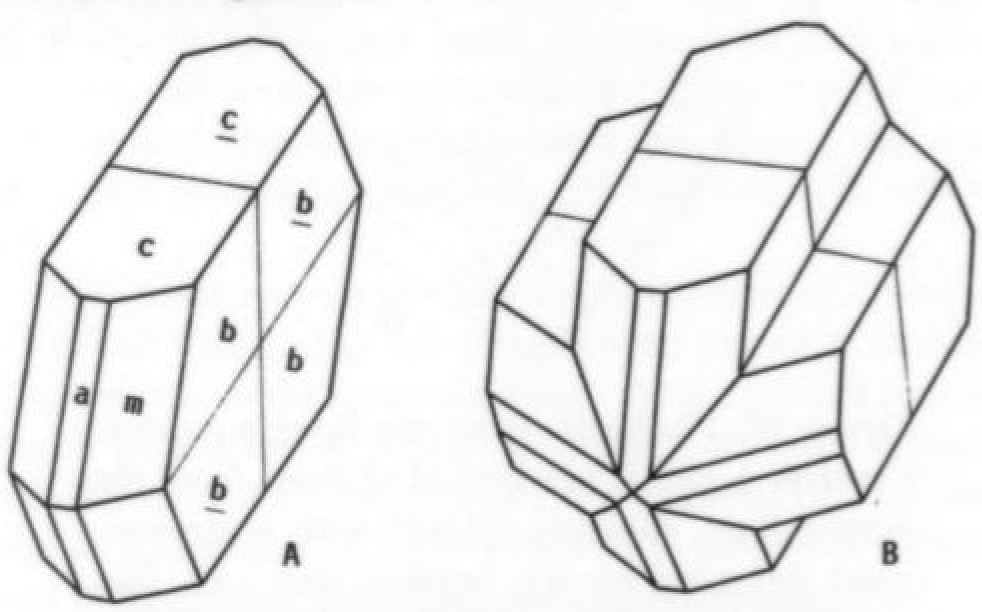


Figure 33. **Typical habits of Willy Wally Gully phillipsite showing the forms *c*{001}, *a*{100}, *b*{010} and *m*{110}. Crystal A is twinned on (001), while crystal B is also twinned on (011) to produce a more complex cruciform habit. Brian M. England specimens and drawings.**

Phillipsite $(K,Na,Ca)_{1-2}(Si,Al)_8O_{16}\cdot 6H_2O$

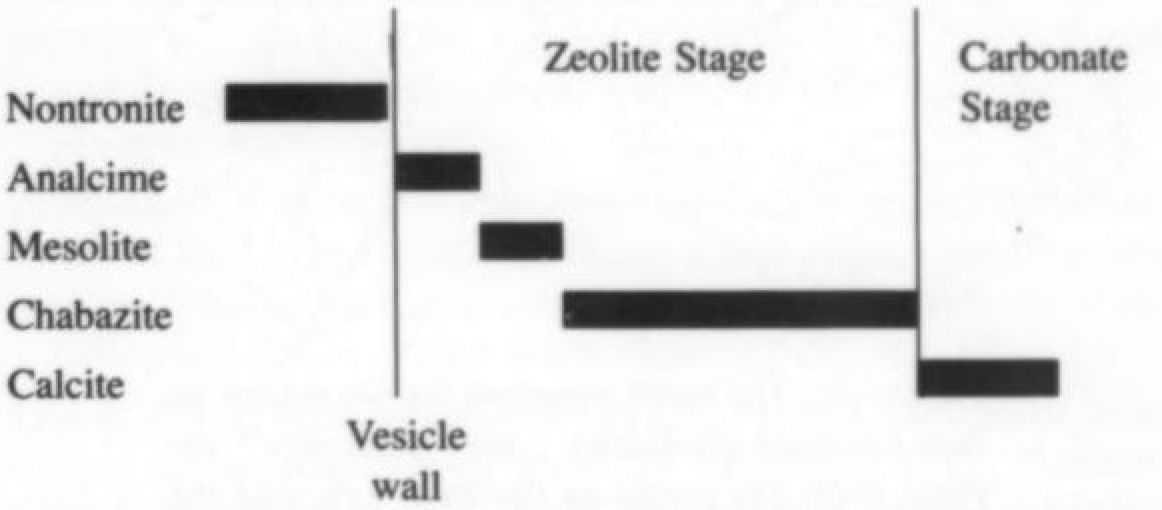
One of the less common zeolites, phillipsite is invariably associated with earlier chabazite. Crystals are creamy yellow in color, transparent to translucent and reach 8 mm in diameter. The forms present include *c*{001}, *a*{100}, *b*{010} and *m*{110}, with ubiquitous twinning on *c*{001} producing habits simulating orthorhombic forms. These simple twins are occasionally united by further twinning on *e*{011} to produce more complex cruciform twins. Phillipsite is also present as compact spherulites of radiating crystals with only the termination faces visible.

Ben Lomond

Tertiary basalts capping the Great Dividing Range at Ben Lomond, between Guyra and Glen Innes in the New England region, have provided exceptional specimens of chabazite associated with analcime, mesolite and calcite, making this one of the premier locations for zeolites in New South Wales. The finest specimens were collected during excavation of the "Big Cutting" on the Northern Railway Line, 1.6 km north of the Ben Lomond Railway Station, where vesicles reached a diameter of over 30 cm. Although this occurrence was first reported in 1888 (Porter, 1888), one of the authors (B.M.E.) was able to collect several superb specimens of chabazite as recently as 1969. Specimens have also been collected from cuttings on the New England Highway 6 km to the east of Ben Lomond.

An observed paragenetic sequence, based on the examination of specimens in the Australian Museum and Brian M. England collections, is shown in Table 5.

Table 5. **Observed paragenetic sequence of zeolites and associated secondary minerals from Ben Lomond, New South Wales.**



Analcime $NaAlSi_2O_6\cdot 2H_2O$

Transparent glassy crystals of analcime averaging around 2 mm commonly line small vesicles in the basalt and are occasionally associated with later chabazite. The principal habit appears to be the trapezohedron *n*{211}.

Calcite $CaCO_3$

Calcite is only occasionally present in the vesicles, usually as pale amber rhombohedra of the form $M\{40\bar{4}1\}$ reaching 3 cm in length, but also as the scalenohedron $v\{21\bar{3}1\}$. Although often found alone, it is more commonly associated with the earlier zeolites, especially chabazite. Spherulitic forms are also present.

Chabazite $Ca(Al_2Si_4)O_{12}\cdot 6H_2O$

Chabazite is the most prolific species found in the vesicles in the Ben Lomond area. It is most commonly seen as the multiply twinned variety "phacolite," with the *c*-axis as the twin axis and the forms $r\{10\bar{1}1\}$, $s\{02\bar{2}1\}$ and $e\{01\bar{1}2\}$ predominating. The crystals are colorless to white, reach a maximum diameter of 4.5 cm and occur as isolated individuals or thick encrustations on the walls of vesicles. Most are strongly striated parallel to the r/e intersections. Simple rhombohedra $r\{10\bar{1}1\}$, heavily striated parallel to the edges r/r′ and r/r″, and unequal penetration twins have also been found. Although these different habits

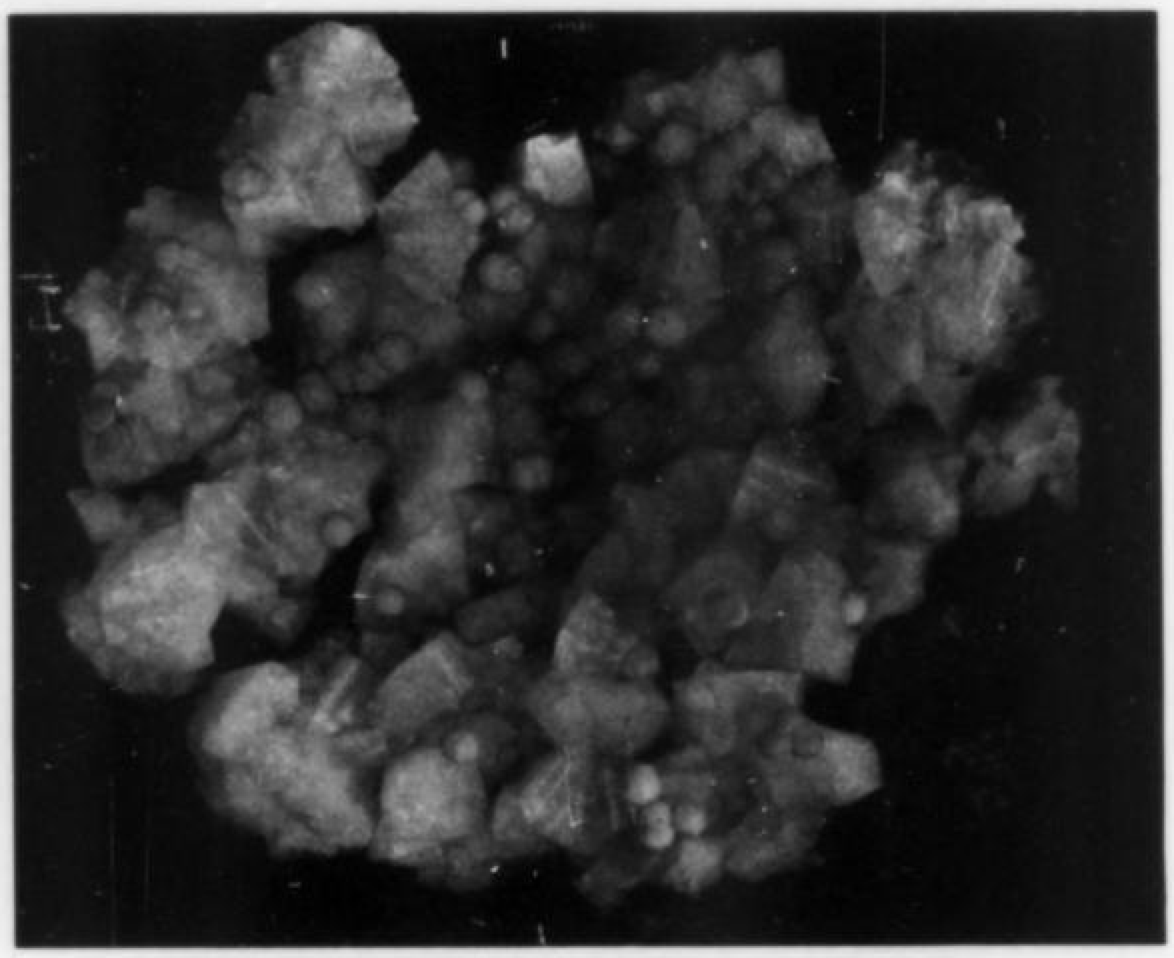


Figure 34. **Spherulitic calcite on white to colorless chabazite crystals to 2 cm across lining a vesicle in Tertiary basalt from the railway cutting at Ben Lomond, New England region of New South Wales. Crystals show penetration twinning on the *c*-axis. Specimen is 12 cm across. Brian M. England specimen (M69.4.2) and photo.**

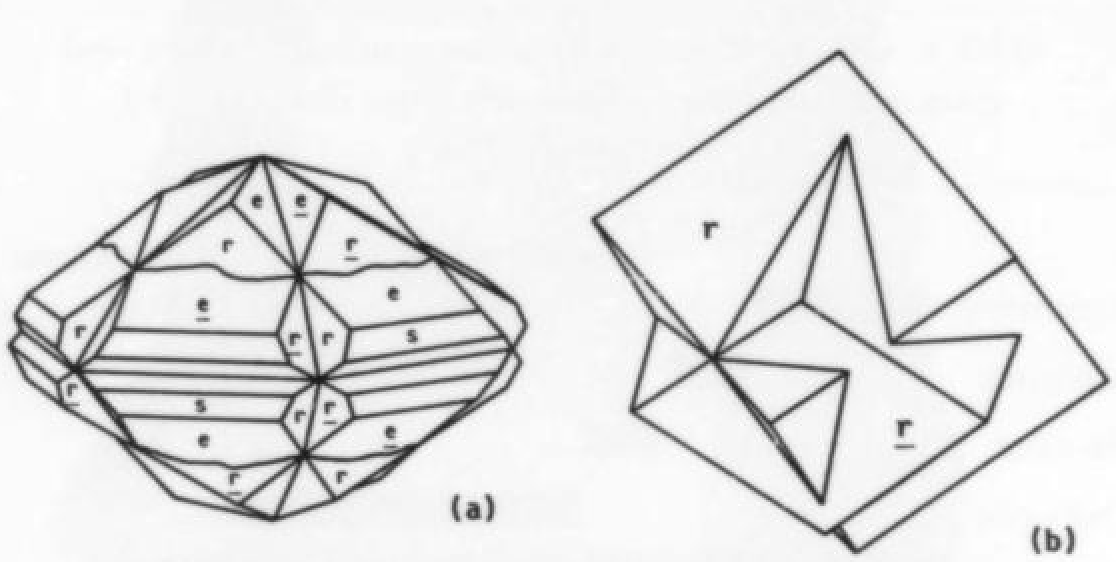


Figure 35. **The most common habits shown by Ben Lomond chabazite : (a) "phacolite" variety, with the *c*-axis as the twin axis and the forms $r\{10\bar{1}1\}$, $s\{02\bar{2}1\}$ and $e\{01\bar{1}2\}$. Redrawn from Anderson (1907). This is only one of the many phacolite habits found at Ben Lomond. (b) Idealized simple interpenetrant twin consisting of $r\{10\bar{1}1\}$. Crystals are usually striated parallel to r/r′ and r/r″, probably due to oscillatory development of faces of the form $e\{01\bar{1}2\}$. Brian M. England specimen (M69.4.2) and drawing.**

are never found in direct association, adjacent vesicles often contain crystals of distinctly different morphology.

Mesolite $Na_2Ca_2(Al_6Si_4)O_{30}\cdot 8H_2O$

Mesolite is common as a thin selvage of downy acicular crystals no more than a few mm thick lining many of the larger vesicles and forming a substrate for subsequent chabazite crystallization. It has also been observed as tufts of white acicular crystals reaching 5 mm in length on analcime. Some of this material may be natrolite (Anderson, 1907).

Nontronite $Na_{0.33}Fe_2^{+3}(Al,Si)_4O_{10}(OH)_2\cdot nH_2O$

The areas of basalt containing zeolites appear to have been hydrothermally altered, as evidenced by the abundance of nontronite as massive, sectile, dark green masses completely filling smaller vesicles. Large vesicles are commonly lined with a thin selvage of nontronite.

Kyogle

A spectacular but restricted zeolite occurrence was quarried on the southern flanks of the Tweed volcano near Kyogle in the early 1920's (Hodge-Smith, 1929). Four basalt flows and a dike formed this exposure at Fairy Mount; the main mineralization was located in a small but broad depression at the top of the second flow. There is now little evidence of this zone in the disused quarry. Cavities between altered basalt blocks were lined with chabazite, encrusting large scalenohedra of calcite and suggesting deposition from thermal waters. The paragenetic sequence listed by Hodge-Smith for the breccia was: intermixed clays and zeolites followed by chabazite, calcite, more chabazite, then mesolite, analcime and calcite. He interpreted this as

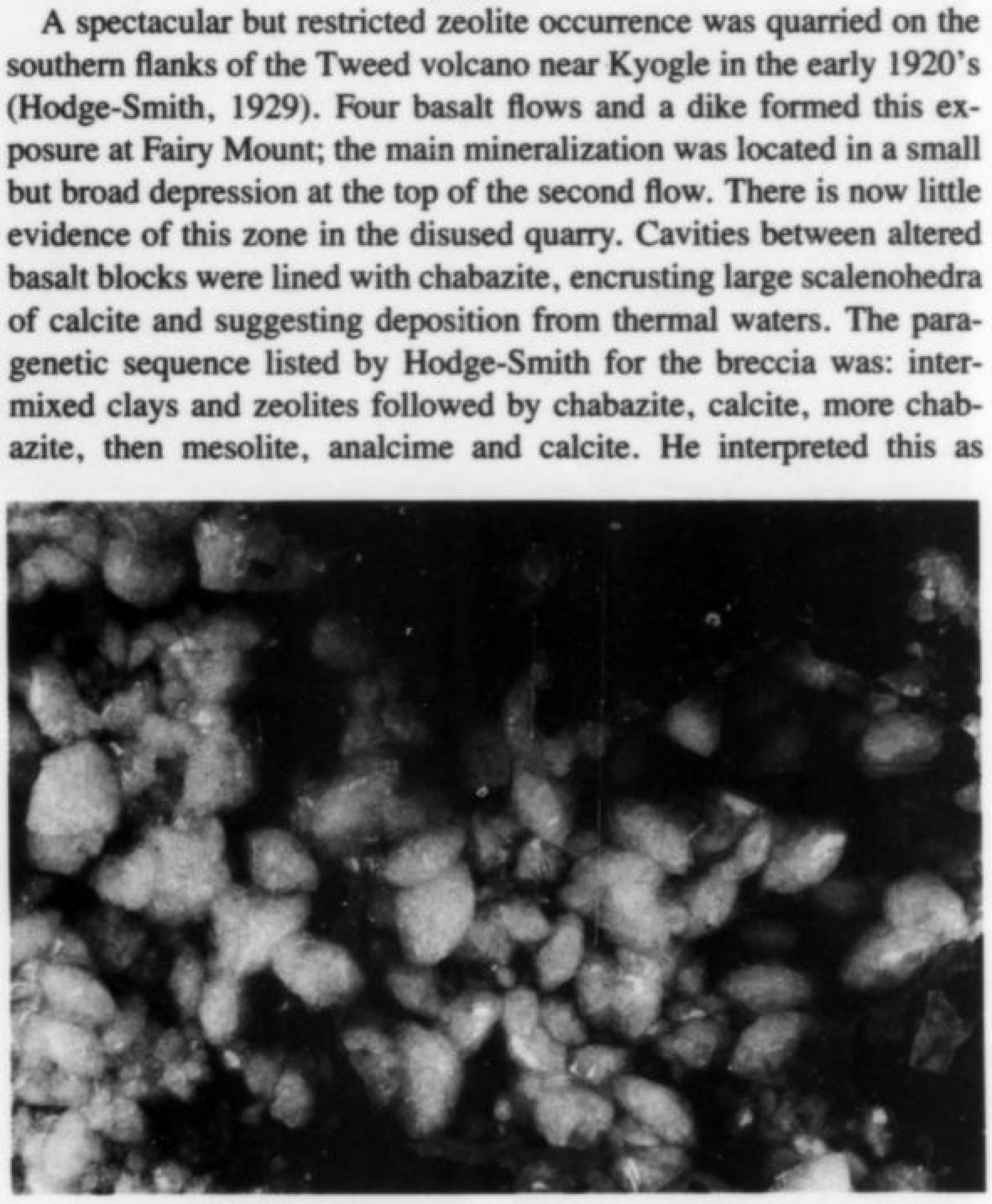


Figure 36. **White to colorless chabazite ("phacolite") crystals to 2.5 cm lining a vesicle in Tertiary basalt from the railway cutting at Ben Lomond, New England region of New South Wales. The specimen is 17 cm across and is in the collection of Brian M. England (M69.4.1). Photograph by Brian M. England.**

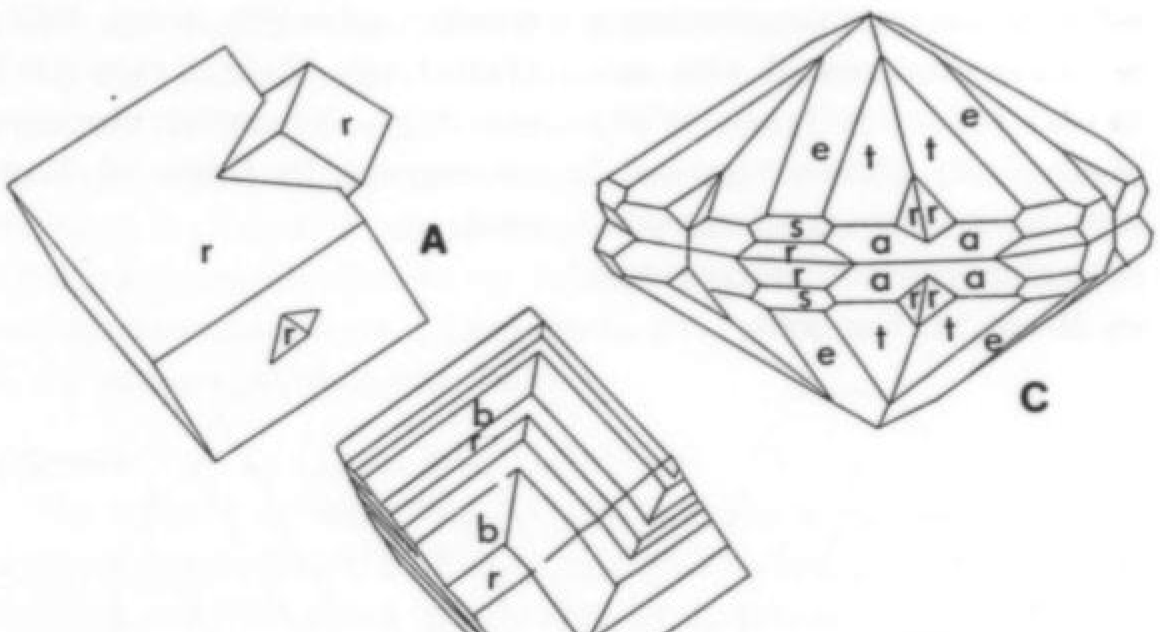


Figure 37. **Chabazite from the Kyogle quarry. Crystals A and B are typical of those from the second flow, showing $r\{10\bar{1}1\}$ with interpenetrant twinning on the vertical axis (A), and alternation between $r\{10\bar{1}1\}$ and $b\{21.2.\overline{23}.25\}$ (drawing B). Drawing C shows a complex phacolite twin from the breccia between the second and third flows; the forms present are $r\{10\bar{1}1\}$, $a\{1120\}$, $t\{11\overline{23}\}$, $e\{01\bar{1}2\}$ and $s\{02\bar{2}1\}$. Redrawn from Hodge-Smith (1929).**

alteration and deposition by solutions heated by the overlying flow, with the initial cycle of chabazite/calcite formed during rapid cooling and the additional zeolite/calcite association formed from less active, cooler waters.

The "phacolite" varieties of chabazite from the breccia typically show the forms $r\{10\bar{1}1\}$, $a\{11\bar{2}0\}$, $t\{1\bar{1}23\}$, $e\{01\bar{1}2\}$ and $s\{02\bar{2}1\}$. Crystals range up to 2.8 cm across. Analyses (Hodge-Smith, 1929; Passaglia, 1970) show more sodic and less calcic and potassic compositions than chabazites from Ben Lomond (Anderson, 1907). The large calcites, invariably coated with chabazite, are zoned, pale amber-colored scalenohedrons modified by $c\{0001\}$ and are sometimes doubly terminated. Mesolite formed delicate tufts and drusy surfaces on the chabazite or in gaps between large calcite crystals.

Small crystals of chabazite showing the simple rhombohedron form $r\{10\bar{1}1\}$ were typically found in the flows underlying the breccia. These crystals are usually twinned on the vertical axis and one larger rhombohedron (1.5 cm) shows modification by the scalenohedron $\{13.10.\overline{23}.\overline{13}\}$. Occasionally analcime is associated with the chabazite as trapezohedrons and rare cubes up to 4 mm across. Small colorless scalenohedral calcite crystals have been found in association with the analcime, or separately in adjacent vugs. Chlorite appeared as basal linings in vesicles within the two flows below the breccia, but was not found in the overlying flows whose vesicles contained poor developments of phacolitic chabazite.

CURRENT STATUS and FUTURE POTENTIAL

Several of the localities covered in this paper are either no longer accessible because of later site redevelopment, or no longer provide collectible material due to deterioration of the available outcrops. However, there is considerable potential for further specimen production from the remainder and the huge area covered by basalts in New South Wales makes the possibility of new discoveries very real.

Soon after the ferrierite-heulandite discovery in 1969, the Unanderra quarry was closed and converted to a garbage disposal site. The quarry has now been filled and developed. Specimens are no longer safely obtainable from nearby roadcuts on the F6 Freeway. Unless new excavations are opened in the Dapto latite, there seems very little prospect of further specimens being found.

In the Garrawilla area, two pastoral properties remain open to collectors, but the remainder are strictly off limits. However the area covered by the Garrawilla volcanics is very extensive.

The Ardglen quarry near Murrurundi remains an important source of fine zeolite specimens and continues to be readily accessible to collectors through prior arrangement with the Way and Works Branch of the New South Wales State Rail Authority. A new quarry is soon to be developed nearby in the upper flow and this promises to add significantly to the supply of specimens from the area.

Uncovered by roadworks in 1968, little of the original exposure at Willy Wally Gully remains intact, the basalt in both roadcut and adjacent embankments having weathered considerably. However, despite the limited remaining outcrop and friable nature of the weathered basalt, small specimens (especially micromounts) can still be collected.

In 1987, roadworks on the New England Highway 7.5 km east of Ben Lomond intersected the amygdaloidal top of a massive flow infilling the base of the basalt sequence. The association here includes chabazite (phacolite) in crystals to 2 cm, phillipsite, natrolite and calcite. While the site currently provides easy collecting, the specimens are not as spectacular as those produced by the older localities described in this paper, which are essentially exhausted.

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The Australian Museum, Sydney, gave one of the authors (B.M.E.) access to the extensive range of Ardglen and Ben Lomond specimens in the collection. Ross Pogson of the Earth Sciences Department provided extensive and invaluable assistance. Photographs of specimens in the collection were made by Museum Photographer John Fields. Copyright on these photographs is retained by the Trustees of the Australian Museum. Final prints of the other photographs used in this paper were prepared by Murray McKean of the C.R.L. photography group.

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Minerals of the
MOONTA AND WALLAROO
Mining Districts, South Australia

●

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Illustrations and Photographs
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The Moonta and Wallaroo mines are perhaps most famous for exceptionally fine atacamite and chalcopyrite crystals but, in addition, over 70 other species have been identified from the mines, including fine specimens of cuprite, cobaltite, sphalerite, and galena.

INTRODUCTION

After the settlement of South Australia in 1836, the young colony struggled to establish a viable agricultural economy. It was the discovery of rich copper deposits at Kapunda in 1842 and Burra Burra in 1845 which firmly established the state's economic prosperity. In most other Australian states gold played a major role in their development; South Australia, though, had no major gold fields, but was the center of a major copper province. Many of the deposits worked in South Australia during the last century, including those at Dome Rock, Mt. Gunson, Spring Creek and Yudnamutana, were quite rich secondary deposits, but proved very small and were worked out within a few years. The Moonta and Wallaroo mines however, were large, rich, primary deposits which were worked continuously for over 60 years.

HISTORY

The Moonta and Wallaroo mines are located on the northern part of Yorke Peninsula. In 1859 this area was occupied by a large sheep run called Wallaroo Station, owned by a retired Merchant Captain, W. W. Hughes. Hughes had earlier found traces of copper on the beach in the area and had instructed his shepherds to keep a lookout for further signs of copper mineralization on the station.

Late in 1859 a shepherd, James Boor, found fragments of copper carbonate in the mound of earth raised by a burrowing marsupial rat and thus discovered what was to become the Wallaroo mines. The mines took their name from the sheep station, and the present town of Wallaroo on the coast was named Port Wallaroo in 1863 (many years later the "Port" was dropped). In the meantime the town of Kadina grew up next to the mines. The Moonta deposits were discovered some months later, in early 1861, by another shepherd, Patrick Ryan, in this case with the unconscious aid of a wombat whose excavations revealed green copper ore. As each deposit was discovered Hughes formed private syndicates to operate them. Although both the Wallaroo and Moonta mines were owned by basically the same group of men they remained separate companies, with almost identical boards of management, until 1889 when they were finally amalgamated. Moonta Mines required very little capital, because development was funded from the enormous profits of mining. The early lodes at Moonta were extremely rich, consisting of almost pure chalcopyrite and bornite. Moonta Mines became the first Australian mining company to pay over £1,000,000 in dividends, a feat achieved by 1876. The Wallaroo mines required somewhat more faith and perseverance before they finally made a profit.

The Moonta and Wallaroo mines were worked continuously for over 60 years, finally closing in 1923. During this period some 6,250,000 tons of ore were produced which yielded 336,000 tons of copper valued at over £20 million. The mines were finally forced to close because of low ore grades, the low world copper price after the first World War and the high costs of mining at a depth of nearly 1000 m.

Soon after the original leases for the Moonta and Wallaroo mines were taken up, other leases were pegged on adjoining blocks. Most produced very little, the Yelta at Moonta and the New Cornwall at Kadina being among the more successful. Over the years these adjoining leases were gradually acquired by the company and were eventually amalgamated with Moonta and Wallaroo mines.

For most of the mines' working lives they were managed by members of the Hancock family. Henry Richard Hancock was appointed Superintendent of the Moonta mines in 1864, at the age of 28, and a few years later he was also made Superintendent of the Wallaroo mines. Until 1898 Hancock ran what were, at the time, the richest

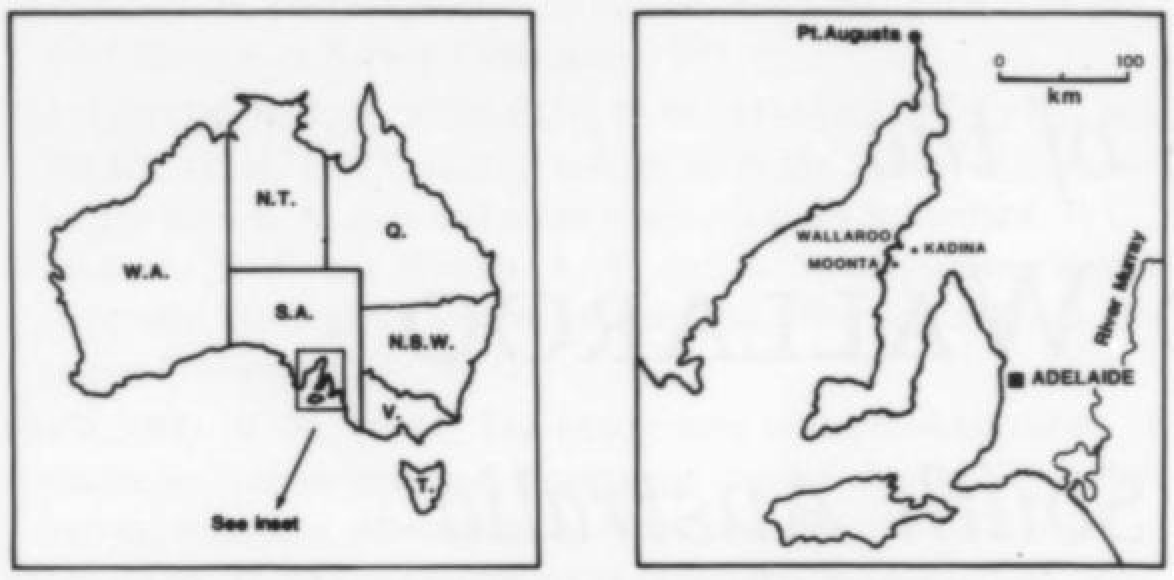


Figure 1. **Map showing Moonta, Kadina and Wallaroo.**

mines in Australia, keeping them in profit despite fluctuating copper prices, strikes, and the demands of greedy shareholders (who between 1860 and 1923 received dividends worth nearly £4.5 million). Hancock was born in Devon, but the mining methods and the miners he employed were largely Cornish. He was an innovative engineer and a shrewd manager, and he was considered by his workers as a stern but kindly father figure. One of his many social innovations was the introduction of compulsory education at night school for the many boys employed around the mines.

The mines were worked for many years by traditional Cornish methods, for nearly all the miners were Cornish and the towns of Moonta and Kadina took on a Cornish character (the town of Wallaroo had a Welsh character, as nearly all workers in the smelting plant there were from south Wales). The mine architecture, featuring large stone pump houses with round stone chimneys, was transplanted straight from Cornwall. In fact these pump houses are all that remain today of the huge complexes of mine buildings at the Moonta and Wallaroo mines.

Most of the ore was mined by tribute teams who tendered for an area underground and were paid on the amount and value of the ore raised. Shafts were sunk and drives opened by lesser miners who worked for wages; this was known as tutwork. A miner began his working life in the mines as a "picky boy," whose job it was to sit at a table or conveyor belt sorting the good ore from the waste. After a few years he would progress to tutwork and later perhaps he would join a tribute team, known as a "pare." The mine workers were supervised by mine captains appointed by the company. The captains were for the most part experienced miners; they were the elite at the mines and were expected to take a leading role in the community outside of the mines. Pryor (1962) provides a very readable account of the history and life at the Moonta mines and a short illustrated history of the mines can also be found in Drexel (1982). A fuller account of the Wallaroo mines is given by Bailey (1985).

The Cornish system of mining worked well and seems to have led to the preservation of many fine mineral specimens. Specimen collecting does not seem to have been discouraged in the mines; in fact, it was part of some captains' duties to collect mineral specimens for the company. John Henry Dunstan was such a captain who worked in the mines for over 30 years, first at Moonta and later at the Wallaroo mines, and many of the specimens from Moonta-Wallaroo that exist in collections today probably passed through his hands. In some ways this article is as much about the mineral specimens collected by this remarkable man as it is about the locality. Most of the specimens illustrated here came from his personal collection, now preserved at the South Australian Museum, Adelaide, and it is worth devoting a few lines to describe his collecting activities.

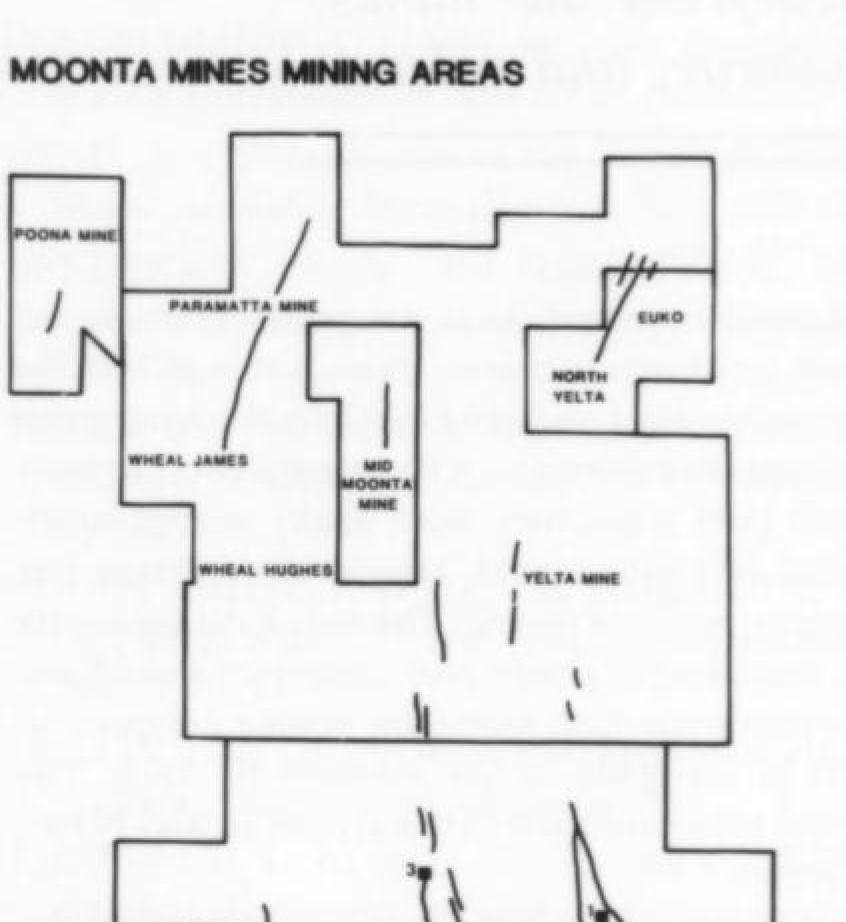


Figure 2. **Map of the lodes at the Moonta mines and adjoining leases. Few of the adjoining mines managed to locate payable lodes and were eventually amalgamated with the Moonta mines (modified from Jack, 1917).**

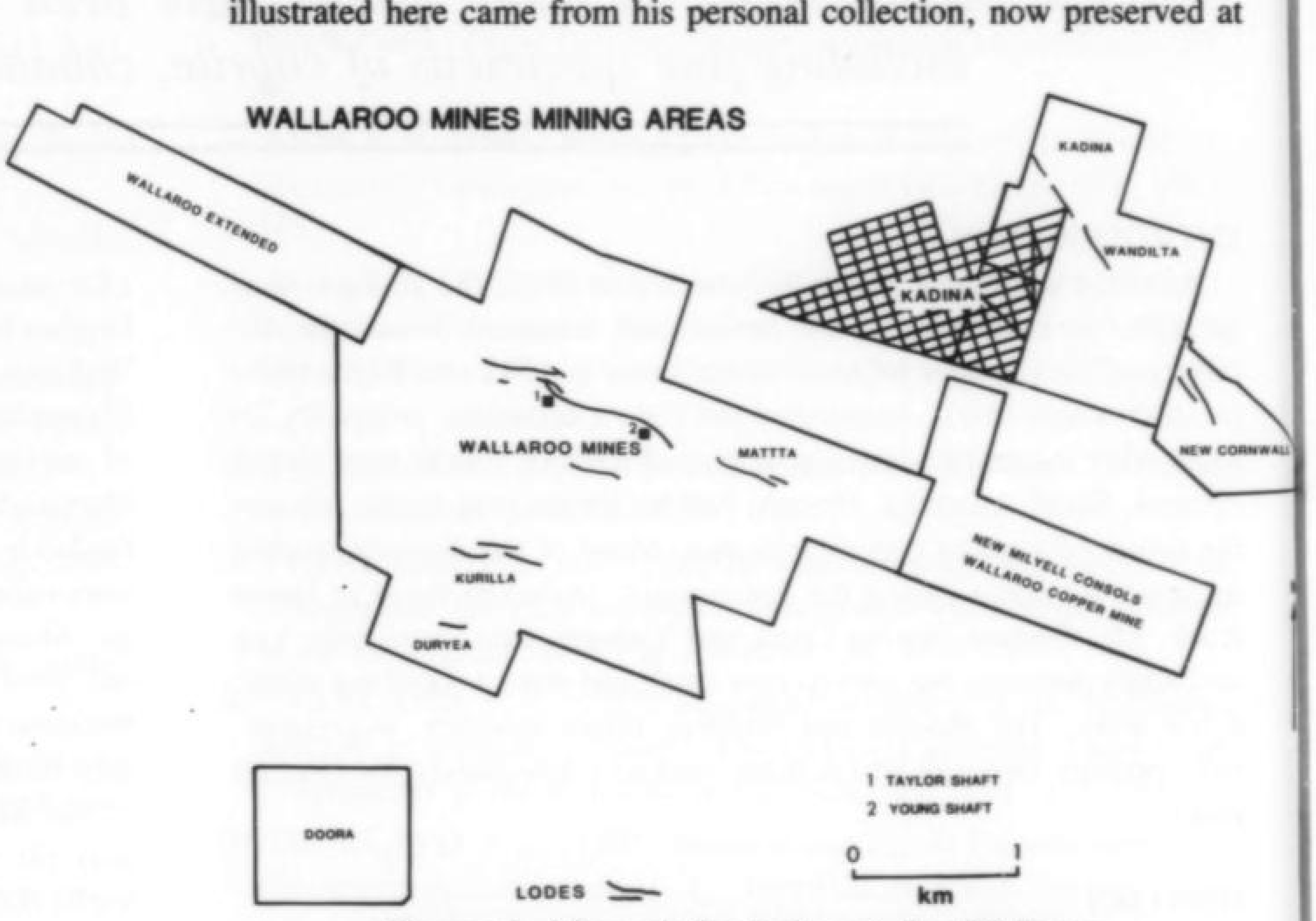


Figure 3. **Map of the lodes at the Wallaroo mines and the adjoining leases around Kadina. The Doora mine in the south and the New Cornwall mine in the east produced very fine atacamite specimens (modified after Jack, 1917).**

Dunstan was born in the parish of Stithians, Cornwall, England, in 1847 and came to South Australia in 1855; later his father, with some relatives, tried their luck on the Victorian goldfields. In 1874 Dunstan moved to Moonta to seek work in the mines. He first worked at the Euko mine before joining a tribute team at the Moonta mines. Later he joined the mine staff as a surface captain and was engaged in sampling and assaying ore and also in collecting specimens. To

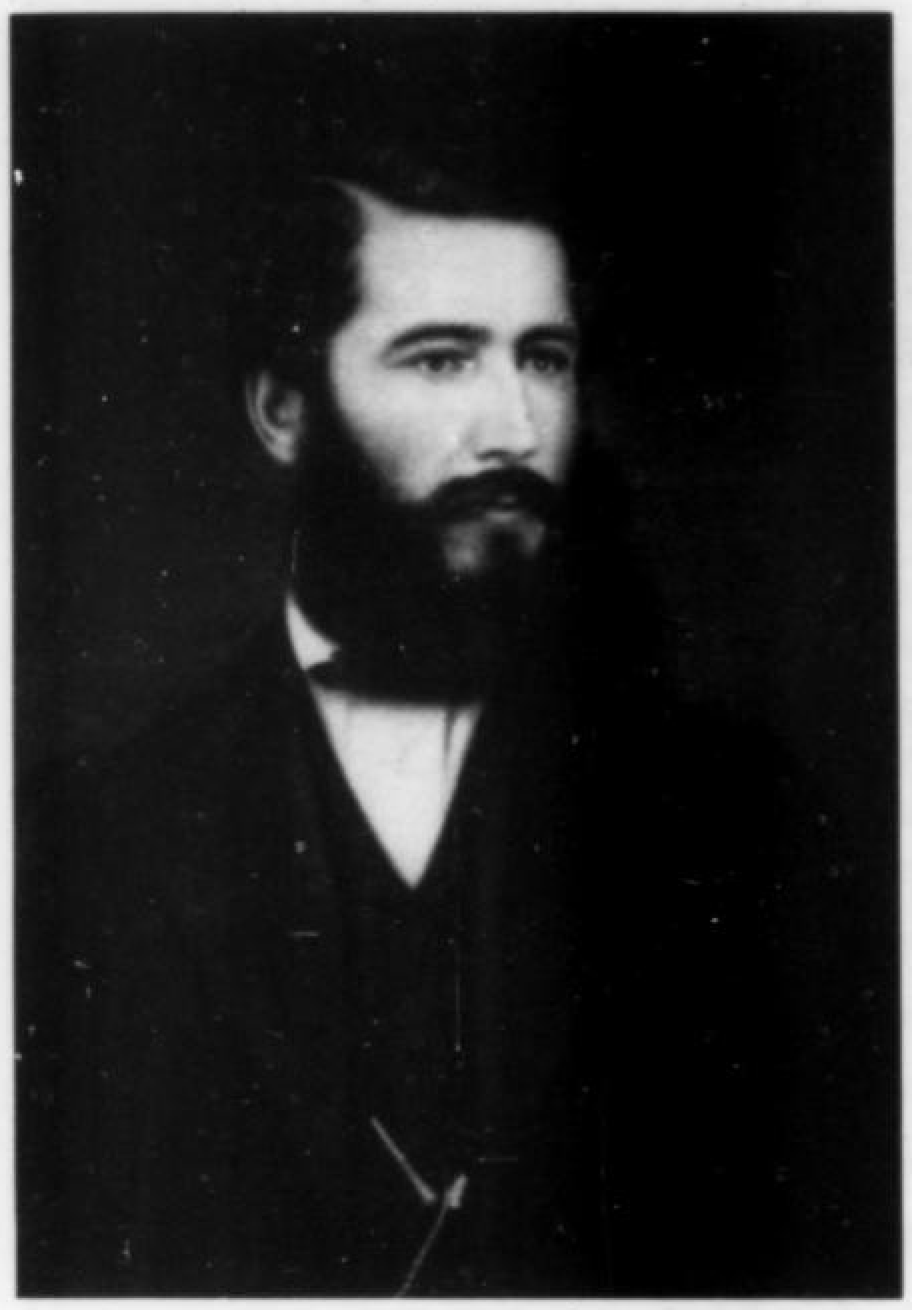


Figure 4. **Captain R. H. Hancock, manager of Moonta and Wallaroo mines. When he retired in 1898 he was succeeded by his son, H. L. Hancock, who ran the mines until shortly before they closed in 1923. (SADME 35770)**

Figure 5. **A group of miners at the Hughes shaft, Moonta mines, 1894. Note candles fixed to their hard hats with balls of clay. (Mortlock Library)**

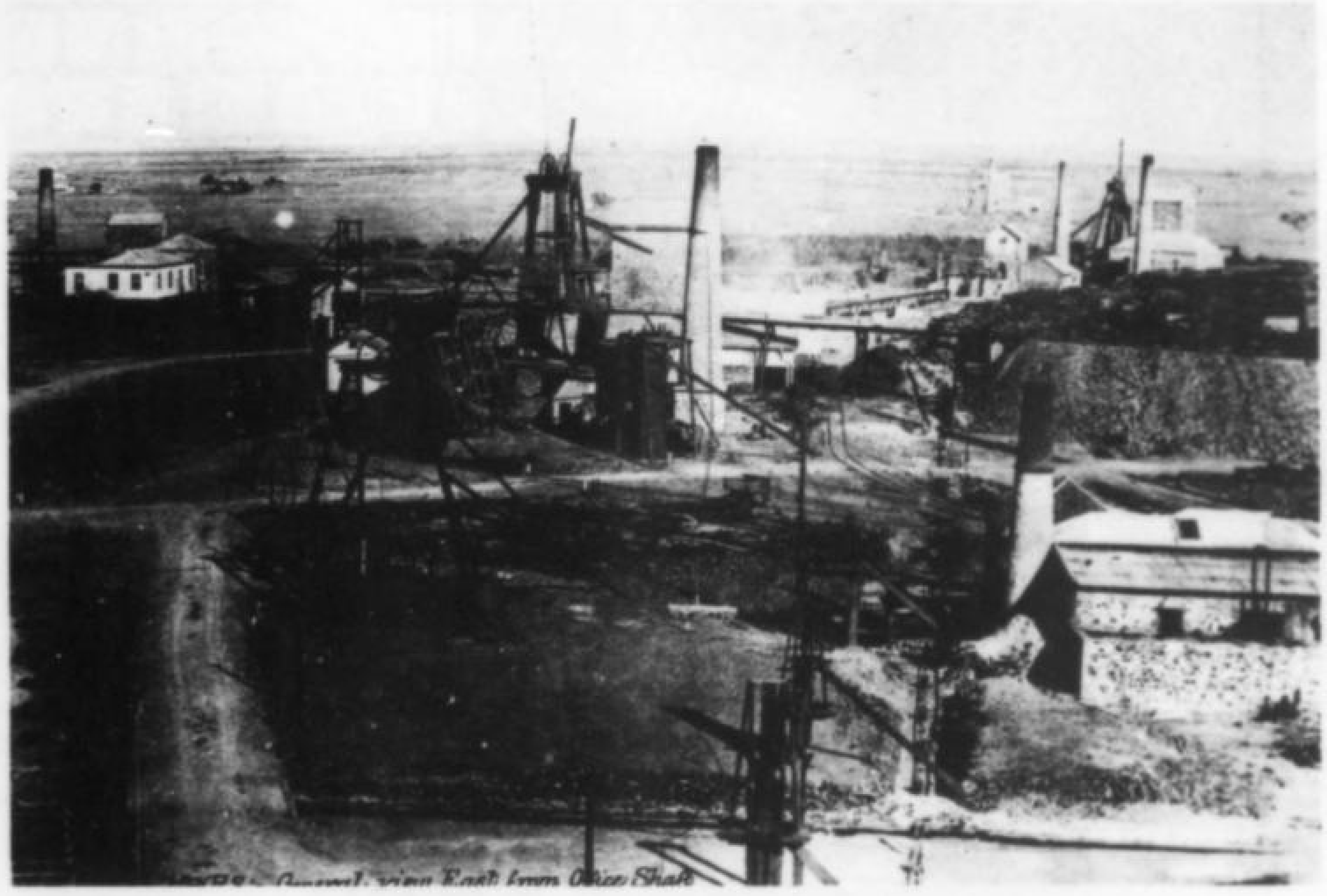


Figure 6. **The Wallaroo mines in 1880. Photograph taken from the top of the Office shaft with Taylor's and Elder shafts in the distance. (SADME 32790)**

familiarize himself with the minerals he was encouraged not only to collect for the company but also for himself. In 1897 he transferred to the Wallaroo mines and continued his collecting duties, finally retiring in 1908. During his time at the mines he established a personal collection of some 4000 specimens, and he also prepared and cataloged a large collection for Henry Lipson Hancock which is also now preserved at the South Australian Museum. He exchanged specimens widely, particularly with the principal mineral dealers of the day—Kranz in Berlin, English in New York, and Foote in Philadelphia—and also with such leading collectors as Washington A. Roebling and A. E. Seaman.

The South Australian Museum purchased part of Dunstan's collection in 1907. A young mineralogist at Adelaide University, Douglas Mawson, was asked by the museum to examine the collection on their behalf. Nearly 50 years later, in 1954, Mawson (by then Professor Sir Douglas Mawson, famous scientist and Antarctic explorer) purchased the remainder of the collection on behalf of the museum from Dunstan's granddaughter. The collection, in addition to containing some of the finest specimens recovered from the Moonta and Wallaroo mines, also contained many very fine specimens from Broken Hill and other Australian locations.

GEOLOGY

The Moonta and Wallaroo mines are situated on a gently undulating, featureless plain at the northern end of Yorke Peninsula, some 160 km from Adelaide. Detailed geological investigations of the district are few, due to an almost total lack of outcrop. The principal works describing the geology and mineralogy of the mining area are two Geological Survey reports by Ward and Jack (1912) and Jack (1917), who had the advantage of access to the extensive underground workings of the mines which today are completely filled with water. A simplified geological map of the area is presented in Figure 8.

The mineralized rocks consist of Archean metasediments intruded by feldspar porphyry, diorite, granite and their derivatives. Volcanic rocks have been noted in the lodes at the Wallaroo mines (Crawford 1965). Overlying the Archean rocks are very gently dipping Cambrian limestones and sandstones which in turn are covered by layers of Tertiary and Quarternary caliche and unconsolidated sands and clays. The main geological feature is the feldspar porphyry, which forms an irregular tear-drop-shaped body with its sharp end pointing northeastwards to within 5 km of Kadina. The porphyry intruded into a series of greywackes, quartzites and gneisses of sedimentary origin distributed beneath the caliche and unconsolidated sediments to the west, north and southeast of Kadina.

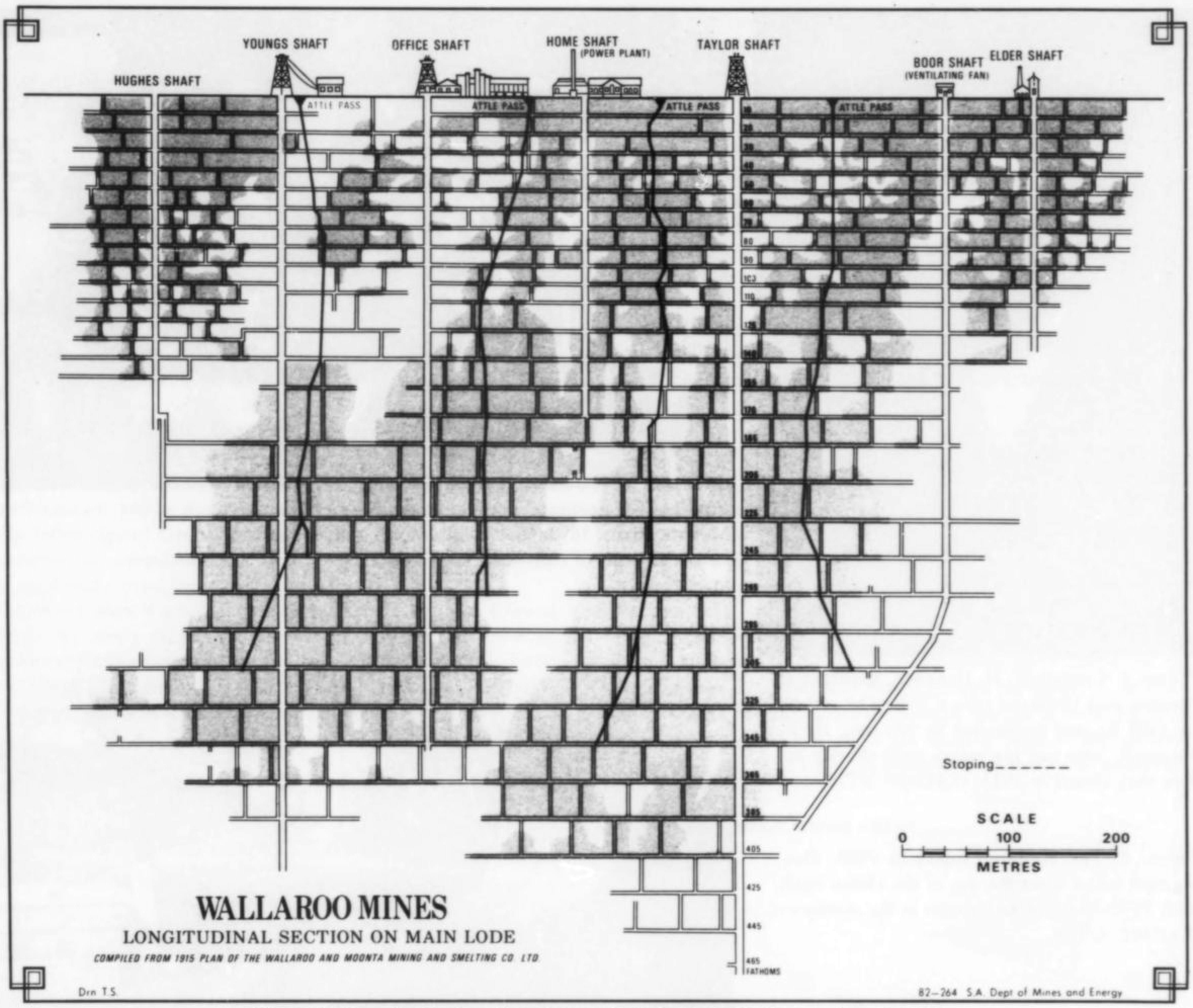


Figure 7. **A longitudinal section of the main lode at the Wallaroo mines showing the extent of stoping and the depth of the shafts. (Courtesy of SADME)**

The orebodies of the Moonta group of mines consisted of pegmatitic and quartzose veins filling fractures along faults in the feldspar porphyry body. All the Moonta lodes lay within the boundaries of the Moonta Porphyry. The principal lodes lay along three main lines of weakness, in concentric arcs parallel to the length of the Moonta Porphyry body. The orebody extended over a distance of some 3 km with individual lodes to 1000 m in length. The orebody dipped 40° to 65° NW and extended to a depth of 700 m.

The principal ore minerals in the Moonta lodes were chalcopyrite and bornite. The gangue consisted of quartz, feldspar and biotite with accessory hematite, schorl, molybdenite and fluorite. The more quartzose portions of the lode were richer in chalcopyrite, while the bornite was associated with the more feldspathic portions.

The geological setting of the Wallaroo group of mines is quite different from that at Moonta, and this is reflected in the mineralogy of the lodes. At the Wallaroo mines the host rocks are metamorphosed sediments, mainly biotite schists which have been partly invaded by dikes and offshoots of the Moonta Porphyry. There were fewer individual lodes at the Wallaroo mines, though they were more extensive. The main lode was mined over a distance of 1000 m and to a depth of 850 m. The lodes were of a replacement type rather than fracture filling. The mineral assemblage of the orebody consisted of chalcopyrite with pyrite and pyrrhotite; minor amounts of galena and sphalerite were also present. The gangue was quartz and carbonates; accessory minerals included schorl, apatite and scapolite.

The structure of Wallaroo deposits is quite simple. The main ore is bounded by a series of three lode shears striking 90° to 120° and dipping 75°S, the northeast shear zones striking 30° to 45° and dipping 70°NW and the northwest-striking fissures dipping SW. The foliation of the metasediments is said to be parallel to the original bedding.

Theories on the origin and interrelationship of the lodes at Moonta and Wallaroo are few and perhaps out of date. Jack (1917) believed that the source of both orebodies could be the Arthurton granite some 26 km southeast of Moonta, and ascribed their differences in character to differences in base rock fracturing and distance from the source. Dickinson (1942) mentioned the possibility of mineral vein formation being a late phase of porphyry intrusion with the possibility that the porphyry also underlies the Wallaroo lodes.

Little progress has been made on theories of ore genesis for these deposits over the past 40 years, work being hampered by the lack of outcrop and the inaccessibility of the mine workings.

MINERALS

The mineralogy of the Moonta and Wallaroo deposits is poorly documented; Jack (1917) is the only detailed work on the subject, although the more recent unpublished thesis of McBriar (1962) is a

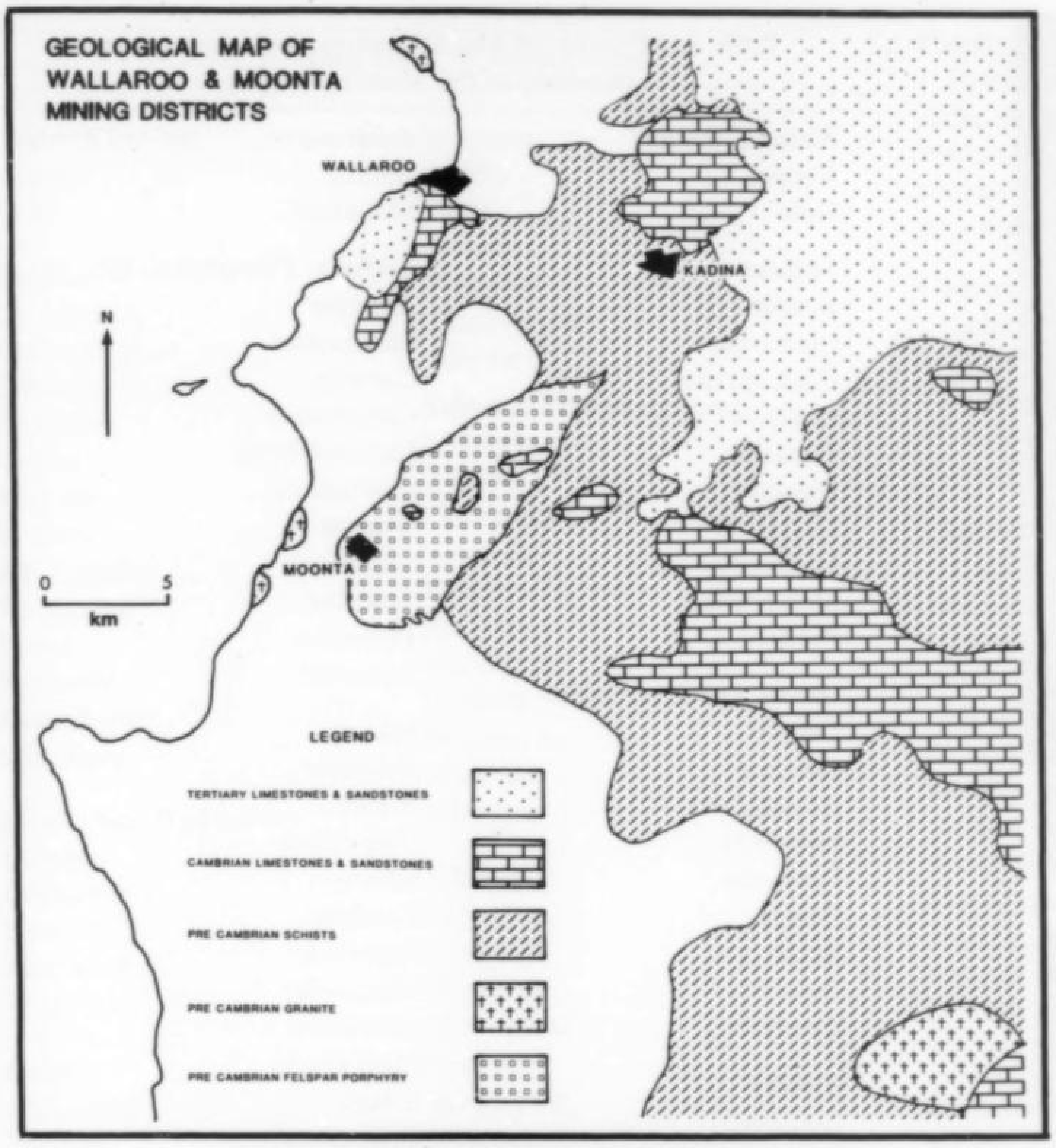


***Figure 8*. Geological map of the Moonta and Wallaroo mining district (simplified from Jack, 1917).**

***Figure 9*. Underground at the Moonta mines, circa 1910. Timbermen replacing timber in a drive. (Mortlock Library B24094)**

***Figure 10*. Working a wide stope at the Wallaroo mines during 1916–1918. The stope was worked by a tribute team of four with four laborers to assist with timbering. (SADME 7167)**

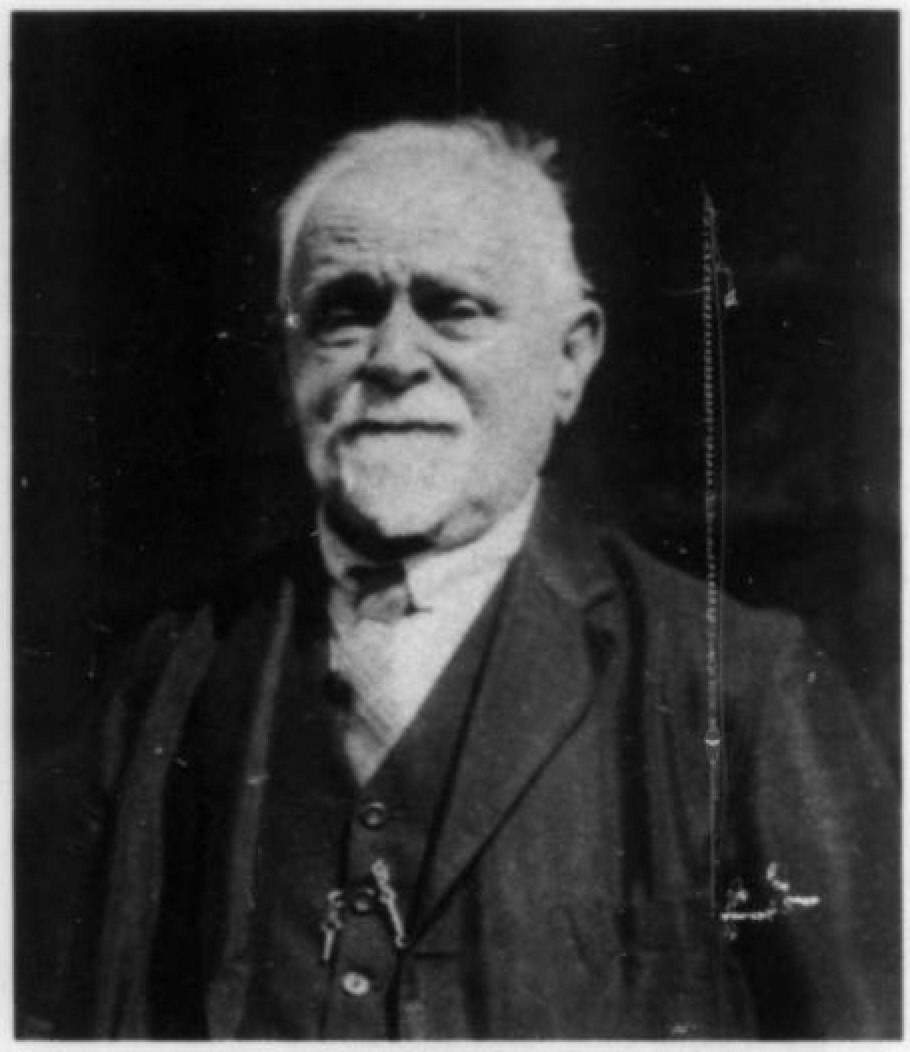


Figure 11. **Captain J. H. Dunstan around 1940. Dunstan was employed by the mines as a surface captain. As part of his duties he selected samples for assay; he also collected specimens for the mines and at the same time assembled a very fine personal collection of minerals from the mines. (Mrs. L. B. Hammond)**

useful source of details on the sulfide mineralogy.

In compiling this section extensive use has been made of both these works, but the principal source of information has been the extensive collections from the mines held at the South Australian Museum. Most of this material was collected by Dunstan and came to the museum either in his collection or in the Hancock and Fairhall collections, both of which appear to have relied on Dunstan for specimens from the Moonta and Wallaroo mines. Unfortunately, few specimens are preserved with exact locality data from within the mines. At most a shaft name is given, so a first-hand account of the mineralogical variation in the lodes is not possible. One must rely on the detailed description of Jack (1917).

Both deposits appear to have similar oxidized zones which extended to a depth of between 30 and 50 m. The saline character of the groundwaters in the area resulted in the formation of large masses of atacamite, and this was the dominant mineral in the oxidized zones. Malachite and azurite were rare and in the lower portion of the oxidized zones, cuprite and chalcocite were the principle species. In the primary ore zone at the Wallaroo mines a chalcopyrite-pyrrhotite-pyrite assemblage was dominant; at the Moonta mines, chalcopyrite-bornite-hematite was the main assemblage. Several small pockets of uranium minerals were found at the Moonta mines associated with the amorphous organic compound, thucolite. These were the subjects of considerable interest and investigation in the early part of the century (Radcliff, 1906; Mawson, 1944) but proved to be of no commercial importance.

The Moonta-Wallaroo area is probably best known as a source of very fine atacamite crystals. Some early workers thought that these specimens came from Burra, South Australia, an error which was unfortunately perpetuated in parts of the literature, notably Brauns (1912) and more recently by Scalisi and Cook (1983).

Over 70 minerals have been identified from the lodes and surrounding country rock at Moonta and Wallaroo. A full list of these minerals is given in Tables 1 and 2. Many of them are known only from petrographic sections or as microscopic inclusions in sulfides and are in need of confirmation. The most important minerals are described below.

***Table 1*. Minerals of Moonta mines, including accessory minerals in the Moonta Porphyry**

Native Elements
Copper
Gold

Sulfides
Bornite
Chalcocite
Chalcopyrite
Covellite
Cubanite[2]
Digenite[2]
Linnaeite[2]
Loellingite[2]
Molybdenite
Pyrite

Oxides and Hydroxides
Cuprite
Goethite
Hematite
Magnetite
Pyrolusite
Quartz
Rutile
Tenorite
Uraninite

Halides
Atacamite
Eriochalcite[3]
Fluorite

Carbonates
Azurite
Malachite

Sulfates, Phosphates, etc.
Autunite[4]
Cacoxenite[3]
Carnotite[5]
Chalcanthite
Ferrimolybdite
Fluorapatite
Gypsum
Melanterite
Scheelite
Torbernite
Turquoise

Silicates
Actinolite
Biotite
Clinochlore
Epidote
Kaolinite
Microcline
Muscovite
Orthoclase
Plagioclase
Schorl
Uranophane
Zircon[4]

References are given for minerals reported elsewhere but not confirmed by the author:
[1] Dickinson (1953)
[2] McBriar (1962)
[3] Nobel *et al*. (1983)
[4] Jack (1917)
[5] Radcliff (1906)

Anhydrite $CaSO_4$

Anhydrite was found in the Wallaroo mines as pale blue masses associated with dolomite, quartz and sphalerite; it appears to have been rather rare in the mines as only a few specimens are known.

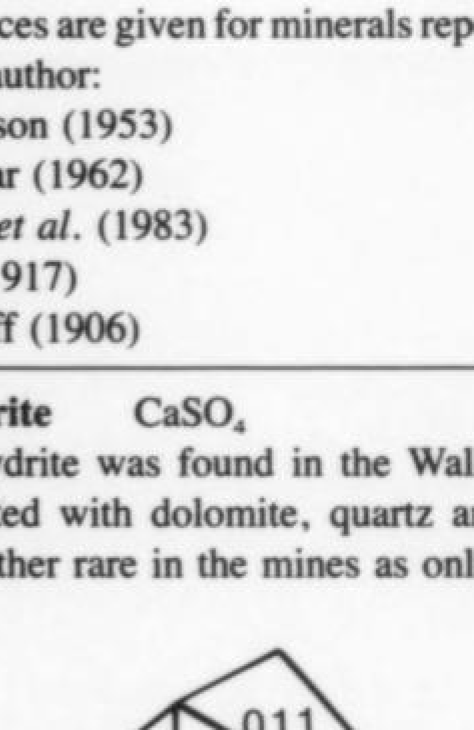


Figure 12. **Atacamite from the New Cornwall mine, Kadina.**

Atacamite $Cu_2(OH)_3Cl$

Atacamite was the most abundant mineral in the upper oxidized zones at both Moonta and Wallaro, where it occurred as large masses and as crystals lining vugs. The New Cornwall mine at Kadina is probably the source of all the world's finest atacamite crystals; here

Table 2. **Minerals of Wallaroo mines**

Native Elements
Copper
Gold

Sulfides
Chalcocite
Chalcopyrite
Cobaltite
Covellite
Galena
Marcasite
Millerite
Molybdenite
Pentlandite
Pyrite
Pyrrhotite
Skutterudite
Sphalerite

Oxides and Hydroxides
Cuprite
Goethite
Hematite
Magnetite[2]
Pyrolusite

Halides
Atacamite
Fluorite
Paratacamite

Carbonates
Ankerite
Aragonite
Azurite
Calcite
Dolomite
Malachite
Rhodochrosite[2]
Siderite

Sulfates, Phosphates, etc.
Anhydrite
Celestite
Chalcanthite
Epsomite
Erythrite
Ferberite
Fluorapatite
Gypsum
Melanterite
Monazite
Scheelite

Silicates
Actinolite
Allanite[2]
Biotite
Chrysocolla
Epidote
Hornblende
Meionite
Microcline
Plagioclase
Schorl
Titanite

References are given for minerals reported elsewhere but not confirmed by the author:
[1] Nobel *et al*. (1983)
[2] Jack (1917)

crystals of exceptional size were found, single crystals to 23 cm in length having been reported (Cloud, 1883). Groups of crystals with individuals over 5 cm in length and 1 cm in diameter were not uncommon. Crystals are typically chisel-shaped, the dominant forms being {110} and {011}. Fine plates of atacamite were found at the Doora mine south of the Wallaroo mines; here the atacamite crystals were not elongated, but typically 6 mm on edge.

Biotite $K(Mg,Fe^{+2})_3(Al,Fe^{+3})Si_3O_{10}(OH,F)_2$

Biotite is a major constituent of the schists at the Wallaroo mines and is an accessory phase in the Moonta Porphyry. Well formed pseudo-hexagonal crystals to 1 cm in diameter were found at Wallaroo mines. Large biotite crystals to 5 cm were found at the Yelta mine, Moonta, associated with chalcopyrite and pyrite.

Bornite Cu_5FeS_4

Small rough dodecahedral crystals of bornite altering to atacamite were found in the Moonta mines, but crystallized specimens are rare. Massive bornite was found in great abundance in the upper levels of the primary ore zone on the Moonta field, intergrown with chalcopyrite and more rarely with digenite. Masses of exceptional purity were found in the Hamley mines, Moonta (Zies and Merwin, 1955). Bornite is rare in the Wallaroo mines but has been found associated with chalcopyrite and biotite.

Calcite $CaCO_3$

Calcite is the second most abundant carbonate mineral after dolomite at the Wallaroo mines but is absent in the Moonta mines. Calcite at Wallaroo occurs as well formed crystals associated with pyrite, chalcopyrite and galena; it was among the last gangue minerals to be deposited.

Chalcocite Cu_2S

Chalcocite was a common mineral in the lower oxidized zones on both fields. At the Wallaroo mines massive chalcocite was found associated with chrysocolla and atacamite. Small, well formed crystals of chalcocite were occasionally found at the Moonta mines but it was generally massive.

Chalcopyrite $CuFeS_2$

Chalcopyrite was the most abundant copper mineral in the deposits, where it was the dominant primary sulfide. Crystalline specimens of exceptional beauty were produced in some abundance at both Moonta and Wallaroo. At the Moonta mines chalcopyrite crystals are associated with smoky quartz and hematite, the most attractive specimens being those with multiply twinned crystals forming 5-cm spheroidal and rhomboidal groups perched on plates of small quartz crystals. Chalcopyrite crystals from the Wallaroo mines are brighter and less tarnished than those found at Moonta and the twinned intergrowths are also generally less complex. The mineral is associated with colorless quartz, galena and dolomite and sometimes sphalerite. Small chalcopyrite crystals also occur enclosed by calcite and gypsum. Bright twinned groups of crystals up to 10 cm on edge were found at both Moonta and Wallaroo.

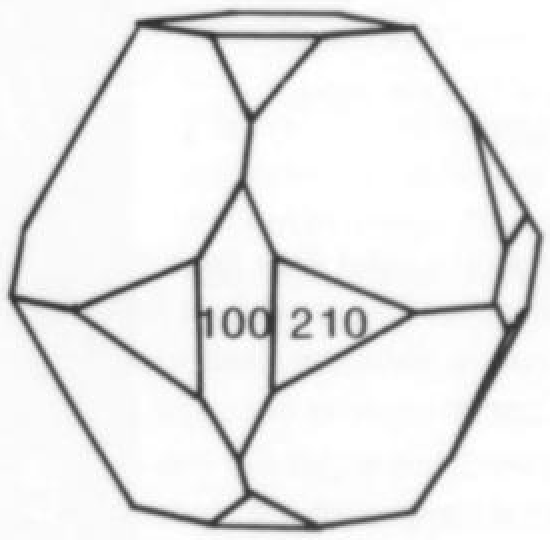


Figure 13. **Cobaltite, Kadina.**

Cobaltite CoAsS

Fine crystals of cobaltite were found enclosed in biotite, quartz and albite at the Kurilla and Wallaroo mines, Kadina. Crystals are generally between 6 mm and 1.5 cm across, although individuals over 2.5 cm in diameter are known. The most common forms are the cube {100}, the octahedron {111}, and the pyritohedron {210}.

Copper Cu

Copper was widespread in the upper oxidized zones of the Moonta mines and less common at the Wallaroo mines; it generally occurred as crude crystallized lumps often composed of many interconnected, rounded dodecahedral crystals, rarely branched or arborescent. At Moonta, native copper was associated with cuprite, chalcocite and schorl, more rarely in kaolinite. At the Wallaroo mines it is often coated with atacamite, and is also found with cuprite, aragonite and paratacamite.

Covellite CuS

Covellite was found in the lower part of the oxidized zone of the Moonta mines, where it occurred as an alteration product of chalcopyrite. No large crystals of the mineral were found, only microcrystals to 1 mm. Covellite was rare at the Wallaroo mines where it occurred only as thin films on chalcopyrite.

Cuprite Cu_2O

Fine octahedral crystals of cuprite were common in the upper levels

Figure 14. **Atacamite from the New Cornwall mine, Kadina. The largest crystal is 4 cm long. Dunstan collection, S.A.M. G1093.**

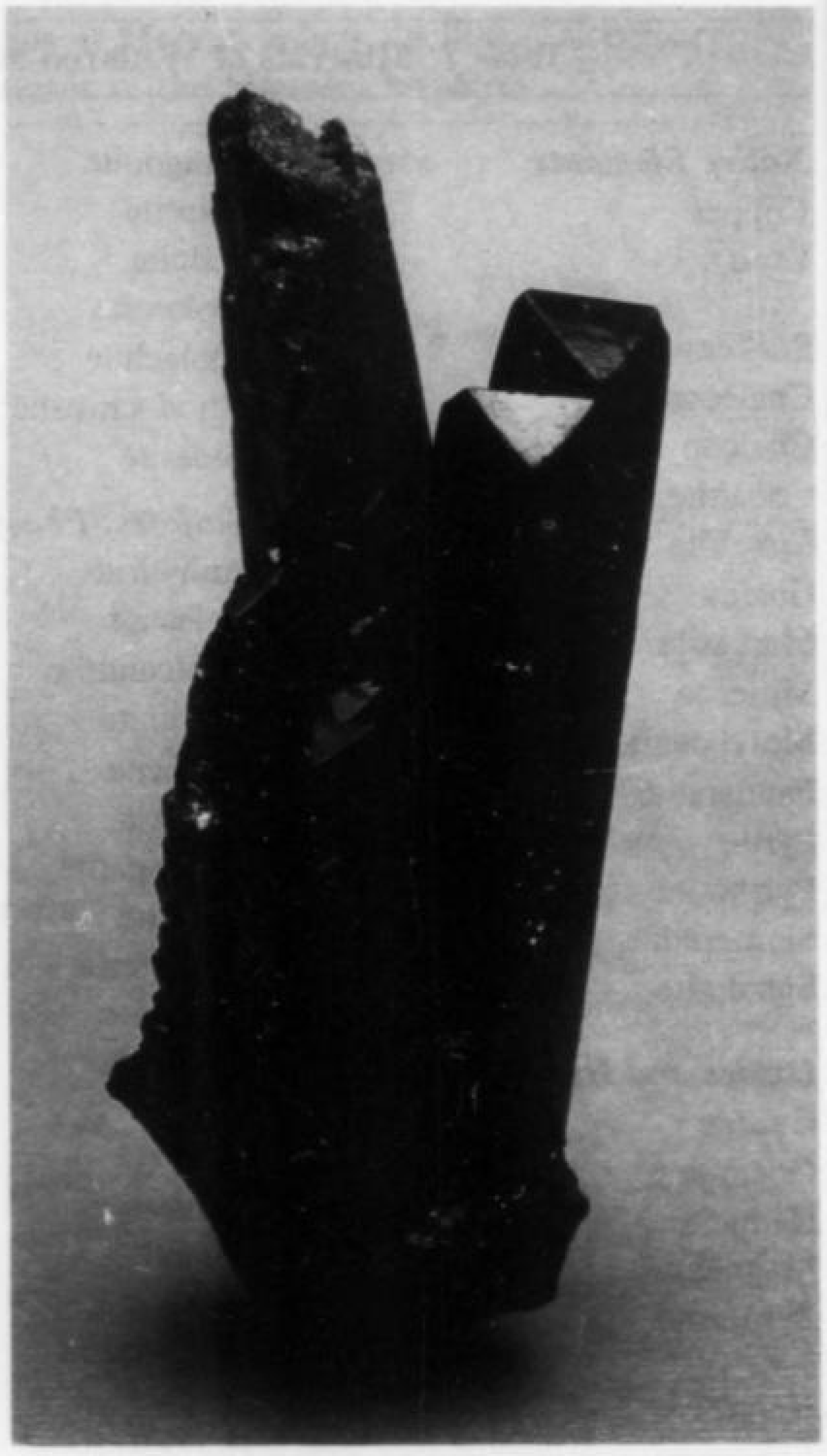


Figure 15. **Atacamite from the New Cornwall mine, Kadina. The specimen is 8 cm tall. Dunstan collection, S.A.M. G1099.**

at the Moonta and Wallaroo mines; in the latter they were often coated with atacamite or altered to paratacamite. The crystals at Moonta were generally larger, sometimes 2.5 cm in diameter, and cleaner, often with a bluish submetallic luster. Cuprite crystals occurred lining large vugs in the altered porphyry and were not generally associated with other copper minerals. Among the most striking specimens from Moonta are groups of interpenetrating octahedra.

Dolomite $CaMg(CO_3)_2$

Dolomite was the principle carbonate gangue mineral at Wallaroo mines. It was commonly found coating the sulfide minerals and quartz, and also as thin plates up to 8 cm in diameter and as casts and coatings over calcite crystals, often with microcrystals of pyrite. Dolomite is not known from the Moonta mines.

Ferberite $Fe^{+2}WO_4$

Crude crystals of ferberite to 8 cm were found in Taylor's shaft, Wallaroo mines, associated with vein quartz, chalcopyrite and scheelite.

Fluorapatite $Ca_5(PO_4)_3F$

Fluorapatite was a minor accessory mineral in the Moonta Porphyry. Well formed, prismatic fluorapatite crystals to 5 cm occurred with chalcopyrite, calcite and biotite at the Wallaroo mines. It also occurred in massive form.

Fluorite CaF_2

Fluorite occurred as a gangue mineral at the Wallaroo mines, associated with calcite, pyrite and chalcopyrite; distinct crystals were rare, the mineral being generally found in pale green and purple masses. At Moonta, small purple crystals to 1 cm were found filling veins with chalcopyrite and quartz in the shattered porphyry in Taylor's lode.

Galena PbS

Fine, interpenetrating galena twins embedded in calcite with chalcopyrite and sphalerite were found in Youngs shaft, Wallaroo mines. It was also found coated with dolomite and chalcopyrite elsewhere in the Wallaroo mines. It has not been found at the Moonta mines.

Gypsum $CaSO_4\cdot 2H_2O$

Large transparent crystals of gypsum to 10 x 20 x 25 cm enclosing dolomite and chalcopyrite were found at the Wallaroo mines. It appears to be the last mineral to form in the carbonate vein sequence. Also found as a post-mining product at the Moonta mines.

Hematite Fe_2O_3

Hematite is an abundant constituent of the Moonta Porphyry and was widespread in the Moonta lodes, where it was found dusting quartz and chalcopyrite crystals. It was also found replacing magnetite in the Moonta mines and at the Yelta and North Yelta mines. It was uncommon at the Wallaroo mines.

Malachite $Cu_2(CO)_3(OH)_2$

Malachite was found sparingly at the Moonta and Wallaroo mines, but was more abundant at the New Cornwall mine, Kadina, where it occurred in fibrous masses with atacamite. It has also been found as a post-mining product at the Moonta mines.

Meionite $3CaAl_2Si_2O_8\cdot CaCO_3$

Meionite was a minor vein mineral at the Wallaroo mines where it occurred in pale greenish white resinous masses up to 4 x 7 x 10 cm.

Molybdenite MoS_2

Molybdenite has been found widely though sparingly throughout the lodes at the Moonta mines; it was slightly more abundant in the Yelta mine; and it occurred as foliated masses in quartz-biotite-mi-

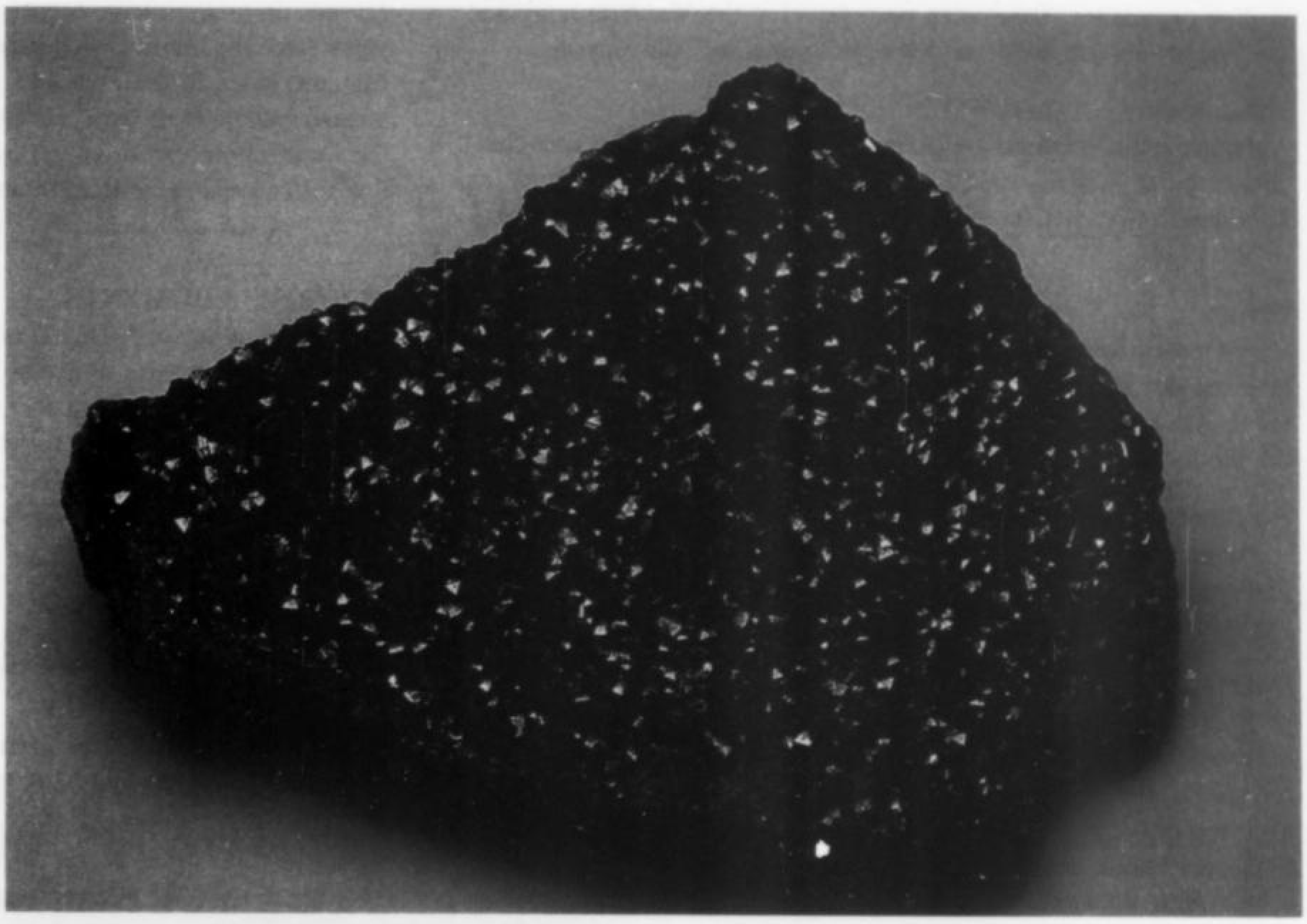
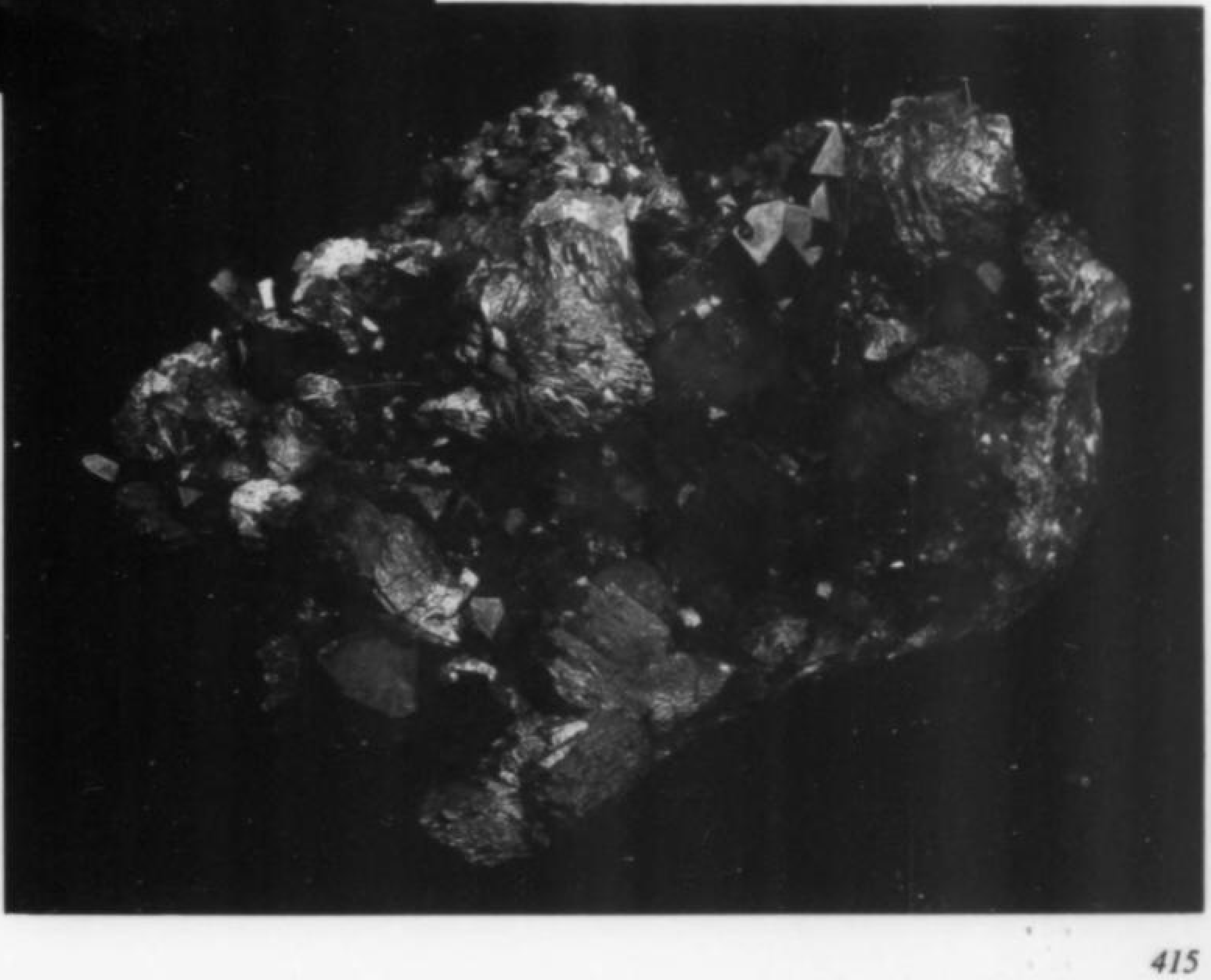


Figure 16. Atacamite crystal from the Doora mine, south of the Wallaroo mines. S.A.M. G1081.

Figure 17. Sphenoid groups of twinned chalcopyrite crystals on quartz crystals from the Moonta mines. The specimen is 8 cm long. Dunstan collection, S.A.M. G600.

Figure 18. An exceptionally fine quartz and chalcopyrite cluster from the Moonta mines. The specimen is 15 x 20 cm; C. Johnston collection. S.A.M. G15024.



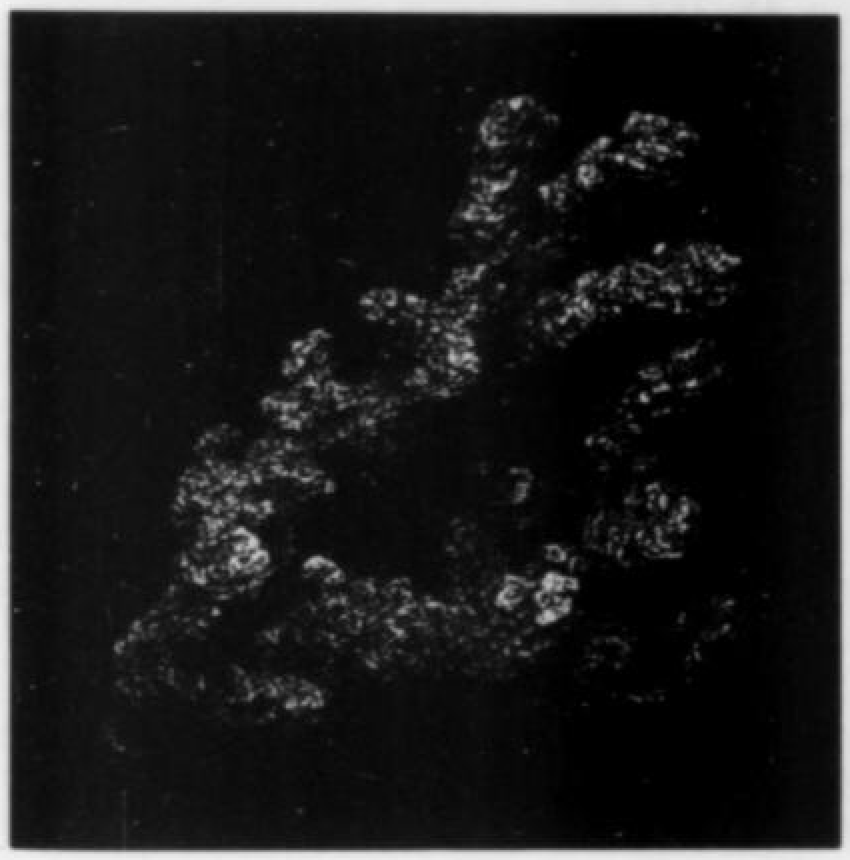


Figure 19. Native copper from the Wallaroo mines. Specimen is 8 x 10 x 10 cm; S.A.M. G145.

croline pegmatites. It has also been found at the Wanditta mine and the Wallaroo mines associated with dolomite and chalcopyrite.

Paratacamite $Cu_2(OH)_3Cl$

Paratacamite occurred replacing cuprite with aragonite and chalcocite at the Wallaroo mines. It was found in some abundance as honeycomb masses with atacamite at the New Cornwall mine (Pring *et al.*, 1987).

Pyrite FeS_2

Pyrite was widespread at the Wallaroo mines where it occurred in large masses and as crude crystals up to 6 cm on edge. More striking are the iridescent films with dolomite. Pyrite was rare in the lodes at the Moonta mines, but fine crystals were found at the Yelta mine.

Pyrrhotite $Fe_{1-x}S$

Pyrrhotite was a major massive vein mineral at the Wallaroo mines, particularly in Taylor's and Young's shafts. It was also found at the Kurilla mine with chalcopyrite and quartz.

Quartz SiO_2

Quartz was a major vein mineral in the lodes on both fields. At Moonta large smoky crystal groups were found studded with sphenoids of chalcopyrite and dusted with silver-grey flakes of hematite. Beautiful colorless groups of quartz crystals were found widely at the Wallaroo mines, often showing phantoms. Crystals are generally coated with dolomite and pyrite. Spectacular casts of quartz over scalenohedral calcite crystals and chalcopyrite were found at the Wallaroo mines.

Scheelite $CaWO_3$

Small amounts of massive scheelite were found associated with ferberite and chalcopyrite at the Wallaroo mines.

Schorl $NaFe_3^{+2}Al_6(BO_3)_3Si_6O_{18}(OH)_{14}$

Well formed crystals of schorl were found in Taylor's shaft and elsewhere at the Wallaroo mines, usually associated with pyrite, chalcopyrite and calcite. Crystals to 6 cm were found at the Yelta and the Karkarilla mines, Moonta, where the mineral was abundant. Schorl was also found in the main lodes at the Moonta mines.

Skutterudite $CoAs_{2-3}$

Small crystals of skutterudite to 0.5 mm were found with calcite and quartz in Hall's shaft, Wallaroo mines. Erythrite is commonly found associated, usually as powdery coatings.

Sphalerite ZnS

Very fine, bright, well formed brown crystals of sphalerite were found in Young's shaft and elsewhere at the Wallaroo mines. Crystals are often coated with dolomite and dusted with chalcopyrite. Clusters of sphalerite, chalcopyrite and quartz coated with dolomite are among the most attractive specimens found in the mines.

Titanite $CaTiSiO_5$

Pale brown crystals and masses of titanite were found at the Wallaroo mines associated with massive chalcopyrite and quartz.

CURRENT COLLECTING

The mines closed over 60 years ago, the shafts are filled with water and little remains of the mine complexes. The large dumps at the Moonta mines were milled and leached to recover the remaining copper before the mines had closed. At the Wallaroo mines the dumps formed a large mountain, which alas was dispersed at the time of the Second World War. Small dumps, however, at some of the outlying mines on both fields still yield specimens. Specimens still may be obtained at the Kurilla and Duryea mines at Kadina and at the North Yelta mine at Moonta. The New Cornwall mine has good potential for collecting. The workings are no longer accessible but fine atacamite crystals up to 3 cm have been found in the area of the dumps. In the years since the mines closed several mining companies have explored for new lodes in the area and several small, rich lodes have been located but nothing large enough for economic mining. Perhaps in the future more extensive deposits will be found in the district and fine chalcopyrite, cuprite and atacamite crystals will again be available.

ACKNOWLEDGMENTS

Thanks are due to J. Drexel of the South Australian Department of Mines and Energy for assistance in locating old photographs of the mines, and to C. Johnston for many useful discussions. We are indebted to L. B. Hammond for providing biographical information of her grandfather, Captain J. H. Dunstan. The financial assistance of the Mark Mitchell Foundation is gratefully acknowledged.

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BROKEN HILL, NEW SOUTH WALES

A Brief Review

●

Wendell E. Wilson
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Tucson, Arizona 85715

> ***"For 100 years Broken Hill has fascinated miners and mineralogists. The broken-backed hill in the Barrier Ranges of far western New South Wales has proved to be one of man's greatest sources of silver, lead and zinc and a treasure-house of exquisite mineral specimens."***
>
> ***Worner and Mitchell, 1982***

INTRODUCTION

A special issue on the mines and minerals of Australia would hardly be complete without at least a brief overview of the famous Broken Hill mine in New South Wales. The definitive review, *Minerals of Broken Hill,* was published in 1982 by Australian Mining and Smelting Limited. That remarkable work (now out of print) was the result of a collaboration by no less than 18 editors, authors, photographers and artists led by Dr. Howard K. Worner, Robert W. Mitchell and Dr. E. Ralph Segnit.

For the benefit of readers who were not fortunate enough to have obtained a copy of *Minerals of Broken Hill* while it was available, the following brief background has been summarized from it, and supplemented with a selection of specimen photos also drawn from the book.

Research continues on the mineralogy of Broken Hill. The article immediately following ("Minerals from the Kintore opencut" by Bill Birch and Arnold van der Heyden) is particularly noteworthy in that it describes one of the few remaining portions of the original oxidation zone of the Broken Hill orebody.

HISTORY

The great value of the Broken Hill orebody, despite its prominent outcrop, was not at all obvious to local prospectors. It was passed over by scores of fortune hunters, and eventually became enclosed within the fenced perimeter of the Mt. Gipps sheep station.

Charles Rasp was a boundary rider for the station. He had come to Australia in 1871 after serving briefly in the Royal Saxon Army. Like others before him, he noticed the heavy black rocks. Thinking they might contain cassiterite, he pegged a claim in 1883 and sent samples to an assayer for analysis. The results showed silver and lead, but not enough to be considered favorable.

Rasps's samples had been taken from the gossan, a leached manganiferous ironstone which capped one of the richest orebodies in the world. It was not until a year later, when samples from deeper down were taken, that Broken Hill was recognized as a major discovery.

By 1886 dividends were being declared for stockholders, and development proceeded swiftly. A government railway with a private spur serving Broken Hill brought in thousands of skilled laborers and miners from South Australia, and from many parts of the world. The chief mining man from the Comstock Lode in Virginia City, Nevada, was hired away at a fabulous salary.

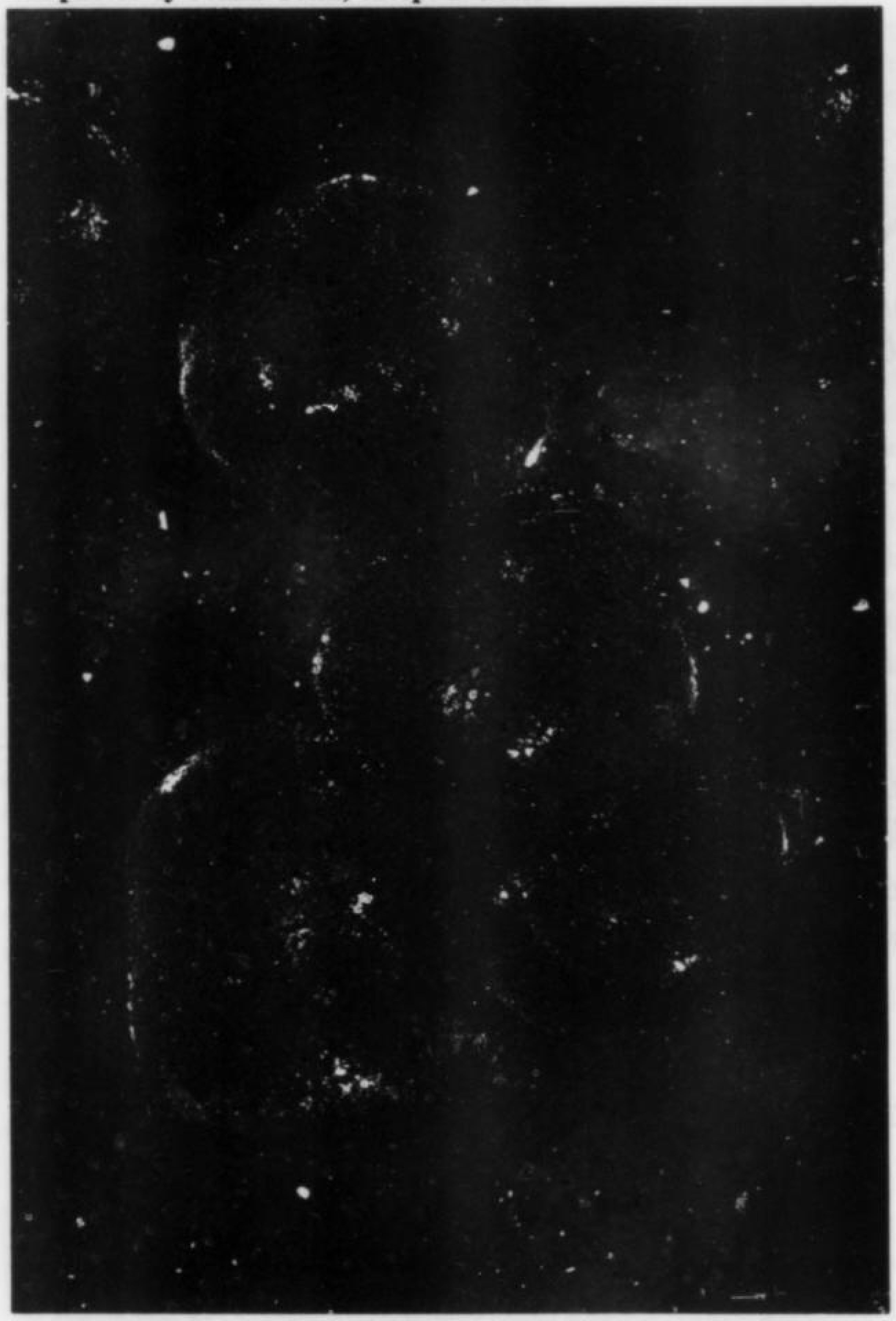
The most prominent of the mining firms involved was the Broken Hill Proprietary Company (BHP), formed in 1885, which is today Australia's largest company. In the early 1890's BHP paid out more dividends in a single year than the richest of the Victoria gold mines paid in its entire lifetime. The company and its satellites controlled nearly all of the rich oxidized ore in the central part of the field.

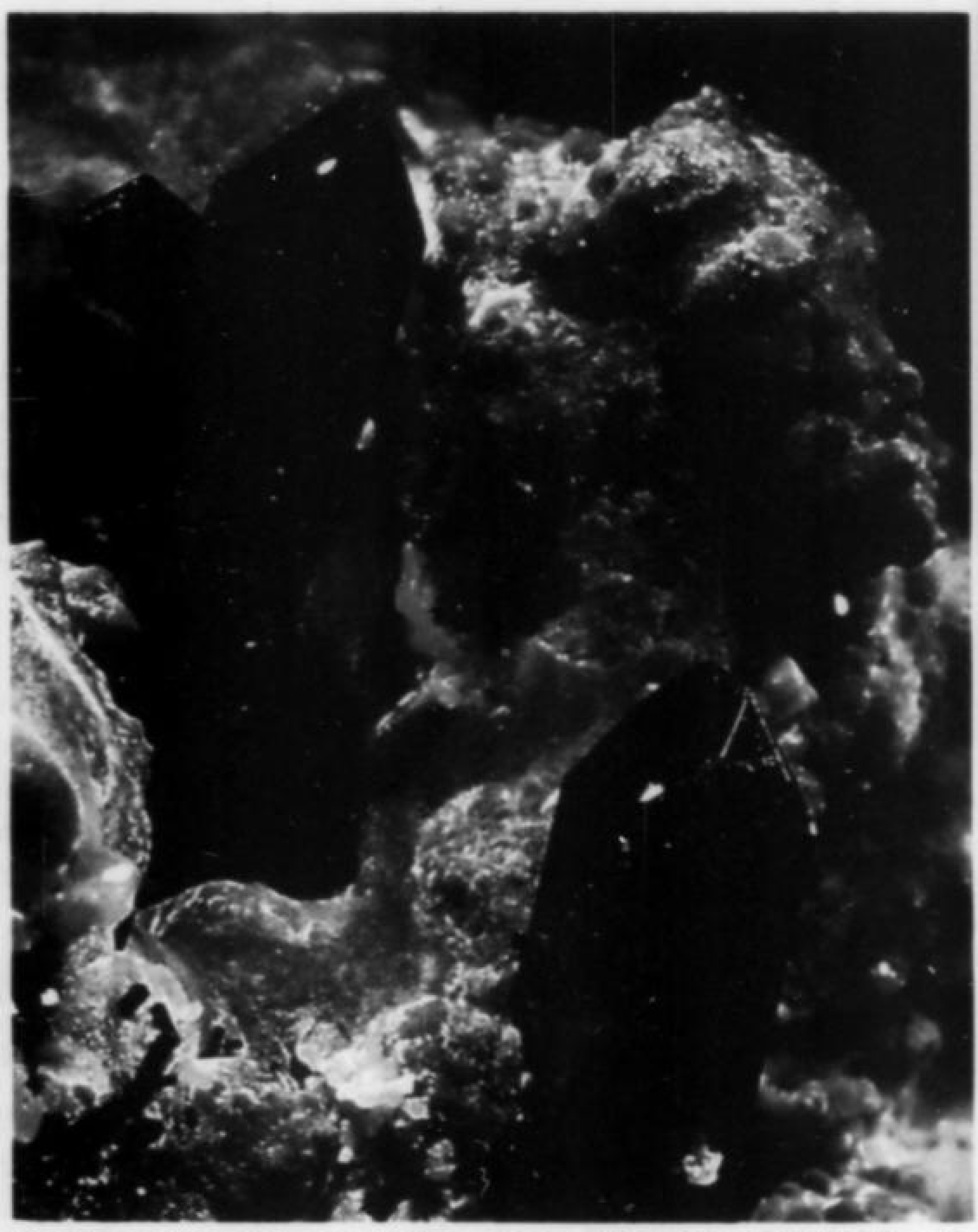
As mining progressed into the oxidation zone, miners and mineralogists were amazed by the constant discoveries of beautiful, crystal-lined vugs and cavities from a few centimeters across to room-size. They managed to preserve a selection of specimens but, as at most mines, the bulk of fine crystallized material usually went to the smelter.

Mineral collectors soon began to hear of the treasure in specimens being unearthed at Broken Hill, and a brisk trade developed. The manager of the Duke of Cornwall Hotel, for example, traded beer for whatever attractive specimens the miners could bring him. Fine pieces were soon being displayed in shop windows, jewelers' stores, hotel shelves, miners' huts and brokerage offices (the latter mostly to stimulate stock sales). A few local collectors such as George Smith, Floss Campbell and Maurice Mawby eventually developed large and extraordinary suites of Broken Hill minerals.

A small lode 600 meters east of the main workings yielded some

All photos by Frank Coffa, except as noted



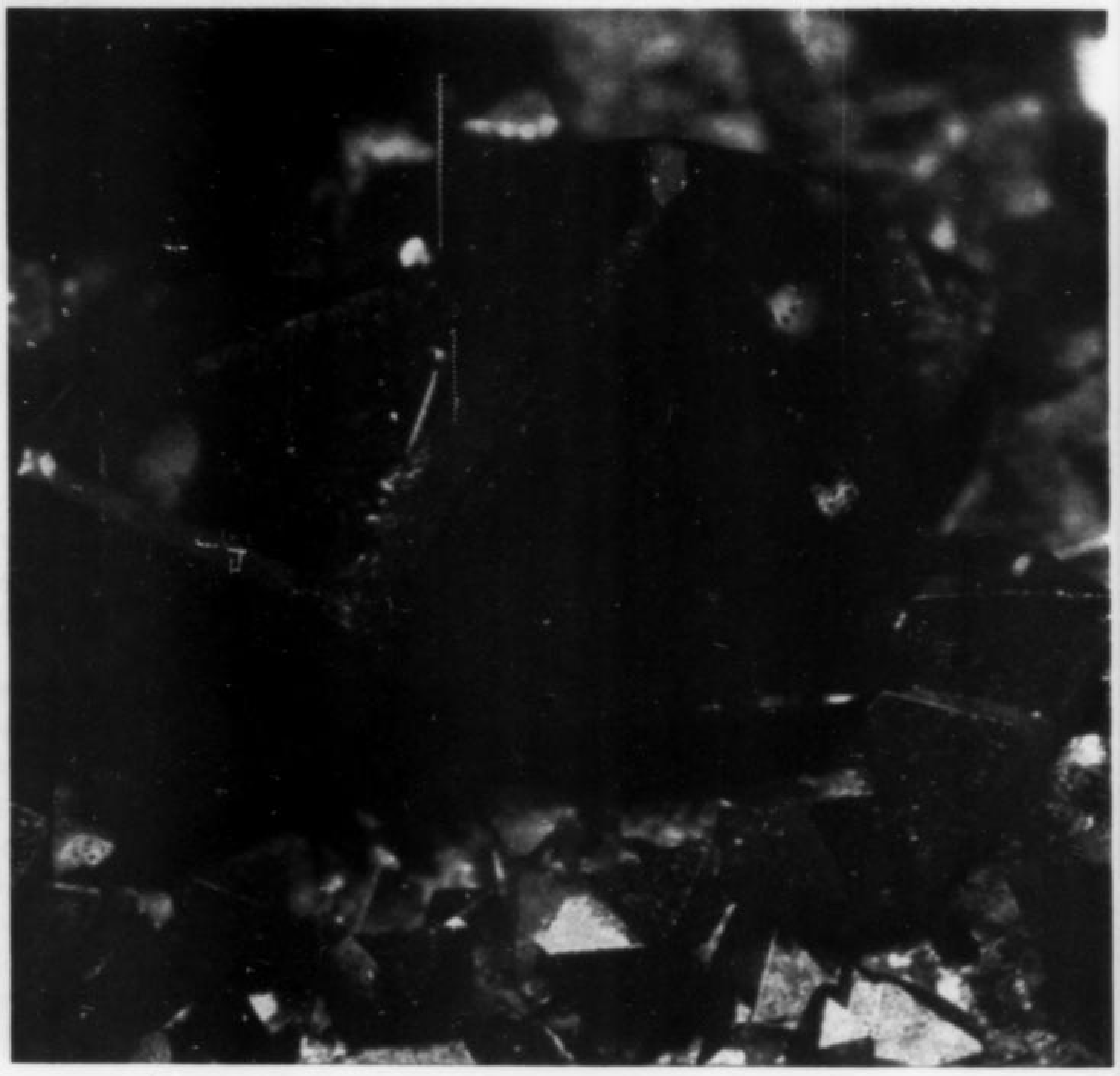


1. (Above) Azurite crystals to 6 mm. Museum of Victoria collection.

Figure 2. (Left) Rhodochrosite spherules to 7 mm, from the Zinc Corporation mine. Museum of Victoria collection.

Figure 3. (Below left) Pyromorphite crystals to 3 mm, from the Old South mine. Museum of Victoria collection.

Figure 4. (Below) Cuprite crystals to 2.5 mm from the Broken Hill Proprietary mine. Geological and Mining Museum collection.



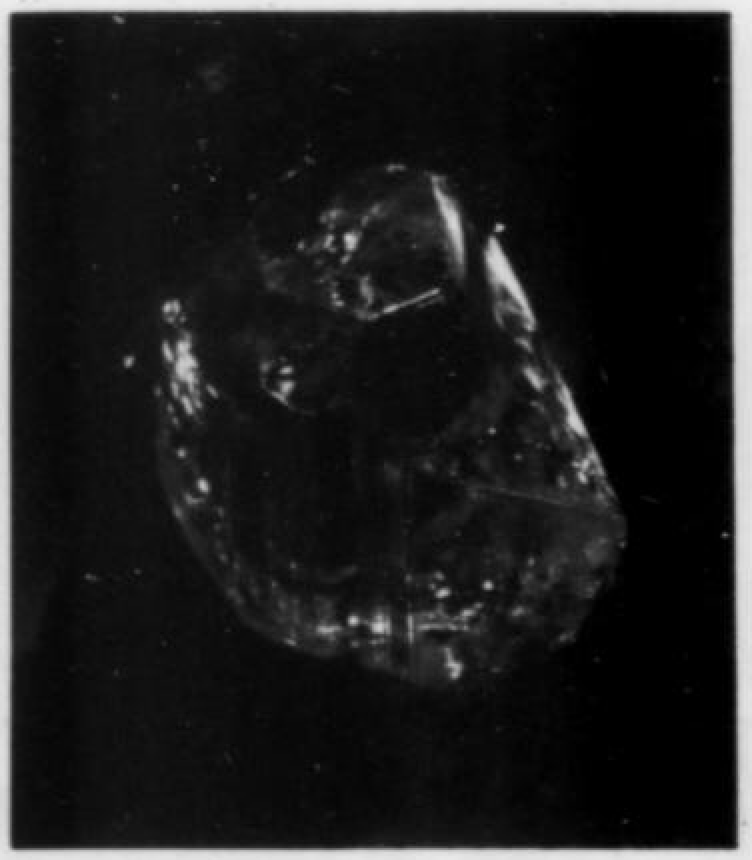
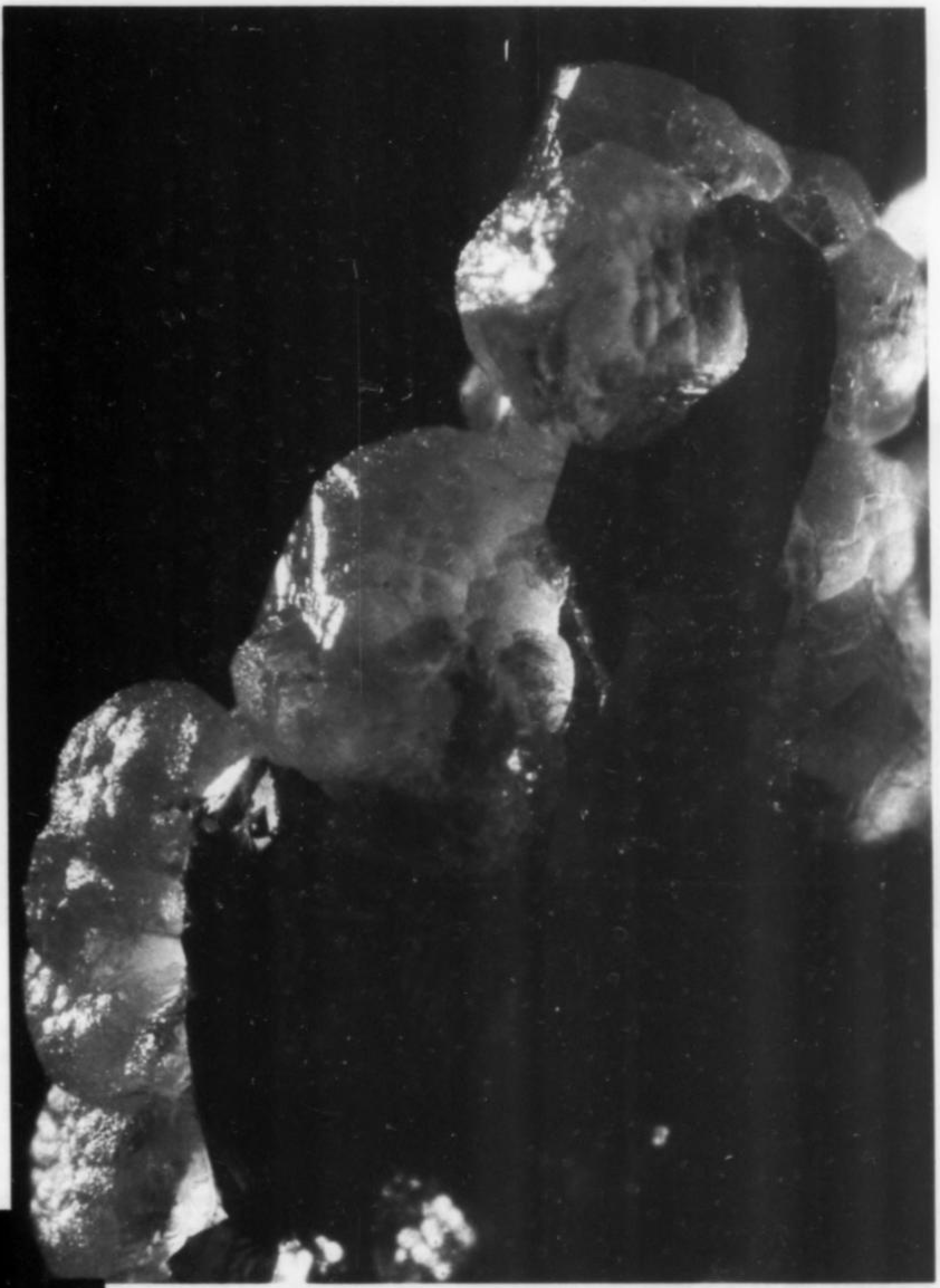


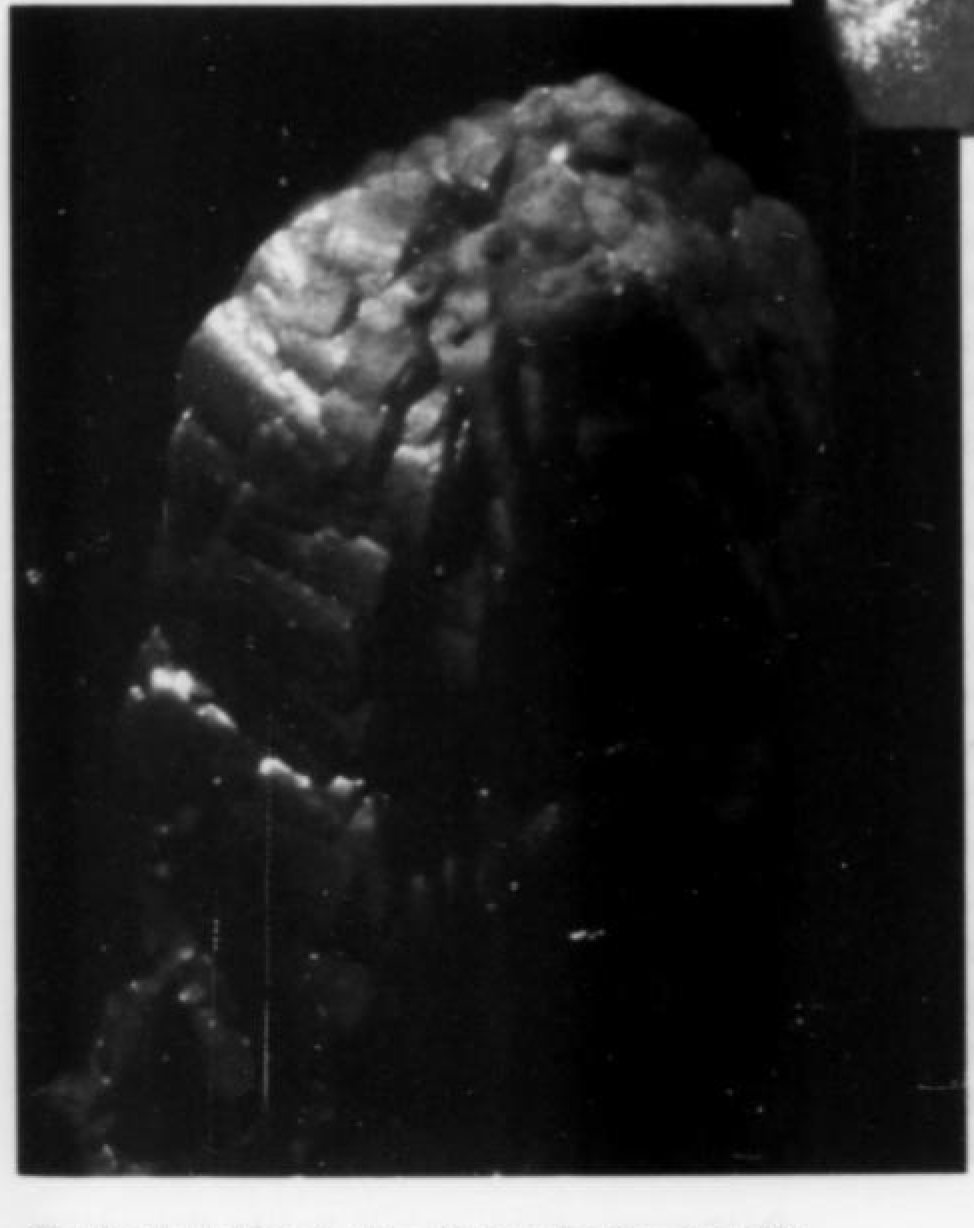
Figure 5. (Above) **Anglesite crystal, 4 mm, from the Broken Hill Proprietary mine. Bureau of Mineral Resources collection.**

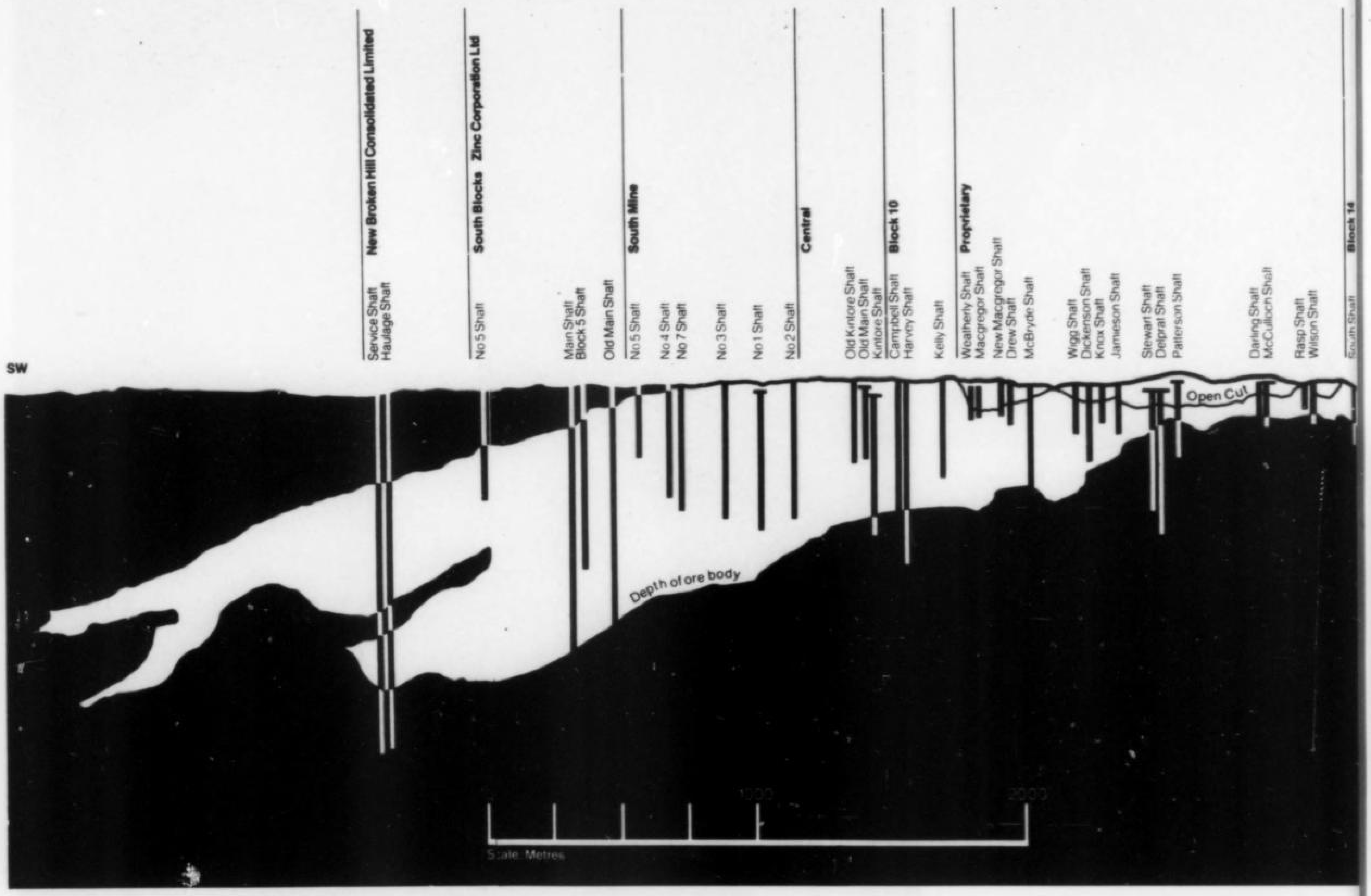
Figure 6. **Pyrargyrite crystals to 1.5 mm, with siderite, from the South mine. Museum of Victoria collection.**

Figure 7. (Below left) **Mimetite crystals to 7 mm. Museum of Victoria collection.**

Figure 8. (Below right) **Stolzite crystals to 3.5 mm, from the Proprietary mine. Museum of Victoria collection.**







amazing nuggets of silver weighing more than a ton apiece. One such slug had the rough shape of a turtle; it contained 84.5% silver, as a nearly pure mixture of metallic silver and dyscrasite. The great silver turtle was long remembered for its sheer beauty, parts of it consisting of lustrous crystal aggregates.

In 1914 there were ten mining companies operating at Broken Hill, employing about 8800 men. As the shallower portions of the lode became exhausted, these companies diminished, and even BHP itself ceased mining there in 1939. The Central mine closed in 1940, leaving only the North and South mines and the Zinc Corporation mine. A new mine called the New Broken Hill Consolidated began to produce ore in 1944 and, with the other three, ruled the field for 25 years. The Broken Hill South mine closed in 1972, but the district nevertheless has remained highly productive and today employs over 4000 men in underground workings exploiting primarily sulfide ore.

COLLECTORS and COLLECTIONS

The wealth of specimen materials at Broken Hill inspired many people to build collections. Professional mineralogists, mine managers and private individuals alike developed a fascination for the beautiful and unusual minerals of the district.

Among the early collectors was George Smith (1861–1944), manager of the Consols mine from 1890 to 1898. He built a magnificent collection specializing in Consols mine rarities, including the first samples of willyamite. He later served as Inspector of Mines for New South Wales, taking full advantage of his position and influence to extract beautiful specimens from the mine managers. He gained the nickname of "Specimen Smith," and exchanged specimens with many museums and private collectors. William F. Foshag, then curator of minerals at the Smithsonian, wrote to Smith complimenting him on the fine specimens he had supplied to American collector Washington A. Roebling. Roebling's collection had been acquired by the Smithsonian, and Foshag considered the Broken Hill subcollection to be the finest in the U.S. The Australian Museum eventually purchased Smith's personal collection, 2200 pieces, in two parts in 1907 and 1927. In 1926 Smith published *A Contribution to the Mineralogy of New South Wales,* the first major work on the mineralogy of the area since Liversidge's *Minerals of New South Wales,* in 1888.

Smith was not the only mine manager of Broken Hill to become involved in collecting, but it was ultimately the museums that were to benefit. W. E. Wainwright, manager of the South mine, personally collected and preserved many fine specimens from the oxidized zone which he later presented to the New South Wales Mining Museum in Sydney (now called the Geological and Mining Museum). Museum staff frequently visited the mines and secured many additional specimens. In 1892, BHP presented to the museum a representative collection of oxidized zone and sulfide zone specimens, and in 1894 the museum purchased the collection of Norman Taylor, a local mineralogist. In 1895 George Smith donated an excellent suit of Consols mine specimens. Many other collections of Broken Hill minerals were acquired by the museum during the following decades, including that of Arthur Combe in 1919. Combe was a true collector, enlisting to work as a miner solely to facilitate his acquisition of specimens; from 1910 to 1915 he worked at four different Broken Hill mines. His detailed labels provide invaluable data on precise locations of specimens.

E. W. Aldridge, the aforementioned owner of the Duke of Cornwall Hotel, assembled a fine collection which was later purchased by Sir Hugh Dixson for distribution to four Australian museums.

The largest Broken Hill collection in Australia (and probably the world) is in the Australian Museum. In addition to minerals obtained

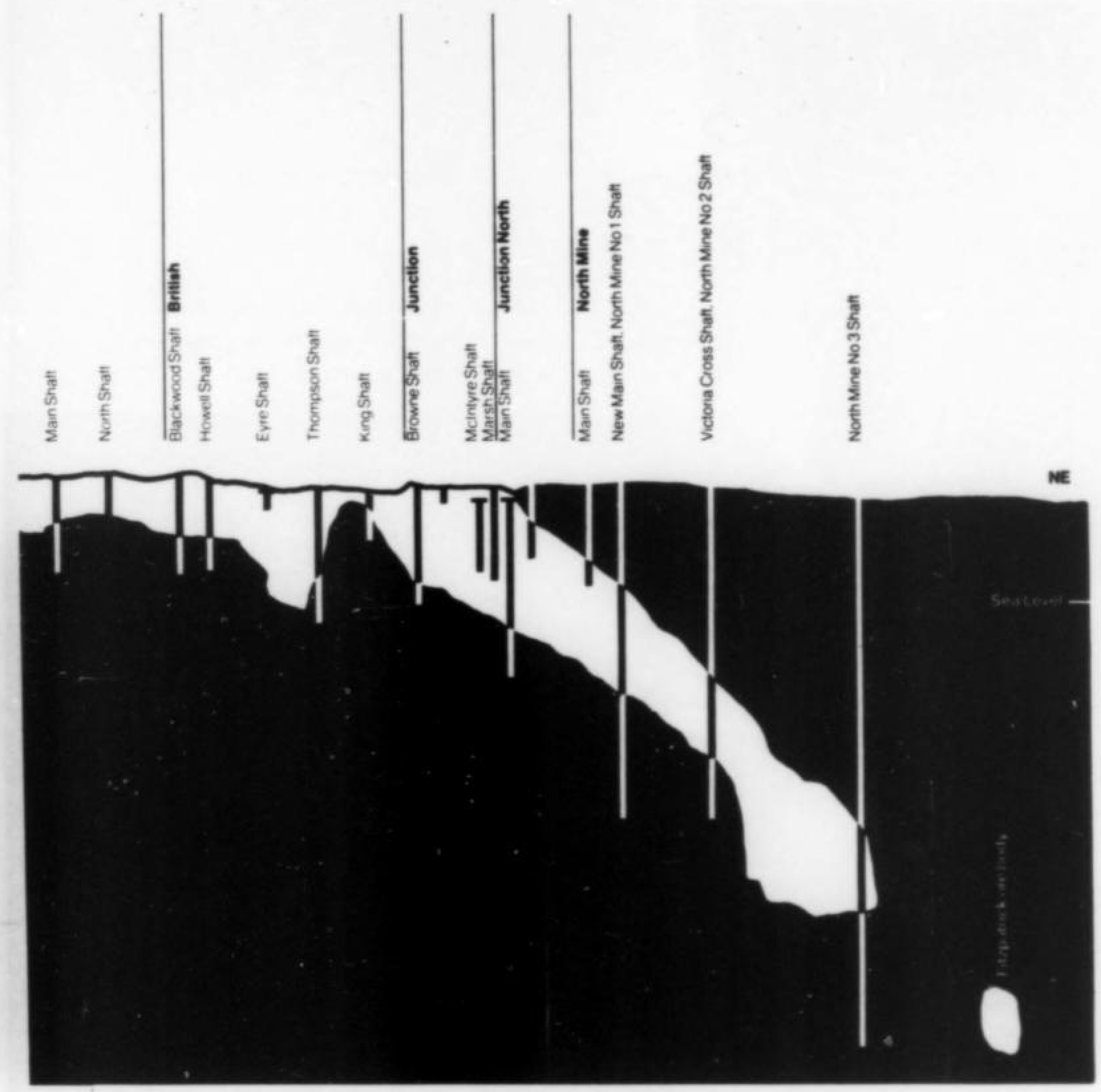


Figure 9. **Principal mine shafts shown on a longitudinal projection of the Broken Hill orebody.**

from George Smith, the museum was given the company collection of the Broken Hill Proprietary Block 14 Company when the Block 14 mine was closed in 1930. Many other collections were also acquired, including Arthur Combe's *second* collection in 1946.

"Floss" Campbell was a mine inspector at Broken Hill; he became well-known for his collecting skill, for being in the right place at the right time, and for being one of the few people permitted to collect in the great open cut. The major portion of his collection was purchased by the Australian Bureau of Mineral Resources in Canberra, and the smaller portion went to the Broken Hill Civic Center.

The Museum of Victoria has an extensive collection of Broken Hill minerals, including the greater part of the fine collection built by Sir Maurice Mawby. The South Australian Museum in Adelaide and the University of Adelaide also have fine representative collections.

A number of excellent Broken Hill collections remain in private hands, notably those of Albert and Doreen Chapman, Warren Somerville, the Vincent Brothers, Frank Pace, George Stacy, John and Margaret Bosworth, Brian Shelton and Howard Worner.

ORIGIN of the DEPOSIT

For many years the Broken Hill orebodies were thought to be replacement deposits. Today, however, most geologists agree that the metals were chemically precipitated on the sea floor during deposition of the surrounding rocks about 1.8 billion years ago, probably as the result of metalliferous hot springs venting on the sea floor. Subsequent burial, metamorphism and folding have brought the deposit into its current configuration. Thus it is classified as a metamorphosed stratiform volcanic exhalative deposit.

The metamorphic event which caused major recrystallization in the deposit occurred about 500 million years ago and is responsible for the formation of many attractively crystallized minerals. These include galena, sphalerite, garnets, rhodonite, bustamite, pyroxmangite and other silicates.

At some time during the Tertiary period, erosion finally exposed a portion of the Broken Hill orebody and oxidation took place typically to a depth of about 90 meters (locally to 200 meters).

The lode is now known to consist of six chemically distinct, superimposed layers. The highest is rich in silver, fluorite and rhodonite; the next is high in lead, calcite and rhodonite; the next two are high in zinc but low in silver; then a layer also high in zinc and low in silver but with more rhodonite; and finally a layer high in zinc and silica and low in silver. A seventh layer is thought to exist but has not yet been accurately characterized.

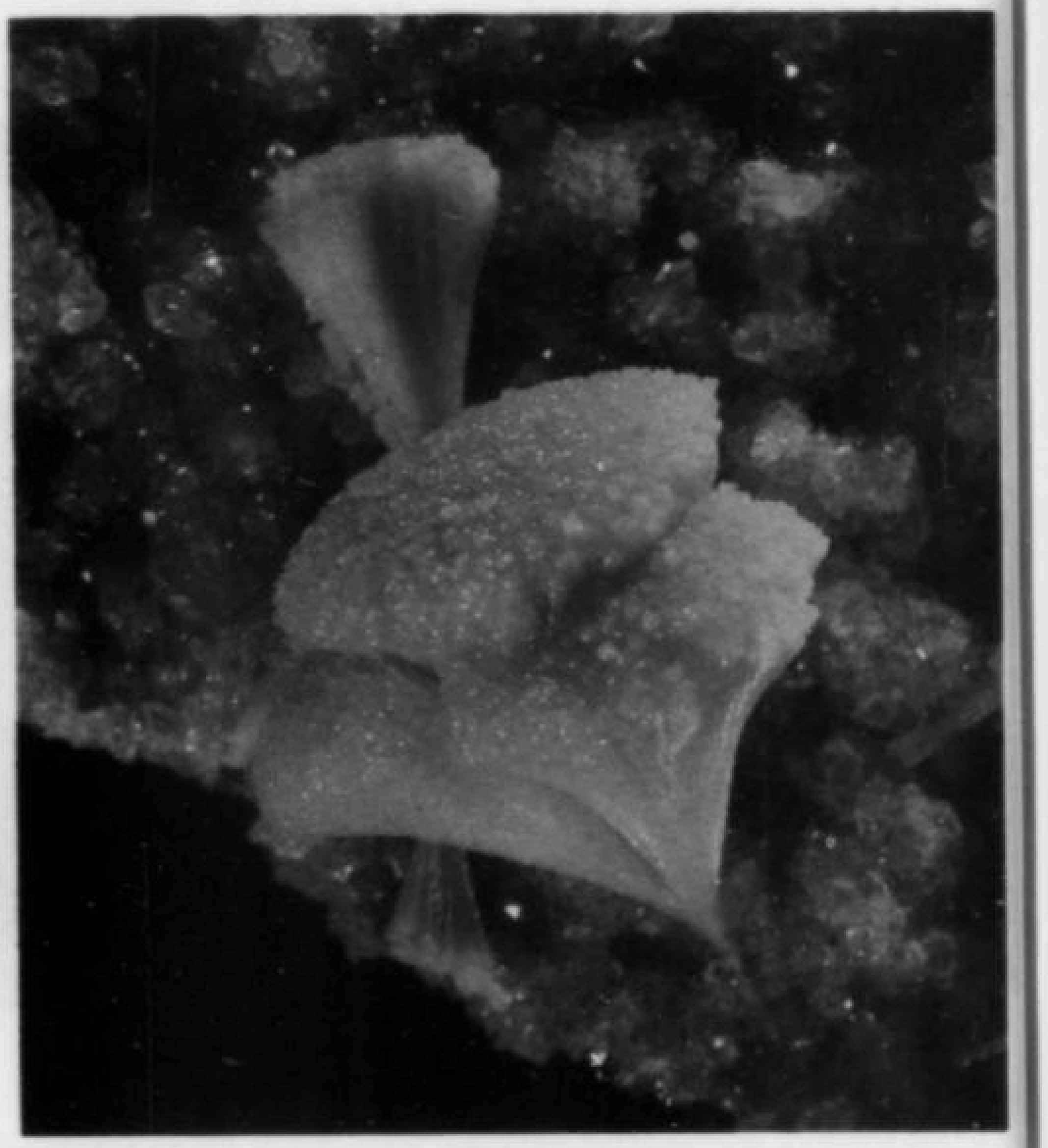
The orebody today is extremely complex due to extensive and repeated metamorphism and deformation. The original sequence of six stratiform lodes has been overturned and folded, the ore squeezed into the crests of folds and discontinuous projections, in some places sheared and brecciated, and finally "stewed in its own juices" so as to mobilize materials into cross-cutting veinlets, fractures, cavities and fault zones. New minerals and textures formed at each stage, resulting in a textural, structural and mineralogical jumble.

Weathering and erosion of the exposed central portion of the deposit is thought to have removed about 60 million metric tons of sulfide rock, one-fifth of the original orebody. What remains near the surface is a gossan composed mainly of iron and manganese oxides and quartz in stalactitic, botryoidal, cavernous and cellular boxworks and replacement structures. The transition from gossan to oxidized zone is not distinct, and there is no significant zone of supergene enrichment.

A prominent collapse zone has developed directly below the oxide zone in some places; the resulting breccia fragments and cavities have become coated with various secondary minerals. Beneath this is a

Figure 10. (Left) **Spessartine crystal, 1.3 cm, in galena from the North mine. B. Shelton collection.**

Figure 11. (Below) **Rhodochrosite sprays to 1.6 cm. C. Kovac collection (now in the Museum of Victoria collection).**



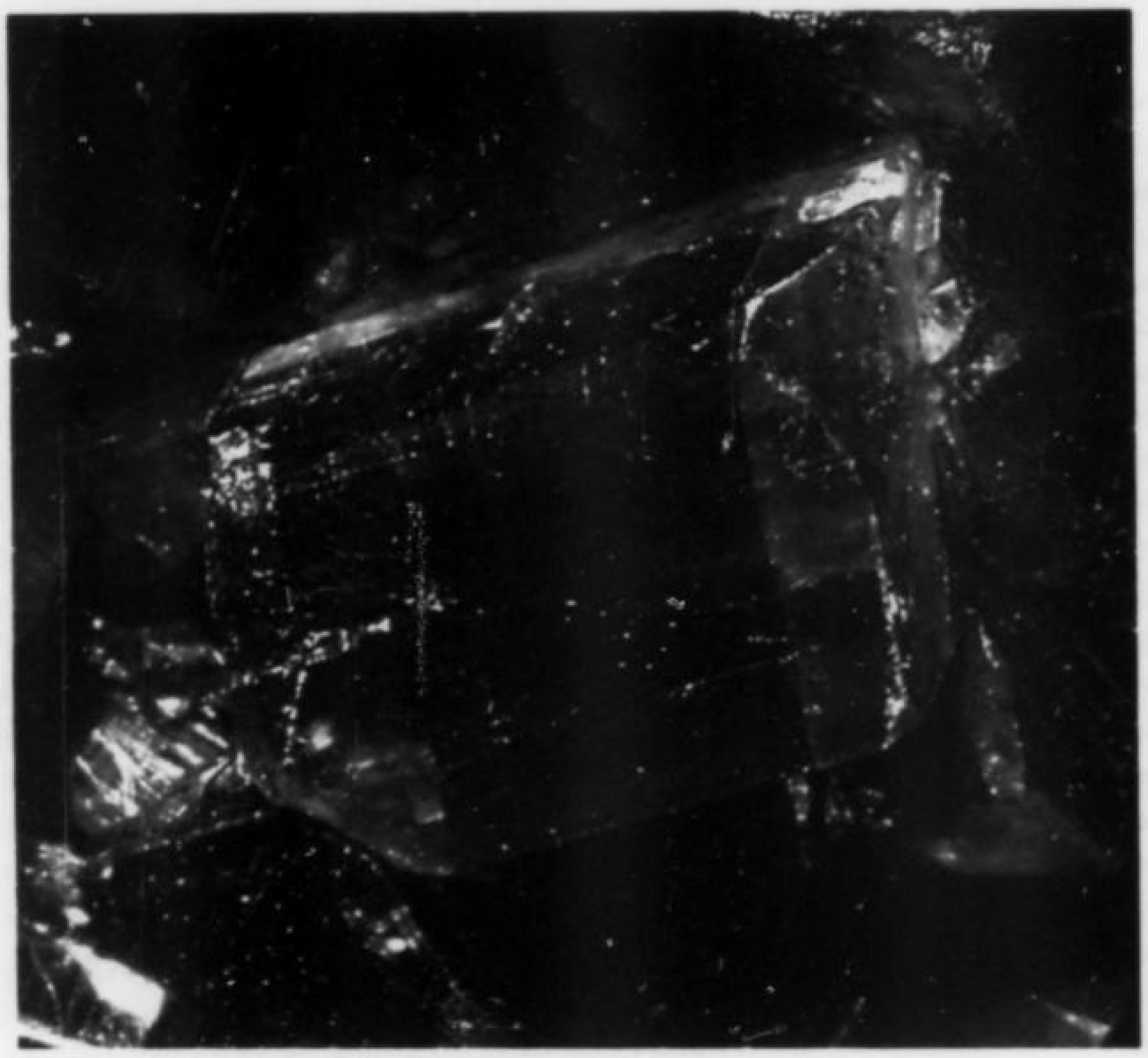


Figure 12. (Bottom left) **Manganoan hedenbergite crystal, 4.5 mm, from the New Broken Hill Consolidated mine. Museum of Victoria collection.**

Figure 13. (Bottom right) **Inesite crystals to 1 cm from the New Broken Hill Consolidated mine. Museum of Victoria collection.**

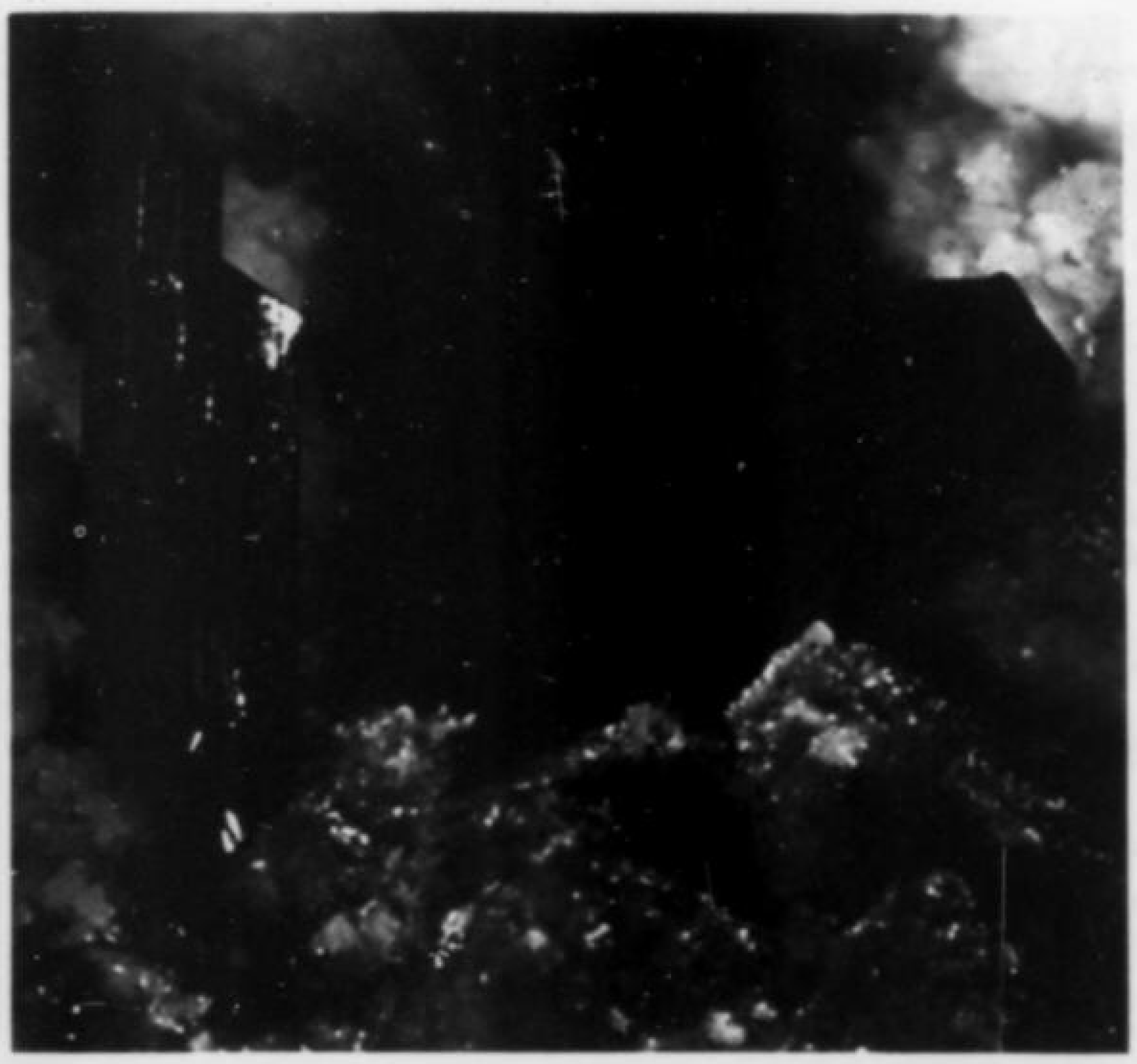


Figure 14. (Above left) Linarite crystals to 3.5 mm, from the Broken Hill Proprietary mine. Museum of Victoria collection.

Figure 15. (Above) Raspite crystal, 1.3 cm, with stolzite from the Broken Hill Proprietary mine. Chapman collection.

Figure 16. (Left) Pyrite group, 10 cm. J. and M. Bosworth collection.

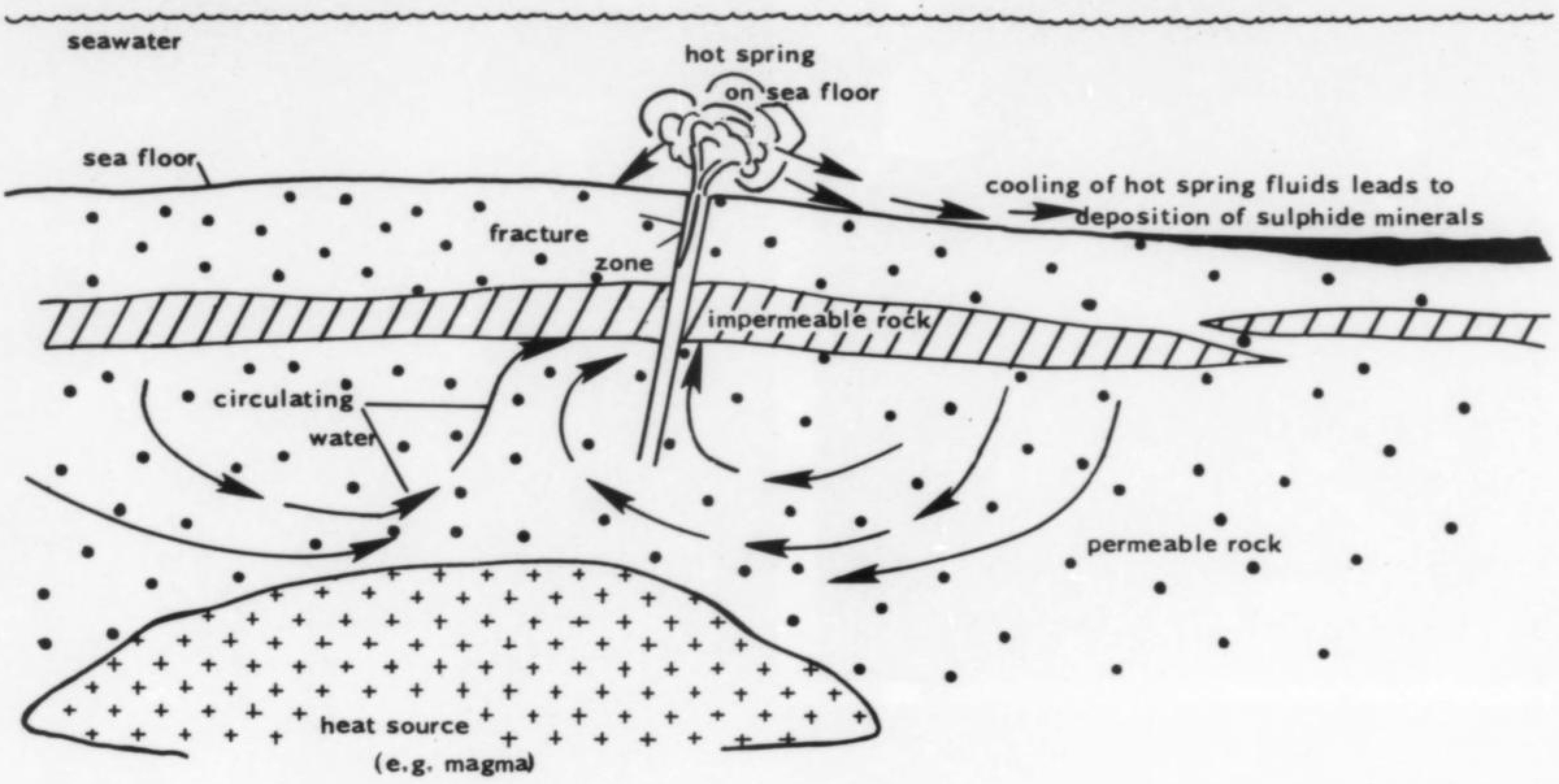


Figure 17. **Diagrammatic cross section showing general concept of formation of a stratiform sulfide deposit, resulting from exhalation of hot spring fluids onto the sea floor.**

phosphate-rich zone (pyromorphite). Overprinting the lower portions of these zones is an irregular zone of complex mineralogy which has yielded rare tungstates, molybdates, arsenates, oxides, silicates, carbonates, sulfates and halides. Beneath this is a zone exceptionally rich in cerussite, with some anglesite toward the base. Finally, there are fragments of a very narrow, discontinuous supergene zone containing rare sulfides of lead, zinc, copper and silver. Below this lies unaltered sulfide ore.

The secondary zone at Broken Hill presents an extraordinary array of rare and unusual, well crystallized minerals. Several factors are thought to have contributed: the primary sulfides were unusual in composition, being high in Pb, Zn, Mn, Ca and Ag but depleted in Fe and Cu. The minor amounts of F, P, As, Sb, Co and Ni also proved important. (Långban, Sweden, and Franklin, New Jersey, are similar examples.) Furthermore, the original mass of sulfides consumed by weathering was extremely large, giving every opportunity for the concentration of minor elements under both temperate and arid conditions.

MINERALS

No attempt will be made here to summarize the nearly 200 mineral descriptions given in *Minerals of Broken Hill*. We can mention, however, some of the more significant of better-known species that Broken Hill collectors have come to admire:

- Anglesite in fine, white to pale yellow, lime-green and orange crystals up to 2.5 cm.
- Tin-white native antimony crystals to 1 cm, heavily striated.
- Axinite crystals, 1 to 5 cm in size, sharp-edged and deep greenish brown in color.
- Azurite crystals, lustrous and varied in habit, up to 15 cm in size.
- Bournonite in well-formed, striated crystals up to 5.5 cm long (recently found).
- Bustamite, as prisms and needles up to 1 meter(!) in length, off-white to brown and reddish pink in color.
- Calcite crystals in a wide range of colors, sizes and habits.
- Cerussite in magnificent crystals and reticulated groups of large size and exquisite quality.
- Copper in crystalline, wire, stalactitic and arborescent groups.
- Cuprite crystals, transparent and ruby-red, over 1 cm on an edge.
- Dyscrasite in large, heavy crystal groups with silver.
- Hedenbergite, blackish to gemmy green, in fine crystals to 5 cm.
- Iodargyrite in lustrous, translucent, pale yellow to yellow crystals to 1.5 cm.
- Malachite as large, botryoidal specimens and as fine pseudomorphs after azurite.
- Green plumbian microcline ("amazonite") in translucent, twinned crystals to 10 cm.
- Mimetite in stout, hexagonal prisms of yellow to brown color.
- Pyrargyrite in gemmy, blood-red crystals to 1.5 cm.
- Pyromorphite in a wide variety of sizes, colors and habits.
- Pyrosmalite and manganpyrosmalite in beautifully formed, lustrous red crystals to 4 cm.
- Raspite, as brilliant, gemmy orange crystals to 1.3 cm.
- Gemmy rhodonite crystals to 5 cm.
- Siderite in large, fine groups of 1-cm crystals.
- Silver in large masses, nuggets, crystals, wires and plates.
- Smithsonite in beautiful white to blue botryoidal groups and small crystals.
- Spessartine crystals, gemmy and wine-red, up to 10 cm in size.
- Stolzite crystals, gemmy, and colorless to bright yellow and reddish yellow, up to 2.5 cm in size and occurring in a range of habits.

●

Aside from its fame as a source of beautiful display specimens, Broken Hill is also the type locality for no less than six species: marshite, willyamite, raspite, miersite, costibite and paradocrasite. The list is sure to increase; several possible new minerals are currently under study. A great deal more remains to be learned about the mineralogy of Broken Hill.

Minerals from the
KINTORE OPENCUT, BROKEN HILL
New South Wales

W. D. Birch
Museum of Victoria
285 Russell Street
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Australia

and

A. van der Heyden
Minerals, Mining and Metallurgy Ltd.
Post Office Box 63
Broken Hill South, New South Wales, 2880
Australia

Recent systematic collecting in the Kintore opencut, in the oxidized zone at Broken Hill, New South Wales, has yielded a range of species previously unrecorded from the deposit. Most of the minerals occur as drusy crusts or microcrystals. The range of species and various replacement textures reflect the complex history of the oxidized zone at Broken Hill.

INTRODUCTION

The world-famous Broken Hill silver-lead-zinc deposit in western New South Wales has produced many rare and beautiful crystallized mineral specimens for over a century (Birch *et al.*, 1982). Nearly all of these have come from the extensive oxidized zone, which is now largely mined out. Despite nearly 200 species being recorded from the orebodies, our knowledge of the full extent of species, their compositional ranges and their paragenetic relationships is very limited, particularly for the secondary minerals.

Recent mining of a portion of the remaining oxidized zone in the Kintore opencut has revealed a suite of rare arsenates, phosphates and sulfates previously unrecorded from Broken Hill. Among the assemblage are a number of species which appear to be new to science.

In order to investigate the mineralogy of the Kintore opencut, a systematic collection policy has been implemented by the operating company, Minerals Mining and Metallurgy Limited. Since 1985, representative specimens have been forwarded to the Mineralogy Department in the Museum of Victoria for identification.

These specimens have provided an opportunity to examine the paragenesis of a small portion of the Broken Hill oxidized zone. It also serves as a reminder of the lost opportunities in Broken Hill mineralogy, when systematic collecting of the less spectacular specimens may have revealed an entirely new mineralogical dimension.

LOCATION

The city of Broken Hill, with a population of 24,000, is situated in the Barrier Ranges in the far west of New South Wales, near the South Australian border. It is 500 km by road from Adelaide, 850 km from Melbourne and 1200 km from Sydney. The city is on the route of the "Indian-Pacific" transcontinental railway and has regular air services.

Broken Hill has been built on either side of the "Line of Lode," which dominates the city's skyline with its headframes and dumps. The surrounding semi-arid countryside supports a pastoral industry consisting of large sheep stations producing Merino wool.

HISTORY

Explorer Captain Charles Sturt led the first expedition through the Barrier Ranges in 1844–46. By the 1860's squatters had taken up large tracts of land in the area for grazing. Silver ore was first found in the district on Thackaringa sheep station where Patrick Green established the first mine, the Pioneer, in 1876 (Kearns, 1982). Small mines sprang up throughout the Ranges in the early 1880's at places such as Silverton, the Apollyon Valley and Purnamoota.

The "Broken Hill" was derisively called the "hill of mullock" by the local miners because of low silver assays on samples taken by a local storekeeper (Koenig, 1983). Undaunted, Charles Rasp pegged

Figure 1. **Location map.**

the first claim, Block 12, on September 5, 1883, thinking the hill contained tin. Later that month the "Syndicate of Seven," including Rasp, pegged the entire crest of the hill as Blocks 10 to 16. Thomas Nutt pegged Block 9 in 1884.

The Kintore opencut straddles three of the original mining leases, Blocks 9, 10 and 11, so only the history of these leases will be traced. The "Syndicate" became the Broken Hill Proprietary Company Limited (BHP) in 1885, retaining Blocks 11, 12 and 13; its other leases were re-established as separate companies. The BHP Block 10 Company began in 1888 and was in production until 1923. A year later it was sold back to BHP, which finally closed its mine in 1939. Today BHP is Australia's largest company. Block 9 became the Sulphide Corporation's Central Mine until its closure in 1940.

Broken Hill South Limited acquired these leases during the early 1940's and carried out underground remnant mining and dump retreatment until July 1972. Minerals Mining and Metallurgy reopened the South Mine in October of 1972. Underground mining ceased in 1976 and the operation continued with surface mining and dump retreatment. Development of the Kintore opencut commenced in 1984 to mine ore remnants and stope fill left behind by underground mining.

GEOLOGY

The Broken Hill deposit occurs within the early Proterozoic Willyama Supergroup. This sequence consists of gneisses, amphibolites, migmatites and "lode horizon" rocks which were deposited as marine sediments and volcanics 1820 million years ago (Willis *et al.*, 1983). They were subjected to prograde metamorphism up to granulite facies, two phases of deformation, and anatexis during the Olarian Orogeny at 1660 million years. During later retrograde metamorphism, a third phase of deformation occurred and major schist zones developed along large faults (Stevens, 1986). These events folded and remobilized the orebody, which is regarded as a stratiform volcanic exhalative deposit, into its present configuration within the overturned limb of a regional nappe fold (Marjoribanks *et al.*, 1980). At later stages, acid and basic intrusions were emplaced regionally.

The orebody has the shape of a crumpled sheet folded into a broad arch which is buried at the ends, with the crest cropping out and partially eroded away. It is 7.3 km long, 850 m deep and 120 m wide. The orebody actually consists of several conformable lenses striking southwest to northeast and generally dipping steeply northwest within the southeast limb of the Hanging Wall Synform (Laing *et al.*, 1978). Before mining, the deposit contained approximately 250 million tonnes of silver-lead-zinc ore (Stevens, personal communication), making it one of the world's largest massive sulfide deposits.

The oxidized zone at Broken Hill has had a long and complex history, which is reflected in the complexity of its mineralogy. Erosion has removed an estimated 60 million tonnes of ore (Plimer, 1984).

KINTORE OPENCUT

A number of lodes are present in the Kintore opencut, but the most important orebody is No. 3 lens. Its primary minerals are coarse grained galena and sphalerite with minor chalcopyrite and arsenopyrite-loellingite in a quartz-spessartine gangue. However, at present the Kintore opencut is in the oxidized zone, where 3 lens is represented by rocks consisting of quartz, iron and manganese oxides (principally goethite and coronadite), kaolinite and spessartine, with secondary Pb, Zn, Cu and Ag minerals.

Other lodes are also present in Kintore as oxidized quartz-spessartine-gahnite lode horizon units; they are mostly unmineralized. Barren sillimanite gneisses separate the lodes.

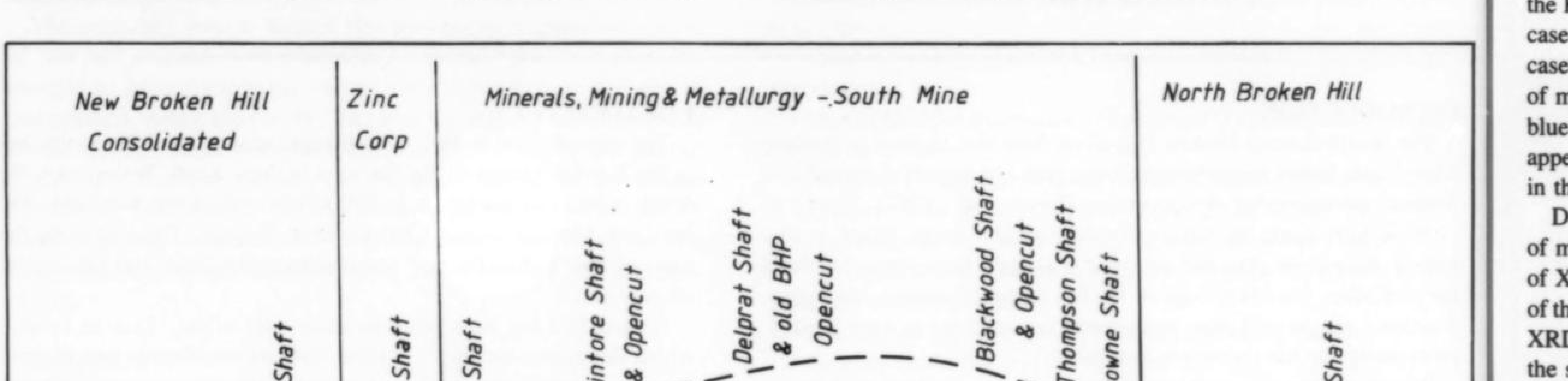

Figure 2. **Longitudinal cross section of the Broken Hill orebody showing location of the Kintore opencut.**

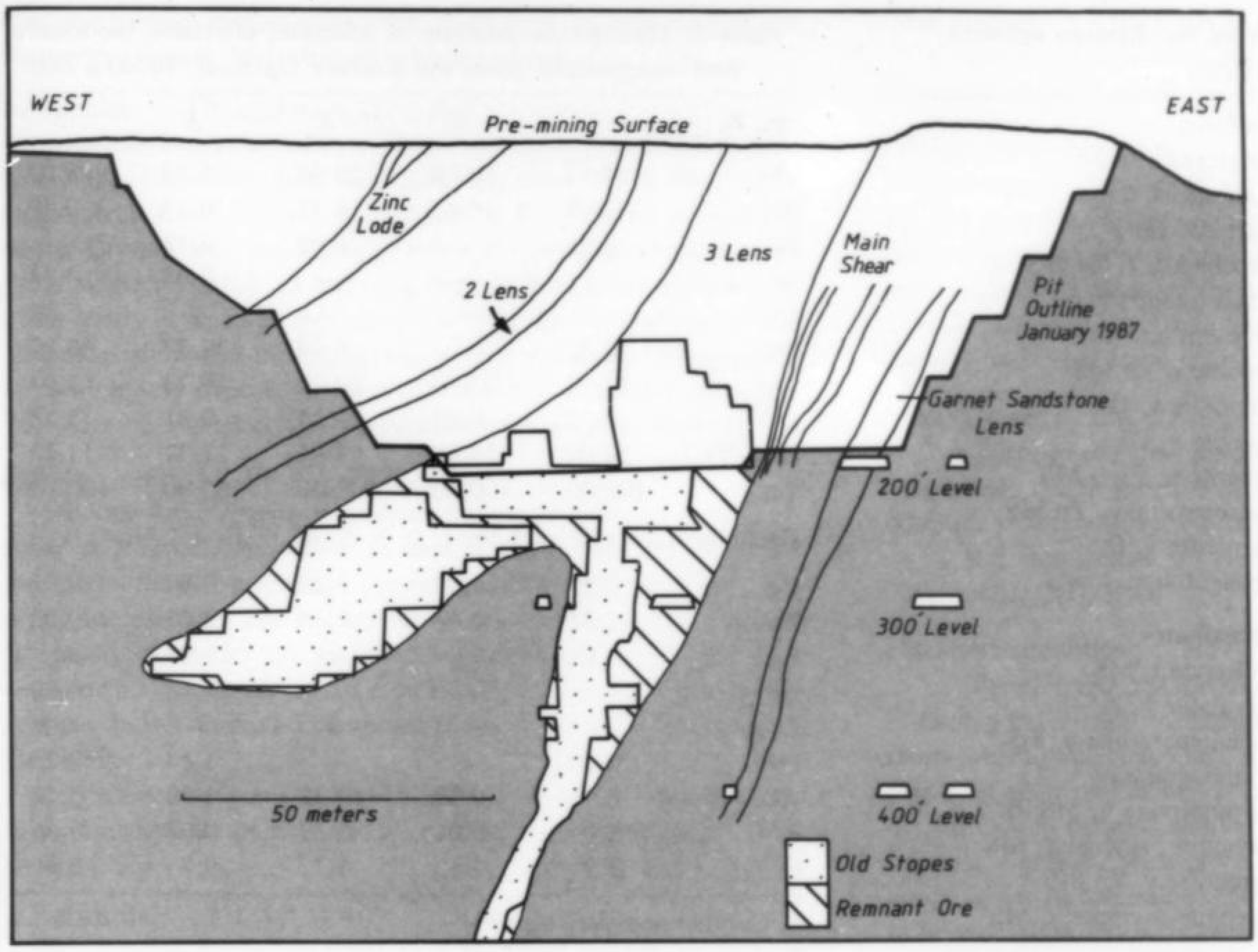

***Figure 3.* Cross section (looking north) through the Broken Hill orebodies at the north end of the Kintore opencut.**

Most of the newly recorded minerals occur in a lens of weathered "garnet sandstone" (a friable rock composed almost entirely of fine grained spessartine) within the Main Shear. This lens is situated to the east of 3 lens in the northeast corner of the Kintore opencut. Many specimens have also been collected from dumps of material taken from the opencut.

MINERALOGY

Over 70 primary and secondary minerals occur in the vicinity of the Kintore opencut. These are listed in Table 1, together with, in the case of the secondary minerals, the lodes in which they occur. In most cases, the rarer secondary minerals are found as crusts or aggregates of microcrystals on a matrix of weathered to fresh garnet sandstone, blue quartz lode or quartz gneiss. Because of their unspectacular appearance in hand-specimen, many have probably been overlooked in the past.

Due to the small crystal size and, in many cases the small amount of material available, identification has been made by a combination of X-ray powder diffraction and electron probe microanalysis. Many of the minerals fall into solid solution series or groups and have similar XRD patterns, so that chemical analysis is the only way to determine the species.

The collecting at Kintore has yielded 25 species previously unrecorded at Broken Hill. At least five are considered to be potential new species. Only the more interesting or significant species are described in the following notes.

Adamite (cuprian)-**Olivenite** (zincian) $(Zn,Cu)_2AsO_4(OH)$-$(Cu,Zn)_2(AsO_4)(OH)$

Members of this series are among the most common minerals in the Kintore suite. They occur in a variety of habits, of which the most common are drusy bluish green crusts and sub-spherical to sheaf-like or "bow-tie" aggregates of crystals, usually on a heavily iron oxide impregnated quartz-rich matrix. Aggregates rarely exceed 1 mm across. Other habits include stumpy prismatic crystals up to 0.5 mm long and flattened olive-green prisms up to 1 mm long.

***Figure 4.* Zincian olivenite crystals to 1 mm.**

Those members of the series which have been analyzed fall into two compositional groups, defined by As:P ratios of close to 0.75:0.25 and 0.96:0.04 respectively. Within each group, Cu:Zn values show a narrow range from 0.60:1.40 to 1.30:0.70.

Neither habit nor color appears to be diagnostic. The most frequently associated minerals are bayldonite, mimetite and a powdery yellow to greenish beudantite or plumbogummite-like mineral.

A few specimens of cuprian adamite and olivenite were collected from the old Proprietary mine opencut in the 1960's (Lawrence, 1968, 1961).

Antlerite $Cu_3(SO_4)(OH)_4$

Pale blue-green, chalky pseudomorphs up to 1 mm long, in cavities in heavily oxidized quartz-rich ore, are antlerite after anglesite. The latter mineral may be found as remnant cores in the pseudomorphs; native copper also occurs as inclusions within the antlerite. Associated minerals also include covellite, serpierite, brochantite and linarite. Analysis shows that small amounts of zinc are present in the antlerite.

Table 1. **Minerals recorded from the Kintore opencut, Broken Hill.**

Native Elements
Copper r, 2 3
Graphite x
Silver v, D
Sulphur u, Zn

Sulfides
Galena c, A
Sphalerite c, 2 3 MS
Arsenopyrite u, MS 3
Chalcopyrite u, MS 3
Covellite r, MS 3

Oxides
Coronadite a, A
Cuprite r, 2 3
Gahnite c, A
Goethite a, A
Cryptomelane r, Zn

Halides
Bromargyrite v, 3
Boleite x, Zn
Atacamite r, 3 MS
Paratacamite x, 3
Chlorargyrite,
  bromian c, Zn 2 3
Iodargyrite x

Carbonates
Aragonite r, 3
Azurite u, Zn 2 3
Calcite u, 3
Cerussite c, A
Dolomite c, 3
Hydrocerussite v, 3
Malachite c, A
Smithsonite c, 3 Zn MS
Rosasite-zincrosasite u, 3, MS

Silicates
Quartz a, A
Opal, var. hylaite r, D
Chrysocolla r, 3
Hemimorphite v, MS
Spessartine c, A
Kaolinite a, A

Sulfates
Anglesite r, 3 Zn
Antlerite v, 3
Barite v, Zn 3
Brochantite r, Zn MS
Chalcanthite r, D
Gypsum u, 3 MS
Jarosite r, Zn MS
Ktenasite v, D
Langite v, D
Linarite u, Zn 3 MS
Natrojarosite u, Zn MS
Serpierite v, D
Spangolite x, ?

Phosphates
Dufrenite r, MS
Hinsdalite c, A
Pseudomalachite v, MS
Plumbogummite v, 2
Pyromorphite u, MS Zn 2
Tarbuttite, zincian x, MS
Turquoise v, Zn MS
Strengite-variscite v, MS

Arsenates
Adamite, cuprian c, MS
Bayldonite r, Zn MS
Carminite x, MS
Conichalcite x, MS
Conichalcite x, MS
Cornwallite x, MS
Duftite x, MS 3
Hidalgoite c, A
Mimetite c, A
Olivenite r, 3 MS
Pharmacosiderite v, MS
Scorodite x, MS

Phosphate-Sulphate
Corkite u, MS

Arsenate-Phosphate-Vanadate
Vauquelinite-fornacite v, MS
Mottramite x, MS

Molybdate
Wulfenite r, MS

Abundance
a—abundant
b—common
u—uncommon
r—rare
v—very rare
x—extremely rare

Lodes
Zn—Zinc lode
2—2 lens
3—3 lens
MS—Main Shear
A—all lodes
D—dumps

Aragonite $CaCO_3$

Fibrous masses of pale yellow-green needle-like aragonite crystals up to several centimeters long occur rarely, associated with calcite, in a massive goethite-coronadite matrix. Aragonite has also been found as scattered clusters of white crystals up to 6 mm long on joints in garnet sandstone.

Table 2. **Microprobe analyses of adamite, olivenite, bayldonite and vauquelinite from the Kintore Opencut, Broken Hill.**

wt. %	1	2	3	4	5
Cu	14.79	30.06	29.65	25.49	8.03
Zn	32.78	16.15	16.87	0.57	0.19
Fe	0.18	—	0.05	0.11	—
Al	—	—	—	0.05	0.14
Cr	—	—	—	—	5.87
Pb	0.32	—	0.15	32.37	60.83
As	27.37	27.75	20.99	19.73	5.61
P	0.52	0.08	3.34	0.31	5.15
O (diff)	24.04	25.96	28.95	21.37	14.18
Total	100.00	100.00	100.00	100.00	100.00
Formulae: (As + P = 1 for 1, 2, 3, 5; As + P = 2 for 4)					
Cu	0.61	1.27	1.20	2.94	0.97
Zn	1.31	0.66	0.66	0.07	0.02
Fe	0.01	—	—	0.01	—
Al	—	—	—	—	0.02
Cr	—	—	—	—	0.87
Pb	0.004	—	—	1.14	2.25
As	0.96	0.99	0.72	1.93	0.44
P	0.04	0.01	0.28	0.07	0.56
O	3.9	4.3	4.7	9.7	6.8

1. Cuprian adamite, M38304
2. Zincian olivenite, M38146
3. Zincian olivenite, M36792
4. Bayldonite (average of 5 analyses)
5. Vauquelinite-fornacite, M38173.

NOTE: All microprobe analyses (Tables 2–7) were obtained at 15 kV, and a specimen current of between 0.015 and 0.020 μA. Standards used were metals for Cu, Zn and Cr, hematite, wollastonite for Ca, arsenopyrite for As, fluorapatite for P.

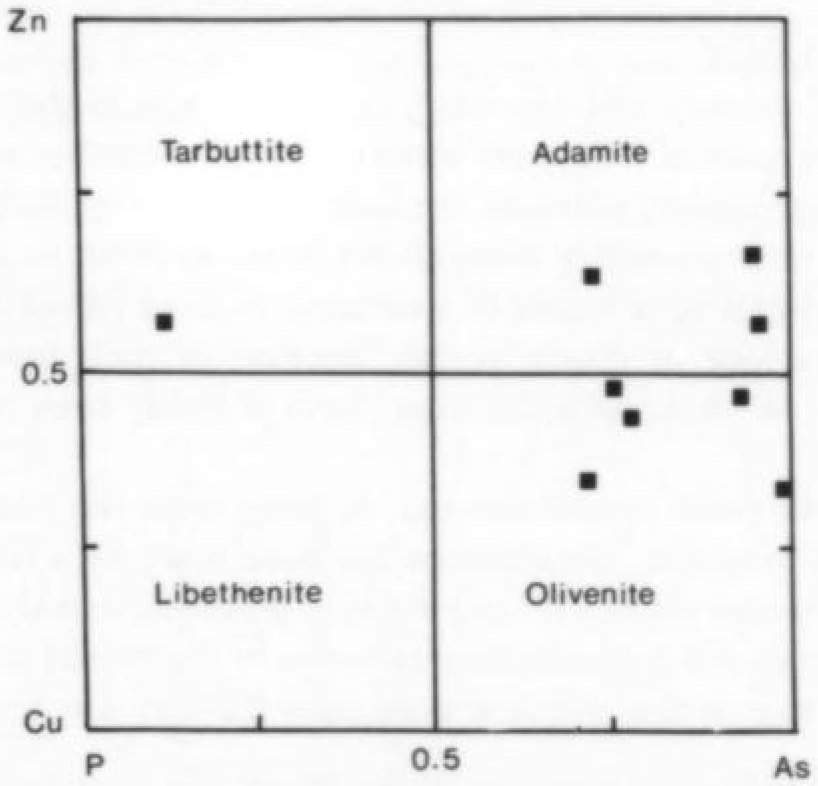

***Figure 5*. Compositional diagram showing analyses of adamite, olivenite and tarbuttite (?) from the Kintore opencut.**

Atacamite $Cu_2Cl(OH)_3$

Groups of transparent, deep green, platy crystals of atacamite up to 3 mm across and with edges somewhat rounded, occur scattered on a thin, dark brown, globular crust of iron-manganese oxides on garnet sandstone.

Barite $BaSO_4$

Barite is extremely rare in the oxidized zone at Broken Hill, but a few specimens have recently been collected at Kintore. The barite occurs as pale yellowish brown or fawn-brown tabular to blocky crystals up to 3.5 mm on edge, often in clusters, on massive iron and manganese oxides. Malachite may be associated.

Bayldonite $PbCu_3(AsO_4)_2(OH)_2 \cdot H_2O$

Bayldonite is relatively rare at Kintore, forming crusts of tiny globules with a distinctive light emerald-green color which show up as bright green stains on garnet sandstone in the exposed mineralized zones. Crystals are rare, although one specimen shows bright grass-green single crystals 0.15 mm long with yellowish natrojarosite and white shells of arsenian pyromorphite. Microprobe analyses of five specimens show that the bayldonite is very uniform in composition, containing only trace amounts of Zn and P. It is usually associated with adamite-olivenite, pyromorphite or jarosite-group minerals.

Boleite $Pb_{26}Ag_{10}Cu_{24}Cl_{62}(OH)_{48} \cdot 3H_2O$

Only one small specimen in which boleite crystals occur has been found at Kintore. They cover an area of about 1 cm by 2 cm on a specimen of massive-granular cerussite replacing galena which is altering to covellite. The boleite forms lustrous, deep blue crystals, essentially octahedra but modified by small cube faces and often intergrown. The largest crystal is only 0.6 mm across. A microprobe analysis gave a formula in reasonable agreement with that accepted for boleite.

Only a few specimens of boleite crystals have ever been recovered from elsewhere in the Broken Hill oxidized zone (Liversidge, 1894; Pring, 1985).

Brochantite $Cu_4(SO_4)(OH)_6$

This mineral is rare as crusts of deep green crystals on remnant sulfides and on limonite-stained lode rocks. It is usually associated with linarite.

Bromargyrite AgBr

This rare silver halide forms soft, rough, flattened "crystals" up to 1.5 mm across, with a deep grayish green alteration veneer, probably due to the effects of light. Internally the crystals are bright yellow with a greasy appearance. They occur on crusts of white dolomite crystals on pieces of massive quartz-coronadite rock in stockpiles above the Kintore opencut. Surrounding each bromargyrite crystal is a bright yellow zone coating the dolomite.

Qualitative analysis shows that the crystals also contain small amounts of Cl and I.

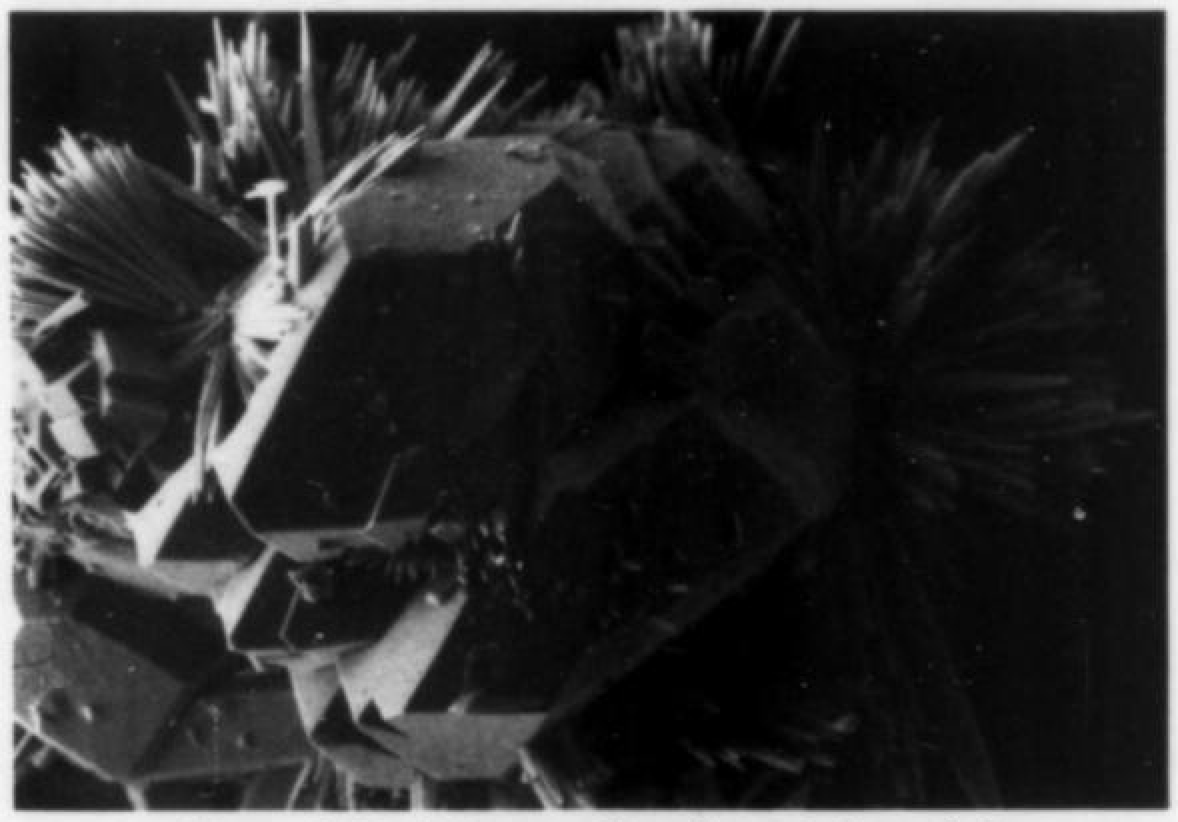

Figure 6. **Radiating needles of carminite on 0.3-mm scorodite crystals.**

Carminite $PbFe_2^{+3}(AsO_4)_2(OH)_2$

Carminite occurs on only one known specimen, as tufts of red crystals up to 0.2 mm long, enclosed within blocky scorodite crystals, on a matrix of massive quartz-bustamite rock with scattered arsenopyrite crystals. The carminite needles occasionally protrude through the scorodite crystals to form delicate radiating aggregates.

Chalcanthite $CuSO_4 \cdot 5H_2O$

Thin seams, up to 0.6 mm thick, of pale blue vitreous chalcanthite have been found in garnet sandstone.

Chlorargyrite (bromian) Ag(Cl,Br)

Some superb, translucent, yellow-green crystals of bromian chlorargyrite have been found on cavernous coronadite lined with a velvet druse of goethite. The crystals are up to 3 mm across and generally show cube faces modified by octahedron faces. Recently some fine vermiform masses have been found, mostly a few centimeters across, but with one exceptional matrix specimen measuring 2 x 7 x 15 cm.

Conichalcite $CaCu(AsO_4)(OH)$

One specimen of garnet sandstone found in Kintore is covered with translucent, bright green conichalcite globules, 0.1 to 0.2 mm in diameter. Scattered over the conichalcite are hemispherical clusters, up to 0.5 mm across, of deep bluish green cornwallite crystals [$Cu_5(AsO_4)_2(OH)_4 \cdot H_2O$].

Corkite-Beudantite $PbFe_3^{+3}(PO_4)(SO_4)(OH)_6$—
$PbFe_3^{+3}(AsO_4)(SO_4)(OH)_6$

Among the minerals occurring at Kintore are yellowish to greenish crusts which, when examined under the microscope, may be seen to consist of acute rhombohedral crystals. The minerals give x-ray powder diffraction patterns similar to species within the beudantite and crandallite groups. Microprobe analysis is essential if the individual species are to be determined. This has revealed a number of specimens to be within the series corkite-beudantite.

Table 3. **Microprobe analyses of corkite-beudantite, hinsdalite and hidalgoite from the Kintore Opencut, Broken Hill.**

wt. %	1	2	3	4
Cu	1.97	1.34	2.18	1.52
Zn	0.49	0.39	0.33	0.23
Fe	21.35	20.13	0.47	0.13
Al	0.24	1.16	11.16	11.08
Pb	31.98	33.83	35.51	36.10
As	5.24	2.37	1.08	12.34
P	3.36	5.82	5.07	—
S	3.13	2.41	3.85	4.05
O (diff)	32.34	32.55	40.35	34.55
Total	100.00	100.00	100.00	100.00
Formulae: As + P + S = 2				
Cu	0.23	0.14	0.23	0.17
Zn	0.05	0.04	0.03	0.02
Fe^{+3}	2.79	2.44	0.05	0.01
Al	0.07	0.29	2.81	2.83
Pb	1.12	1.10	1.15	1.20
As	0.50	0.22	0.09	1.13
P	0.79	1.27	1.10	—
S	0.71	0.51	0.81	0.87
O	14.7	13.8	16.9	14.8

1. Corkite-beudantite (dark brown crusts), M38145
2. Corkite (yellowish to grayish green crystals), M38533
3. Hinsdalite (pale blue crusts), M36887
4. Hidalgoite (bluish green pseudomorphs), M36882

Covellite CuS

Covellite has been observed as crusts of deep metallic blue crystals associated with sulfates such as serpierite, linarite, antlerite and brochantite. It also occurs as fine grained replacements of primary sulfides, especially galena, in partially oxidized ore.

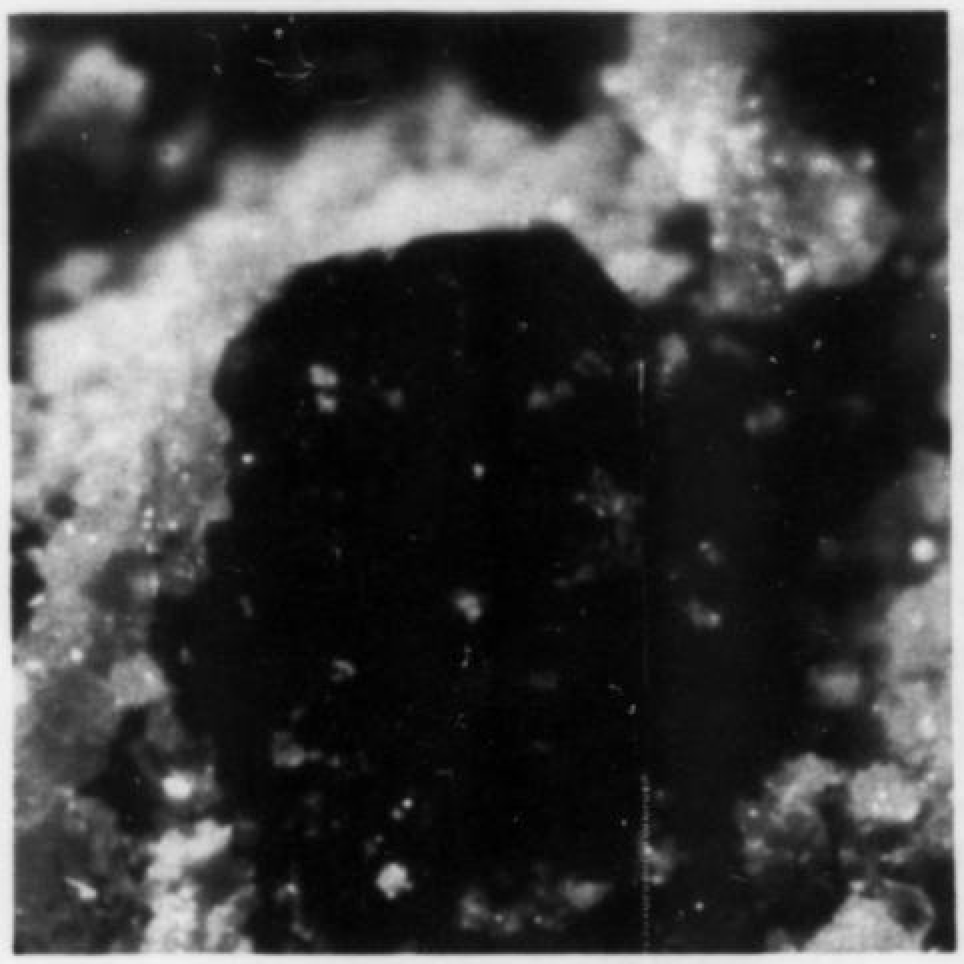

Figure 7. **Boleite crystal, 0.6 mm.**

Dolomite $CaMg(CO_3)_2$

Dolomite is locally abundant in the opencut, as white globular crusts and hemispheres consisting of intergrown, colorless rhombohedra with characteristic curved faces, on massive or stalactitic coronadite. Prismatic, slightly barrel-shaped crystals up to 2 or 3 mm long are less common.

Dufrenite $Fe^{+2}Fe_4^{+3}(PO_4)_3(OH)_5\cdot 2H_2O$

One of the number of dark green iron phosphates which form thin crystalline crusts on fractures in garnet sandstone is dufrenite. It is associated with yellow natrojarosite crystals. Microprobe analysis reveals a small amount of zinc replacing iron in the dufrenite.

Duftite $PbCu(AsO_4)(OH)$

One small specimen of garnet sandstone has been collected from Kintore on which a few very dark green bipyramidal crystals of duftite are scattered on a thin coronadite film.

Graphite C

Graphite crystals up to 3 mm across have been found in massive goethite and on quartz gneiss in the Kintore opencut and on spoil heaps.

Hidalgoite-Hinsdalite $PbAl_3(SO_4)(AsO_4)(OH)_6$—
$(Pb,Sr)Al_3(PO_4)(SO_4)(OH)_6$

These minerals of the beudantite group are quite common in the Kintore opencut, almost always as pseudomorphs after pyromorphite or mimetite. They range in habit from massive cryptocrystalline crusts and seams resembling clay, to cavernous aggregates of drusy crystals forming shells in the shape of hexagonal prisms. Colors range from pale greenish or bluish white to bluish and yellowish green and olive-green. Bright yellow mimetite crystals and tiny black dufrenite or mottramite crystals occur in some cavities between pseudomorphs.

Microprobe analyses reveal little solid solution in terms of P and As, so most compositions are close to the end-members. Small amounts of Cu may be responsible for the more bluish varieties.

Hydrocerussite $Pb_3(CO_3)_2(OH)_2$

White chalk-like pseudomorphs after cerussite crystals, usually with a black coating, and consisting of a mixture of hydorcerussite, cerussite and a lead oxycarbonate, occur on quartz-rich lode rocks from 3 lens. The pseudomorphs may be the result of old underground fires.

Ktenasite $(Cu,Zn)_5(SO_4)(OH)_6\cdot 6H_2O$

This Cu-Zn sulfate has not previously been recorded from Broken Hill, but a few specimens have recently been discovered on stockpiles

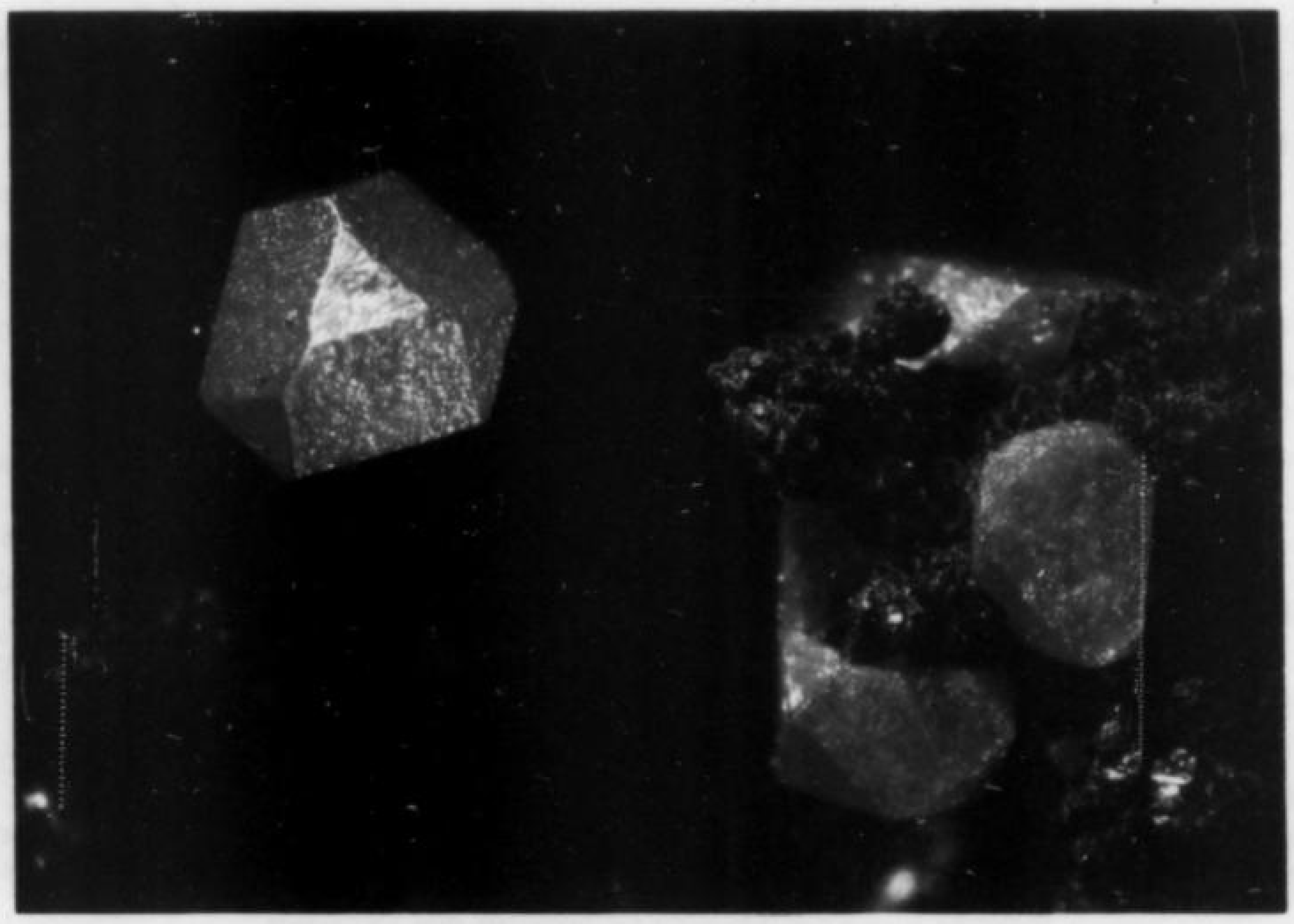

Figure 8. **Bromian chlorargyrite crystals to 2 mm.**

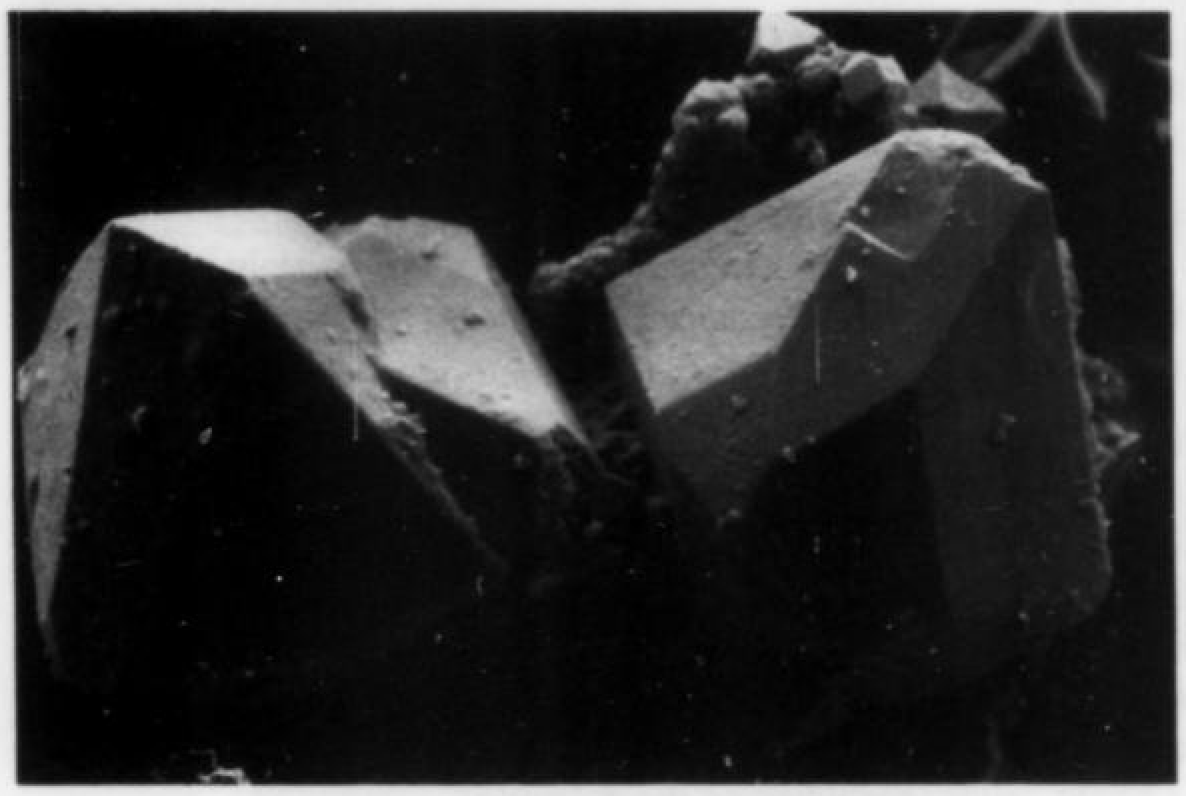

Figure 9. **Duftite crystals to 0.25 mm.**

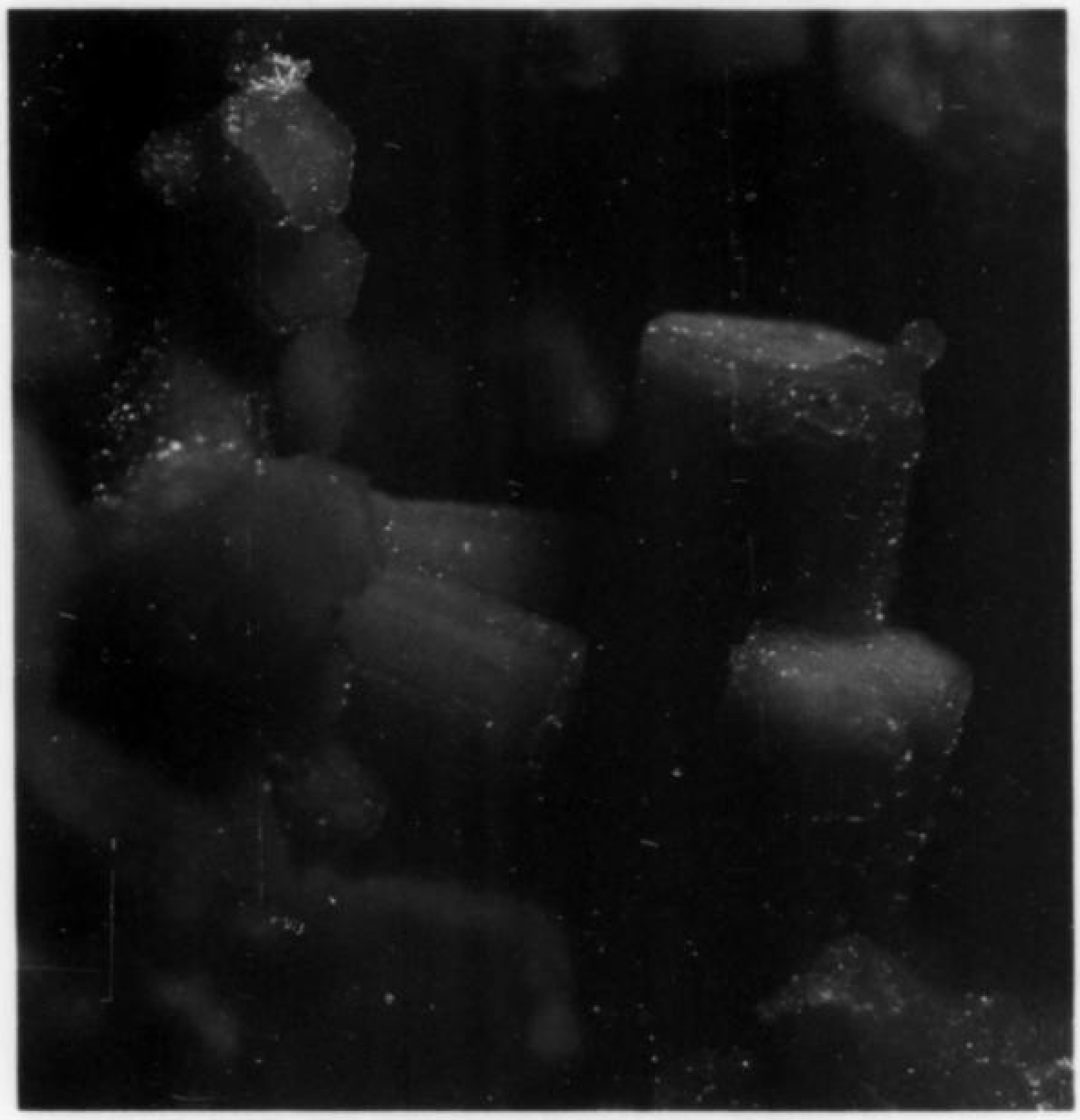

Figure 10. **Hidalgoite pseudomorphs after pyromorphite crystals to 1.2 mm.**

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of ore taken from the Kintore opencut. The ktenasite ranges in habit from pale blue earthy coatings to crusts of translucent intergrown crystals, glassy blue hemispheres up to 0.5 mm in diameter with a radiating fibrous habit and, more rarely, transparent, deep sky-blue tabular crystals up to 1.2 mm across. It is usually associated with serpierite, but minor rosasite and langite have also been detected in X-ray diffraction patterns of massive ktenasite.

Microprobe analyses of the Kintore ktenasite reveal variable Cu and Zn contents fitting the formula suggested by Raade *et al.* (1977). It is possible that a zinc analog of ktenasite occurs at Kintore.

Linarite $PbCu(SO_4)(OH)_2$

Linarite forms bright royal-blue crusts of fibrous or platy crystals associated with malachite, serpierite, antlerite and brochantite, often encrusting partially altered sulfides such as galena. It is easily confused with azurite in hand specimen.

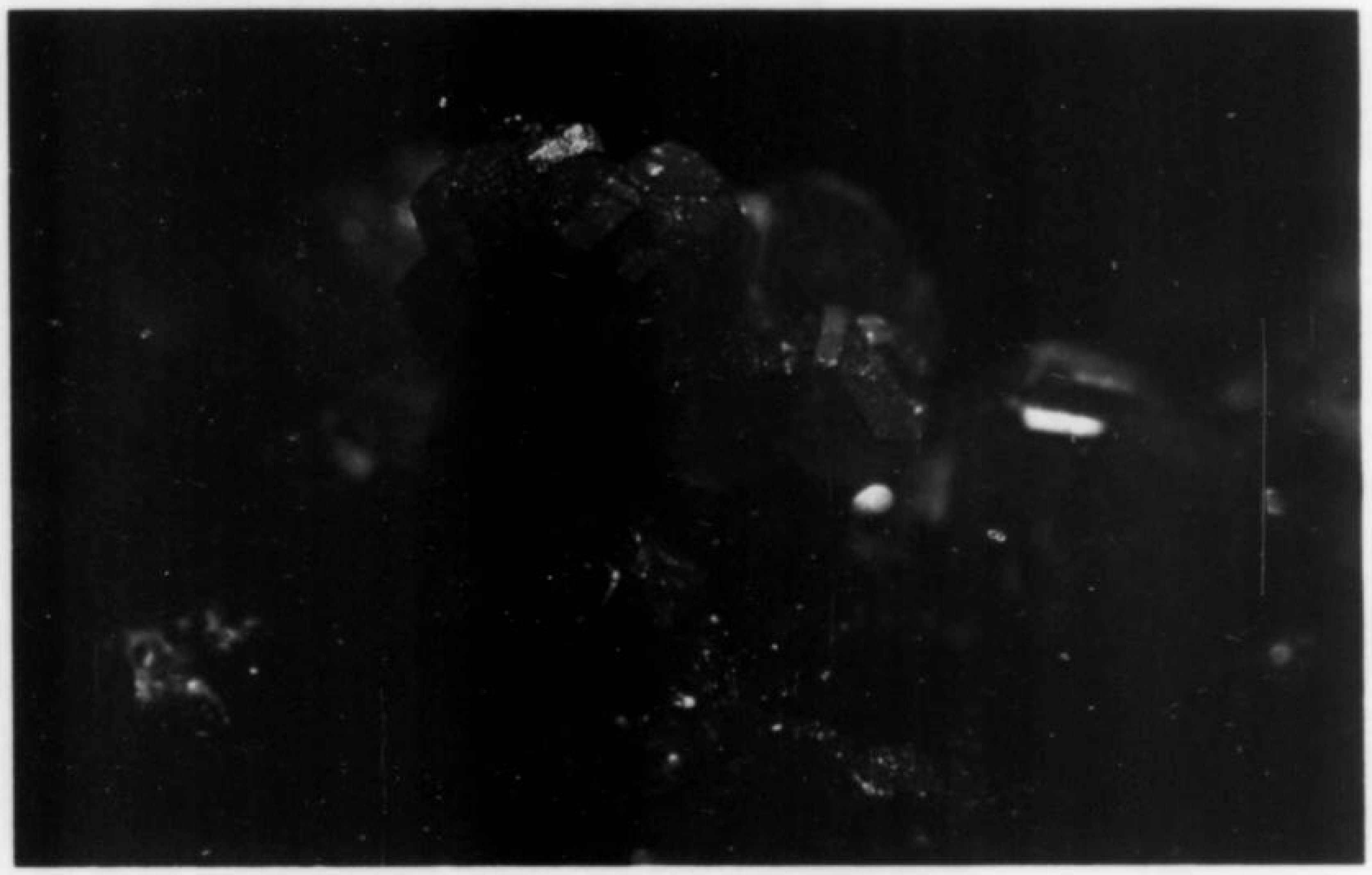

Figure 11. **Mimetite crystal group, 5 mm across.**

Mimetite $Pb_5(AsO_4)_3Cl$

Mimetite is the most abundant arsenate at Kintore and is more common and widespread than pyromorphite. Kintore mimetite specimens, although not forming large crystals, show a wide variety of habits and colors. Perhaps the most attractive crystals are groups of reddish, interpenetrating combinations of prism, pyramid and basal pinacoid, up to 3 mm long, on coronadite. Drusy red to orange crusts of prismatic mimetite crystals accompany tabular red wulfenite crystals up to 5 mm on edge. Flattened yellow-orange hexagonal crystals, and more elongated types ranging from colorless to brown and often with a brilliant luster, occur both as scattered individuals and as crusts on quartz-rich rocks, often cemented by manganese oxides.

Microprobe data indicate that nearly all Kintore mimetites (and pyromorphites) are close to end-member composition. However several analyses were obtained of intermediate compositions, i.e., phosphatian mimetite. These included aggregates of very pale brown, transparent prisms up to 7 mm long associated with corkite-beudantite.

Mottramite $PbCu(VO_4)(OH)$

Lustrous, black crystals to 0.2 mm, in cavities in massive hinsdalite, have been identified as mottramite.

Natrojarosite $NaFe_3^{+3}(SO_4)_2(OH)_6$

Natrojarosite occurs as drusy crusts and individual groups of transparent yellowish to orange brown crystals up to 0.5 mm across on garnet sandstone. It may be accompanied by pharmacosiderite, iron phosphates such as dufrenite, and grayish white crystals and globular crusts of strengite-variscite. Earthy aggregates of yellow natrojarosite scales have also been found enclosing small relict spessartine garnets.

Analyses show that natrojarosite is the most common mineral in the jarosite group at Kintore. However, on one corroded quartz specimen, yellow brown globules of lead-bearing and potassium-bearing natrojarosite accompany bayldonite and arsenian pyromorphite.

Paratacamite $Cu_2(OH)_3Cl$

This is a very rare mineral at Kintore but has been identified as transparent, deep bluish green crystals lining small cavities in quartz-cuprite ore and in massive hinsdalite-cerussite.

Pharmacosiderite $KFe_4^{+3}(AsO_4)_3(OH)_4 \cdot 6\text{-}7H_2O$

Brilliantly reflective crusts of nearly colorless, pale green or dark brown crystals of pharmacosiderite may be found occasionally on garnet sandstone. Individual cubic crystals, never more than about 0.2 mm on edge, are also found enclosing ferrian turquoise, which imparts a light green color to the pharmacosiderite. Other associated minerals include natrojarosite and strengite-variscite.

Table 4. **Microprobe analyses of mimetite and pyromorphite from the Kintore Opencut, Broken Hill.**

wt. %	1	2	3	4
Pb	67.98	73.27	69.16	74.74
Ca	5.49	—	—	—
As	0.44	3.15	12.13	8.25
P	7.99	5.20	1.02	2.70
Cl	nd	nd	nd	nd
Total	81.90	81.62	82.31	85.69
Formulae: As + P = 3				
Pb	3.73	5.10	5.14	5.50
Ca	1.56	—	—	—
As	0.07	0.59	2.49	1.68
P	2.93	2.41	0.51	1.32

1. Calcian pyromorphite (white needles), M38305
2. Arsenian pyromorphite (white shells), M36800
3. Mimetite (orange crystals with wulfenite), M38234
4. Phosphatian mimetite (pale brown prisms), M38172

Plumbogummite $PbAl_3(PO_4)_2(OH)_5 \cdot H_2O$

On one specimen of garnet sandstone, pseudocubic yellow crystals up to 0.2 mm on edge are scattered on a massive white mineral.

Microprobe analysis of the crystals and the crust gave composition in the plumbogummite-hinsdalite series, but closer to plumbogummite.

More widespread is a suite ranging from pale yellow microcrystalline coatings on pulverulent limonite, to yellowish green crusts of acute rhombohedral crystals and, at its most attractive development, lustrous greenish yellow rhombohedra up to 0.5 mm long, either as individuals, subparallel intergrowths or spherical clusters on limonite. Microprobe analysis of this suite shows that it forms a series within the crandallite group with compositions between $PbFe_3^{+3}(PO_4)_2(OH)_5$ and $PbFe_3^{+3}(AsO_4)_2(OH)_5$. This appears to be a new compositional series, although Scott (1987) refers to a mineral from Pegmont, Queensland, with similar composition to the PO_4 end-member at Kintore, as aluminian lusungite. Work is currently in progress to define the extent of this series.

***Table 5.* Microprobe analyses of plumbogummite group minerals from the Kintore Opencut, Broken Hill.**

wt. %	1	2	3
Cu	0.13	.89	0.63
Zn	0.35	—	2.42
Fe	0.31	21.58	21.77
Al	10.91	0.52	—
Pb	37.54	32.69	29.66
As	0.25	2.74	12.12
P	6.70	6.76	3.07
S	4.36	0.85	0.17
O (diff)	39.45	33.97	30.16
Total	100.00	100.00	100.00
Formulae: As + P + S = 2			
Cu	0.01	0.10	0.07
Zn	0.03	—	0.28
Fe	0.03	2.74	2.92
Al	2.28	0.14	—
Pb	1.02	1.12	1.07
As	0.02	0.26	1.21
P	1.22	1.55	0.75
S	0.77	0.19	0.04
O	13.9	15.0	14.2

1. Plumbogummite (yellow pseudo-cubic crystals) M36883
2. Plumbogummite group, unnamed Pb-Fe-PO_4 member (pale yellow crusts), M36934
3. Plumbogummite group, unnamed Pb-Fe-AsO_4 member (yellowish green globules), M38564

Pseudomalachite $Cu_5(PO_4)_2(OH)_4 \cdot H_2O$

Deep green vitreous crusts of pseudomalachite, which closely resembles brochantite, occur rarely on garnet sandstone.

Pyromorphite $Pb_5(PO_4)_3Cl$

Pyromorphite is not as widespread or as common as mimetite in the Kintore opencut. Most crystals are pale to dark brown or green (the superb groups of lustrous yellow crystals collected recently are from Block 14, not Kintore). Large oxide-coated brown crystals up to 4 cm long and 1.5 cm thick have been found in Kintore. Several unusual varieties of pyromorphite have also been collected. These include small, fragile, hollow white shells of arsenian pyromorphite occurring with bayldonite and natrojarosite, and clusters of white needle-like crystals up to 2 mm long of calcian pyromorphite in cavernous goethite.

Rosasite-Zincrosasite $(Cu,Zn)_2(CO_3)(OH)_2$—$(Zn,Cu)_2(CO_3)(OH)_2$

Rosasite is quite common at Kintore as soft, pale to bright blue fibrous crystals forming hemispherical aggregates up to 0.4 mm across, often associated with sprays of hemimorphite blades. It may also occur as earthy seams and crusts associated with cerussite and smithsonite.

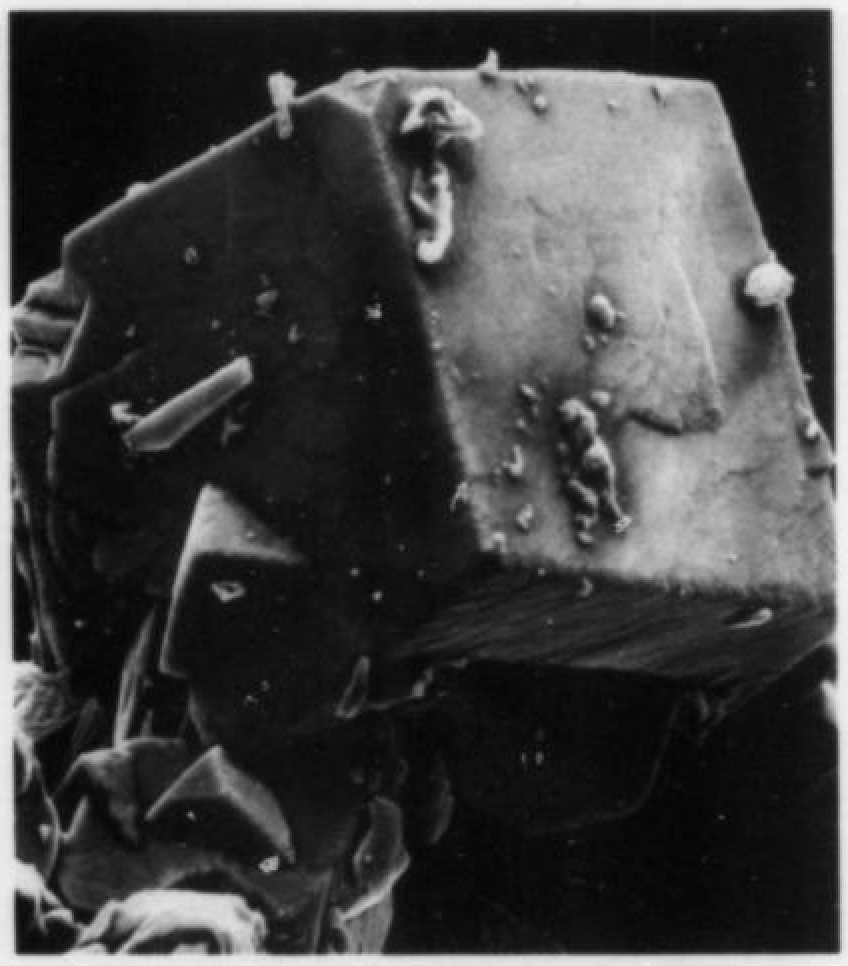

Figure 12. **Plumbogummite crystal, 0.1 mm.**

Microprobe analysis shows that compositions range from zinc-rich rosasite to at least the midpoint of the rosasite-zincrosasite series.

Scorodite $Fe^{+3}AsO_4 \cdot 2H_2O$

Pale green crusts of scorodite crystals ranging from irregular prisms up to 0.5 mm long to aggregates of blocky crystals, which are occasionally yellowish brown, occur rarely on arsenopyrite-bearing garnet sandstone. The scorodite may enclose fibrous aggregates of carminite crystals.

Figure 13. **Zincian serpierite crystals to 0.15 mm.**

Serpierite $Ca(Cu,Zn)_4(SO_4)_2(OH)_6 \cdot 3H_2O$

Serpierite has not previously been recorded at Broken Hill, but has now been found on specimens from dump material taken from the Kintore opencut. It usually occurs as delicate hemispherical sprays or earthy looking crusts of pale blue needles, but it may form subparallel groups of blocky, transparent, blue crystals up to 0.3 mm across or short, sword-shaped crystals up to 0.5 mm long in radiating groups. Associated minerals include antlerite, brochantite and linarite; the matrix is usually a corroded siliceous sulfide ore. Microprobe analysis indicates that it is zincian serpierite, with Cu:Zn around 2.5:1.

Spangolite $Cu_6Al(SO_4)(OH)_{12}Cl \cdot 3H_2O$

This mineral has been found as minute, flattened sky-blue crystals encrusting small rosettes of white cerussite crystals on a gneiss matrix.

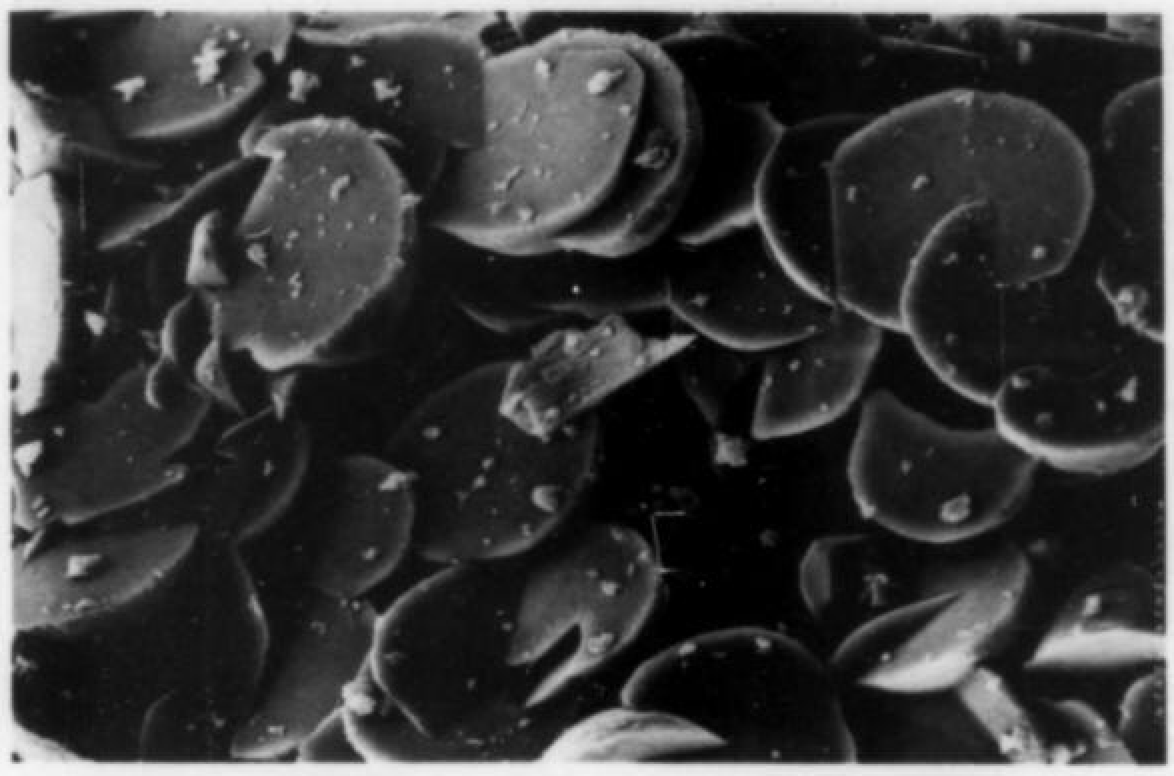

Figure 14. **Unusual disc-shaped crystals of spangolite to 0.03 mm.**

Table 6. **Microprobe analyses of serpierite, ktenasite and antlerite from Kintore Opencut, Broken Hill.**

wt. %	1	2	3
Cu	26.94	24.15	29.62
Zn	11.89	20.09	4.02
Pb	0.41	—	0.31
Fe	0.09	—	—
Al	—	—	0.17
Ca	5.41	—	—
S	9.97	9.20	5.23
O (diff)	45.29	46.56	60.65
Total	100.00	100.00	100.00
Formulae:			
Cu	2.73	2.65	2.86
Zn	1.17	2.14	0.37
Pb	0.01	—	0.01
Fe	0.01	—	—
Al	—	—	0.04
Ca	0.87	—	—
S	2.00	2.00	1.00
O	18.3	20.3	23.2

1. Zincian serpierite (blue sword-shaped crystals), M36757
2. Ktenasite (transparent blue crystal), M38154
3. Antlerite (chalky blue pseudomorphs), M38228

Strengite-Variscite $Fe^{+3}PO_4 \cdot 2H_2O\text{-}AlPO_4 \cdot 2H_2O$

Minerals in this series occur as well formed, lustrous, pyramidal crystals up to 0.25 mm across, with colorless rims and grayish white cores, and as white to gray translucent globules and warty looking botryoidal crusts on garnet sandstone. Associated minerals include natrojarosite, pharmacosiderite and an unidentified dark green iron phosphate. Microprobe analysis shows that the crusts and globules are zoned from cores of aluminian strengite to rims of ferrian variscite, but with significant replacement of P by As in some intermediate zones.

Tarbuttite (cuprian)(?) $(Zn,Cu)_2(PO_4)(OH)$

A few blue-green globules up to 0.3 mm in diameter occurring with azurite on a small specimen of garnet sandstone have a composition plotting in the tarbuttite field. X-ray diffraction analysis is required to confirm the identification.

Turquoise $CuAl_6(PO_4)_4(OH)_8 \cdot 5H_2O$

Turquoise occurs very sparsely as cavernous masses of intergrown spheres up to 0.6 mm in diameter, each sphere being an aggregate of bluish green crystals. It may also occur as isolated pale greenish hemispheres overgrown by pharmacosiderite. Analysis shows it is iron-bearing turquoise.

Table 7. **Microprobe analyses of dufrenite, turquoise, strengite and varscite from Kintore Opencut, Broken Hill.**

wt. %	1	2	3	4
Cu	—	7.42	—	—
Zn	2.53	0.42	—	—
Fe	32.63	12.99	15.70	4.61
Al	8.84	9.94	7.13	18.05
A	2.83	0.23	5.06	0.74
P	13.31	13.53	14.94	23.32
O (diff)	47.86	55.47	57.17	53.28
Total	100.00	100.00	100.00	100.00
Formulae: As + P = 3 (1, 3, 4); As + P = 4 (2)				
Cu	—	1.06	—	—
Zn	0.25	0.05	—	—
Fe	0.94	—	—	—
Fe	2.80	2.12	0.51	0.11
Al	0.20	3.35	0.48	0.88
As	0.24	0.03	0.12	0.01
P	2.76	3.97	0.88	0.99
O	19.2	31.5	6.5	4.4

1. Zincian dufrenite (dark green crust), M38233
2. Ferrian turquoise (blue green spheres), M38079
3. Aluminian strengite, M36816
4. Ferroan variscite, M36816

Vauquelinite-Fornacite $Pb_2Cu(CrO_4)(PO_4)(OH)$—$(Pb,Cu)_3[(Cr,As)O_4]_2(OH)$

A few patches of thin, deep greenish brown, wedge-shaped crystals, usually individuals but sometimes intergrown and up to 0.2–0.3 mm long, have been found on a matrix of drusy yellow mimetite associated with dark brown pharmacosiderite crystals. A microprobe analysis gave a composition intermediate between vauquelinite and fornacite.

Whitmoreite (?) $Fe^{+2}Fe_2^{+3}(PO_4)_2(OH)_2 \cdot 4H_2O$

A few minute clusters of pale brownish needles occur on a specimen of garnet sandstone, associated with crusts of a dark green iron phosphate. Microprobe analysis gave a composition which could be referred to as zincian whitmoreite, but X-ray diffraction is required for confirmation.

Unknown Minerals

Iron-zinc phosphates

A number of dark green iron-zinc phosphate minerals occur in garnet sandstone, as thin fracture linings with a greasy to vitreous luster, and as botryoidal coatings consisting of hemispherical aggregates of radiating fibrous crystals. Dufrenite is the only species positively identified so far, although another appears to be a zinc-rich rockbridgeite. Microprobe analyses of the other minerals, most of which are poorly crystalline, give formulae similar to $(Fe,Zn)(Fe,Al)_3(PO_4)_3$, but remain unidentified. They are associated with natrojarosite and variscite/strengite.

Copper-iron-lead arsenate

Soft, bright yellow aggregates of minute crystals occur as rough outlines of hexagonal pseudomorphs in association with yellowish brown drusy corkite-beudantite, on garnet sandstone. Microprobe

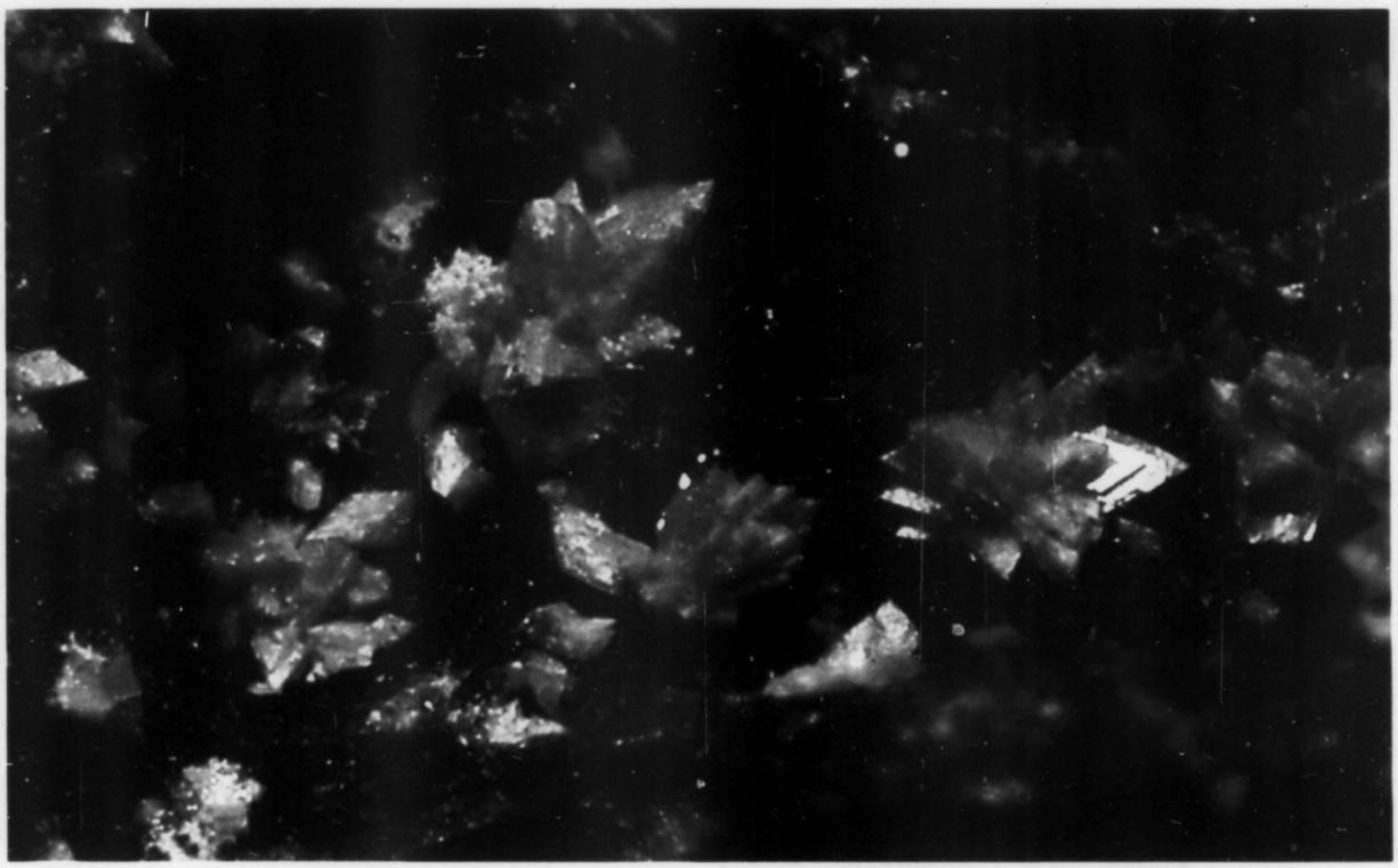

Figure 15. **Plumbogummite-group mineral (Pb, Fe, As-P) crystals to 1 mm.**

analysis indicates the mineral is a copper-iron-lead arsenate, but it has not been identifiable by X-ray diffraction.

Copper-zinc sulfates

Several copper-zinc sulfates have yet to be identified, due mainly to the difficulties associated with obtaining microprobe analyses from very small, hydrated crystals. These minerals include minute, pale blue, pseudohexagonal plates accompanying serpierite and anglesite in granular quartz-rich rocks and resembling schulenbergite in both composition and X-ray diffraction pattern. A second mineral occurs as irregular, sky-blue, earthy to subvitreous crusts associated with cuprite and native copper. The X-ray diffraction pattern resembles that of parnauite, but microprobe analyses show it is a sulfate.

PARAGENESIS

It is not possible to present a simple paragenetic picture for the Broken Hill secondary zone. The diversity of its species arises not only from the vast mass of primary sulfides and their unusual and variable composition, but also from a long and complex history of erosion and weathering in both temperate and arid climates. Quaternary oxidation, which was episodic, leading to changes from relatively high to low water tables, has been superimposed on an older, early or pre-Tertiary secondary zone (Plimer, 1984).

The region of the Kintore opencut yielding the species described in this article represents only a minute portion of the Broken Hill oxidized zone, which on average is 90 meters thick. The absence of any detailed overall study of the oxidized zone means that the Kintore assemblages must be considered in isolation.

Mineral zonation at Kintore begins with a barren gossan at the surface, passing down to a supergene silver zone (50 g/t Ag as chlorargyrite) containing dolomite, smithsonite, aragonite, bromargyrite, mimetite and Fe-Mn oxides. Below this is a carbonate zone with cerussite, malachite, azurite, smithsonite, chlorargyrite and rosasite, followed by leached sulfide ore with brown pyromorphite, anglesite and smithsonite. Most of the rare arsenates/phosphates/sulfates occur

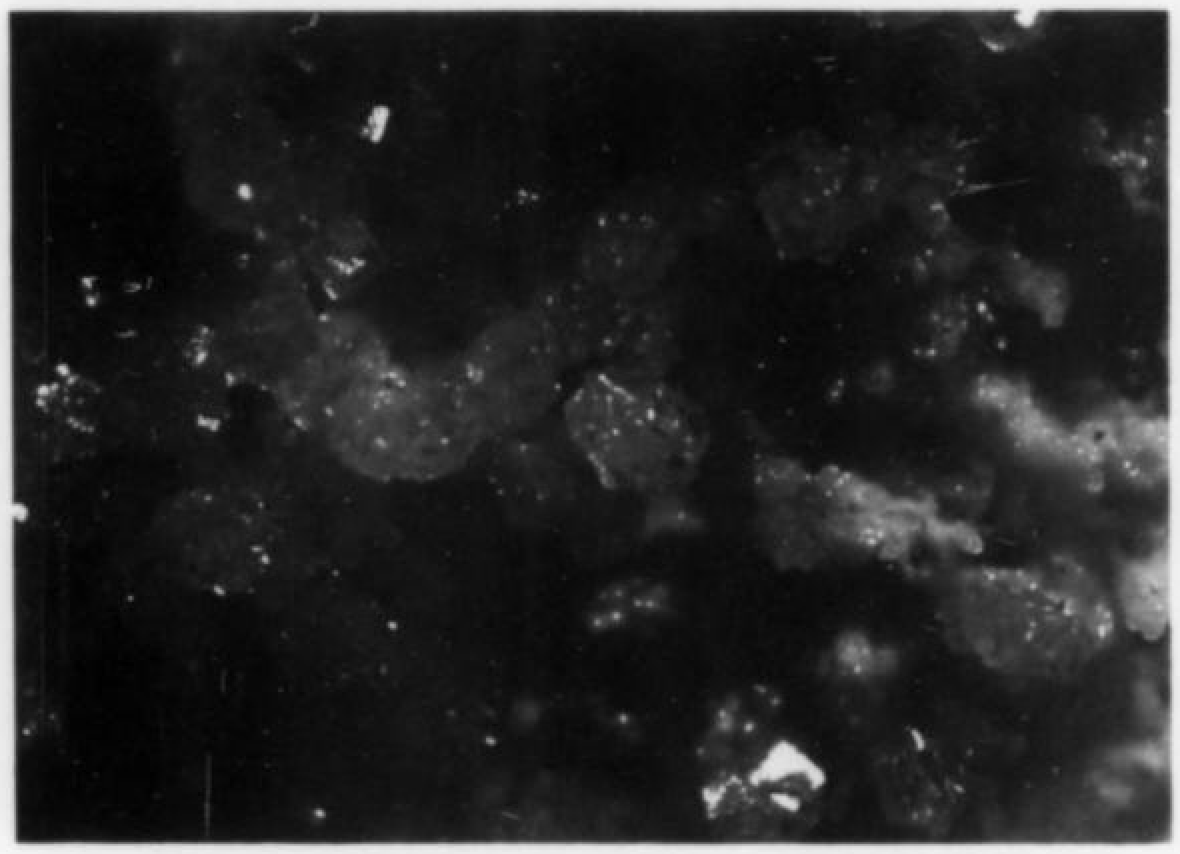

Figure 16. **Plumbogummite crystals to 0.2 mm.**

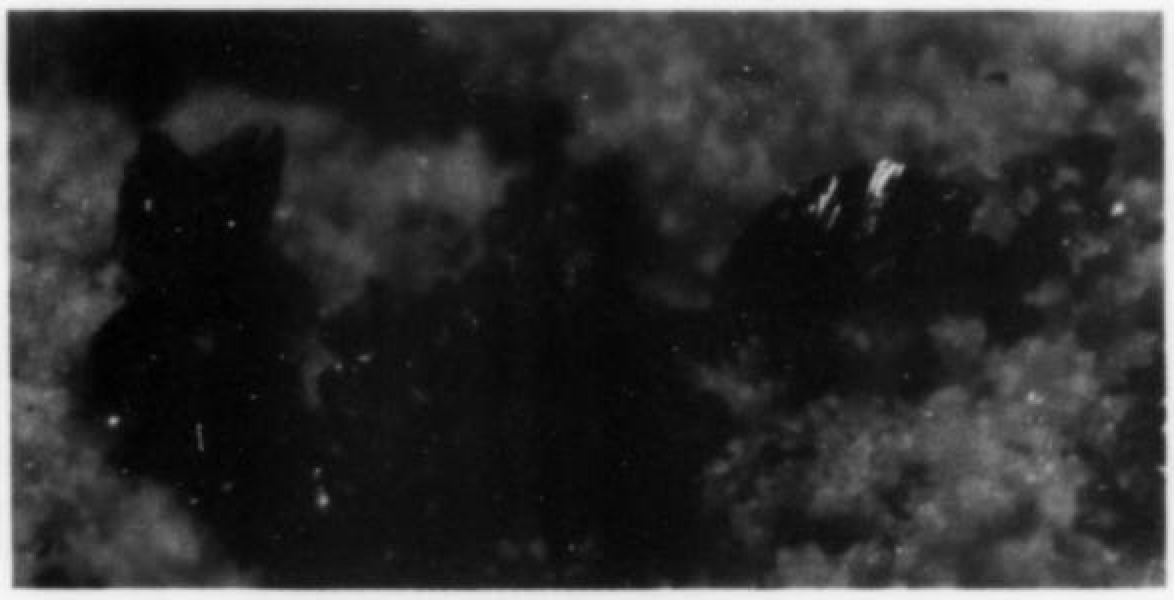

Figure 17. **Vauquelinite-fornacite crystals to 0.3 mm on pyromorphite.**

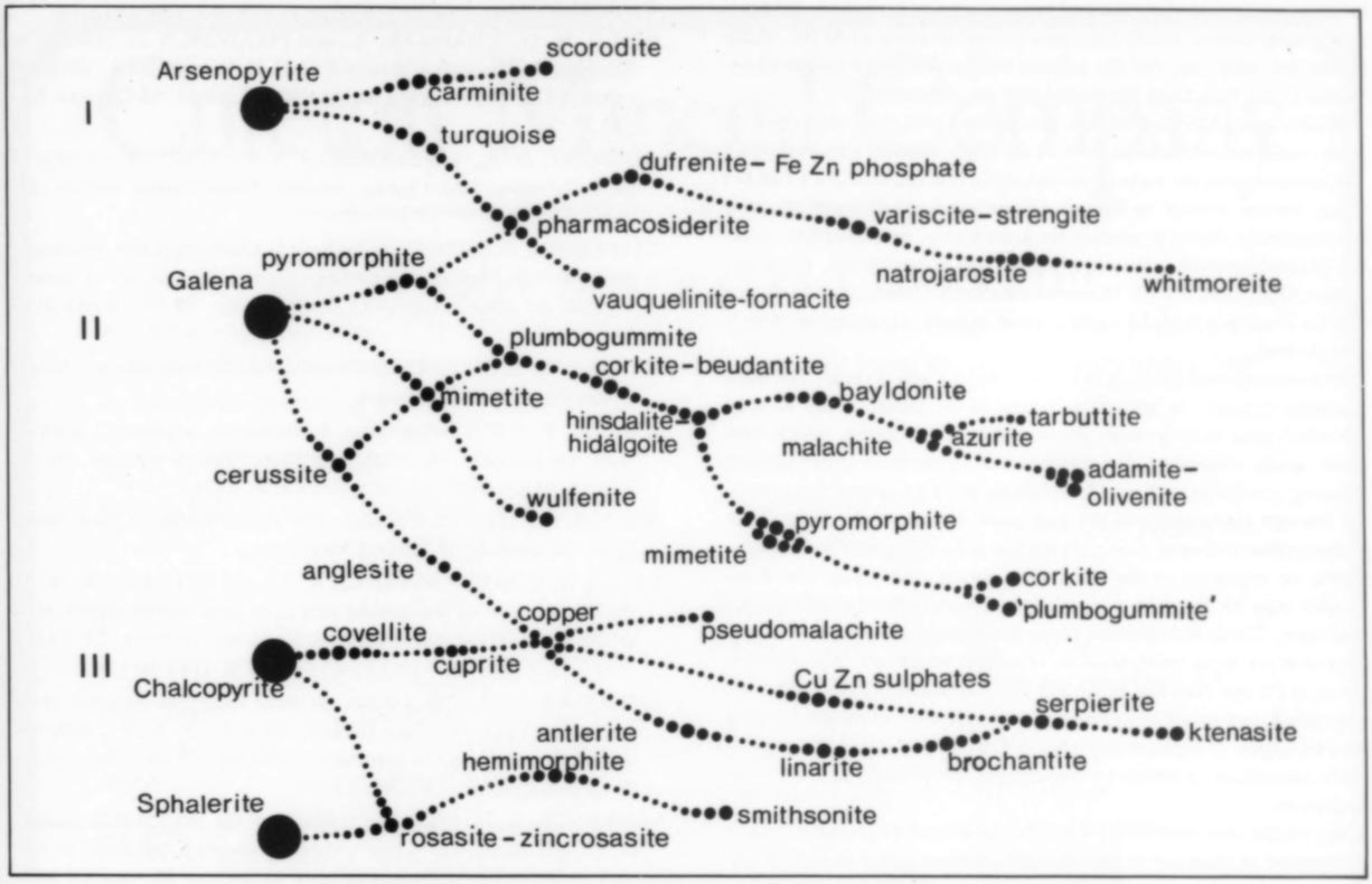

Figure 18. **Paragenetic sequences (I, II, III) observed in the Kintore opencut assemblages.**

in the Main Shear, at a depth of around 50 meters, and away from the strongly zoned lenses. This Main Shear association is probably best described as a complex arsenate/phosphate zone.

A number of features observed in Kintore indicate that oxidation has been episodic. Replacement structures are common and include cubic boxworks of hinsdalite after galena, pseudomorphs and overgrowths of hinsdalite-hidalgoite after pyromorphite-mimetite and pseudomorphs of goethite and/or coronadite after cerussite. The presence of two or three generations of a single species on one specimen, e.g., cerussite, mimetite or natrojarosite, also suggests a complex oxidation history.

The minerals which are synonymous with Broken Hill, such as cerussite, anglesite, azurite, stolzite and smithsonite, are restricted largely to the carbonate zone at Kintore and are not associated with the rarer arsenate/phosphate/sulfate minerals. The minerals recently recorded are not unexpected, however, as their existence and eventual discovery may have been predicted by analogy with oxidized zone mineralogy of other diverse sulfide orebodies, both large, such as Tsumeb (e.g., Keller, 1977) and Cap Garonne (Mari and Rostan, 1986), and small, such as the Killie mine (Dunning and Cooper, 1987).

A number of limited and apparently unrelated associations have been observed in Kintore. Only one or two specimens showing these associations exist.

1. conichalcite and cornwallite
2. carminite and scorodite
3. covellite, linarite, boleite and cerussite
4. rosasite and hemimorphite
5. pharmacosiderite, calcian pyromorphite and vauquelinite-fornacite
6. cerussite, wulfenite and mimetite
7. cerussite and spangolite

Most of the species recorded can be divided into three broad associations, although no sequence is observed in full on any one specimen.

I. An essentially Fe-rich series, derived from phosphate, arsenate and sulfate-bearing solutions: ferrian turquoise, pharmacosiderite, dufrenite (or unknown iron phosphate), variscite-strengite and natrojarosite-whitmoreite(?)

II. An arsenate-rich series, mainly of Pb, but with locally enriched Cu and P species: (a) pyromorphite, plumbogummite, corkite-beudantite, bayldonite, adamite-olivenite; and (b) pyromorphite-mimetite, hinsdalite-hidalgoite, corkite and plumbogummite-like mineral.

III. A series rich in sulfates of copper and zinc: covellite, copper, antlerite, linarite, brochantite, serpierite and ktenasite.

In the paragenesis figure the main associations are shown in a general way, with the latest forming minerals to the right-hand side of each branch. However, reversals and gaps may occur on individual specimens. The younging to the right can in no way be taken to indicate any overall changes in physicochemical conditions such as Eh or pH, since the relative stabilities of many of the species are not known and the assemblages as a whole will have experienced multiple fluctuations in conditions. Nor does the diagram indicate relative time intervals between crystallization of each species, either within or between the three main associations.

All three associations have their origins in ground water dissolution of the primary sulfides, mainly sphalerite, galena and chalcopyrite, giving rise to acid solutions rich in sulfate. Local concentrations of arsenopyrite, particularly in the garnet sandstones, would yield arsenate-rich solutions, while weathering and acid attack on the host rocks in general would provide phosphate, as well as Al, Ca, Na and K. Although the Broken Hill orebody is rich in manganese, it is locked up in stable silicates such as spessartine and rhodonite which generally resist weathering, so that Mn is not an important element in secondary mineral formation. Silver-bearing tetrahedrite would provide Ag for halides such as chlorargyrite and boleite precipitating from chlorine-rich ground waters. Small amounts of molybdenite may be the source of Mo for wulfenite, but the sources of chromium for vauquelinite-fornacite and vanadium for mottramite are unknown.

Which secondary assemblage precipitated will have depended on subtle variations in concentrations of the major metallic ions in solution and fluctuations in the main physicochemical parameters. For a number of the species present in Kintore, the relative stabilities of the stoichiometrically ideal compounds are known (e.g. pyromorphite, corkite, plumbogummite, cerussite; Nriagu, 1984; bayldonite, olivenite, duftite; Guillemin, 1956). However when substitution such as As for P, S for P and As, Zn for Cu, etc., occur, stability relations are further complicated.

The arsenate-rich series is the most complex and diverse. The most abundant minerals in the initial stages of oxidation in the Kintore secondary zone were probably pyromorphite and mimetite, which form under acidic conditions. Pyromorphite is stable even under slightly reducing conditions and may therefore be more persistent than mimetite through fluctuations in the supergene environment. Apart from pyromorphite-mimetite, finely crystalline yellowish green corkite-beudantite or members of the crandallite group resembling plumbogummite may be the first minerals precipitated directly onto garnet sandstone. These and minerals in the hinsdalite-hidalgoite series may form directly from more alkaline solutions which are relatively depleted in Pb and enriched in Al and Fe. Alternatively, such solutions may attack and dissolve existing pyromorphite or mimetite forming pseudomorphs or replacement shells. Corkite and hinsdalite form a stable association in alkaline environments, particularly at low P concentrations.

Bayldonite and adamite-olivenite, sometimes with malachite, have precipitated in response to the influx of solutions richer in copper and zinc, probably also under alkaline conditions. Guillemin (1956) has shown that solutions with excess copper sulfate favor crystallization of olivenite over bayldonite and duftite while conichalcite may form by reaction between arsenate solutions and copper and calcium carbonates. Probably the youngest minerals in the arsenate-rich assemblage include scattered crystals, groups and crusts of mimetite, calcian pyromorphite and the Pb-Fe arsenate-phosphates in the plumbogummite group, all of which may occur unaccompanied in cavernous and stalactitic goethite.

The iron-rich series usually begins with a thin seam of poorly crystalline, dark green iron phosphate lining both sides of narrow fractures in garnet sandstone. On some specimens however, both ferrian turquoise and pharmacosiderite may precede it. Variscite-strengite, natrojarosite and very rarely whitmoreite complete the sequence. This assemblage is characterized by high concentrations of P, Al and Fe, which favor species such as turquoise in arid weathering zones.

The copper and zinc sulfate-rich association usually consists of thin crusts and coatings of two or three minerals on cavernous granular quartz. On some pieces, these minerals, typified by serpierite, ktenasite, brochantite and linarite, may occur on covellite or cuprite and native copper. These minerals are probably post-mining, at least in part, as they may occur on both sulfide ore and old slags.

Further collecting in the Kintore opencut, combined with careful investigation of any remaining portions of the oxidized zone at Broken Hill, will undoubtedly modify this proposed subdivision.

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TASMANIA

Near Dundas	Barbertonite, Stichtite
Lord Brassy M.	Heazelwoodite, Zaratite
Mt. Lyell	Mawsonite
Red Lead Mine	Crocoite, Dundasite, Gorceixite, Hidalgoite

VICTORIA

Parwan Cave	Taranakite
Skipton Caves	Newberryite, Struvite

WESTERN AUSTRALIA

Carr Boyd Mine	Carrboydite, Chalconatronite, Georgeite, Glaukosphaerite
Coppin Pool	Perroudite*
Dingo Donga Cave	Arcanite
Kalgoorlie	Calaverite, Coloradoite, Gold, Melonite
Kambalda	Hydrohonessite, Kambaldaite
Marda	Sodium Pharmacosiderite
Mount Keith	Mountkeithite
Pilbara	Nullaginite, Otwayite
Walgidee Hills	Jeppeite, Priderite, Wadeite

* New minerals not in 1987 glossary.

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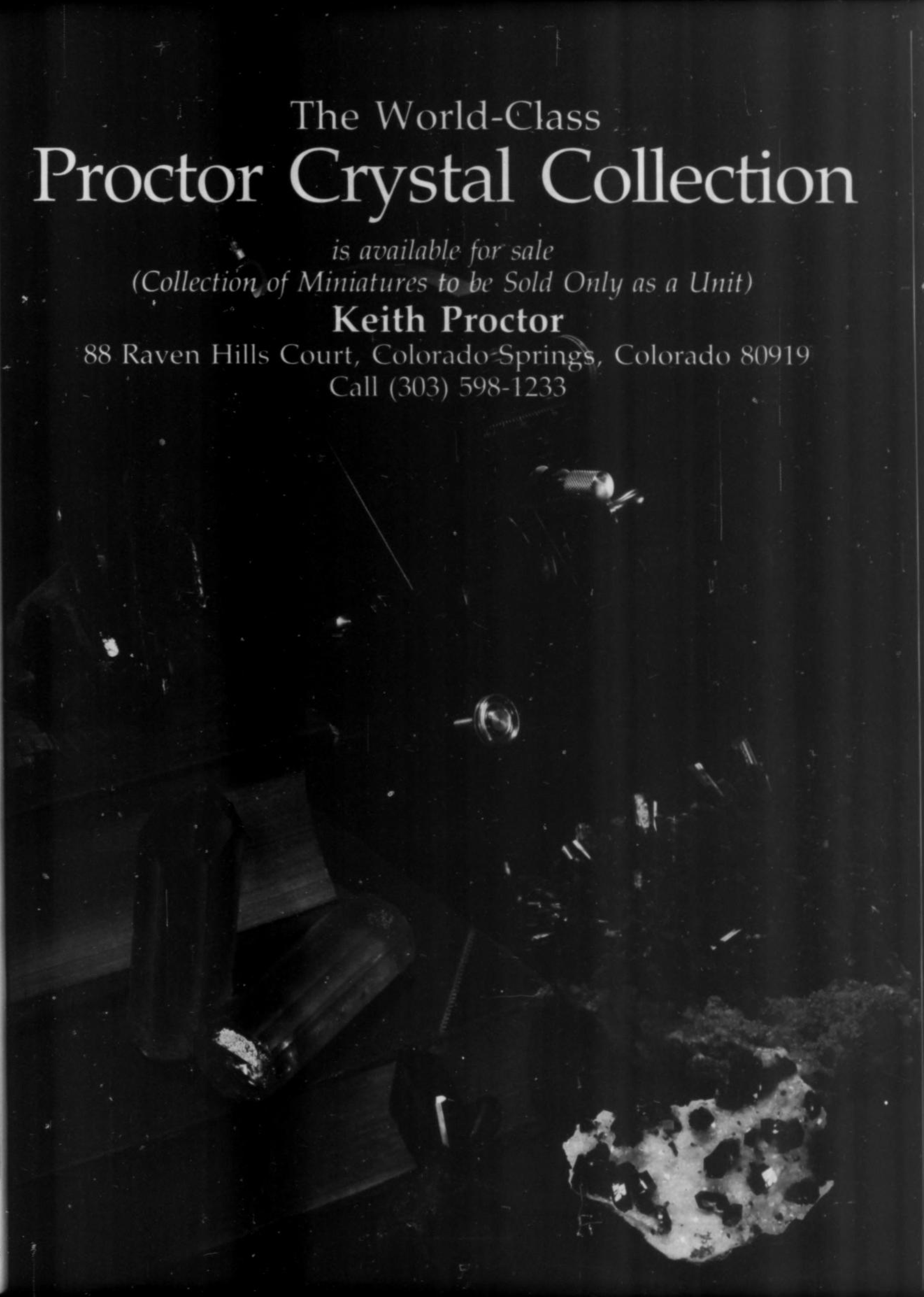

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Mimetite and Duftite from the MOUNT BONNIE MINE

Northern Territory

●

Brian M. England
Broken Hill Proprietary Company Limited
Research and New Technology
Central Research Laboratories
P.O. Box 188,
Wallsend, N.S.W. Australia 2287

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4 Cronulla Street
East Ballina, N.S.W. Australia 2478

The Mount Bonnie mine has been a source of beautifully crystallized mimetite and duftite for many years. Although the gossan lodes were recently mined and processed for their gold and silver content, a considerable quantity of fine specimens was removed beforehand by one of the authors.

INTRODUCTION

The Mount Bonnie mine is located 44 km northwest of Pine Creek and 180 km south-southeast of Darwin, in the Northern Territory, Australia. The region is one of moderate relief, with maturely dissected rounded hills (one of which is Mount Bonnie) and ridges, flanked to the east and southwest by sandstone plateaus with an average elevation of 300 m, and to the north and northwest by coastal plains. The Margaret River flows within a few hundred meters of the mine, although it is often reduced to nothing more than a series of waterholes in the dry season.

The area experiences a severe monsoonal climate with a winter dry season of 7 to 9 months. Most of the annual rainfall of around 1000 mm falls within a November to April wet season. Rainfall intensity is high, leading to very active erosion on major slopes and bare surfaces, as well as moderate flooding. As a result, road access into the area is not possible during the wet season. Dry season daily temperatures rarely exceed 33°C, with an average nocturnal low of 20°C (Walpole *et al.*, 1968). The dominant vegetation in the mine area is open eucalyptus forest (savanah woodland). There is no tropical jungle.

Both the gossan and sulfide orebodies have been investigated for their economic potential on several occasions since their discovery around 1902, but only in 1982 did actual mining for gold and silver commence. This resulted in complete removal of the gossan orebodies, apparently with total disregard for the world-class mimetite and duftite specimens within them. The preservation of many thousands of fine specimens from Mount Bonnie was largely due to the efforts of one of the authors (N.R.), who systematically and single-handedly mined the gossan specifically for specimens over a period of 19 months between 1977 and 1979.

HISTORY

Initial development of the Mount Bonnie deposit took place in 1902 with the sinking of an 18-m shaft adjacent to a prominent outcrop of leached cellular hematitic gossan on the western slopes of Mount Bonnie. Although this shaft, sunk by a Mr. Sabine in association with the Northern Territory Mining and Smelting Company, penetrated an orebody containing significant lead, silver and gold values the property was abandoned. Evidently the Company wanted copper, not lead! (Jensen *et al.*, 1915).

In 1912 the property was acquired by an Adelaide development company (Messrs. Bull & Barrows) and in 1913 considerable development work was carried out. A 92-m tunnel was driven to intersect the orebody, which was described as a leached gossan with vugs of cerussite. From the end of the tunnel a drive was carried both north and south along the orebody, and an inclined shaft was sunk within the orebody from the surface to the tunnel level. From this development work the ore reserves were calculated at around 43,000 tonnes (Jensen *et al.*, 1915). However, there is no record of any ore having been sent to the nearby Iron Blow Smelter for treatment during this period.

Further development work, in the form of exploratory drives along

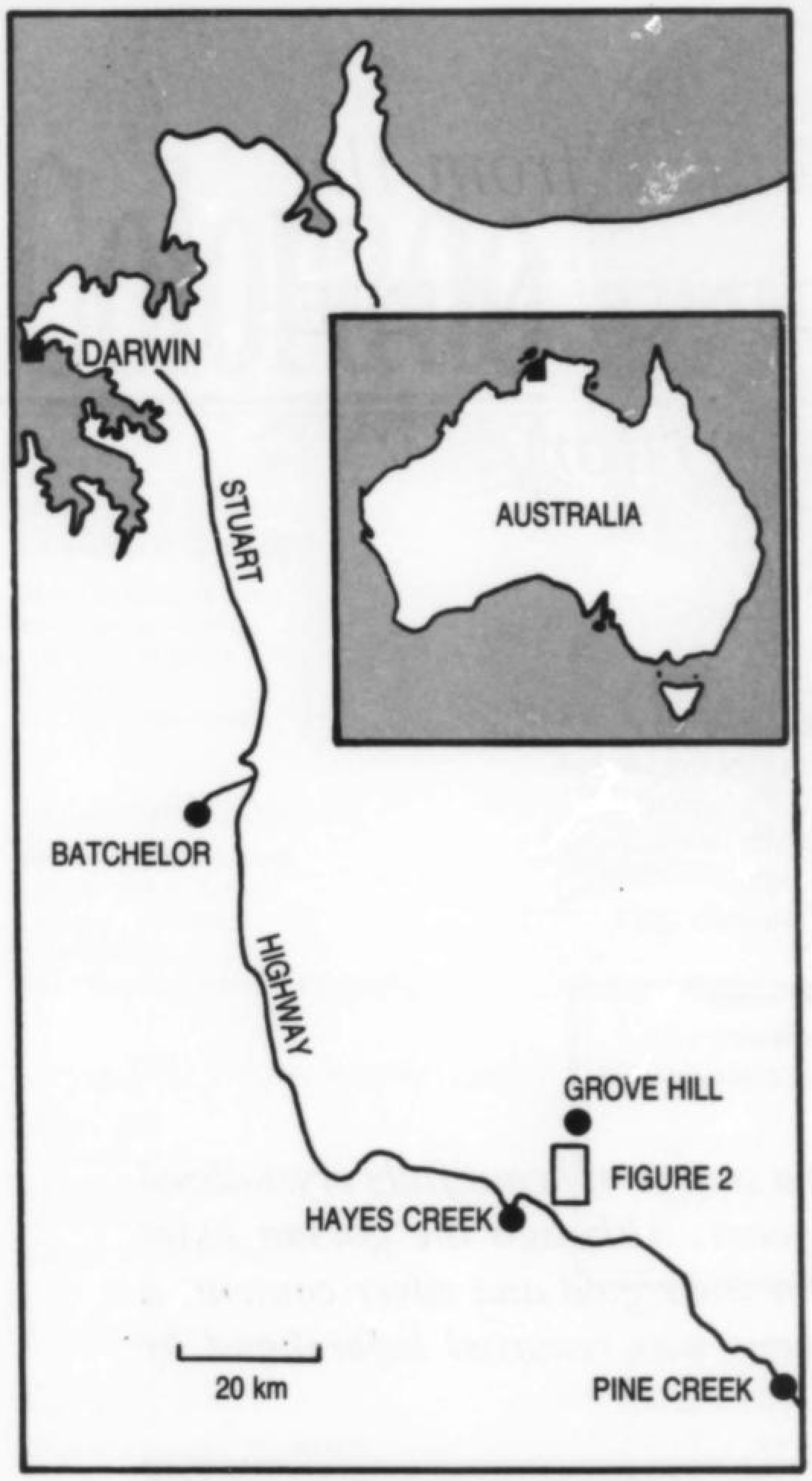


Figure 1. **Map showing the location of the Mount Bonnie mine area in the Northern Territory, Australia.**

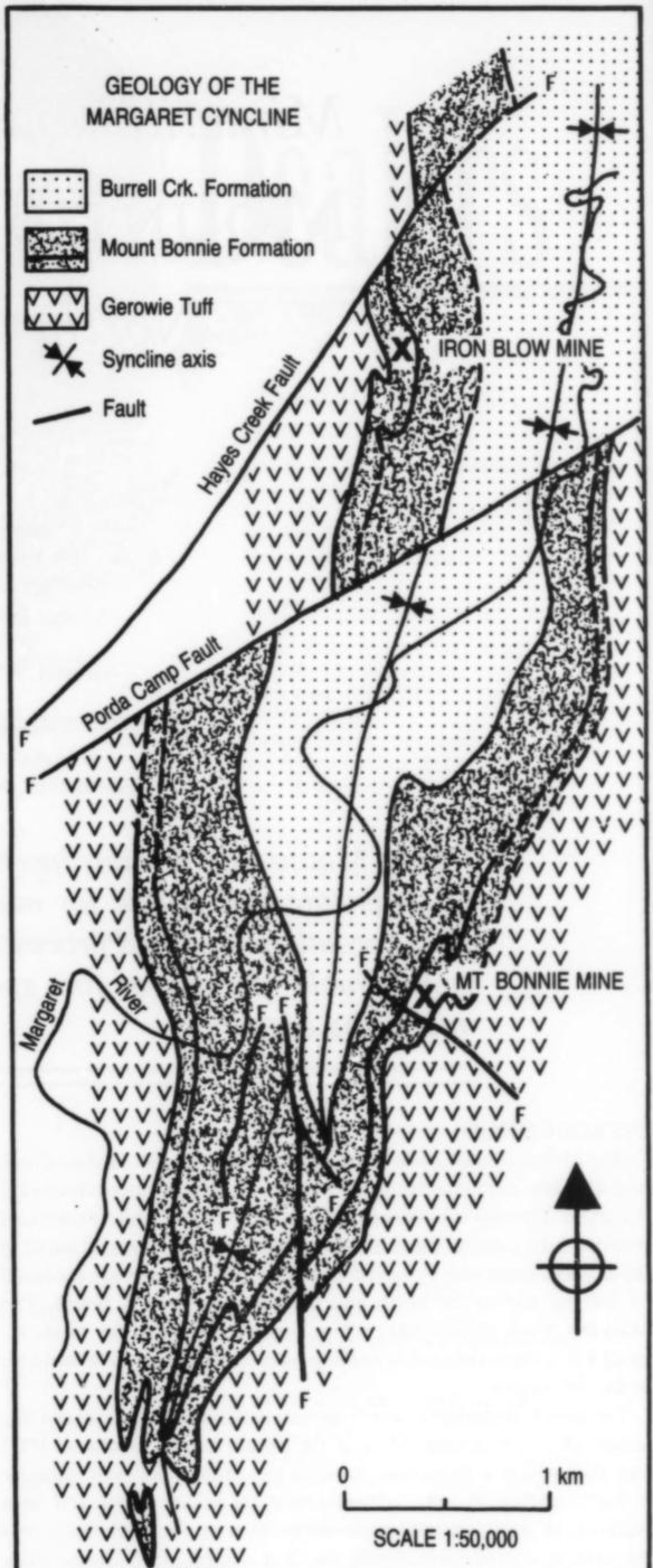


Figure 2. **Geological map of the Margaret Syncline showing the location of the Mount Bonnie mine and its relationship to major rock formations (modified from Goulevitch, 1980).**

the orebody, crosscuts and raises, was undertaken between July 1915 and December 1916, when the mine was closed because of the disappointing grade of the ore intersected and the objectionable quantity of zinc present (Anonymous, 1917). During 1917–1918 three diamond drill holes were put down to test ore extension at depth. However only one of these holes intersected mineralization.

After a long period of disinterest in the Mount Bonnie mine, renewed exploration took place in April-May, 1957, when Australian Mining and Smelting Company Limited carried out detailed mapping of the underground workings in an effort to determine the structure and lateral extent of the orebody. This investigation failed to result in any mining activity.

Sampling of both the adit and shaft levels was again undertaken in 1969 by Secured Loans and Development Limited and in 1972 a joint venture consisting of Central Pacific Minerals, Horizon Minerals N.L. and Jingellic Minerals N.L. drilled exploratory holes in the sulfide zone of the orebody. Drilling indicated 480,000 tonnes of possible ore with an average grade of 0.4% copper, 1.5% lead, 7.7% zinc, 16.7 grams/tonne silver and 1.5 grams/tonne gold over a strike length of 65 m and ranging in width from 6 to 17 m (Anonymous, 1983). During this period a small tonnage of gossan was mined from the outcrop and carted to the nearby Mount Wells Battery.

By the mid-1970's a joint venture by Peko Exploration Limited and B.P. Mining Development Australia Proprietary Limited had begun to reinvestigate the sulfide orebody by diamond drilling. It was during this period that one of the authors (N.R.) worked the upper sections

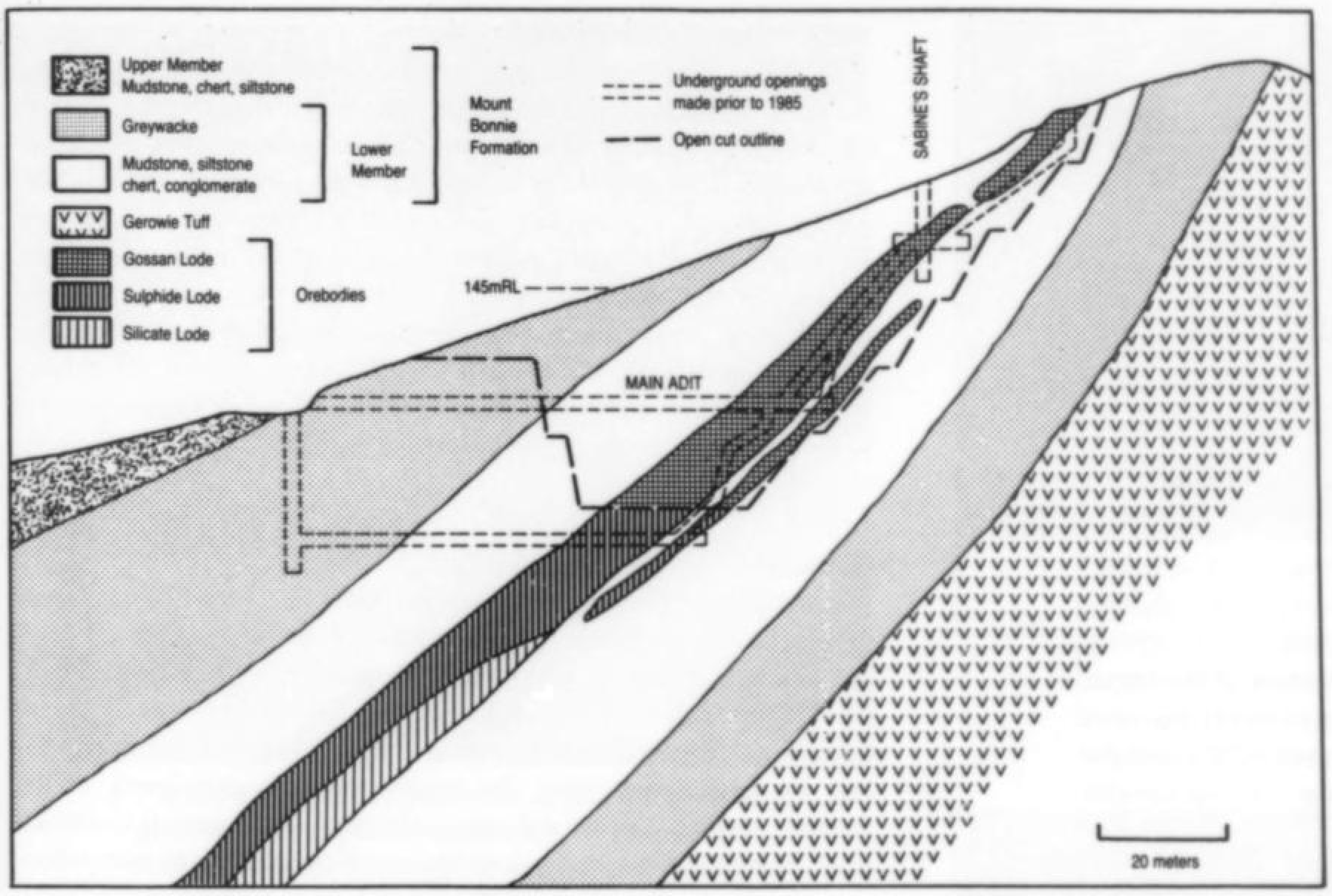


Figure 3. **Generalized geological cross-section of the Mount Bonnie mine (modified from Rich *et al.*, 1984).**

of the mine for mineral specimens. In 1979–1980, with the escalating price of gold, the Peko/B.P. joint venture resampled the accessible workings and carried out diamond drilling within the gossan zone (Rich *et al.*, 1984). In the same period, Jingellic Minerals N.L. extracted a small tonnage of oxidized ore from the open cut, but this was never treated.

Actual mining of the Mount Bonnie orebodies did not commence until 1982, when a locally controlled mining group (Douglas partners, Messrs. Henry, Walker, Bailey and Wright of Darwin) began open pit development of the gossans as a source of silver and gold. Reserves were estimated at 100,000 tonnes of oxidized ore averaging 8 grams of gold and 230 grams of silver per tonne. The right to mine the gossan orebodies was purchased from the Peko/B.P. joint venture, who still owned the mining leases covering Mount Bonnie but regarded the orebodies as too small to be worth developing within their own corporate structures (Rich *et al.*, 1984). The sale of the mining rights provided Peko/B.P. with substantial immediate income to offset exploration costs.

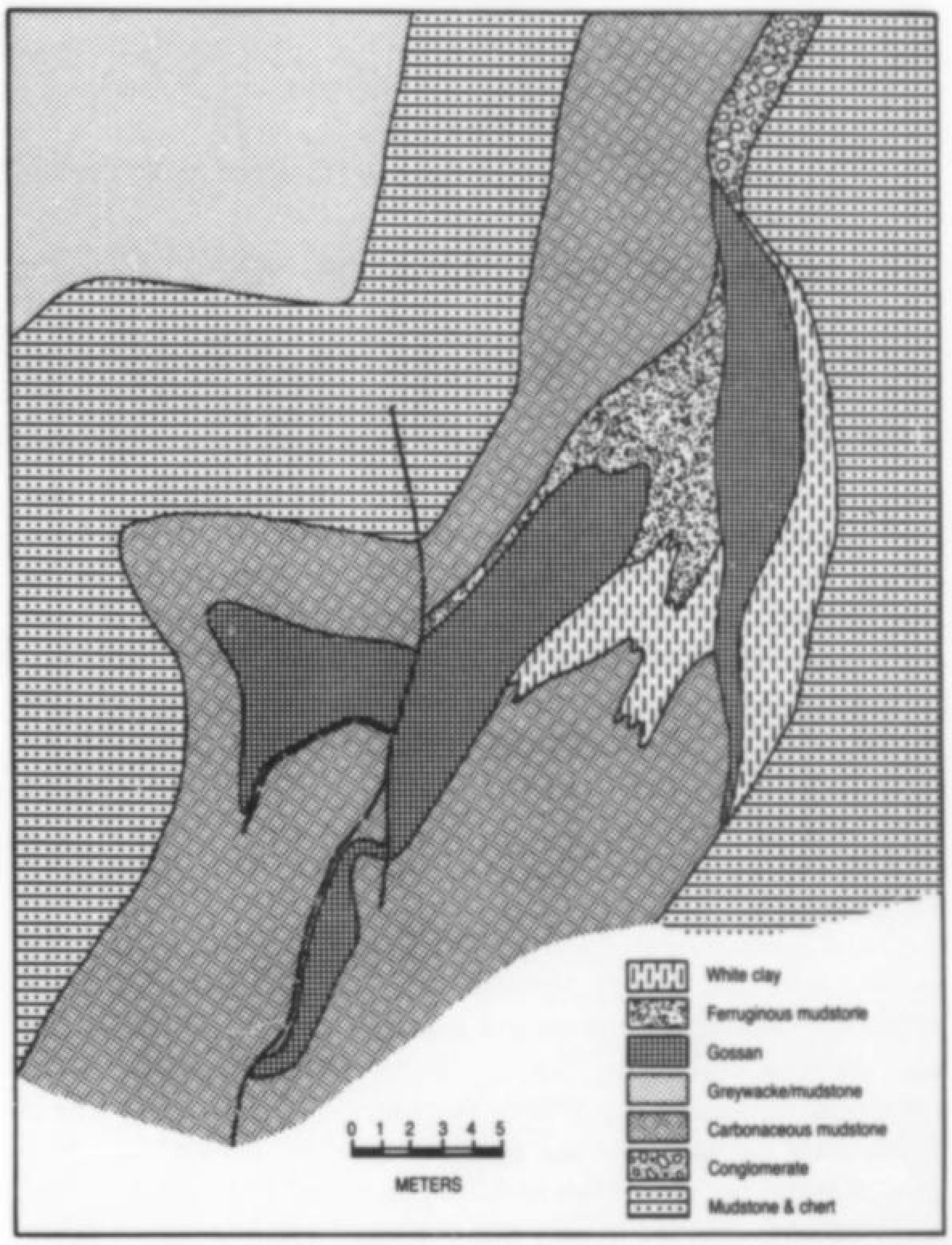
By the end of 1985 the three gossan orebodies had been mined out and stockpiled ore was being processed by an on-site treatment plant (described in detail in Rich *et al.*, 1984). Total production between 1982 and the end of the 1985–1986 financial year amounted to 376,170 grams of gold and 3,968,944 grams of silver from 57,252 tonnes of ore treated (Anonymous, 1986).

The sulfide orebody remains unexploited and is presently considered sub-economic.

GEOLOGY and MINERALIZATION

The host rock for primary mineralization at Mount Bonnie is an ash-stone sequence within the 200–300 m thick Mount Bonnie Formation (Kapalga Formation of Goulevitch, 1980) which forms the upper portion of the Lower Proterozoic South Alligator Group, exposed on the flanks of the Margaret Syncline (Fig. 2). The Mount Bonnie Formation itself consists of interbedded gray-black carbonaceous siltstone and mudstones, chert, ash-stone, tuff and tuffaceous cherts, siltstone, mudstone and minor banded iron formation (B.I.F.). Toward the base of the sequence are two prominent graywacke marker beds which delineate the Lower Mount Bonnie Formation. A turbidity current origin for the graywacke is indicated by graded bedding and other textural features, while the ash-stone and tuffaceous chert are assumed to be rhyodacitic volcanic derivatives (Goulevitch, 1980).

Figure 4. **Geological plan of the Mount Bonnie mine at the 145-m level (modified from Rich *et al.*, 1984).**



Base metal mineralization occurs as discrete, massive, stratiform sulfide-silicate-carbonate lenses up to 30 m thick and 150 m across, containing 40–50% sulfide and located towards the base of the Lower Mount Bonnie Formation. The ore lenses are stratabound within ash-stone sequences between the two prominent graywacke marker beds and strike approximately north-south, with a moderate dip to the west (Fig. 3). Rocks of the hangingwall are ferruginous, while the footwall is marked by abundant kaolinite (Fig. 4). The association of the sulfide lenses with very restricted developments of pebble breccias suggests a sea-floor trough as the most likely localization control for mineralization (Goulevitch, 1980).

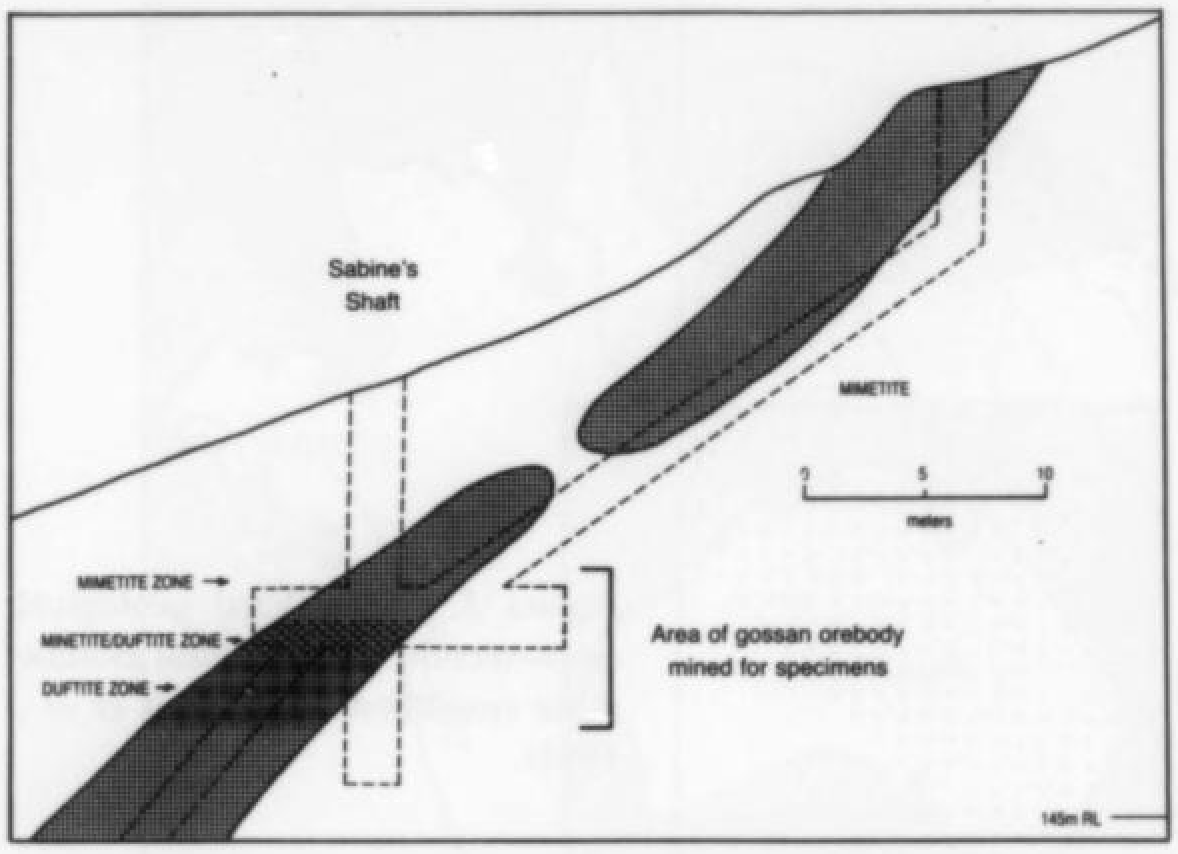


***Figure 5*. Geological cross-section of the upper part of the gossan orebodies showing the area mined for specimens in the mid-1970's and the observed vertical zoning of the arsenate species (see Fig. 3 for legend).**

The principal sulfides are pyrrhotite and sphalerite with minor amounts of pyrite, galena, chalcopyrite, arsenopyrite, tetrahedrite and traces of boulangerite, stannite, friebergite and marcasite (Rich *et al.*, 1984). Silicate gangue minerals include talc, chlorite, quartz, actinolite, phlogopite and minor garnet. Calcite is the dominant carbonate species present. The abundance of pyrrhotite in a supposedly normal sea-floor depositional environment is unusual, but can be explained in terms of a temperature of at least 100°C and/or relatively low activity of sulfur in solution (Goulevitch, 1980).

The sulfide lenses have been almost completely oxidized to 90 m down dip, leading to the development of cellular gossans containing mimetite, duftite, scorodite, plumbojarosite and coronadite. "Limonite" became increasingly abundant with depth. Gold was distributed through the gossan as very fine free gold and electrum. Silver has been identified in the form of native silver (in grains between 1 mm and 1 µm in diameter), electrum, silver-copper alloy and silver-mercury alloy. The silver content of the gossan increased with depth. The gossan was also found to contain significant bismuth, antimony and tin, but the mineralogy of these elements has not been investigated (Rich *et al.*, 1984).

Within the area intensively mined in the mid 1970's, mimetite and duftite occurred lining steeply dipping subparallel fissure networks produced by shearing of the original sulfide/silicate orebody and were zonally distributed (Fig. 5). Near the surface, relatively large prismatic to tabular mimetite crystals predominated, occasionally in association with reniform coronadite. Below this lay a zone in which earlier-formed duftite became the predominant species, with mimetite present as abundant microcrystals and apparent epitaxial overgrowths. With greater depth, the proportion of duftite increased and mimetite eventually became confined to very thin coatings on duftite crystal aggregates towards the base of the mined area. This depositional sequence reflects progressive changes in Eh/pH and hence the geochemical effects of a falling water table. The environmental conditions required for mimetite crystallization progressively overlapped those for duftite, which apparently crystallized at deeper levels within the gossan nearer the water table. Mimetite crystals at the top of the mimetite zone show advanced stages of dissolution consistent with the downward migration of the mimetite stability zone. Reprecipitation of this mimetite in solution produced secondary overgrowths on mimetite toward the base of the mimetite zone as well as the spectacular bright yellow crystal groups on duftite in the mimetite/duftite zone.

SECONDARY MINERALS

Of the oxidized species reported in the Mount Bonnie gossan orebodies, only mimetite and duftite are of interest to the collector. Despite the former abundance of these minerals in some sections of the underground workings, there is apparently no record of any arsenate species having been recorded prior to 1980. Although the presence of cerussite was recorded in early accounts of the mineralogy of the Mount Bonnie mine (Jensen *et al.*, 1915), no mention was made of mimetite. It is very likely that the mimetite which must have been abundant in at least some of the early intersections of the gossan orebodies was mistaken for cerussite. Recent specimen mining failed to reveal any cerussite in the accessible workings.

Coronadite $Pb(Mn^{+4},Mn^{+2})_8O_{16}$

Coronadite appears to have been the first of the secondary minerals to form at Mount Bonnie. Identification was based on chemical composition determined by scanning electron microscopy/energy dispersive X-ray microanalysis (SEM/EDS). Coronadite was common throughout the oxidized orebodies as thin reniform to botryoidal coatings on gossan, providing the matrix for many specimens of the arsenate species. Occasional vugs adjacent to the footwall contained small stalactitic masses of coronadite on which colorless to pale yellow crystals of mimetite subsequently formed.

Mimetite crystals have been observed almost completely enveloped by a thin coating of coronadite and where coronadite deposition was followed by further mimetite crystallization, unusual secondary overgrowths resulted (Fig. 6). Here addition of material to the mimetite lattice continued at tiny isolated "clean" areas on the faces of the original mimetite crystals. The resulting small overgrowths were able to extend laterally beyond the gaps in the coronadite coating and partially envelop the original crystal, gradually occluding the coronadite coating and retaining the morphology and crystallographic orientation of the earlier-formed mimetite.

Duftite $PbCu(AsO_4)(OH)$

Duftite reached its greatest abundance towards the bottom of Sabine's shaft (see Fig. 5), where it formed dark green, lenticular to platy masses of microcrystals to 5 mm in maximum dimension, either scattered on coronadite-coated gossan (Fig. 7) or, less commonly, completely encrusting gossan fragments.

While duftite at first appeared to be the only arsenate species present at greater depths within the gossan orebodies, all crystal aggregates examined by SEM/EDS were found to be at least partially enveloped by a thin coating of mimetite (Fig. 8). In addition, X-ray powder diffraction (XRD) studies on mimetite-coated duftite from the base of the worked area revealed the presence of small quantities of admixed finnemanite [$Pb_5(AsO_3)_3Cl$] and cotunnite [$PbCl_2$].

Distinct, well formed crystals of duftite are unknown from Mount Bonnie and only rarely are crystal faces even discernible. Most specimens display either sub-parallel, rough, bladed crystals (Fig. 9) or anastomosing platy aggregates (Fig. 10) in which specific crystal forms are unrecognizable.

Associated with green mimetite microcrystals in cellular, dark brown limonite gossan exposed at the end of the main adit were lustrous, translucent, bright yellow-green bipyramidal to platy crystals of duftite reaching 1 mm in length. However, while having the appearance of well formed single crystals under the stereo microscope, these are again composite in nature with each consisting of a multitude of smaller crystals in parallel growth (Fig. 11). The mimetite coating present on duftite aggregates from the vicinity of Sabine's shaft appears to be absent in specimens from the main adit. These crystals contrast sharply with their dark brown limonite matrix, providing exceptional micromounts.

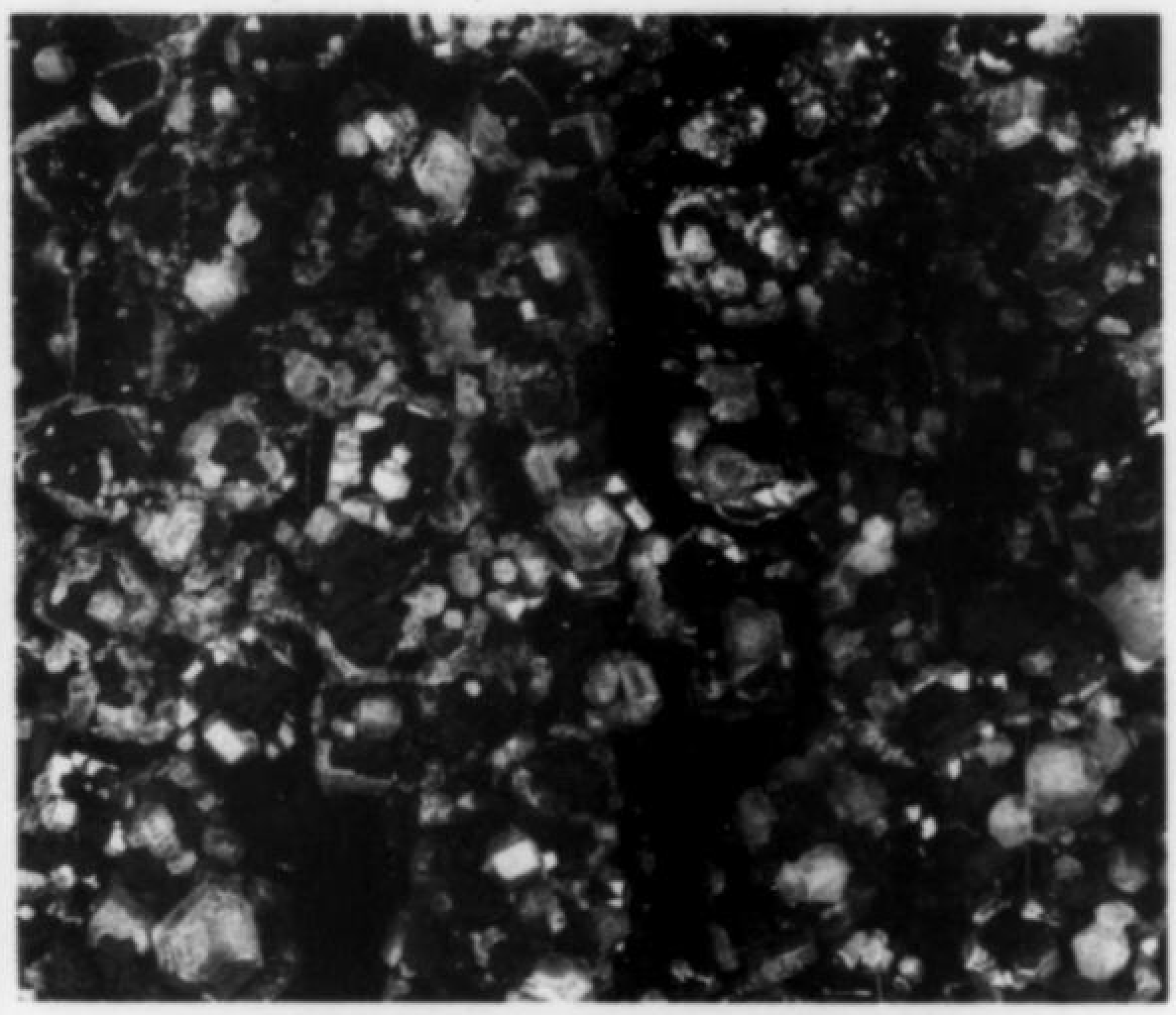


Figure 6. **Prismatic mimetite crystals showing growth interruption, deposition of coronadite coating and the subsequent partial overgrowth of additional mimetite in the same orientation. Field of view is 4 cm across. Norman Robinson specimen. Photograph by Brian M. England.**

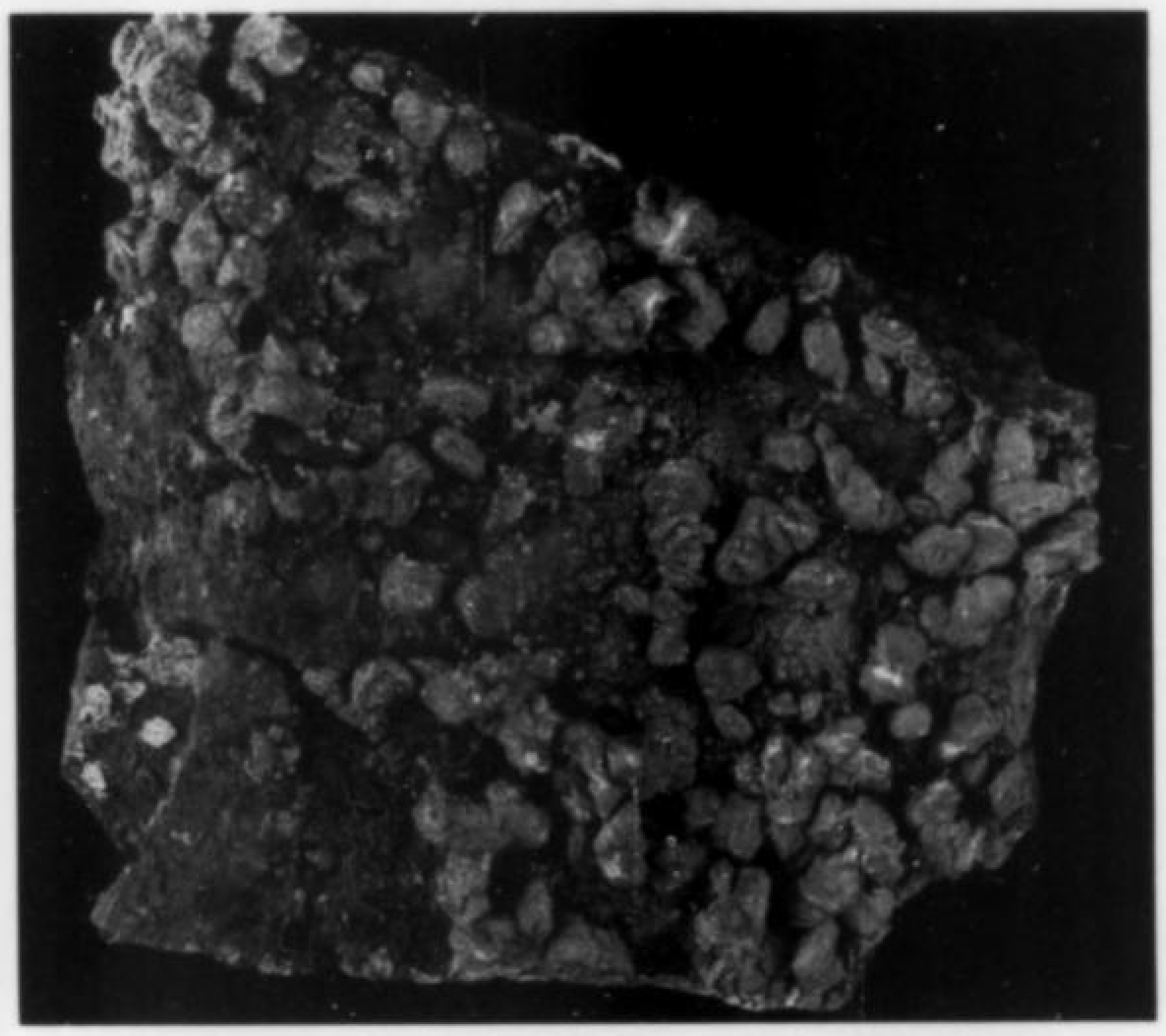


Figure 7. **Dark green duftite crystal aggregates on coronadite-coated gossan. Specimen is 7 cm across. Norman Robinson specimen. Photograph by Brian M. England.**

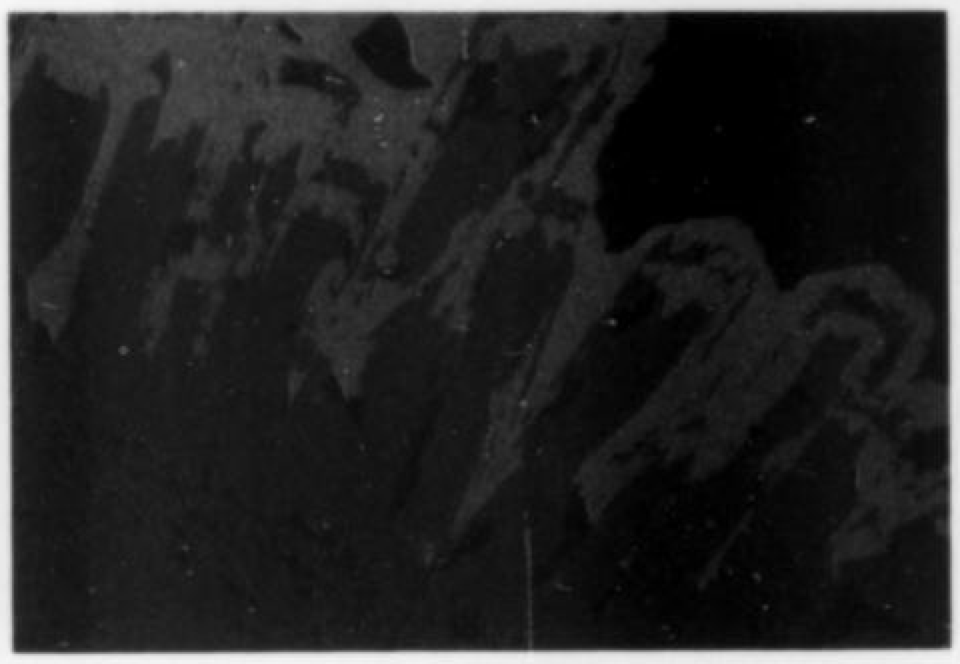


Figure 8. **Polished section of duftite aggregate showing thin mimetite overgrowth (light gray). Scanning electron micrograph, backscattered electron image. Field of view is 0.5 mm in length. Brian M. England specimen and photograph.**

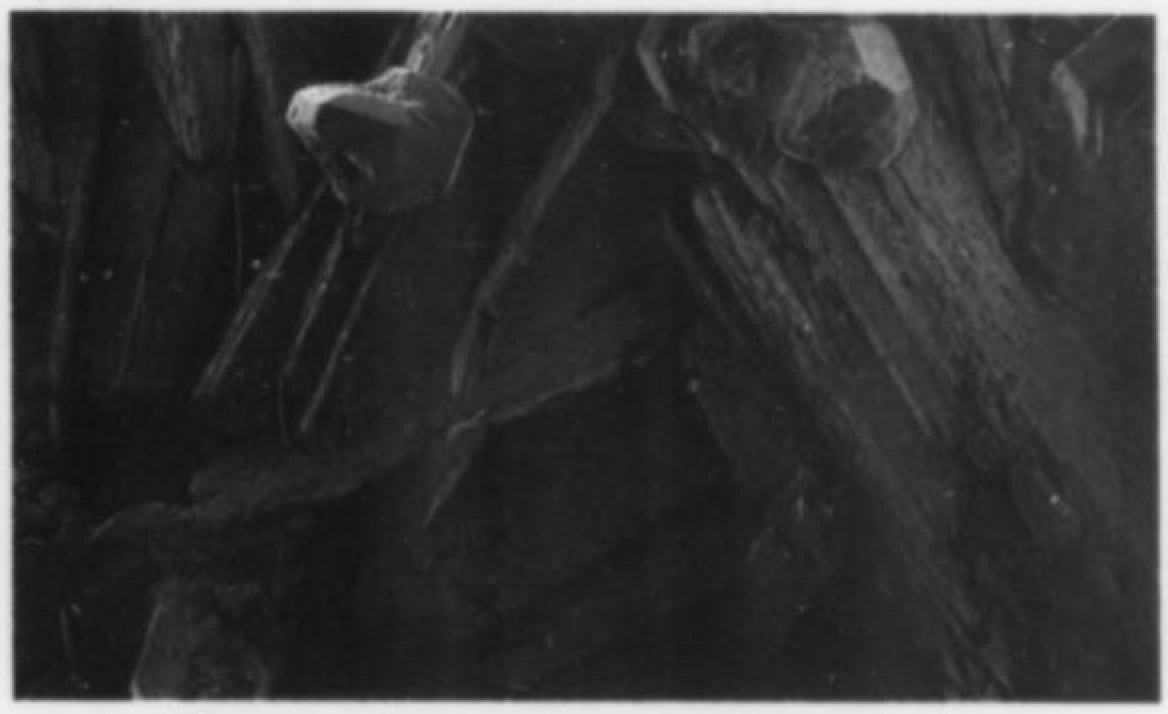


Figure 9. **Groups of subparallel rough bladed crystals of dark green duftite, with partial overgrowth of euhedral mimetite. Specimen from the mimetite/duftite zone. Field of view is 1 mm in length. Scanning electron micrograph by Brian M. England.**

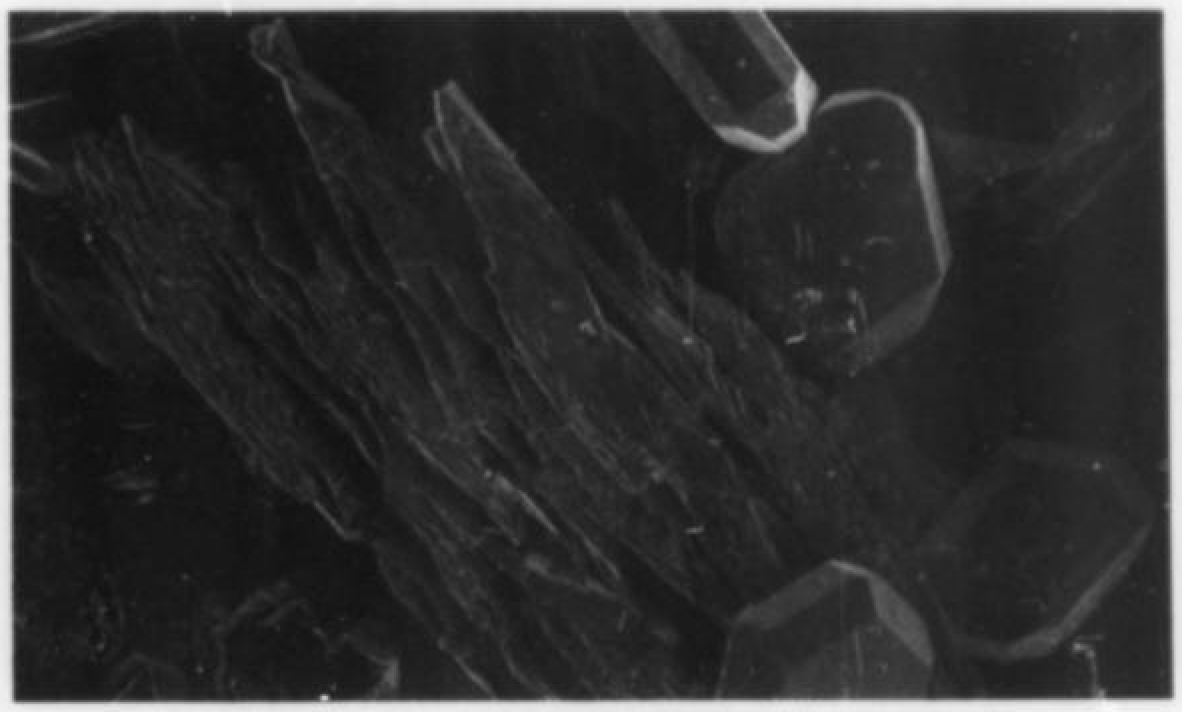


Figure 10. **Anastomosing dark green platy crystals of duftite partially overgrown by crystallized pale yellow mimetite. Mimetite/duftite zone. Field of view is 0.4 mm across. Scanning electron micrograph by Brian M. England.**

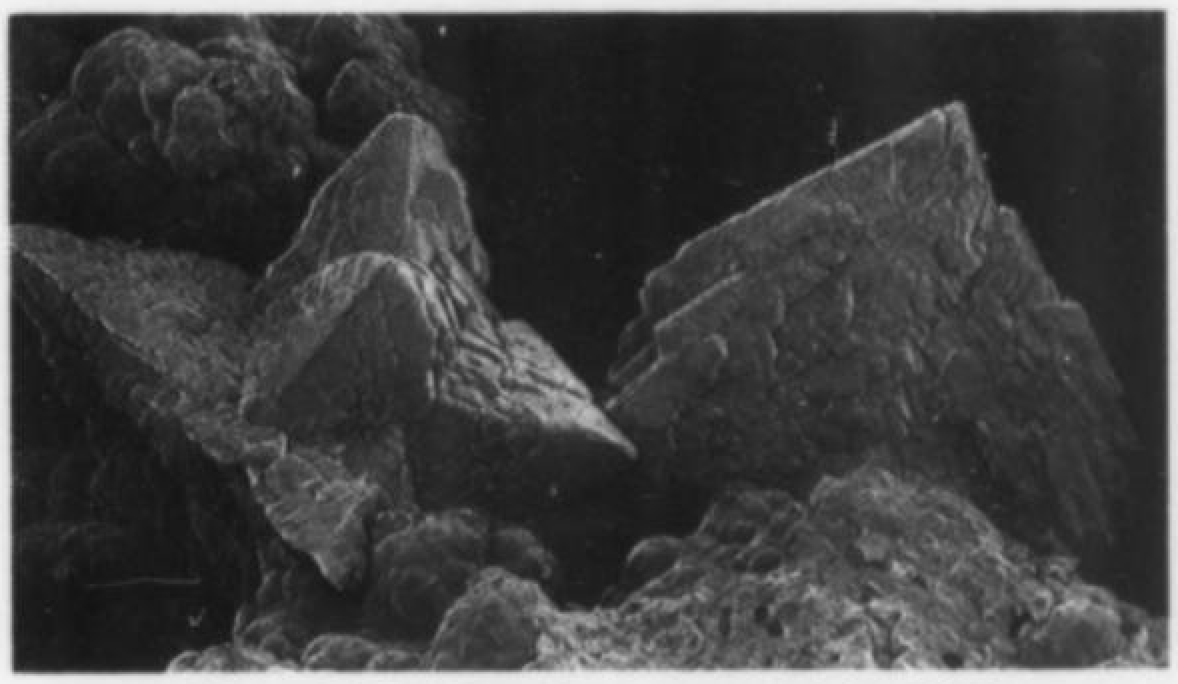


Figure 11. **Bright yellow-green crystals of duftite, each 1 mm across, on dark brown microbotryoidal limonite from the Main adit. Scanning electron micrograph by Brian M. England.**

Mimetite $Pb_5(AsO_4)_3Cl$

Mimetite is the most spectacular of the arsenate species found at Mount Bonnie, with crystals in the upper sections of the gossans reaching a maximum diameter of 2 cm. However, with increasing depth, crystal size decreased markedly and in the mimetite/duftite zone crystals rarely exceeded a few mm.

Larger crystals are characteristically tabular in habit, with the forms $c\{0001\}$ and $x\{10\bar{1}1\}$ predominating and occasionally accompanied by the rare form $y\{20\bar{2}1\}$ (Figs. 12 and 13). The prism $m\{10\bar{1}0\}$ may also be present to a varying degree, resulting in thick tabular to short prismatic habits (Figs. 14 and 15). The $c\{0001\}$ faces are often frosted in appearance due to the development of a multitude of minute $x\{10\bar{1}1\}$ faces across their surfaces. Crystals usually occur scattered on gossan matrix or as random intergrowths, but rosettes consisting of several individuals in parallel growth are known (Fig. 16).

Smaller crystals associated with earlier-formed duftite in the mimetite/duftite zone show a greater diversity of crystal forms, with the presence of second and even third-order prisms and bipyramids giving rise to habits of considerable complexity. The range of crystal habits shown by Mount Bonnie mimetite can be seen in Figure 17.

Toward the base of the mimetite/duftite zone, mimetite occurred as curious canary-yellow, tabular crystals in near-parallel growth arranged in sixlings around a prominent central cavity (Fig. 19). These may represent a repeated version of the simple contact twins observed from Johanngeorgenstadt, East Germany (Blount and Schulman, 1977).

Within the area mined for specimens during the mid-1970's, the arsenate species were characteristically associated with a pale to dark brown leached silicate rock and/or limonitic gossan. Occasionally the arsenates crystallized on a thin reniform crust of black coronadite, with which they contrast very sharply in color. Earthy yellow-brown limonite was a common associate in the hanging wall of the orebody and occasionally thick deposits of this residual material formed on the upper surfaces of the mimetite crystals in the mimetite zone, marring their appearance. In the footwall zone, mimetite was often found associated with a white kaolinite matrix.

Mount Bonnie mimetite shows a wide range of color. Large crystals from the hanging wall of the mimetite zone are characteristically pale yellow to fawn-brown in color, while the few specimens recovered from the kaolinitic footwall show a very unusual lemon-gray (Fig. 14). Small colorless crystals on stalactitic coronadite (Fig. 18) were found in a small isolated pocket adjacent to the footwall. Crystals from the mimetite zone are normally cloudy to opaque and, while well formed and apparently smooth-faced, commonly do not show the bright resinous luster typical of mimetite. Toward the base of the mimetite/duftite zone, the mimetite shows a uniformly bright canary-yellow coloration and bright resinous luster, which contrast sharply with the bright green of the earlier-formed duftite on which the crystals have grown. Such combinations provide attractive cabinet and superb micromount specimens (Fig. 21).

A zone of cellular dark brown limonite gossan exposed in the main adit, well below the area mined for specimens (see Fig. 3), contained abundant microcrystals of both mimetite and duftite. Here the mimetite crystals were most commonly green in color, rarely reaching more than 3 mm in size, and differed from those recovered from higher levels in the gossan in showing a significantly greater length-to-width ratio. These crystals characteristically show the prims $m\{10\bar{1}0\}$ modified by the faces of a less pronounced second-order prism and terminated by severely pitted and often indistinct $c\{0001\}$ faces (Fig. 20). Occasionally the pitted $c\{0001\}$ terminations are replaced by a multitude of minute columnar to fibrous crystals in parallel growth extending beyond the termination. Cavernous terminations are quite common (Fig. 22).

At least two generations of mimetite crystallization are evident in the main adit samples, with occasional specimens showing the pris-

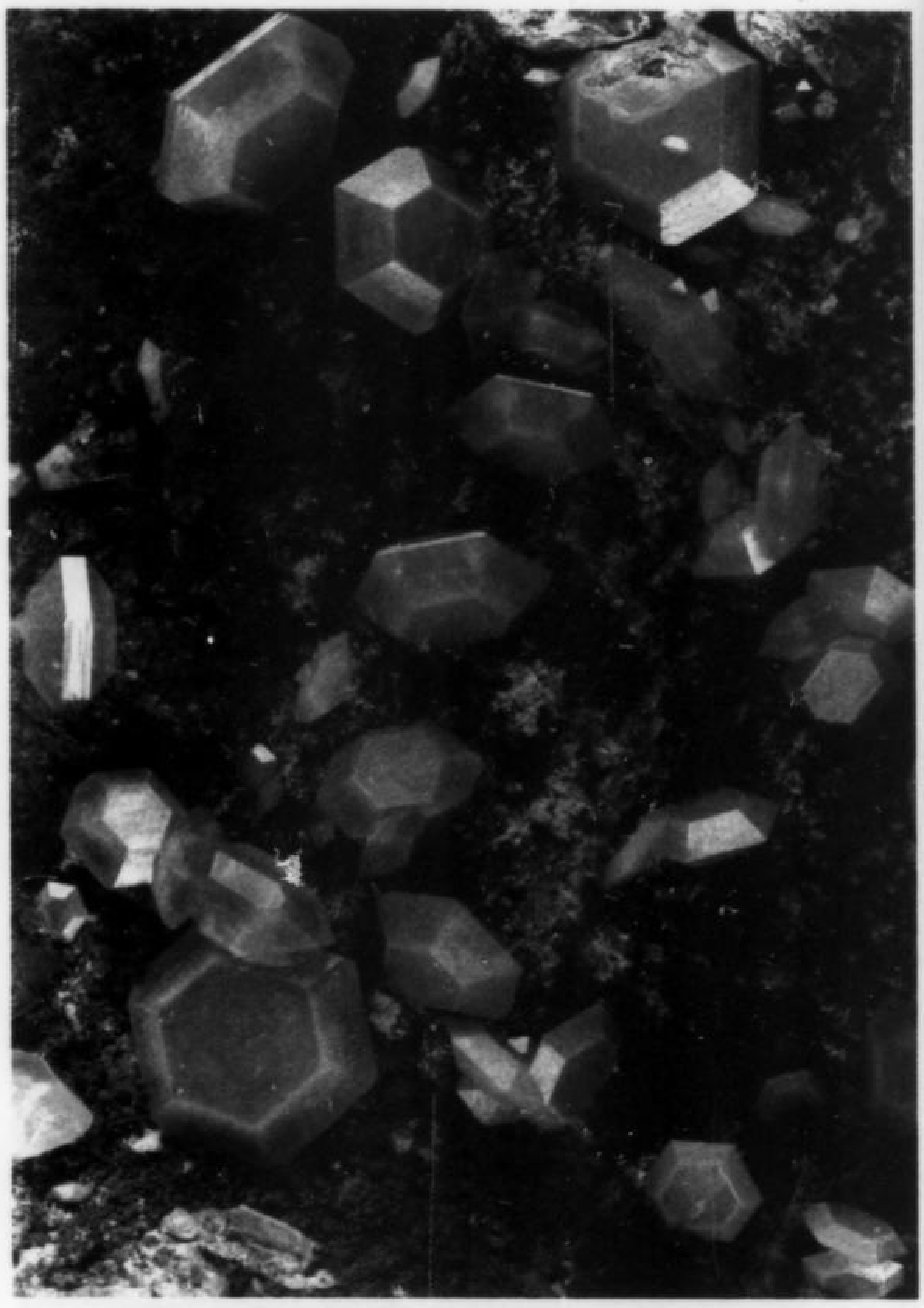


Figure 12. **Tabular mimetite crystals showing predominant $c\{0001\}$ and $x\{10\bar{1}1\}$ with only occasional development of $m\{10\bar{1}0\}$ on gossan. Field of view is 6 cm in diameter. Norman Robinson specimen. Photograph by Brian M. England.**

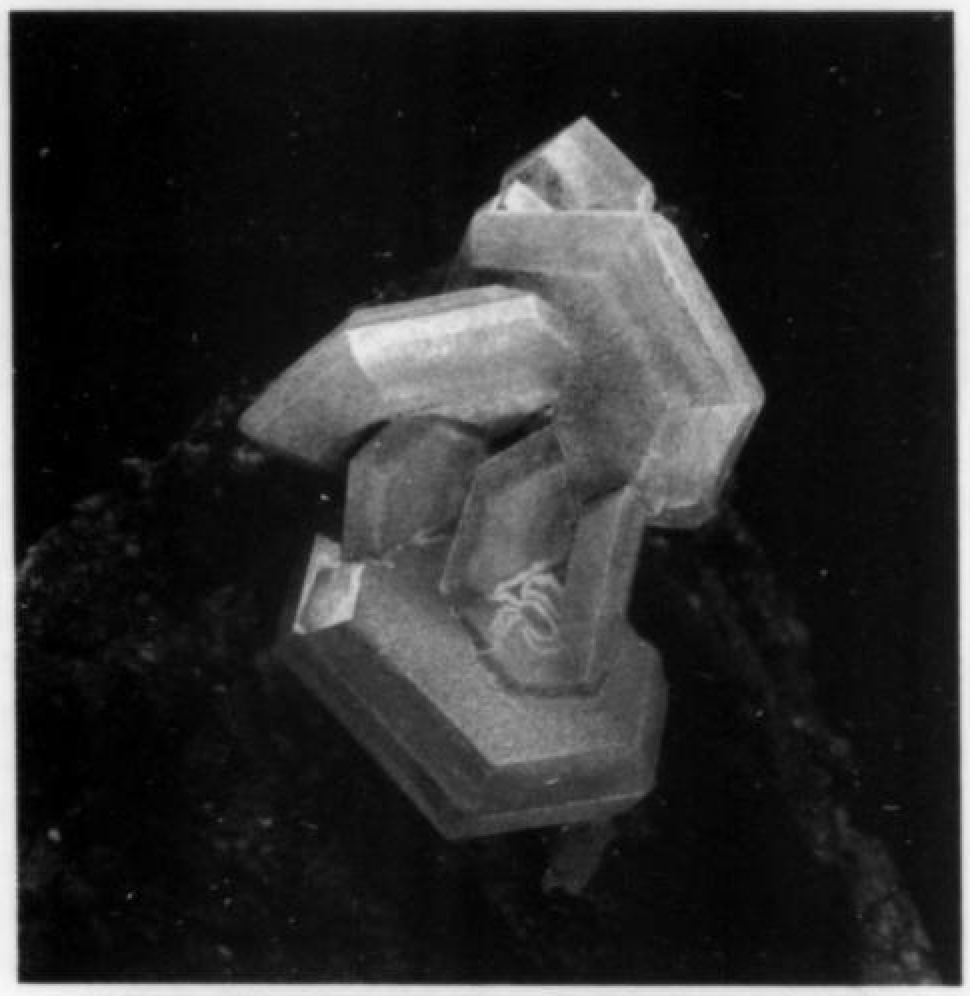


Figure 13. **Cream-colored tabular mimetite crystals showing the forms $c\{0001\}$, $x\{10\bar{1}1\}$ and $m\{10\bar{1}0\}$ on gossan partially coated with coronadite. Mimetite group is 3.5 cm in maximum dimension. Brian M. England specimen and photograph.**

Figure 14. **Lemon-gray tabular mimetite crystals showing uniform morphology consisting of $c\{0001\}$, $x\{10\bar{1}1\}$ and $m\{10\bar{1}0\}$ on a matrix of spongy mimetite impregnated with kaolinite. The specimen is 8.5 cm in longest dimension. Norman Robinson specimen. Photograph by Brian M. England.**

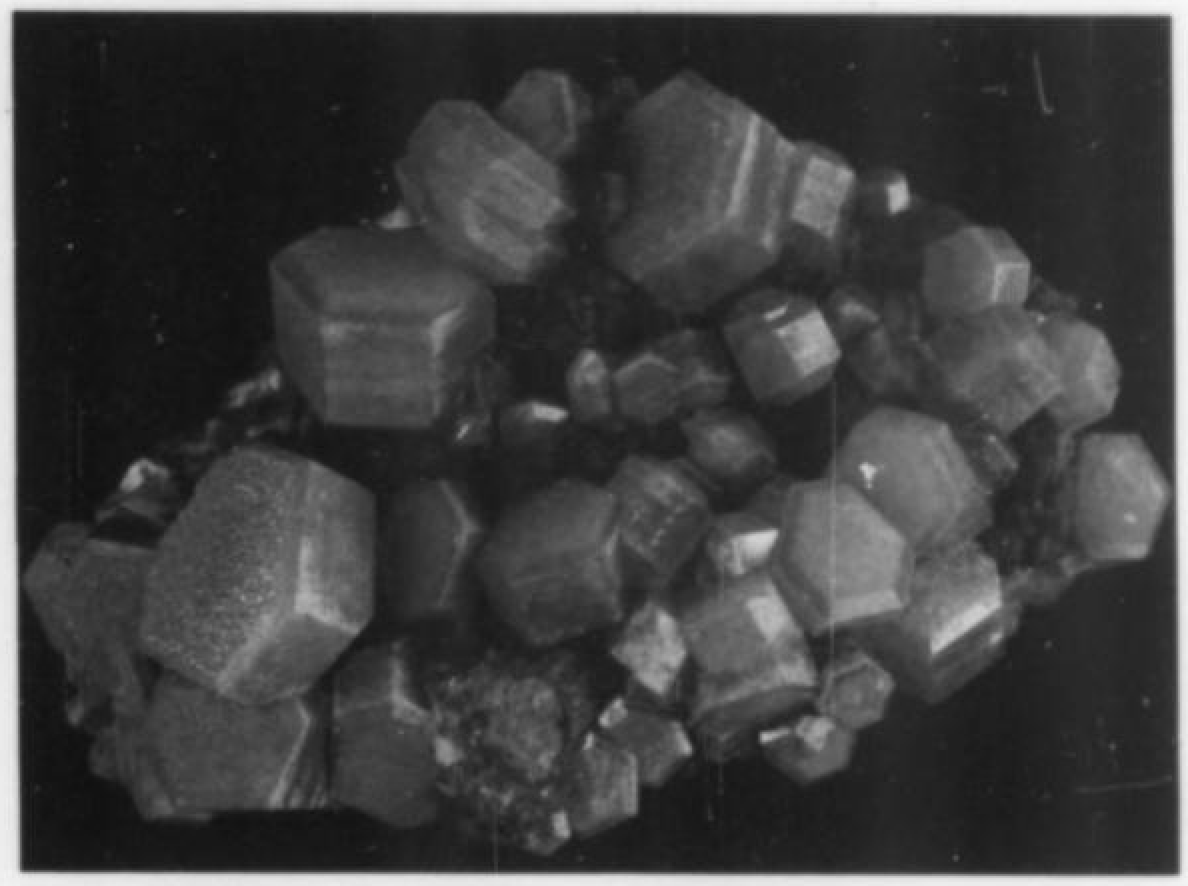
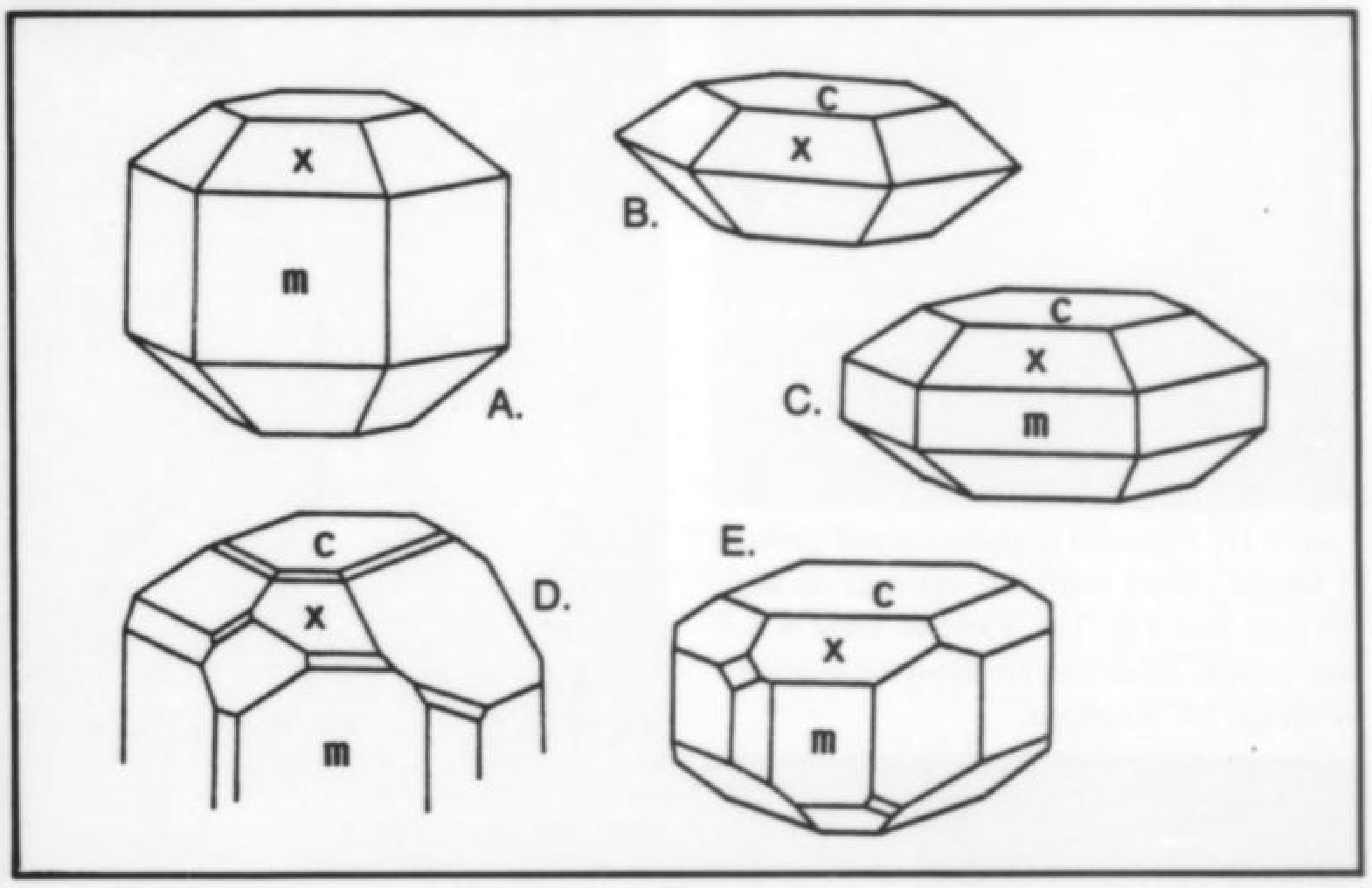


Figure 15. **Prismatic mimetite crystals showing the forms $c\{0001\}$, $x\{10\bar{1}1\}$ and $m\{10\bar{1}0\}$ on coronadite matrix. Note the frosted appearance of $c\{0001\}$. The specimen is 7 cm across. Norman Robinson specimen, now in the B. M. England collection. Photograph by Brian M. England.**

Figure 17. **The range of crystal habits shown by Mount Bonnie mimetite. Crystals A, B and C are from the mimetite zone. Crystals D and E are from the mimetite/duftite zone. Drawings by Brian M. England from specimens in the Norman Robinson and Brian M. England collections.**



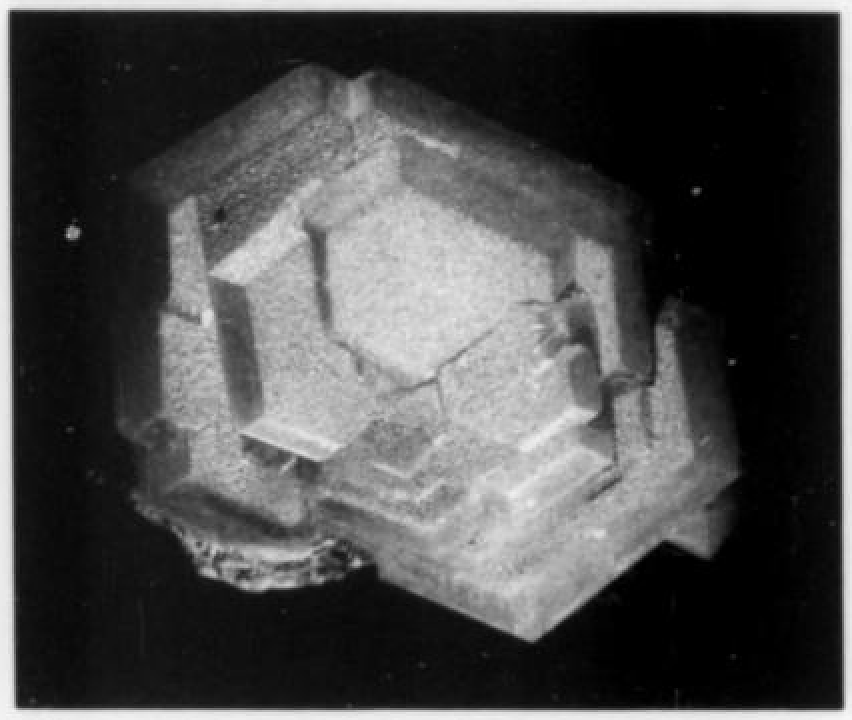


Figure 16. **Rosette of pale creamy yellow tabular mimetite crystals on gossan. Specimen is 2 cm in diameter. Norman Robinson specimen. Photograph by Brian M. England.**

matic green crystals described above deposited epitaxially on earlier crystals of a translucent golden yellow color. The earlier crystals show the simplest habit of all the Mount Bonnie mimetites, consisting of only the $m\{10\bar{1}0\}$ and $c\{0001\}$ forms.

CHEMICAL ANALYSES

Analytical Technique

Polished cross-sections of several mimetite and duftite crystals from different locations within the oxidized orebodies were chemically analyzed using an EDAX model PV9100/65 energy-dispersive X-ray spectrometer (EDS) attached to a Philips model 505 scanning electron microscope. The analyses were performed under the following instrumental conditions: accelerating voltage 14.0 KV; beam current 2.00 nA; tilt angle 0.0° and take-off angle 25.5°. Standards used were: PbF_2(Pb), InAs(As), RbCl(Cl), GaP(P) and Cu(Cu). Spectrum deconvolution, background subtraction and ZAF corrections were carried out using an EDAX implementation of the NBS FRAME C program (Myklebust *et al.*, 1979) modified and extended by Russ (1979). The EDS detector used in the analyses is only able to detect fluorine in major concentrations.

Initial analysis runs, carried out several days after surface prepa-

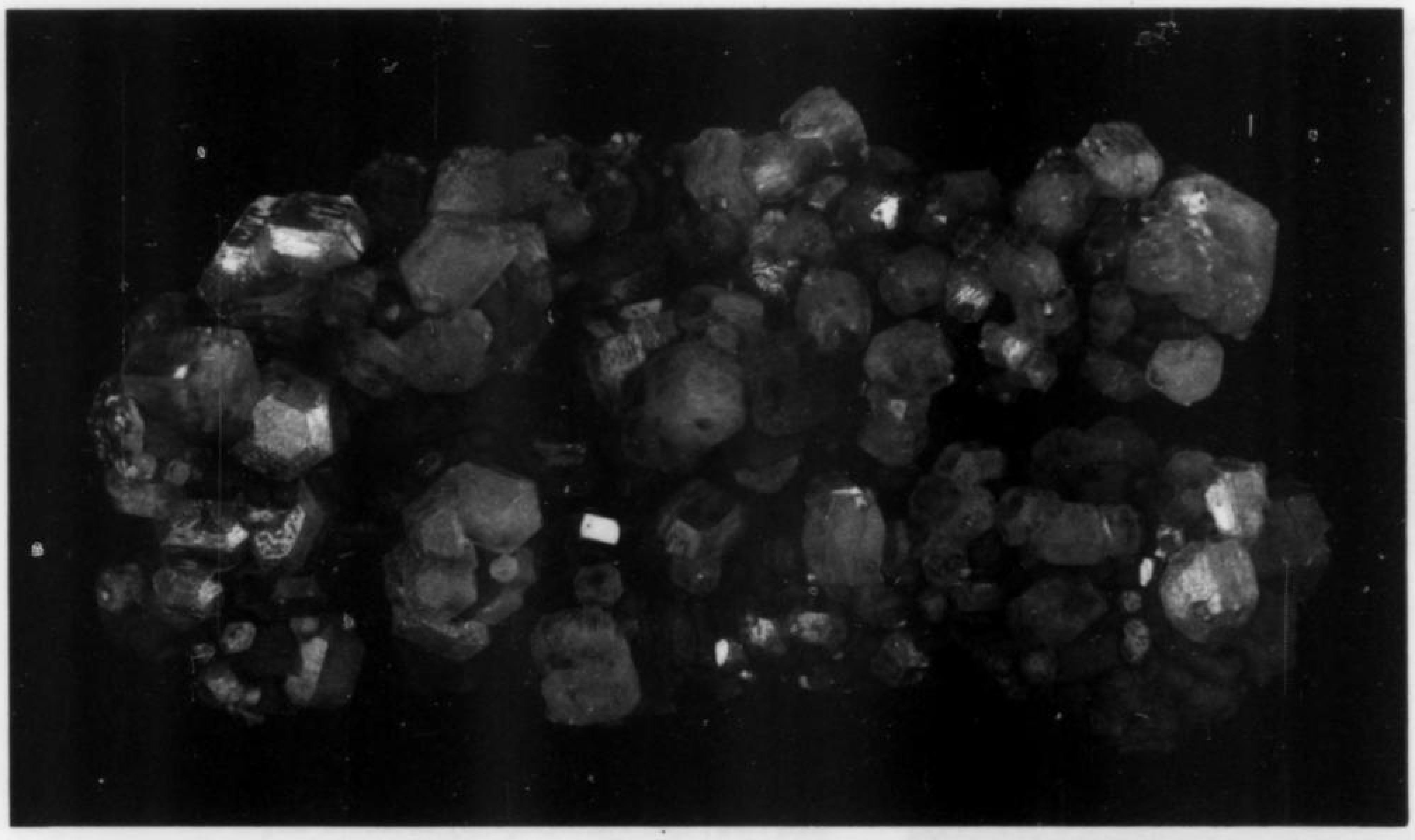


***Figure 18*. Colorless prismatic to tabular mimetite crystals on stalactitic coronadite 3 cm in length. Norman Robinson specimen. Photograph by Brian M. England.**

***Figure 19*. Unusual hopper-shaped groups of bright yellow mimetite crystals on duftite (see also Fig. 21). Field of view is 2.5 mm across. Scanning electron micrograph by Brian M. England.**

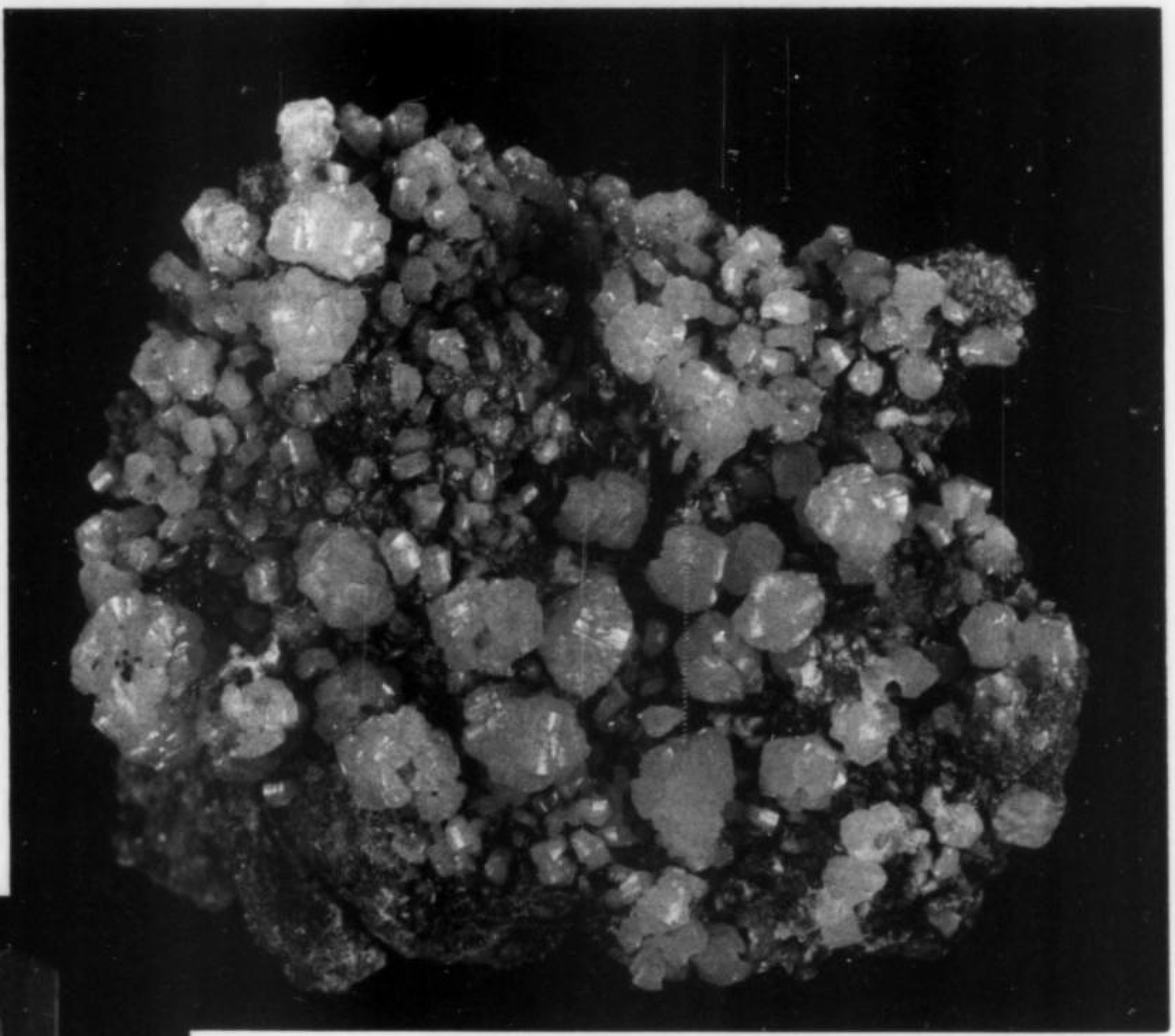


***Figure 21*. Bright canary-yellow mimetite crystals on bright green duftite. The complex nature of the mimetite crystals is shown more clearly in Figure 19. The specimen is 4 cm in diameter. Norman Robinson specimen. Photograph by Brian M. England.**

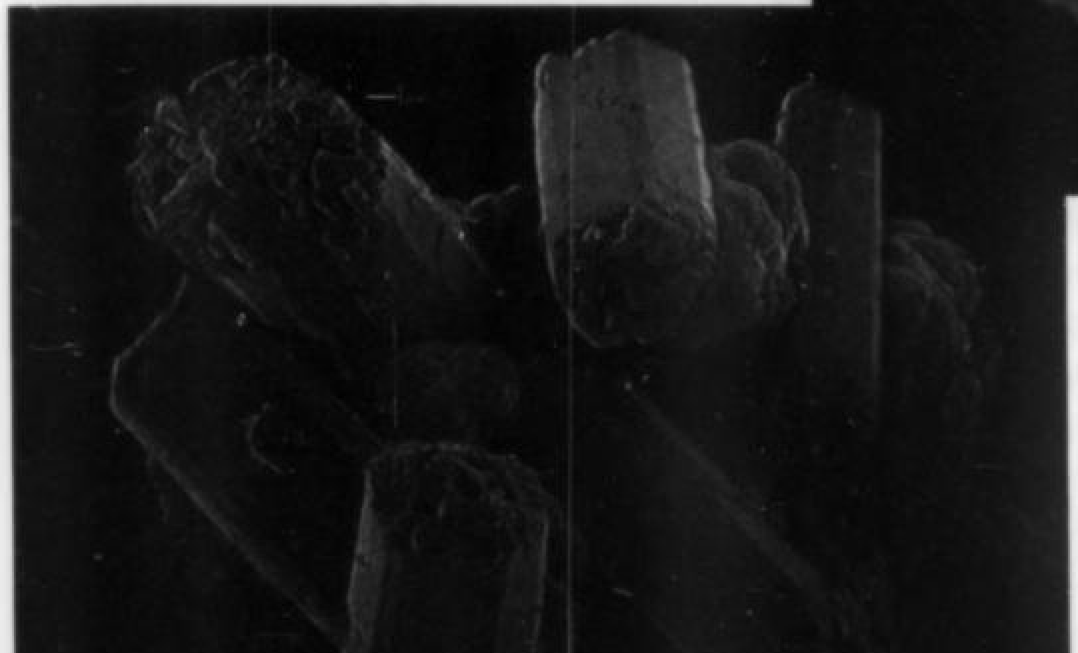


***Figure 20*. Prismatic crystals of green mimetite showing first and second-order prism forms and ragged terminations on a matrix of botryoidal limonite. Field of view is 1.5 mm across. Scanning electron micrograph by Brian M. England.**

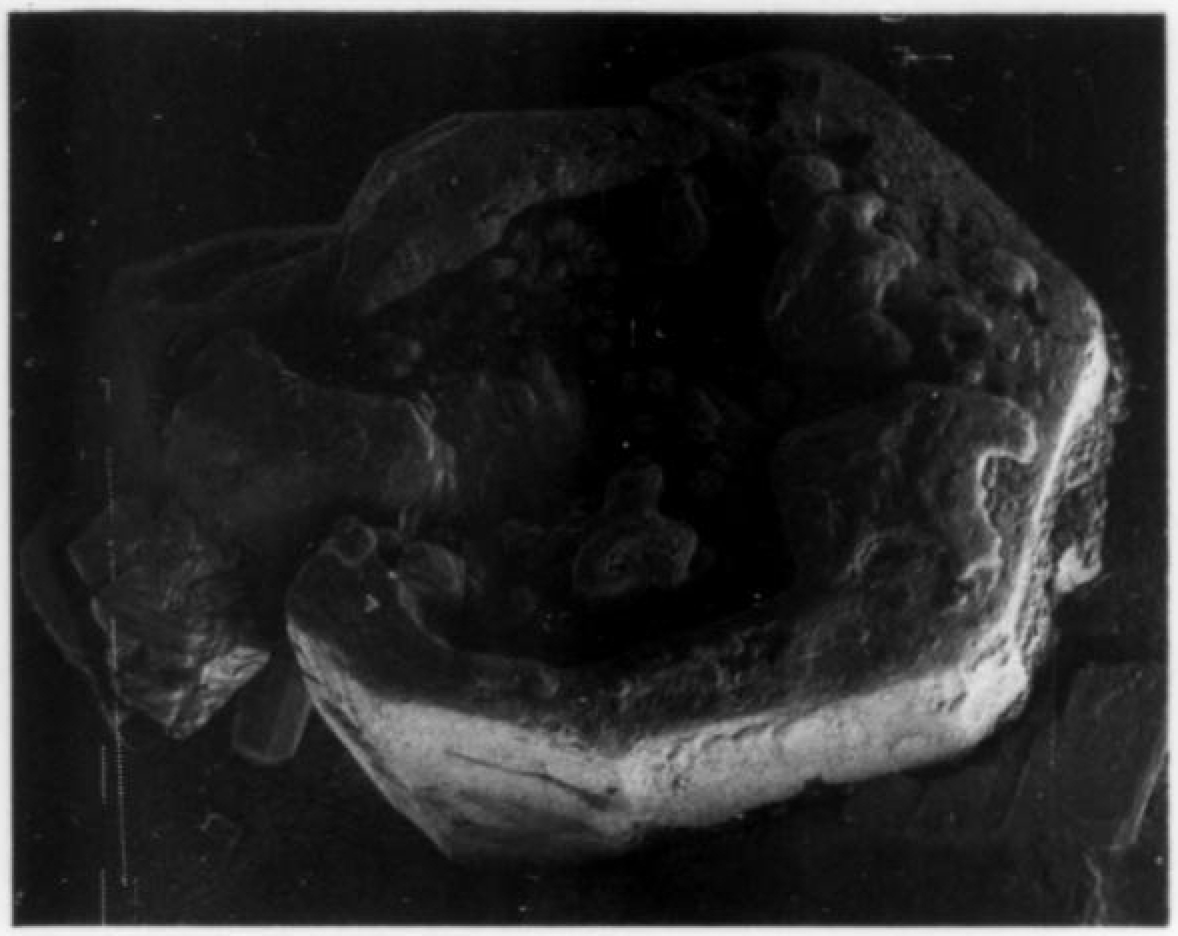


***Figure 22*. Tabular crystal of green mimetite 0.6 mm in diameter, showing cavernous termination. Matrix is dark brown limonite. Scanning electron micrograph by Brian M. England.**

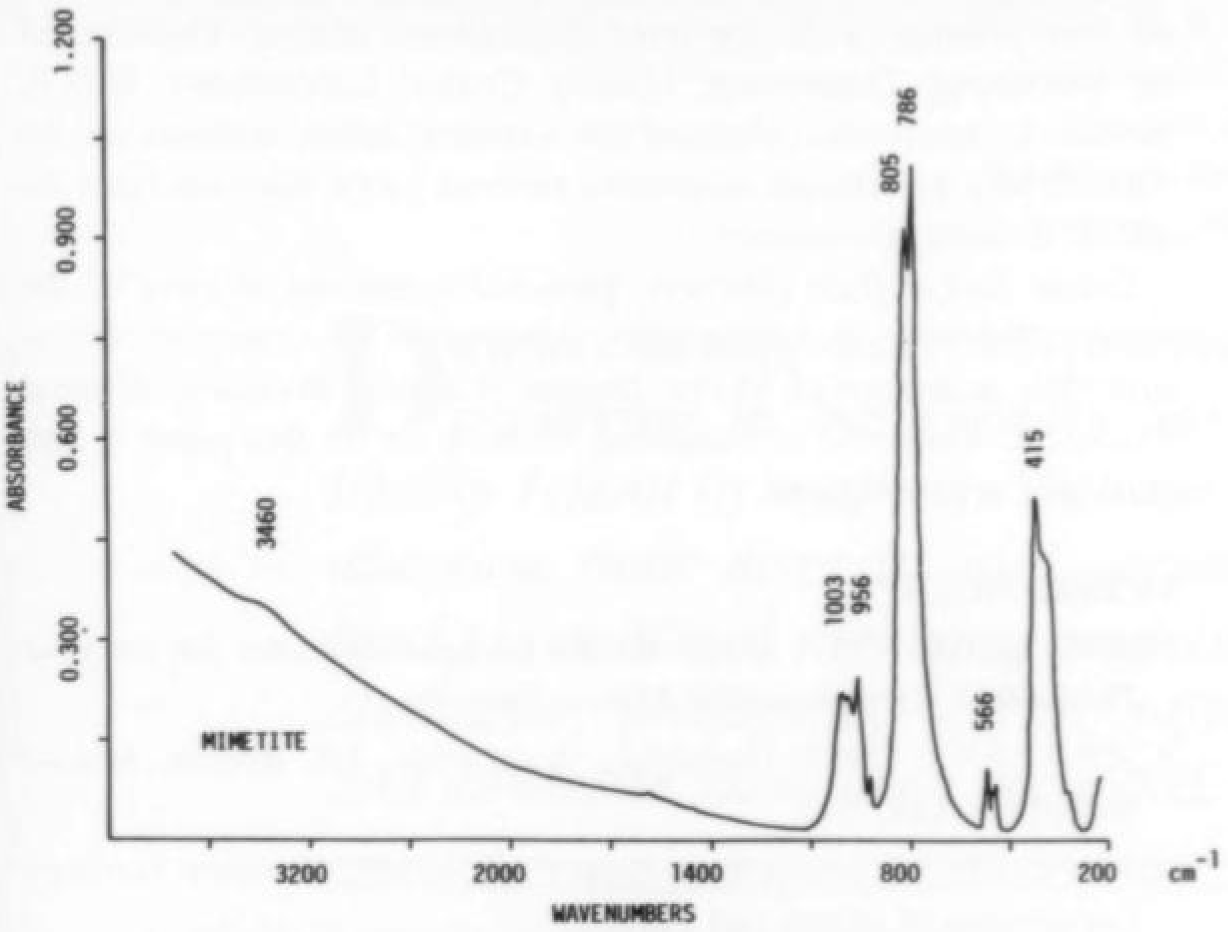


***Figure 23*. Fourier transform infrared spectrum of mimetite from the Mount Bonnie mine. The anhydrous nature of the mimetite is demonstrated by the absence of any significant peaks in the range 2930–3650 cm^{-1}.**

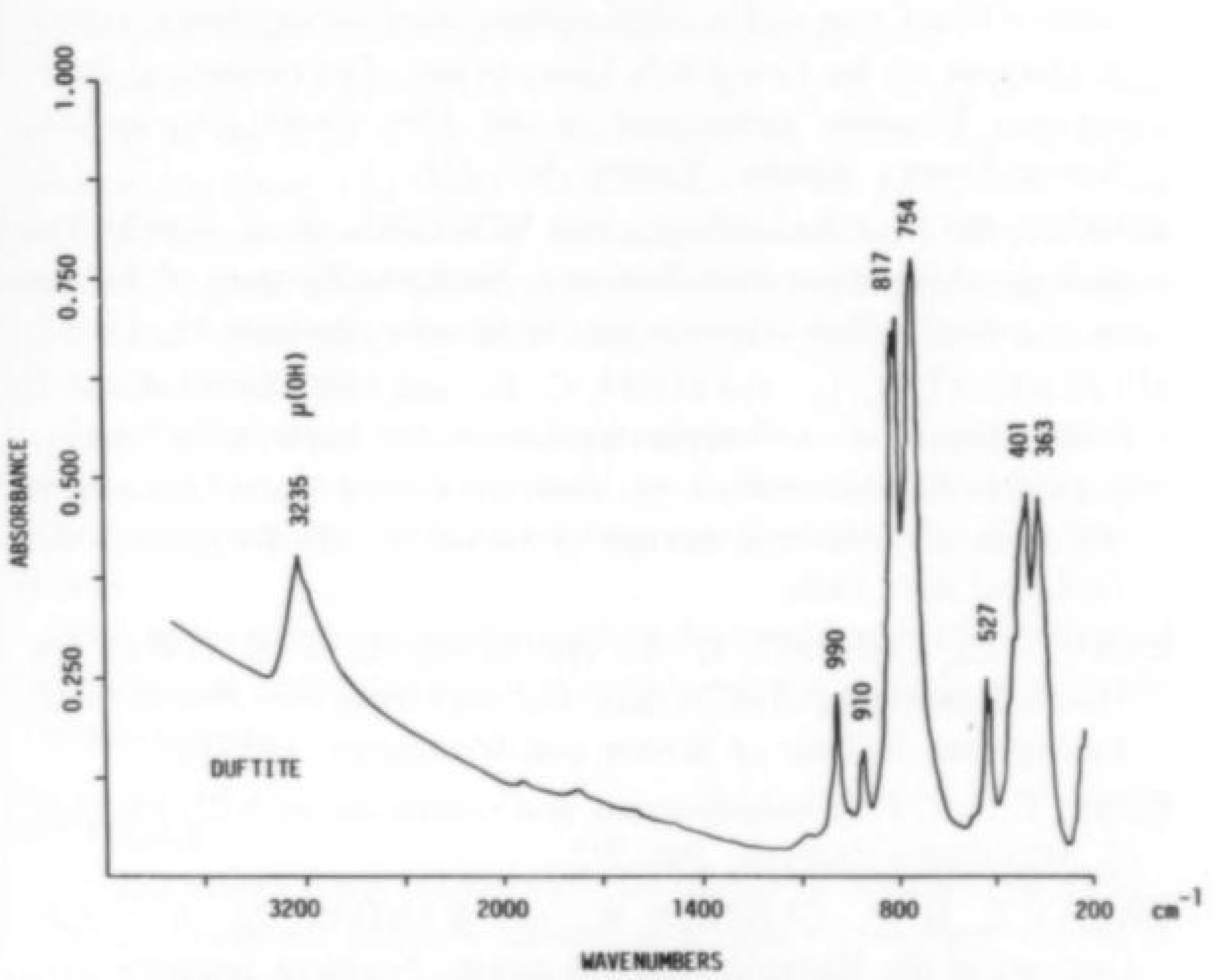


***Figure 24*. Fourier transform infrared spectrum of duftite from the Mount Bonnie mine.**

ration of the samples, gave abnormally low analytical totals (around 92 weight %). However, subsequent analysis of the same samples carried out under identical conditions but immediately after polishing provided more acceptable results, suggesting that alteration of the polished surfaces had invalidated the original analyses. The exact nature of this phenomenon remains unknown, although the rapid formation of a thin porous film of arsenolite [As_2O_3] and/or finnemanite [$Pb_5(As^{+3}O_3)_3Cl$] is suspected.

Problems also arose from the existence of serious overlaps between the PbM lines in the spectrum and those of PK and ClK, which are the only lines available for quantitative analysis of these elements. The EDAX software makes no allowance for these specific overlaps, although it handles the more commonly observed overlaps inherent in EDS extremely well. Unless corrected for, these overlaps lead to significant over-estimation of phosphorus and chlorine contents. This was overcome by applying correction factors obtained by analyzing the PbF_2 standard for both phosphorus and chlorine under identical analysis conditions to those used for the arsenate species. No overlap problems were experienced in the analysis of duftite, which contained no phosphorus or chlorine.

In the quantitative analysis of duftite, the difference between the total formed from the analyzed species as oxides and 100 weight % was assumed to be (OH) and included as oxygen in the ZAF corrections.

Mimetite

EDS analyses of mimetite are presented in Table 1. Although samples could not be analyzed for fluorine or oxygen, the presence of chlorine in slight excess of the theoretical value suggests that the presence of either fluorine or (OH) is very unlikely. Strontium, calcium and barium, which may be expected to substitute for lead in the mimetite structure, were not present in detectable amounts. Low analysis totals may be the result of inherent microporosity, which would also explain the characteristic cloudy appearance of the crystals. The absence of water or (OH) was clearly demonstrated by Fourier transform infrared analysis (F.T.I.R.) (Fig. 23).

All crystals analyzed showed a distinct systemmatic variation in the ratio between mimetite and pyromorphite end-members, with P_2O_5 content either increasing (analyses B1-B4 and D1-D5) or decreasing (analyses A1-A5) towards the center of the crystals. The decrease in PbO content with increase in the As_2O_5/P_2O_5 ratio is a function of the greater atomic weight of arsenic (74.91) compared to phosphorus (30.974). Complex yellow crystal aggregates from the mimetite/duftite zone showed the greatest range in P_2O_5 content, with phosphorus substitution extending to 10.4 weight % P_2O_5. This represents zones within the crystals containing approximately 67 % of the pyromorphite end-member. No pure end-member mimetite was found among the crystals analyzed, the minimum P_2O_5 content observed being 1.1 weight %.

Chemical formulae calculated on the basis of Σ (As + P) = 3 atoms using the data in Table 1 show a significant deficiency in lead and associated charge imbalance. However, analysis of available lead standards and the close agreement of the duftite analyses (Table 2) with the theoretical composition suggest that this apparent deficiency in lead (or arsenic surplus) is real. Independent wavelength-dispersive microprobe analyses of both the PbF_2 standard and the arsenate species support the data for both lead and arsenic presented in Table 1. This phenomenon is possibly due to the presence of finely admixed contaminant species, such as cotunnite, finnemanite and/or arsenolite. Both finnemanite and cotunnite have been identified by XRD in samples of mimetite/duftite from the duftite zone.

Table 1. **Quantitative energy-dispersive x-ray analysis of mimetite, Mount Bonnie mine, Northern Territory, Australia**

	PbO	As_2O_5	P_2O_5	Cl	Total
Theory**	73.3	24.3		2.4	100.0
$A1_{edge}$	74.2	12.6	7.9	2.7	97.4
A2	73.6	13.4	7.9	2.8	97.7
A3	71.4	20.5	2.0	2.4	96.3
A4	71.1	22.1	1.3	2.5	97.0
$A5_{center}$	71.6	22.7	1.1	2.6	98.0
$B1_{edge}$	71.9	21.4	2.2	2.8	98.3
B2	73.8	13.3	7.4	2.5	97.0
B3	74.2	9.3	9.7	2.7	95.9
$B4_{center}$	75.2	8.5	10.4	2.7	96.8
C1	72.2	21.7	2.0	2.5	98.4
C2	72.0	22.1	1.4	2.4	97.9
$D1_{edge}$	70.2	21.8	1.1	2.6	95.7
D2	71.0	22.0	1.3	2.6	96.9
D3	71.3	20.8	2.0	2.6	96.7
D4	71.8	19.6	2.9	2.6	96.9
$D5_{center}$	71.9	18.8	3.6	2.7	97.0

A1-A5: Pale creamy yellow dull-lustered crystal from the mimetite zone.
B1-B4: Lustrous canary-yellow crystal aggregate from the mimetite/duftite zone.
C1-C2: Mimetite coating duftite from duftite zone.
D1-D5: Green crystal from the Main adit.
**Pure mimetite is $Pb_5(AsO_4)_3Cl$ (Fleischer, 1987).

Table 2. **Quantitative energy-dispersive x-ray analysis of duftite, Mount Bonnie mine, Northern Territory, Australia**

	PbO	CuO	As_2O_5	(OH)**	Total
Theory*	51.9	18.2	25.9	4.0	100.0
Analysis 1	51.8	20.4	24.8	3.0	100.0
Analysis 2	52.2	18.8	25.5	3.5	100.0
Analysis 3	51.3	18.6	25.5	4.6	100.0
Analysis 4	49.1	18.0	24.3	8.6	100.0
Analysis 5	48.8	18.4	23.1	9.7	100.0

*Theoretical formula for duftite is $PbCu(AsO_4)(OH)$ (Fleischer, 1987).
**By difference
Analyses 1-5 represent sequential analysis points from edge to center of a single duftite crystal from the mimetite/duftite zone.

Duftite

EDS analyses of Mount Bonnie duftite are presented in Table 2. Independent wavelength-dispersive microprobe analyses of the same duftite samples support the data for both lead and arsenic. These analyses conform well with the theoretical composition of duftite, with no apparent substitution of calcium for copper or phosphate for arsenate within the detection limits for the analysis technique. However, the crystals are unusual in that, assuming an absence of microporosity (which lowers analysis totals), the (OH) content (as determined by difference) increases away from the crystal faces. Towards the center of the crystals the assumed (OH) content becomes too great to maintain charge balance in the calculated formulae and the presence of water, as well as (OH), must be assumed. These variations in assumed (OH)/water content are consistent with a medium to dark green color zonation observed under the optical microscope in reflected light.

The chemical formula, calculated on the basis of As = 1 atom from analysis 2 in Table 2, is shown below. Additional (OH) has been added for charge balance.

$$Pb_{1.05}Cu_{1.06}(As_{1.00}O_{4.00})(OH)_{1.22}$$

Mount Bonnie duftite was also subjected to F.T.I.R. analysis. The presence of significant (OH) is made clearly evident by the existence of the characteristic μ(OH) peak at 3235 cm^{-1}.

ACKNOWLEDGMENTS

Appreciation is expressed to the Management of B.H.P. Research and New Technology, Central Research Laboratories, for the use of the equipment and resources of the laboratories. Ken Turner, of the above laboratories, gave considerable assistance in understanding the chemistry of the arsenate species, while Jules Dubrawski carried out the XRD investigations and Ann-Louise Carter ran the F.T.I.R. spectra. Murray McKean, of the C.R.L. photography group, carried out the final printing of the specimen illustrations. Michael Griffiths, of the Metallurgy Department, Quality Control Laboratories, B.H.P. Newcastle Steelworks, checked the mimetite/duftite analyses on the ARL SEMQ wavelength-dispersive electron probe microanalyzer installed at these laboratories.

Dehne McLaughlin (Darwin) provided a detailed account of the history of mining, including much information not otherwise obtainable. The assistance of Morrie Duggan (Curator, Bureau of Mineral Resources, Canberra) in compiling information for this paper is also gratefully acknowledged.

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ZEOLITES FROM PHILLIP ISLAND AND FLINDERS

Victoria

●

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Despite having been discovered in the 1850's, the zeolite suites occurring in the Tertiary basalts in the Flinders region and on Phillip Island in southern Victoria have not received the mineralogical attention their diversity and accessibility deserve. Attractively crystallized assemblages involving analcime, natrolite, thomsonite, gmelinite, chabazite, phillipsite, levyne, offretite, heulandite, stilbite, ferrierite and cowlesite have been recorded.

INTRODUCTION

The zeolite minerals found within the Tertiary basalts exposed in cliffs along the southern coastlines of the Mornington Peninsula and Phillip Island in Victoria (Fig. 1) form a spectacular suite. Although only 12 species have been identified so far, the variety of crystal habits and associations, together with the likelihood of rarer species being discovered, make the localities popular with collectors.

Despite the first geological surveys of the region being undertaken as early as the 1850's, the zeolites themselves excited little research interest for about 120 years. As Coulsell (1980) points out, in the most comprehensive review of the zeolites found near Flinders on the southeast corner of the Mornington Peninsula, "it is surprising to find that there exists today so little literature devoted to such a notable collecting area."

The Phillip Island zeolite suites are even less documented and it is only since they were "discovered" by collectors in the 1980's that preliminary descriptive lists have been compiled (Leach, 1974; Birch, 1988).

This paper presents a brief review of the main zeolite and associated species from both localities; it is not intended as a guide to the main collecting sites.

HISTORY

Phillip Island is the southern of two islands in Western Port (Bay), a large, sheltered, partially mangrove-fringed embayment named in 1798 by George Bass at the most westerly reach of his exploratory voyage from Sydney. The first substantial geological observations were not made until 1857, when William Blandowski reported on his expedition to the Western Port region in 1855. He noted the wide variety of basaltic rocks and provided the first mineral descriptions, of analcime from Point Grant, on the southwestern end of Phillip Island. He also noted "mesotype," an old term for fibrous zeolites, from unspecified localities, and pebbles of chalcedony and flint. The descriptive lists of Victorian minerals compiled by Atkinson (1896) and Walcott (1901) both refer to zeolite minerals from "Western Port" but without precise locality details.

On the Mornington Peninsula, the first survey was undertaken by A. R. C. Selwyn in 1854, but no zeolites were noted until the 1890's, when Krause (1896) and Atkinson (1896) briefly recorded analcime, gmelinite, chabazite and natrolite from the Flinders coastline. Walcott (1901) added phillipsite; Mitchell (1931) added stilbite (which is still unverified) and "sphaerostilbite" (which may be thomsonite or globular dolomite) and Rew (1969) recorded thomsonite. In the past few years, additional collecting has revealed levyne, offretite and cowlesite (Birch, 1980; 1988).

Most of the zeolites at Flinders have been collected between what has been known as Simmons Bay and West Head (Fig. 2). Recent advice from the Victorian Place Names Committee indicates that the correct name is Cairns Bay, not Simmons Bay. The suites to the west of Cairns Bay are not so well known.

GEOLOGICAL NOTES

The Mornington Peninsula is an up-faulted block with a core of Lower Paleozoic marine sediments, separating the Port Phillip and Western Port Sunklands. A series of subparallel, roughly northeast-

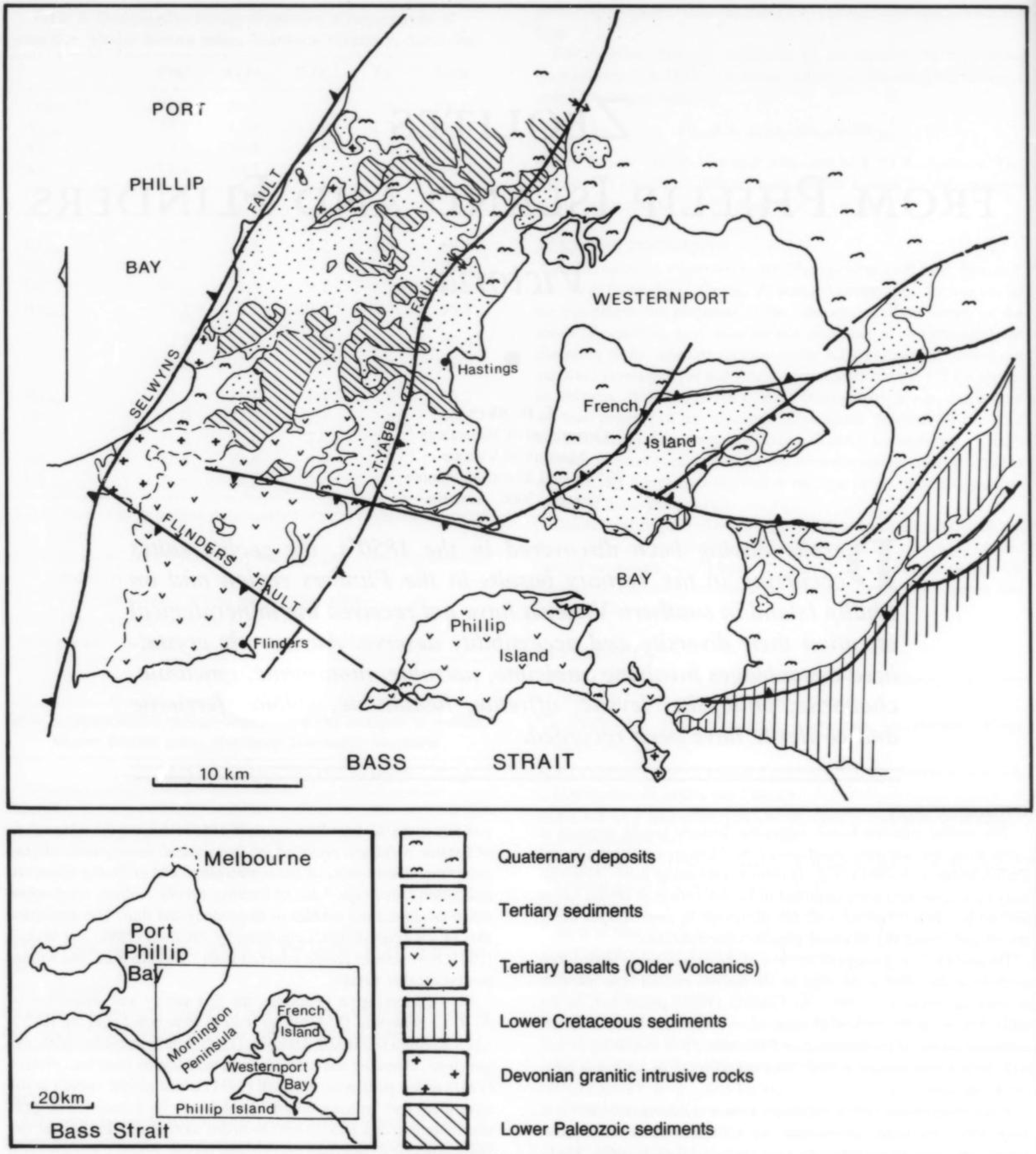


***Figure 1*. Simplified geologic map of the Mornington Peninsula and Westernport region of Victoria (after Spencer-Jones *et al.*, 1975).**

southwest trending faults, active since at least the Jurassic, have influenced the physiographic features and the distribution of volcanic and sedimentary rocks during the Tertiary (Marsden and Mallett, 1975).

The outcrop distribution of the so-called Older Volcanics is shown in Figure 3 in relation to the main structural features (after Spencer Jones *et al.*, 1975). The lavas, which are mainly olivine basalts with interbedded pyroclastic rocks, are widespread over the southern part of the Mornington Peninsula, most of Phillip Island (Edwards, 1945) and the southern margin of French Island. Radiometric dates of 42 million years at Flinders and 47 million years on Phillip Island indicate a mainly Eocene age for the basalts. At depth the Older Volcanics extend over most of the Western Port Sunkland and are thickest south of the Flinders Fault where a bore hole exceeding 400 meters did not

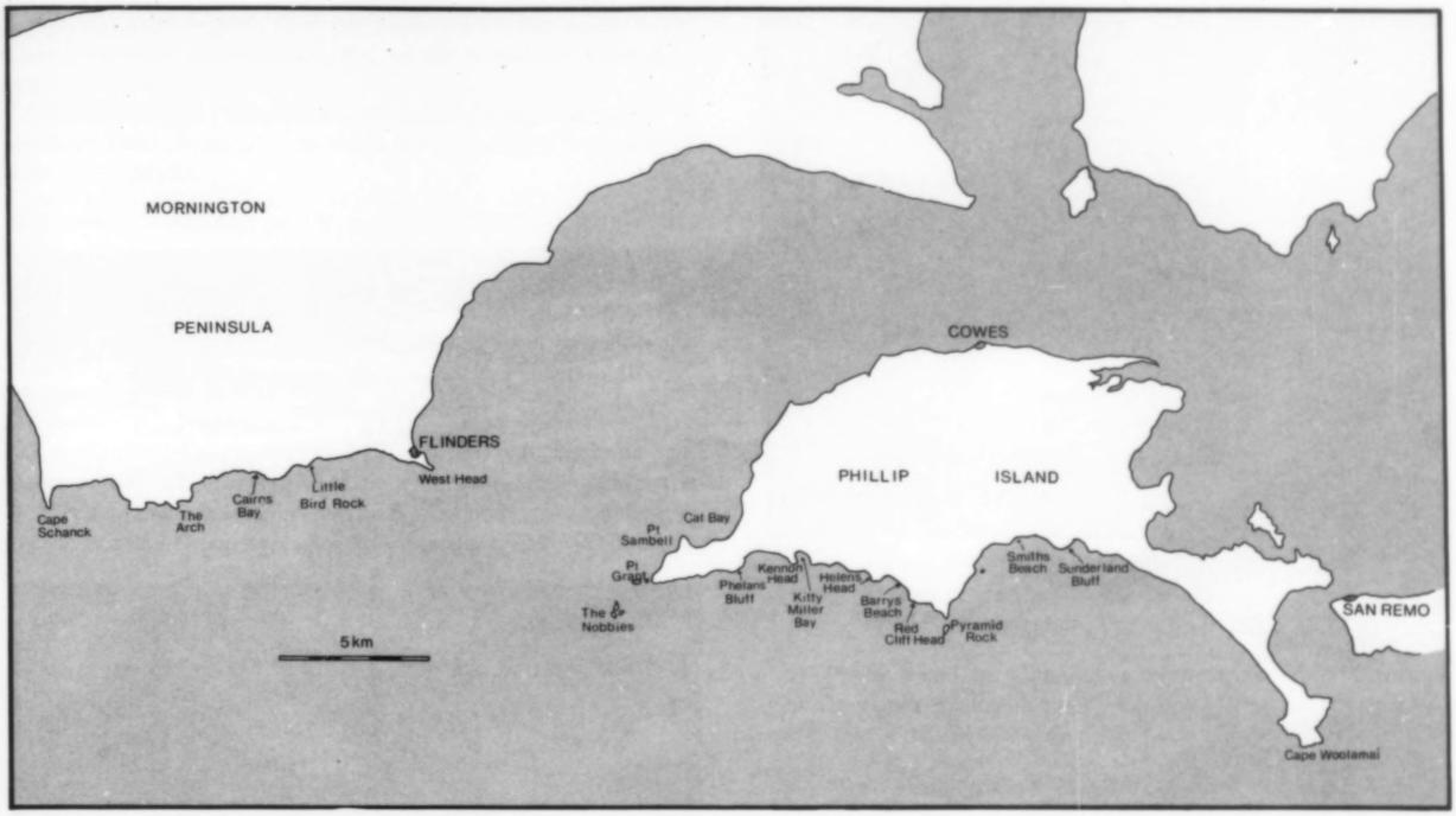


Figure 2. **Map of the coastlines in the Flinders and Phillip Island zeolite areas showing the main locations mentioned in the text.**

reach bedrock. On Phillip Island, the thickness varies, probably averaging about 60 meters and with the base always below sea level. Source vents for the volcanics are believed to be to the north, with lavas flowing down ancestral drainage to accumulate in thicknesses up to 600 meters in a subsiding basin in the Flinders region (Keble, 1950).

The best exposures of the zeolite-bearing lavas are in the cliff faces and short platforms between West Head and Cape Schanck on the Mornington Peninsula and between The Nobbies and Sunderland Bluff on Phillip Island (both stretches of coastline are rugged and dangerous, being exposed to swell from the Southern Ocean and Bass Strait). The individual basalt flows, which range in thickness from about 5 meters to 30 meters, are close to horizontal in outcrop.

Although the zeolite associations on Phillip Island and the Mornington Peninsula must clearly be related, there has been no examination of zonation, either vertically or horizontally in the lava sequence. Correlation across the Tyabb Fault, between Phillip Island and Flinders, could be complicated by a vertical movement estimated to be at least 60 meters (Keble, 1950).

MINERALS

The zeolites and associated minerals recorded from the Western Port region are listed in Table 1. The assemblages are similar, but cowlesite has not yet been recorded on Phillip Island; stilbite, ferrierite and heulandite are absent in the Flinders-Cape Schanck sequence. Although museum collections contain plentiful specimens, the majority of the early-collected pieces are labeled merely Flinders, Phillip Island or Western Port. Only for recently collected specimens have more precise locality details such as the names of bays and headlands been recorded. A major field program to determine the horizontal and vertical distribution of particular species is required.

Table 1. **Zeolites and their associated species from the Flinders and Phillip Island sequences.**

Flinders		**Phillip Island**	
analcime		analcime	
chabazite		chabazite	
cowlesite		ferrierite	
gmelinite		gmelinite	
levyne		heulandite	
natrolite		levyne	
offretite		natrolite	
phillipsite	aragonite	offretite	aragonite
thomsonite	calcite	phillipsite	barite
	connellite	stilbite	calcite
	copper	thomsonite	dolomite
	digenite?		montmorillonite
	dolomite		paratacamite
	montmorillonite		quartz (chalcedony)
	paratacamite		

Principal associations

1. (Montmorillonite)-calcite-analcime-natrolite-chabazite/gmelinite-dolomite
2. (Montmorillonite)-analcime-natrolite-thomsonite-calcite-dolomite
3. Phillipsite-analcime-natrolite
4. Chabazite-montmorillonite-heulandite-ferrierite-barite-calcite (Phillip Island only)
5. Levyne-offretite-montmorillonite
6. Chabazite-stilbite (Phillip Island only)
7. Thomsonite-chabazite
8. Cowlesite-analcime (Flinders only)

Figure 3. **Berry's Beach and Red Cliff Head, Phillip Island. F. Robinson photo.**

Zeolites

Analcime $NaAlSi_2O_6 \cdot H_2O$

Analcime is the most abundant and usually the earliest-formed zeolite in the Flinders sequence, forming sparkling water-clear to translucent white trapezohedral crystals up to about 8 mm across, lining vesicles. It may be unaccompanied, but is frequently associated with later-formed natrolite, gmelinite, chabazite and carbonates. On Phillip Island, analcime is locally abundant and reaches a maximum development as translucent white crystals up to 2 cm across on the western side of Kennon Head.

Chabazite $CaAl_2Si_4O_{12} \cdot 6H_2O$

The most common form of chabazite in the Flinders sequence is simple to interpenetrating pseudocubic rhombohedral crystals, usually pale pink to orange and up to 3 or 4 mm on edge. The more impressive habits are those which appear to be hexagonal dipyramids formed by complex twinning. Crystals with these "phacolitic" habits range from small, colorless individuals 3 or 4 mm across to clusters of pale pink, orange or white crystals up to 3 cm across. Triangular growth platforms are often observed on these crystals and may give rise to a skeletal appearance. X-ray diffraction (Birch, 1976) revealed that many of these large, pink, twinned crystals consist of an intergrowth of chabazite and gmelinite structures, a widely observed feature (Gottardi and Galli, 1985).

On Phillip Island, most of the chabazite crystals are simple rhombohedra, similar to those in the Flinders sequence. Distinctive brick-red to orange crystals up to 1 cm on edge occur as vesicle linings near Red Cliff Head, in association with ferrierite, heulandite and barite.

Cowlesite $CaAl_2Si_3O_{10} \cdot 5\text{–}6H_2O$

Cowlesite occurs as thin, delicate, radiating plates up to 0.5 mm long forming soft, white, pearly linings in vesicular basalt just east of Cairns Bay, near Flinders (Birch, 1988). Only a few small vesicles up to 8 mm across have been collected. Transparent analcime crystals may occur with the cowlesite, while adjoining cavities may contain levyne/offretite, chabazite, analcime or montmorillonite.

Ferrierite $(Na,K)_2MgAl_3Si_{15}O_{36}(OH) \cdot 9H_2O$

Ferrierite was first collected from weathered basalt several hundred meters west of Pyramid Rock on Phillip Island (Birch and Morvell, 1977). Since then, it has been found in a number of localities to the west, as far as Berry's Beach. The best specimens come from vesicular basalt on Red Cliff Head, where ferrierite forms linings to irregular vesicles associated with chabazite, heulandite, barite and calcite.

Ferrierite ranges from delicate fibrous crusts with a velvet sheen to more compact globular coatings with a greasy luster. The individual crystals are thin plates around 0.1 mm across and several mm long. The aggregates vary from snow-white through pale pink to greenish or bluish gray; staining may impart yellow or brownish colors.

Gmelinite $(Na_2,Ca)Al_2Si_4O_{12} \cdot 6H_2O$

The most common variety of gmelinite in the Flinders sequence forms pale orange to pale pink hexagonal dipyramidal crystals which are almost always an intergrowth of chabazite and gmelinite. The amount of gmelinite relative to chabazite varies—in general the pinker and more opaque the crystal, the higher the ratio gmelinite/chabazite. Lustrous aggregates of these crystals, up to 4 cm across, make spectacular specimens.

Gmelinite also occurs in the Flinders sequence as platy single crystals or aggregates, often flattened or skelétal, showing a rough circular or sub-hexagonal outline. They may be up to 1 cm across, and while actually colorless, may appear bright red due to hematite staining on internal fractures.

On Phillip Island, cream-colored hexagonal dipyramidal crystals of gmelinite/chabazite up to 7 mm across have been found with natrolite near Point Sambell.

Heulandite $(Na,Ca)_{2-3}Al_3(Al,Si)_2Si_{13}O_{36} \cdot 12H_2O$

Transparent, colorless crystals of heulandite up to 4–5 mm long and with the familiar, stout, coffin-shaped or blocky habits occur in vesicles in basalt near Red Cliff Head on Phillip Island. They are associated with red to orange chabazite, calcite and grayish montmorillonite. Heulandite has not been recorded at Flinders.

Levyne $(Ca,Na_2,K_2)Al_2Si_4O_{12} \cdot 6H_2O$

Levyne is locally abundant on Phillip Island, particularly on Sunderland Bluff, where it forms vesicle linings and infilling masses of interlocking cream-colored crystals up to 3 or 4 mm across and showing typical hexagonal outlines with bevelled edges. Other cavities are occupied by chabazite and/or thomsonite, but the levyne is always unaccompanied. At Red Cliff head, colorless levyne crystals have often been found thickly overgrown with fibrous offretite, oriented perpendicular to the {0001} faces; in turn these levyne/offretite aggregates may be completely enclosed by pale grayish green montmorillonite.

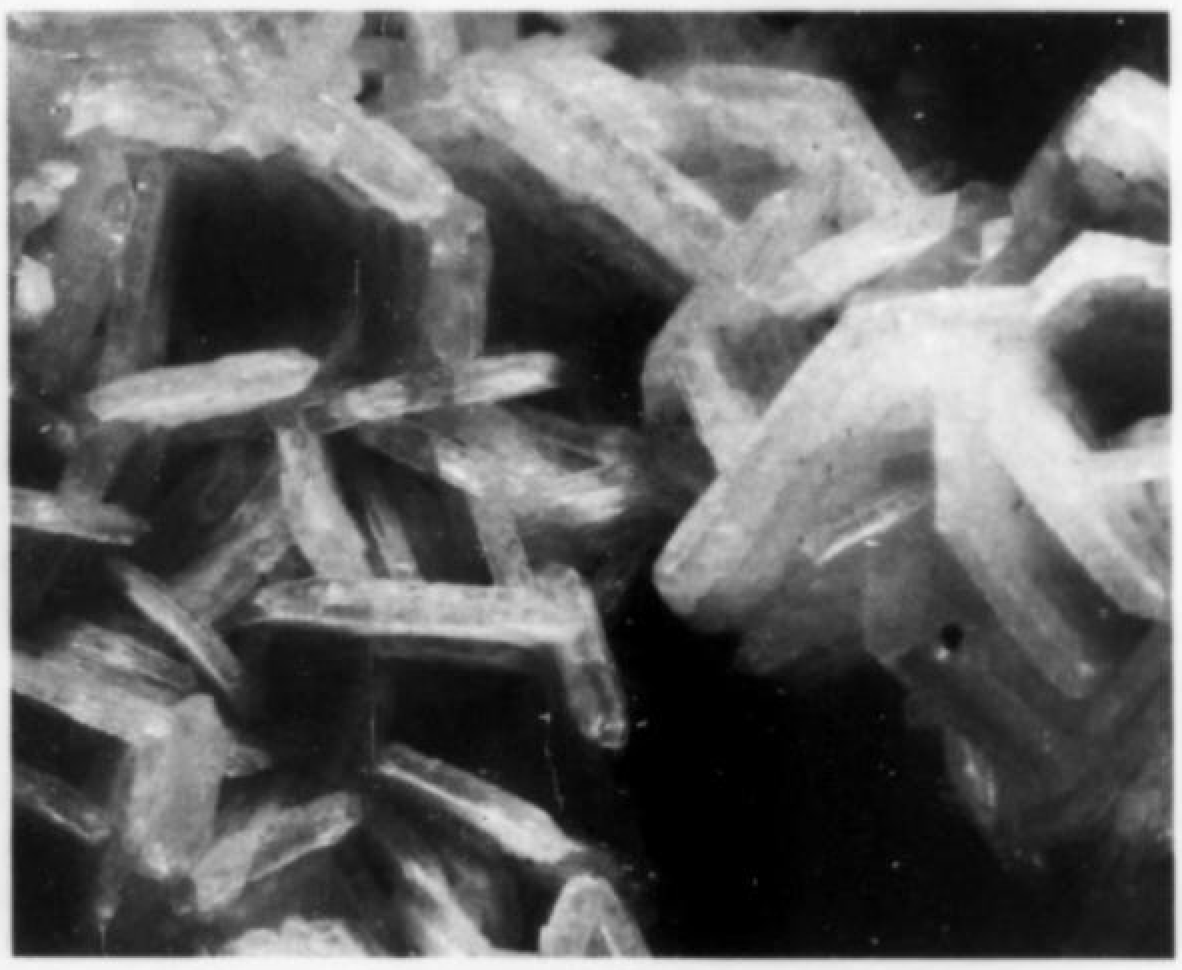


Figure 4. **Aggregate of white levyne crystals to 4 mm, from Sunderland Bluff, Phillip Island. David Vince collection; photo by Frank Coffa.**

At Cairns Bay, in the Flinders region, a few small cavities about 1 cm across have been found containing levyne crystals up to 2 mm across with offretite overgrowths (Birch, 1980).

Natrolite $Na_2Al_2Si_3O_{10} \cdot 2H_2O$

Natrolite is widely distributed in the Flinders sequence, generally as compact white cavity linings which open out into globular and hemispherical tufts of delicate prisms up to 5 mm long. Natrolite has often nucleated on analcime, and when occurring with gmelinite or dolomite forms particularly attractive combinations, especially if the natrolite needles are tinted pink or cream. In a number of Flinders specimens, natrolite needles occur intimately associated with clusters of platy thomsonite crystals. It may be difficult to distinguish between prismatic crystals of natrolite and thomsonite, but as a rule, natrolite prisms have close to square cross sections and are terminated by a low angle pyramid, whereas thomsonite is rectangular in cross section. Unusual curved groups of natrolite "whisker" crystals from Flinders were described by Henderson and Garland (1986).

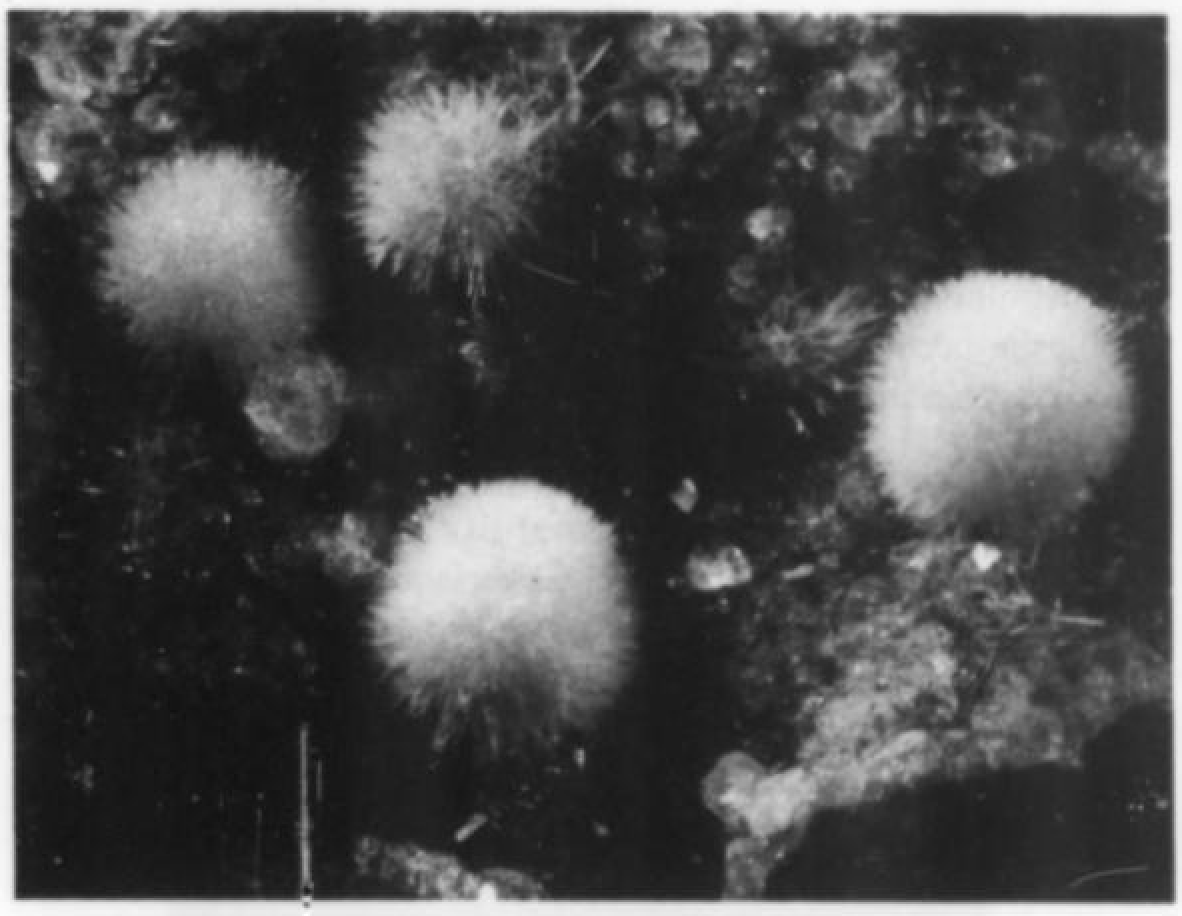


Figure 5. **Natrolite in spherical clusters 8 mm across, on analcime, from Flinders. Museum of Victoria collection; photo by Frank Coffa.**

On Phillip Island, natrolite is quite common, forming white to pale pink sprays on analcime. In general, the Phillip Island natrolite crystals are distinctly thicker and longer than those from Flinders.

Offretite $(K_2Ca)_5Al_{10}Si_{26}O_{72} \cdot 30H_2O$

The offretite overgrowths on levyne have been identified by X-ray diffraction and electron microprobe analysis. However, considering that Gottardi and Galli (1985) have suggested that offretite is always intergrown with erionite, it is possible that more detailed investigation would confirm the presence of erionite. Recently, colorless, prismatic crystals of offretite up to 0.5 mm long have been found near Sunderland Bluff.

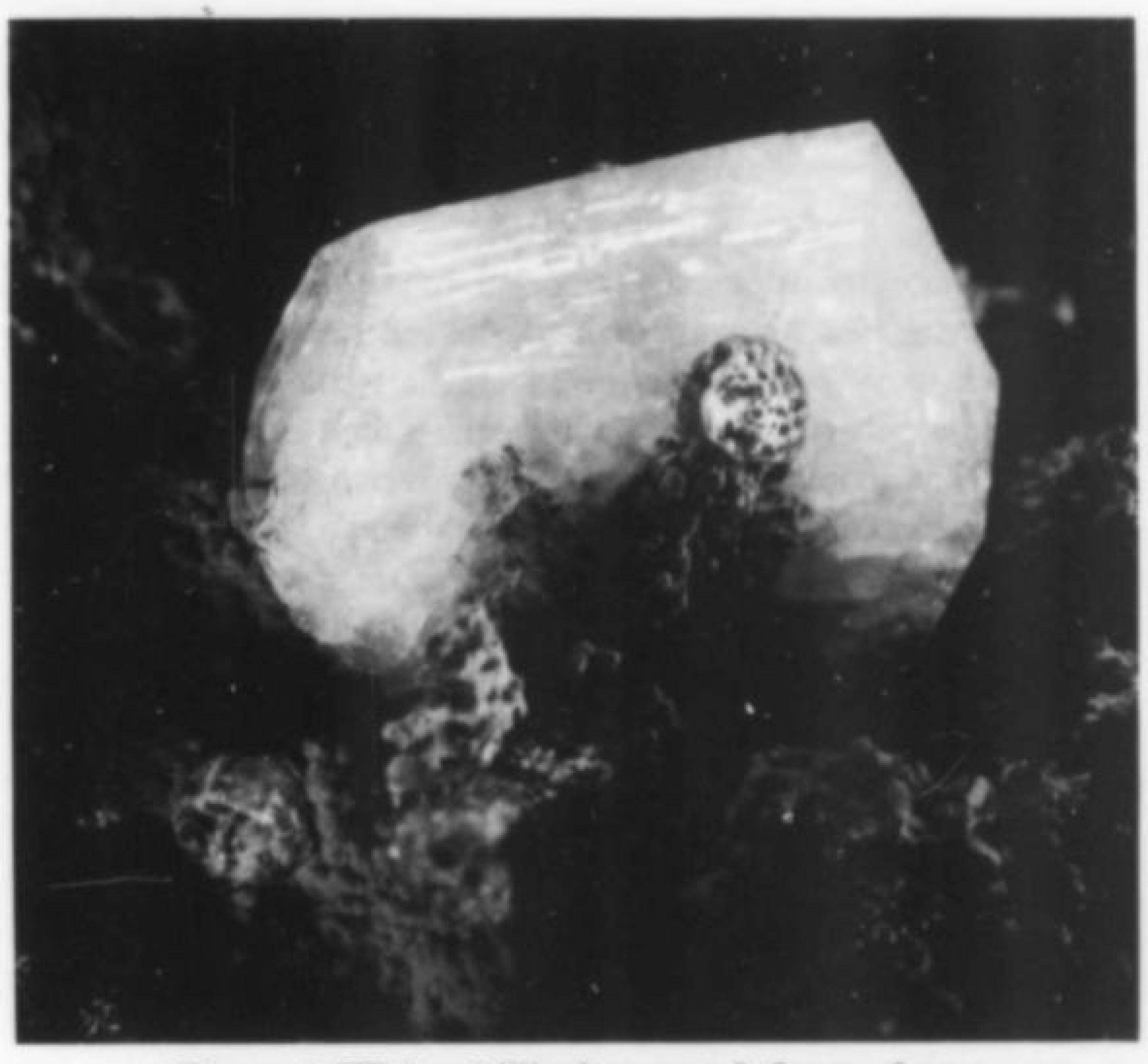


Figure 6. **White phillipsite crystal, 8 mm, from Flinders. Museum of Victoria collection; photo by Frank Coffa.**

Phillipsite $(K,Na,Ca)_{1-2}(Si,Al)_8O_{16} \cdot 6H_2O$

Only a few cavities containing crystals of phillipsite have been found in the Flinders sequence. The crystals are opaque and pale pinkish to white, usually between 2 and 4 mm long, with with one exceptional crystal reaching 1 cm high. Most of the crystals are stumpy prismatic fourlings, with near-square cross sections. The pattern of marked striations on the {110} faces suggests these are twinned again on (011).

Phillipsite has recently been found at the eastern end of Sunderland Bluff, occurring as stumpy fourlings up to 3 mm long and colored brick-red by hematite films. They occur in cavities with analcime and rare natrolite. An unusual fibrous form of pale orange or cream-colored phillipsite occurs as cavity linings 2 cm thick or vesicle infillings, also near Sunderland Bluff.

Stilbite $NaCa_2Al_5Si_{13}O_{36}\cdot 14H_2O$

Small pale orange to yellow sheaf-like crystals of stilbite up to about 5 mm long have been found in association with orange chabazite and heulandite at Helens Head on Phillip Island (Bussat and Birch, 1975). Rectangular, blocky white crystals up to 2 mm long have since been found with chabazite at Sunderland Bluff. Stilbite is unconfirmed in the Flinders sequence.

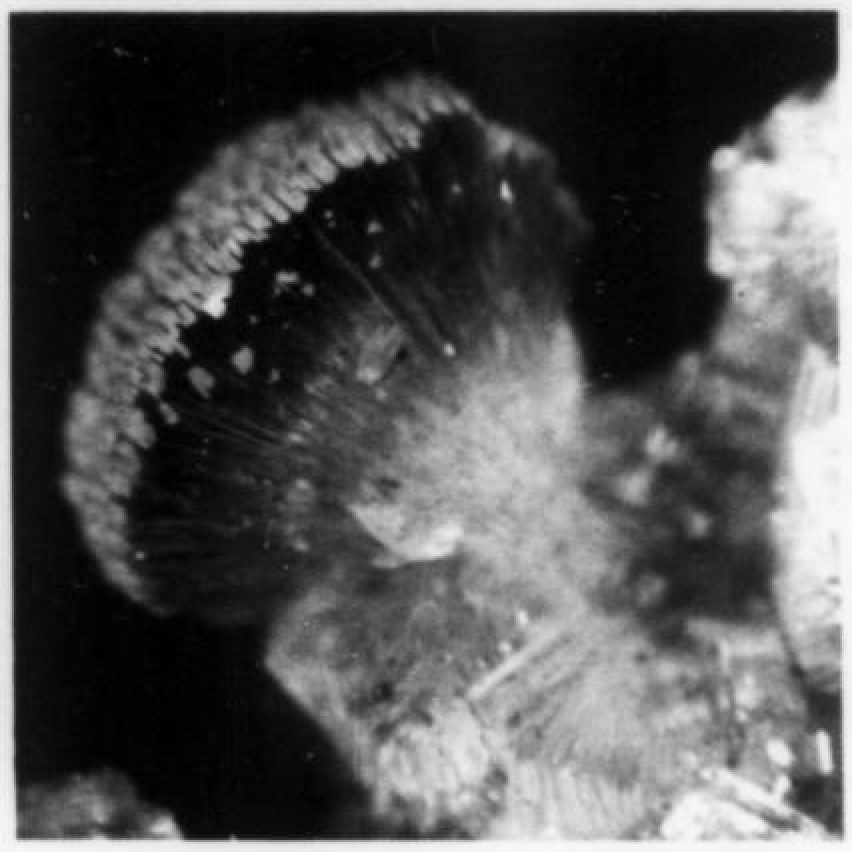


Figure 7. **Fan-shaped thomsonite aggregate 3 mm across, from Flinders. Peter Hall specimen and photo.**

Thomsonite $NaCa_2Al_5Si_5O_{20}\cdot 6H_2O$

Thomsonite forms distinct associations at Flinders and Phillip Island. In the best known location, between Cairns Bay and Little Bird Rock, thomsonite occurs in vesicles in a pale gray basalt or in cavities in weathered, brown, fragmental basalt veined by pale greenish clay. The thomsonite forms colorless rectangular plates stacked together in radiating aggregates up to 3 or 4 mm across. the closeness of the stacking determines the luster of the aggregate; thus the terminal faces of crystals in contact along (010) provide a pearly luster, while a more open spacing produces a silky luster. Prisms of natrolite may project from the aggregates. Thomsonite may also form pearly white linings in vesicles. A few specimens from near West Head contain fibrous white thomsonite with pale orange chabazite.

At Sunderland Bluff, on Phillip Island, thomsonite forms white to cream cavity linings and hemispherical clusters of crystals up to 2 mm long, generally associated with pale orange chabazite. The basalt at this locality is highly vesicular, with thomsonite/chabazite frequently occurring adjacent to cavities containing only levyne. Close by, rare specimens showing isolated sprays of natrolite prisms with pale pink thomsonite plates at their base have been collected.

Non-zeolites

Aragonite $CaCO_3$

Aragonite is not as abundant as calcite, but groups of colorless to translucent white crystals up to 3 cm long occur occasionally in vesicles in the Flinders sequence. At Cape Schanck, bands of reddish tuff are cemented by fibrous aragonite, which sometimes opens out into free-formed single crystals up to 3 cm long. On Phillip Island, groups of frosted, cream-colored, stumpy prisms of aragonite have been found at several localities. Transparent, pale mauve crystals have been reported from Kitty Miller Bay.

Figure 8. **White barite crystals to 1.3 cm on yellow chabazite from Red Cliff Head, Phillip Island. Jack Leach collection; photo by Frank Coffa.**

Barite $BaSO_4$

Snow-white aggregates of platy barite crystals up to 7 mm across form attractive combinations with orange chabazite at Red Cliff Head on Phillip Island. Similar barite crystals have also been observed with ferrierite, calcite or chalcedony at Red Bluff and several other localities.

Calcite $CaCO_3$

Calcite is very common in the Older Volcanics in both sequences and is widespread as a vesicle mineral with zeolites and filling veins in weathered basalt and pyroclastics. Various crystal habits have been recognized, from different rhombohedra to scalenohedral and prismatic forms. Most crystals are rounded and frosted in appearance. Notable occurrences are at Kennon Head on Phillip Island, where pale yellowish brown prismatic crystals up to 10 cm long are found on large white analcime crystals. Groups of white, stumpy prismatic crystals have been collected at Phelans Bluff. The Flinders sequence has yielded radiating groups of sharp prismatic crystals up to 4 cm long, encrusted with analcime and superb, rounded, pale yellowish scalenohedral crystals up to 12 cm long with natrolite.

Connellite $Cu_{19}Cl_4(SO_4)(OH)_{32}\cdot 3H_2O$

Clusters of acicular sky-blue needles, 0.04 mm long and with hexagonal cross sections, were found with paratacamite at Flinders (Birch and Pearson, 1982). They were identified as connellite on the basis of their appearance and chemical characteristics.

Copper Cu

Minute crystals of native copper have been found with analcime and natrolite near Flinders (Birch and Pearson, 1982).

Digenite (?) Cu_9S_5

Several groups of deep bluish black crystals up to 2 mm across on natrolite from Flinders have been tentatively identified as digenite.

Dolomite $CaMg(CO_3)_2$

Dolomite is widespread in the Flinders sequence, forming greasy looking cream-colored to grayish botryoidal crusts on zeolites or calcite crystals, and as individual globules or rough crystals. On Phillip Island, dolomite has been found at Berry's Beach as rosette-like aggregates of white intergrown flattened rhombohedra. An unusual pale mauve dolomite occurs as rough, rounded crystals up to 6 mm across on analcime at Kennon Head.

Montmorillonite $(Na,Ca)_{0.3}(Al,Mg)_2Si_4O_{10}(OH)_2 \cdot nH_2O$
Pale to dark greenish gray clay is a common vesicle lining and infilling mineral in both sequences, particularly in the Flinders region. It has generally been referred to as montmorillonite.

Paratacamite $Cu_2(OH)_3Cl$
Scattered deep green globules and pseudo-octahedral crystals of paratacamite, up to about 0.1 mm across, occur on orange chabazite at Sunderland Bluff on Phillip Island. At Flinders, a few specimens of minute platy crystals of paratacamite, associated with sky-blue connellite, were described by Birch and Pearson (1982). Both minerals have probably formed by reaction of sea water with native copper or copper sulfide.

Quartz SiO_2
A few specimens of amethystine quartz crystals have been collected at Kitty Miller Bay, on Phillip Island. This locality has also yielded numerous attractively banded chalcedony pebbles, colored in grays, browns, reds and white. Seams and nodules of colorless chalcedony have been reported from a number of other localities. Most of these varieties of silica probably originate from weathered basalts and tuffs.

CHEMISTRY

Considering the range of species, habits and associations of the Flinders and Phillip Island zeolites, there are far too few chemical analyses available to establish any definite compositional ranges for species. Most of the known analyses are shown in Tables 2 through 5 and were obtained by electron microprobe, operating at 15 kV and

Table 2. **Analyses of chabazite and gmelinite.**

	1	2	3	4	5	6	7	8
SiO_2	50.57	49.00	49.48	50.78	46.67	46.17	50.16	49.91
Al_2O_3	19.43	19.34	19.24	18.61	20.73	19.89	18.36	19.08
MgO	—	—	—	0.66	0.15	—	—	0.02
CaO	4.64	4.48	0.71	0.21	0.75	0.15	0.36	0.68
Na_2O	5.40	5.08	7.35	5.63	7.59	10.67	10.42	10.12
K_2O	1.21	1.67	4.27	6.25	4.99	0.46	0.45	0.49
BaO	—	—	—	0.08	—	—	—	—
Total	81.15	79.57	81.05	82.22	80.68	77.14	79.75	80.30
Structural formulae based on: 24 O (chab.) and 48 O (gmel.)								
Si	8.28	8.22	8.27	8.40	7.90	16.02	16.76	16.59
Al	3.76	3.83	3.79	3.63	4.16	8.13	7.23	7.48
Mg	—	—	—	0.16	0.04	—	—	0.01
Ca	0.82	0.81	0.13	0.04	0.14	0.06	0.12	0.24
Na	1.72	1.65	2.39	1.81	2.50	7.17	6.83	6.52
K	0.26	0.36	0.91	1.32	1.08	0.21	0.20	0.21
$\frac{\Sigma Al - \Sigma Ch}{\Sigma Ch}$	4.2%	5.3%	6.5%	2.8%	5.6%	8.4%	–0.6%	3.3%
Si/Al	2.20	2.15	2.18	2.31	1.90	1.97	2.32	2.22

1. Chabazite, colourless dipyramidal, Flinders (Museum of Victoria M14192).
2. Chabazite, pink rhombohedral, Flinders (M807).
3. Chabazite, pink rhombohedral, potassian, Flinders (M12825).
4. Chabazite, orange rhombohedral, Cunningham Bay, Phillip Island (M38164).
5. Chabazite, orange rhombohedral, Sunderland Bluff, Phillip Island (M38217).
6. Gmelinite, platy colourless, stained red, Flinders (M27897).
7. Gmelinite, colourless dipyramidal, Flinders (M28705).
8. Gmelinite, bipyramidal, Flinders (Gottardi and Galli, 1985).

Table 3. **Analysis of natrolite and thomsonite.**

	1	2	3	4	5
Sio_2	46.14	36.56	40.31	38.13	37.40
Al_20_3	25.41	29.25	28.57	29.66	29.46
MgO	0.02	0.11	0.03	—	0.02
CaO	0.38	11.78	12.09	11.63	12.05
Na_2O	14.76	3.98	4.41	4.12	4.11
K_2O	0.04	—	—	—	—
BaO	0.06	0.08	0.10	0.09	0.13
Total	86.81	81.76	85.51	83.63	83.17
Structural formulae based on 80 oxygen atoms.					
Si	24.29	20.67	21.72	21.01	20.80
Al	15.77	19.49	18.15	19.27	19.31
Mg	0.02	0.10	0.03	—	0.02
Ca	0.21	7.14	6.98	6.87	7.18
Na	15.06	4.37	4.60	4.40	4.39
K	0.03	—	—	—	—
Ba	0.01	0.02	0.02	0.02	0.03
$\frac{\Sigma Al - \Sigma Ch}{\Sigma Ch}$	1.3%	3.2%	–2.7%	6.0%	2.7%
Si/Al	1.54	1.63	1.52	1.56	1.64

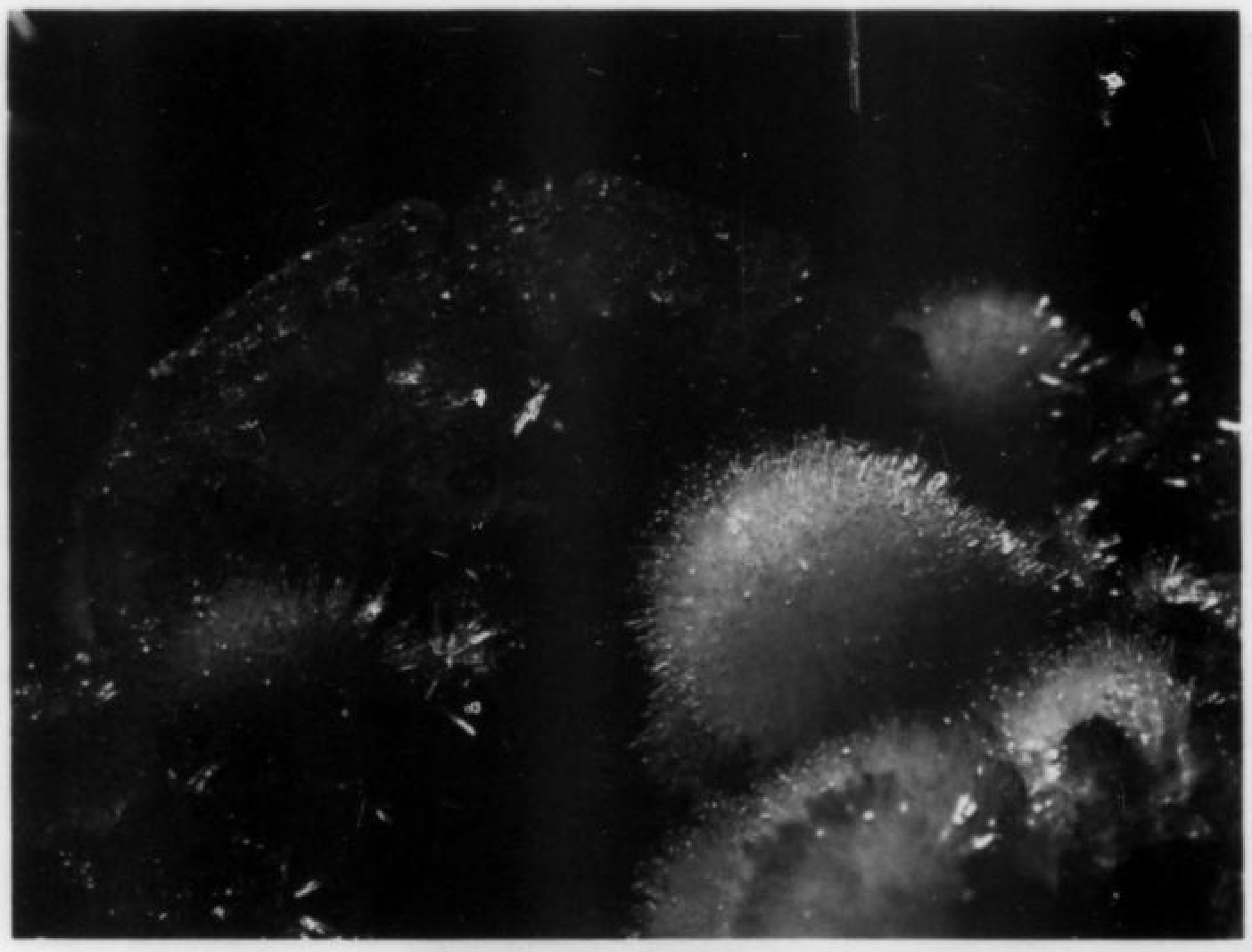
1. Natrolite, Sunderland Bluff, Phillip Island (Museum of Victoria, M38069).
2. Thomsonite (platy red crystals with 1).
3. Thomsonite, with chabazite, Sunderland Bluff, Phillip Island (M38214).
4. Thomsonite, Flinders (M34535).
5. Thomsonite, Flinders (M21694).

Note: Water contents not determined; structural formulae are calculated on an anhydrous basis.

Table 4. **Analyses of phillipsite, levyne and offretite.**

	1	2	3
SiO_2	50.79	51.01	51.50
Al_2O_3	21.63	20.61	17.37
MgO	0.08	0.08	0.21
CaO	2.46	5.56	0.43
Na_2O	5.39	6.06	5.90
K_2O	6.27	0.74	4.64
BaO	1.04	0.02	—
Total	87.66	84.08	80.05
Structural formulae:			
	32 O	36 O	36 O
Si	10.68	12.17	12.95
Al	5.36	5.79	5.15
Mg	0.03	0.03	0.08
Ca	0.56	1.42	0.12
Na	2.20	2.80	2.88
K	1.68	0.23	1.49
Ba	0.09	—	—
$\frac{\Sigma Al - \Sigma Ch}{\Sigma Ch}$	2.3%	–2.4%	8.0%
Si/Al	2.00	2.10	2.51

1. Phillipsite, with natrolite, Sunderland Bluff, Phillip Island (M38169).
2. Levyne, Sunderland Bluff, Phillip Island (M38103).
3. Offretite, with levyne, Sunderland Bluff, Phillip Island (M38068).



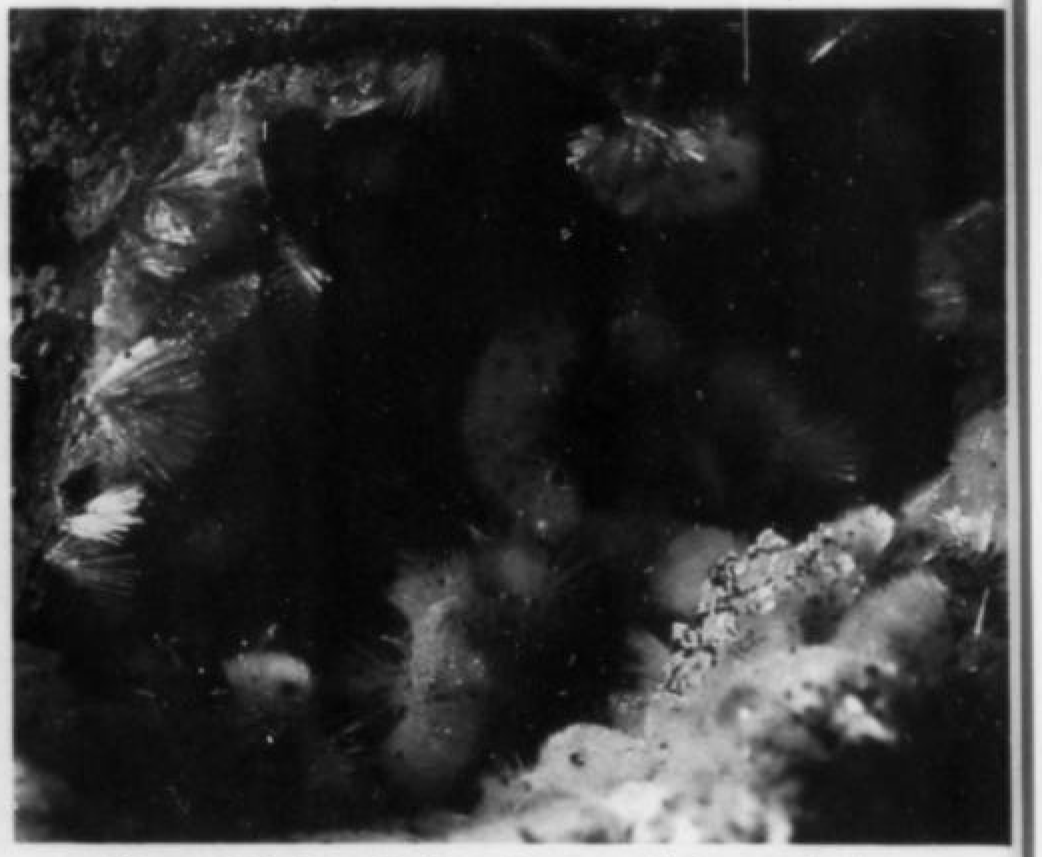


Figure 10. Ferrierite clusters lining a 1.1-cm cavity from near Pyramid Rock, Phillip Island. Museum of Victoria collection; photo by Frank Coffa.

Figure 9. Spherical natrolite groups with gmelinite crystal, 1.6 cm, stained pink by hematite, from Flinders. Museum of Victoria collection; photo by Frank Coffa.

Figure 11. Natrolite needles to 0.3 mm with pink thomsonite on analcime, from Sunderland Bluff, Phillip Island. Museum of Victoria collection; photo by Frank Coffa.

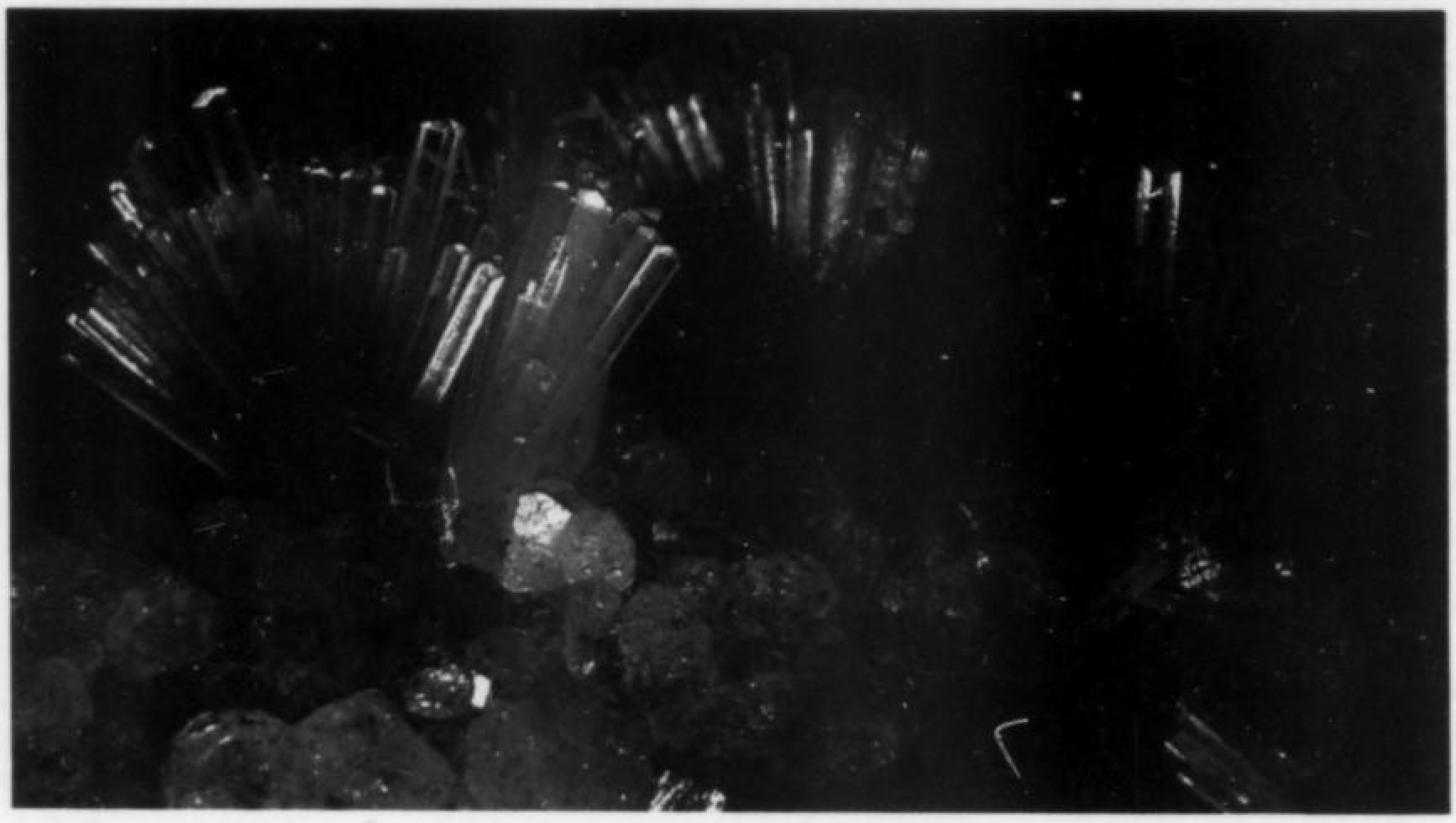


Figure 12. Natrolite crystals to 7 mm on analcime from Phillip Island. Museum of Victoria collection; photo by Frank Coffa.

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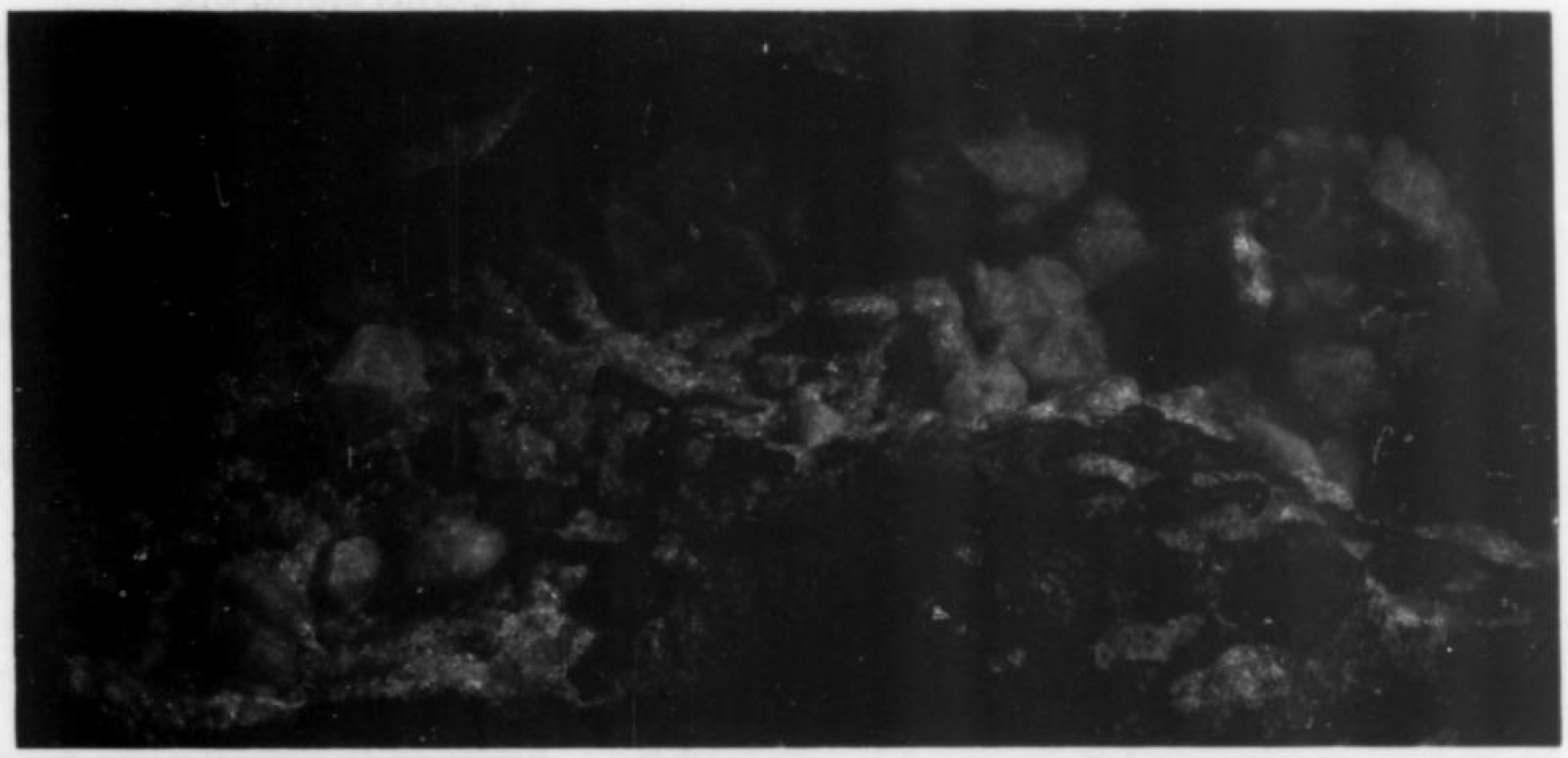
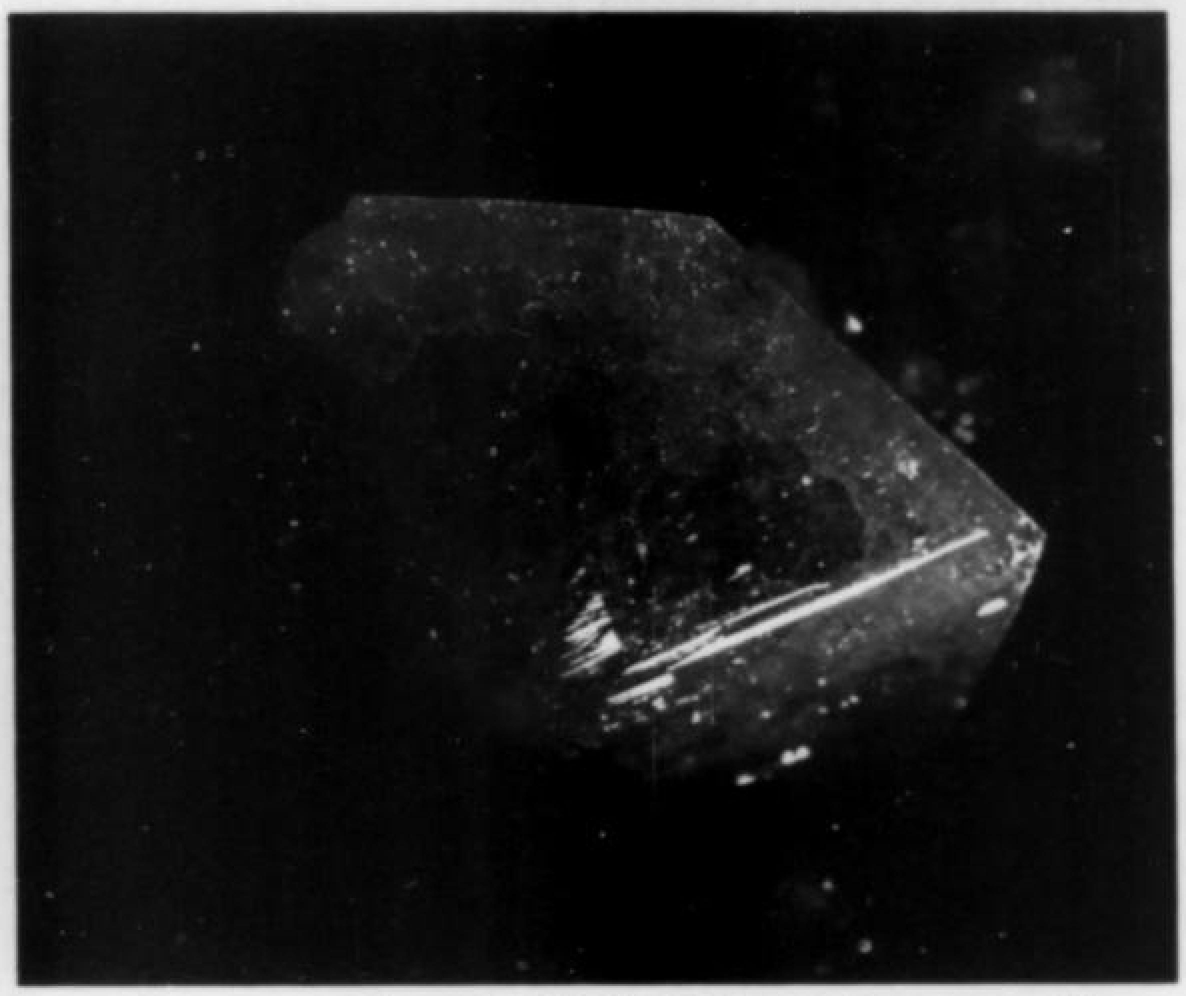


Figure 13. Gmelinite-chabazite crystals to 2 cm, with analcime, from Flinders. Museum of Victoria collection; photo by Frank Coffa.

Figure 14. (Below) Chabazite-gmelinite crystal intergrowth, 1.8 cm. Museum of Victoria collection; photo by Frank Coffa.



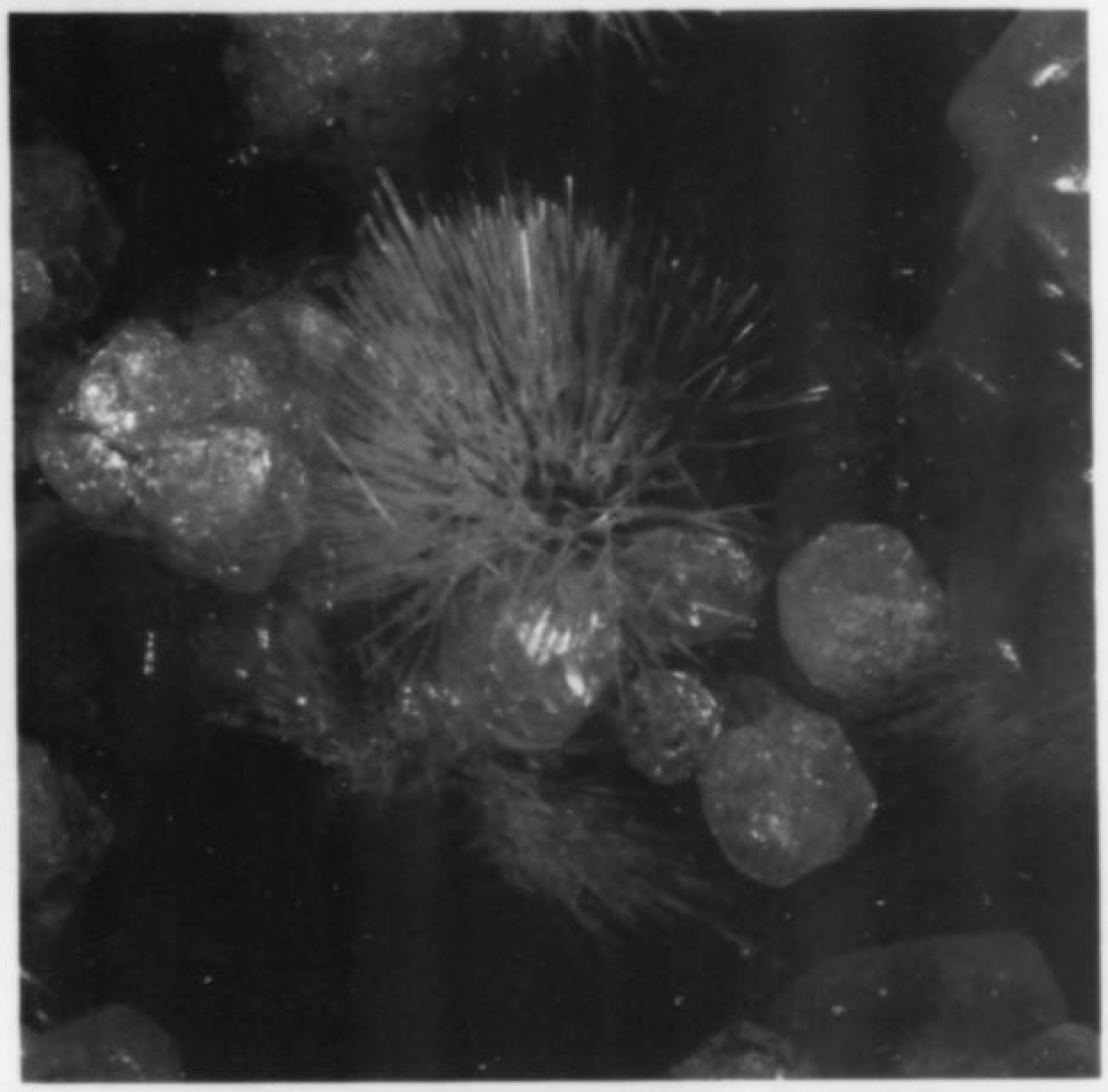


Figure 15. (Right) Pink natrolite sprays, 7 mm, with glassy analcime and frosty dolomite crystals from Flinders. Museum of Victoria collection; photo by Frank Coffa.

Figure 16. Agate, polished, 3.5 cm across, from Kitty Miller Bay, Phillip Island. J. Stewart collection; photo by J. Leach.

Table 5. **Analyses of stilbite, heulandite and ferrierite.**

	1	2	3
SiO_2	61.71	62.61	64.52
Al_2O_3	13.36	16.63	12.47
MgO	1.64	0.36	3.15
CaO	2.64	2.24	0.50
Na_2O	1.53	4.95	0.90
K_2O	1.72	2.63	1.41
BaO	0.09	0.03	0.04
SrO	0.21	—	0.20
Total	82.90	89.45	83.19
Structural formulae based on 72 O atoms.			
Si	28.65	27.48	29.35
Al	7.31	8.60	6.69
Mg	1.13	0.23	2.14
Ca	1.30	1.05	0.24
Na	1.38	4.21	0.79
K	1.02	1.47	0.82
Ba	0.02	0.01	0.01
Sr	0.06	—	0.05
$\frac{\Sigma Al - \Sigma Ch}{\Sigma Ch}$	−1.1%	4.1%	3.2%
Si/Al	3.9	3.2	4.39

1. Heulandite, colorless blocky, Pyramid Rock, Phillip Island (M34186) (Birch and Morvell, 1977).
2. Stilbite, Sunderland Bluff, Phillip Island (M38161).
3. Ferrierite, Pyramid Rock, Phillip Island (M34186) (Birch and Morvell, 1977).

specimen current of about 0.018 μA.

In general, both suites are sodium-rich—the only relatively common calcium-rich zeolite is thomsonite, while cowlesite is extremely rare. Some species, such as stilbite, phillipsite and chabazite, contain more potassium than calcium. In terms of Si/Al, there is a general trend towards more silicon-rich species with time. The Flinders suite is the more limited, with the relatively silicon-rich species stilbite, heulandite and ferrierite only being recorded on Phillip Island.

ORIGIN

Both the Flinders and Phillip Island zeolite suites have hydrothermal origins. The solutions are most likely to have evolved at a late stage in the crystallization of a particular basalt flow, and have then reacted with volcanic glass or calcic or sodic plagioclase surrounding the cavities where fluids were concentrated. Where flows were emplaced in rapid succession, or where ash or agglomeratic layers provided channelways for hydrothermal solutions, zeolite suites may arise from mixing of solutions from different flows.

The detailed chemical variation, flow by flow, within the Phillip Island and Flinders lava sequences is not known, but the compositions of residual glass and plagioclase feldspar would have influenced the activities of Ca, Na, K, Mg, Si and Al and therefore which zeolite assemblage crystallized. However, as two or three different assemblages may exist in adjoining small vesicles in many localities, it is likely that subtle variations in other chemical and physical parameters, such as partial pressures of water and carbon dioxide, played an important role.

The role of sea water in zeolite formation is conjectural, but it can't be dismissed, especially since some of the late-stage copper chlorides probably result from the action of sea water on native copper and copper sulfide. The ion-exchange properties of zeolites may enable limited chemical modification over long periods of exposure to sea water.

ACKNOWLEDGMENTS

The Museum of Victoria has benefited considerably from recent donations of Phillip Island and Flinders zeolites by collectors such as John Stewart, Charlie Stuart, John Haupt, Peter Hall, Jack Leach and Frank Robinson. Mention should also be made of the enthusiastic collecting of the late Hamish Pearson. The author is particularly grateful to John and Grace Stewart for the information they have provided on species localities on Phillip Island. The microprobe analyses were obtained by the author in the Department of Geology, University of Melbourne.

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The Chapman collection is the oldest significant mineral collection in private hands in Australia. Composed entirely of exquisite specimens—as are many world-famous collections—its mineralogical diversity and historical importance set it apart and give it a special quality.

Most of the 1000 specimens in the Chapman collection are hand-sized or smaller and each is a study in perfection. They are the culmination of Albert Chapman's lifetime hobby and the survivors of his critical tests of refinement. Each is generally a combination of several factors: aesthetic appeal, uniqueness, historical importance and national heritage value. Roughly half the specimens are Australian, testifying to his policy of preserving the best Australian minerals. In addition, many of the specimens form entire suites from important localities, making them a valuable record of the best crystallized species to surface since mining began in Australia. Of the foreign material, the most striking aspect apart from its aesthetic appeal is the number of classic specimens from old European localities. Many of these specimens have been acquired from famous collections and have interesting backgrounds.

Albert Chapman is unusual for his time. It was rare for anyone to collect minerals in Australia in the 1920's, and even more unusual for a 12-year-old boy to do so. Collecting became the focus of his life—"something to hang his hat on" when times were tough. Indeed, his collecting has spanned some interesting times: the Great Depression, the war years of 1939–1945, the Australian mineral boom of the 1950's, and Australia's emergence into the field of international science. His first specimens were two pieces of gold in quartz given to him by his father to whet his curiosity. As further encouragement, his father purchased a collection of classic English fluorite, calcite and barite which had belonged to a friend. Albert's early collecting trips were to local quarries, and he was lucky to be around Prospect, near Sydney, when much of the famed prehnite and analcime was found. Several of these self-collected specimens remain in his collection.

Albert made his first purchase at the age of 15 when he bought a collection from two retired Broken Hill miners for ten pounds. This was his introduction to Broken Hill minerals and Albert remembers being dumbfounded at the quality of the specimens. It was every collector's ambition to go to Broken Hill, the Mecca of the mineral world at that time, but Albert had to wait until he received his first holiday six years later. Highlights of his visits were the collecting trips to those famed underground "Aladdin's caves" to search for the specimens for which Broken Hill was renowned, followed by gregarious evenings in the pubs where miner's tall stories and mineral specimens were exchanged over cold beers. Inevitably, his enthusiasm and talent drew him into the company of famous Broken Hill personalities and collectors such as Arthur "Floss" Campbell, George Smith and Sir Maurice Mawby, mining engineer and the first chairman of Conzinc Riotinto Australia. They formed lifelong friendships based on a mutual interest in minerals and frequently exchanged information and specimens.

Broken Hill closed during World War II but reopened later to mine the oxidized zone and extract the pillars which contained many fine secondary minerals. Albert visited Broken Hill regularly about this time to collect for himself and was able to accumulate a reserve of specimens which became the basis of his exchanges. He also purchased from miners who quite often had unusual ideas about specimens. One such miner promised Albert a "top" specimen and dragged a large lump of galena ore into Albert's view. When Albert pointed out that what he really wanted were crystals of garnet and rhodonite, the miner's face went blank with amazement. He turned to his mates and sneered, "He collects bloody mullock."*

A plate of azurite crystals was obtained as a result of another miner's tale. The miner was collecting on his own and he was puzzled as to how he could apply a final tap to release a plate of azurite crystals that he had carefully chipped around, without letting it fall to the ground. He hailed a passing truckie and asked him to put his hand over the top of it. When the specimen came away from the wall the truckie walked away with it in his hand. Hearing this story two years later, Albert followed it up by visiting the truckie. The specimen was sitting on a mantelpiece under layers of dust. When Albert bought it and inquired about others, the man led him to an old fuel stove in the garden, crammed full of fine specimens.

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*Mullock = muck or waste-rock.

Figure 1. **Rhodonite crystals, 5.5 cm high. Broken Hill, New South Wales, Australia. Photo by John Fields.**

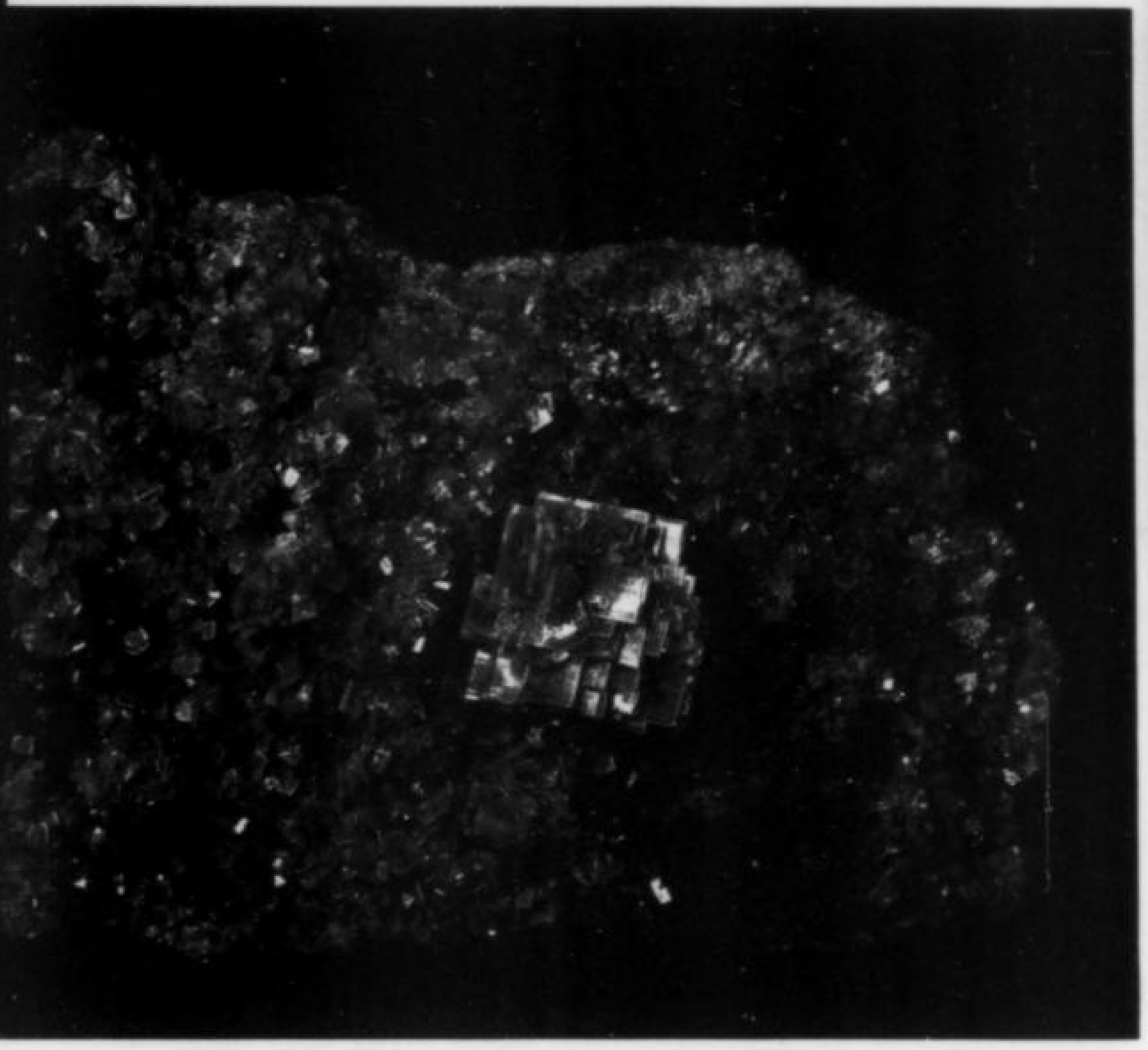


Figure 2. **Saleeite, length of specimen 100 cm. Jabiru, South Alligator River, Northern Territory, Australia. Photo by John Fields.**

About a quarter of Albert's collection comes from Broken Hill. Among the outstanding specimens is a recently acquired, stellate cerussite group of tapering sword-like crystals. One of several splendid azurites is composed of two large, perfect, prismatic crystals on a twinned crystal of cerussite: the largest crystal is 8 cm long. The range not only includes the rare, such as a stolzite, wulfenite, raspite, alabandite, ferroan bannisterite, silver halides and proustite, but also the unexpected, such as a unique green plumbian orthoclase ("amazonite") crystal exhibiting Manebach twinning, and a pyrosmalite composed of 4-cm crystals. The *pièce de résistance,* however, is a deeply colored group of tabular, transparent, red rhodonite crystals, much coveted by collectors and gem cutters. Of the minerals featured in *Minerals of Broken Hill,* a scientifically comprehensive coffee-table book published by Australian Mining and Smelting in 1985, 37% came from the Chapman collection.

One of the most valuable acquisitions Albert has made in terms of national heritage was the Armstrong collection of Cobar material, which he purchased from Armstrong's nephew in the 1950's. Armstrong was the first manager of the Great Cobar mine, founded in 1871, and he put together about 40 pieces to form a complete suite. The azurite and malachite specimens rival any of their kind found elsewhere in the world.

Information about collections came to Albert through various contacts. An antique dealer was responsible for his classic Moonta chalcopyrite and atacamite pieces. Museum curators, restricted by their budgets, would notify him of impending collection sales. Such information enabled him to purchase the Perrett geological collection from the Chevy Chase estate in Armidale, New South Wales. This old country mansion housed masses of natural history paraphernalia which obscured a treasure of crystallized Mt. Hope azurites. However, miners were usually his best source. Two New England miners, Bill Herbert and Horrie Finch, sold him their collections containing a large octahedral fluorite crystal from the Rumsby mine, Emmaville; fine representative wolframite, molybdenite, and native bismuth from Kingsgate; cassiterite from Elsmore and citrine crystals from Torrington. In particular, he consulted with miners who were reopening old mines that had produced good specimens in the past. He was on the spot in western Tasmania in 1971 when the lead mines, which had been closed since 1891, began to produce particularly fine specimens of crocoite. Again in 1982 he approached miners working tin in the old Gulf mine at Emmaville. His advice to them on the value of good specimens and collecting techniques was rewarded with several excellent specimens of cassiterite coating prismatic quartz crystals, a characteristic of this deposit.

Wherever possible, he collected for himself, resulting in a familiarity with most Australian and some foreign mineral localities. His Australian suites, supported by many self-collected specimens, are extensive. Further exceptional pieces include some of the finest Tasmanian crocoite; Burra malachite and azurite; Mt. Isa pyromorphite and cerussite; perfect columbite crystals from Spargoville, Western Australia; an unusual chrysocolla pseudomorph after azurite from Mungana, Queensland; a rare honey-colored scheelite on quartz from Nundle and a remarkable saleeite from the South Alligator River, Northern Territory. Recently, Albert extended his Wolfram Camp

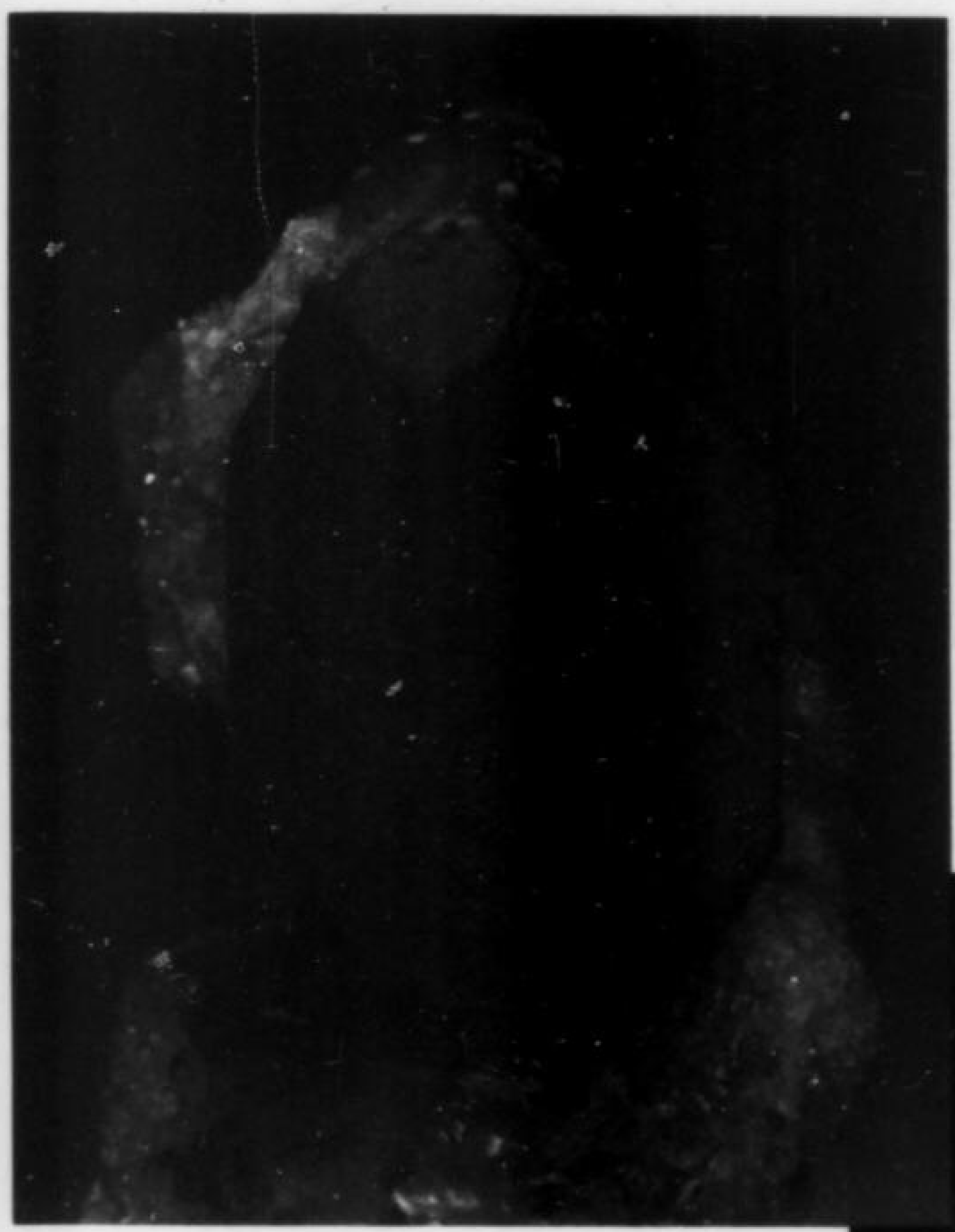


Figure 3. **Cuprite crystal, 10 cm. Onganja, Namibia. Photo by Kate Lowe.**

Figure 5. **Anglesite crystals, the largest is 4 x 7 cm. Touissit mine, Morocco. Photo by Kate Lowe.**

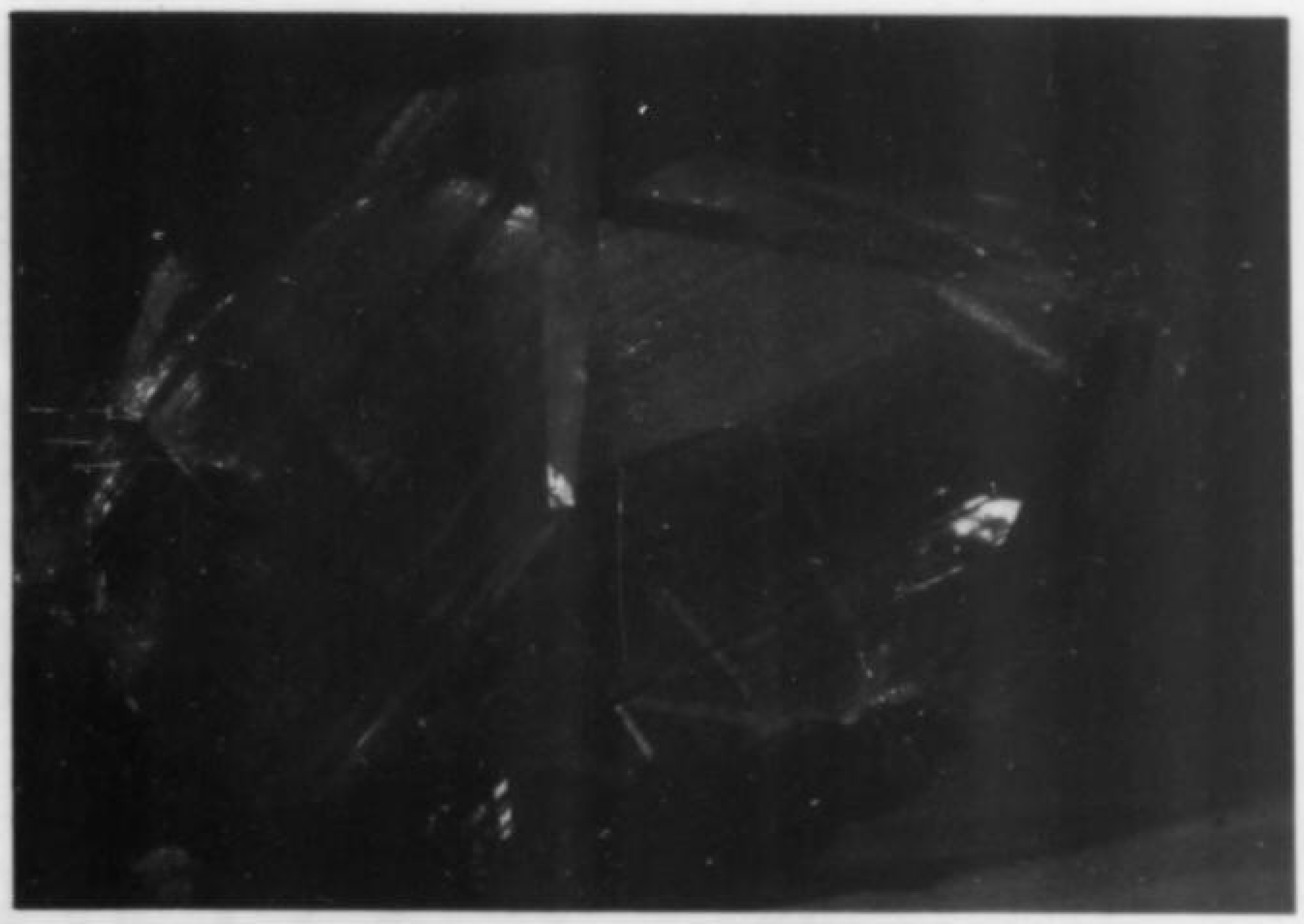


Figure 4. (Top right) **Crocoite, 100 cm high. Dundas, Tasmania, Australia. Photo by Rock Currier.**

collection of scheelite, ferberite, molybdenite and bismuthinite by the addition of a large native bismuth crystal.

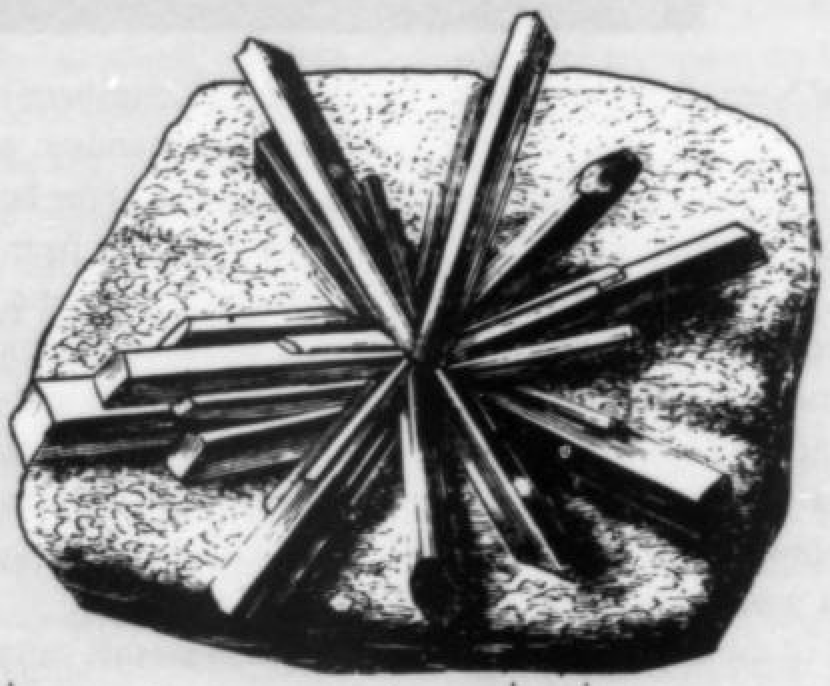
By the 1950's, Albert was internationally recognized as a knowledgeable amateur mineralogist and a discriminating mineral collector. The Chapman house was first port of call for overseas as well as Australian mineralogists visiting Sydney. Albert knew from these contacts and from his foreign exchanges that mineral collecting in Australia was small-time. He decided to travel and, in 1970, became the first Australian collector to visit the Tucson Gem and Mineral Show, spearheading Australian visits to overseas shows. While touring the U.S. and Europe he found that his reputation was his passport to viewing, from the inside, the famous collections of the Smithsonian, the American Museum of Natural History, the British Museum of Natural History, the Sorbonne and natural history museums in Stockholm, Oslo, Munich, Copenhagen and Vienna. He had already exchanged with many of these museums, successfully establishing Broken Hill minerals in their displays and promoting Australian minerals. In exchange, he received classic minerals from their native countries, such as a series of Cornwall sulfides among which is a treasured cogwheel bournonite from the Herodsfoot mine. Occasionally, he repatriated Australian specimens such as a fine vivianite from Wannon Falls, Victoria.

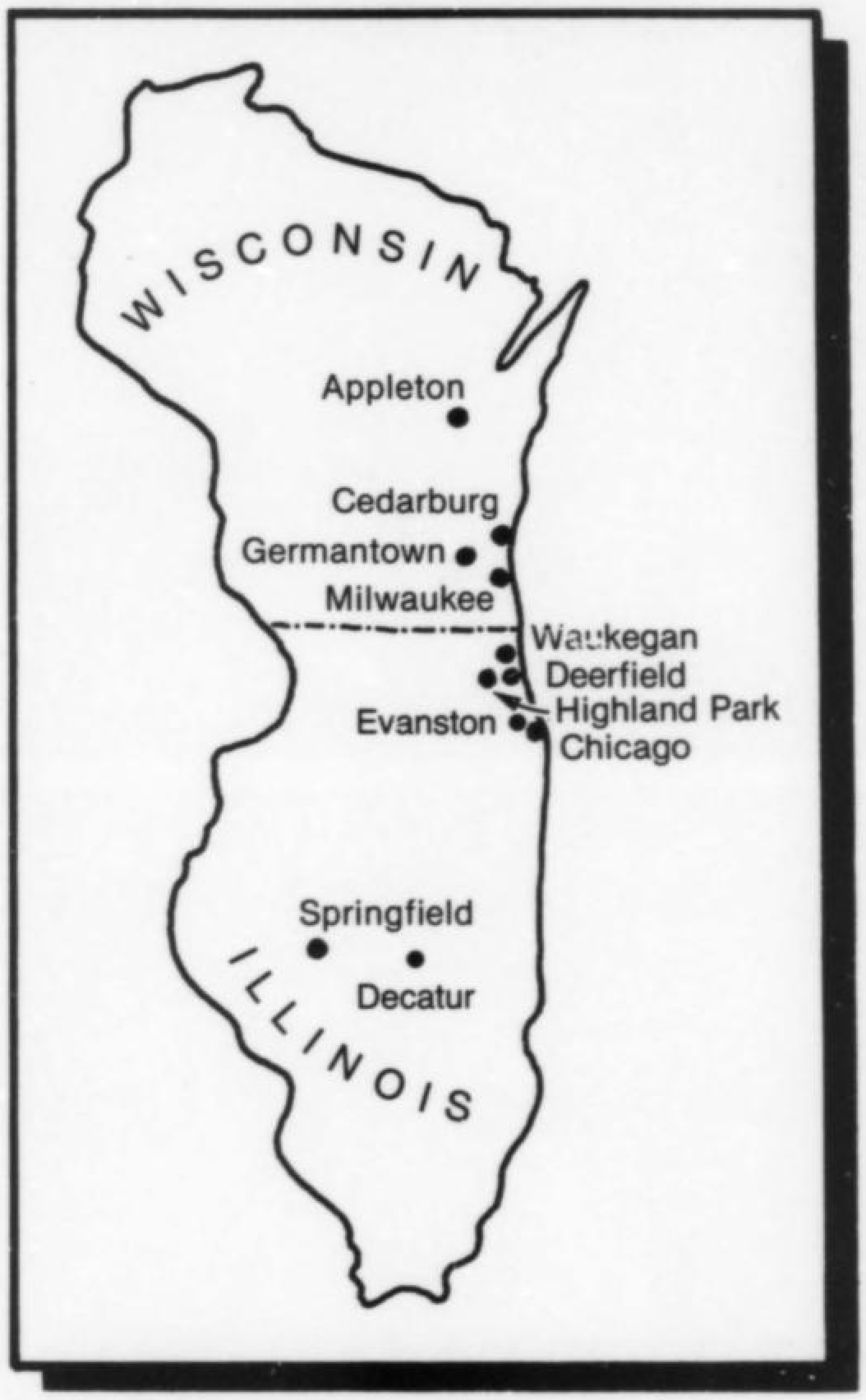
His visits to the Tucson and Munich shows resulted in new strengths for his collection. Some notable acquisitions were classic Swiss pink fluorite crystals; a fragile, twisted epidote from Untersulzbachtal, Austria; a Kongsberg native silver with acanthite crystals; a formidable Mexican legrandite; a perfect 10-cm cuprite crystal on matrix from Namibia; one of the largest powellite crystals from Poona and a lemon-yellow anglesite from Touissit, Morocco, composed of two crystals 3 x 5 and 4 x 7 cms. The collection is strong in Tsumeb minerals, has a number of Pakistan beryls, kunzites and tourmalines, some pristine proustites and a rare cryolite and thomsenolite from Greenland. A hematite "rose" group from St. Gotthard, Switzerland, was prized from a Swiss cafe owner who had two cabinets full of magnificent Swiss minerals, one containing only perfect quartz gwindels of every color.

Other minerals carry proud pedigrees, such as the gem crystals and cut stones from the Baroness Coutts-Burdeaux collection and the specimen of topaz crystals on smoky quartz from Alabaschka, USSR, which was part of the second J. Pierpont Morgan gem collection donated to the American Museum of Natural History in 1901. It was displayed there until its release a few years ago into the commercial world, where Albert quickly recognized its significance.

A tribute to the Chapman collection is the number of invitations Albert receives from international and local organizers to display at their shows. However, being an experienced traveler, he is only too glad to keep it safely at home, intact. And so the mountain comes to Mohammed.

ED. NOTE: The Chapman collection has just recently been purchased by the Geology and Mining Museum, Sydney.





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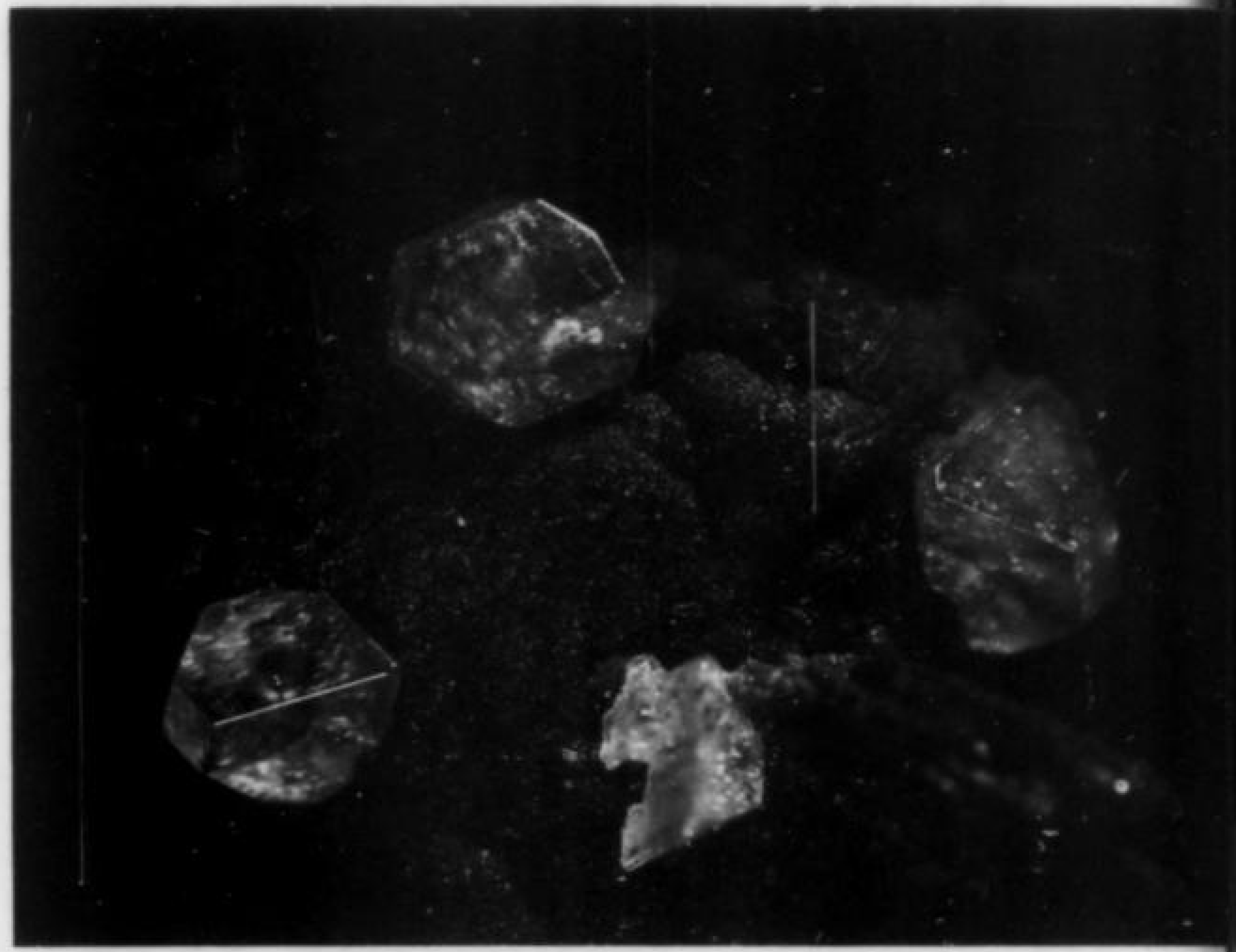
SPECIAL EXHIBIT

Figure 1. **Wulfenite crystals, 2 mm, on ma chite from the Whim Well mine, Whim Cr gold field, Pilbara region of Western Austra Collected in the 1970's. Museum of Victo collection.**



Even in a much enlarged issue like this one, only very selective highlights of Australian mineralogy can be presented. While the best of Australia's specimen mineral deposits, such as Broken Hill and Dundas, rank with the world's best, there are many other localities which are providing, or have the potential to provide, collectors and professional mineralogist with a continuing supply of display specimens, micromounts and rare species. A few localities spring to mind: the superb natrolite, analcime and apophyllite crystals from Cape Grim in northwest Tasmania; the virtually unexploited riches of the Harts Ranges in the Northern Territory, from where large and often gemmy crystals of garnet, epidote, kornerupine, sphene, kyanite, corundum and cordierite trickle occasionally onto the collector's market; the Lake Boga granite quarry in northwestern Victoria, the source of our best fluorapatite crystals and now yielding new phosphate species; the well-crystallized rarities from the Iron Knob quarries in South Australia; the list goes on. . .

Specimens of well crystallized sulfide minerals are just starting to find their way onto the market from the new lead-zinc-copper mines at Hellyer and Que River in Tasmania. We have yet to see the purported large barite and fluorite crystals from the rich copper-gold-uranium deposit on Roxby Downs Station in South Australia. And who knows what the mineralogical future holds for Western Australia, the state which has produced more than half of Australia's type localities and most of its iron, gold, nickel and diamonds? In any case, there is much more to see and discover. As a taste, we present here in this "Special Exhibit" a few things not illustrated elsewhere in this issue, in photos by Frank Coffa.

W. D. Birch

Figure 2. **Opalized gastropod, 1.5 cm, from Coober Pedy, South Australia. Brian Shelton collection. Precious opal is often found as replacements after shells and bone fragments.**

Figure 3. **Pyromorphite crystal cluster, 8 mm, recently collected from the Block 14 lease, Broken Hill, New South Wales. Jack Leach collection.**

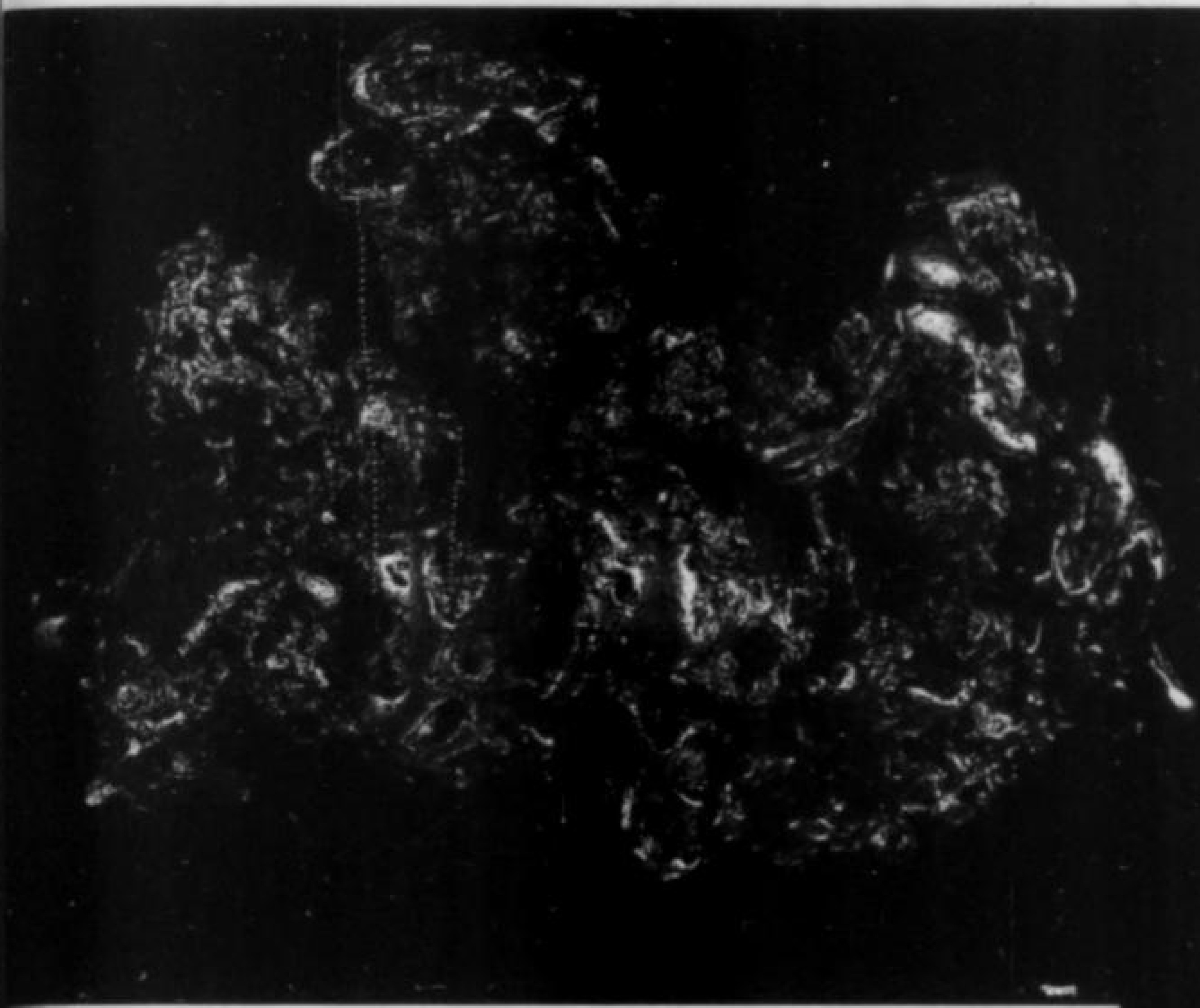


Figure 4. The "Pride of Australia" nugget, 15.5 cm (256 ounces), from Wedderburn, Victoria. Purchased by the State Bank of Victoria in 1984 and now on exhibit in the Museum of Victoria. This is the largest surviving Victorian nugget retained in Australia.

Figure 5. Green mimetite crystal, 1.3 cm, from the Elura mine near Cobar, New South Wales. Museum of Victoria collection.

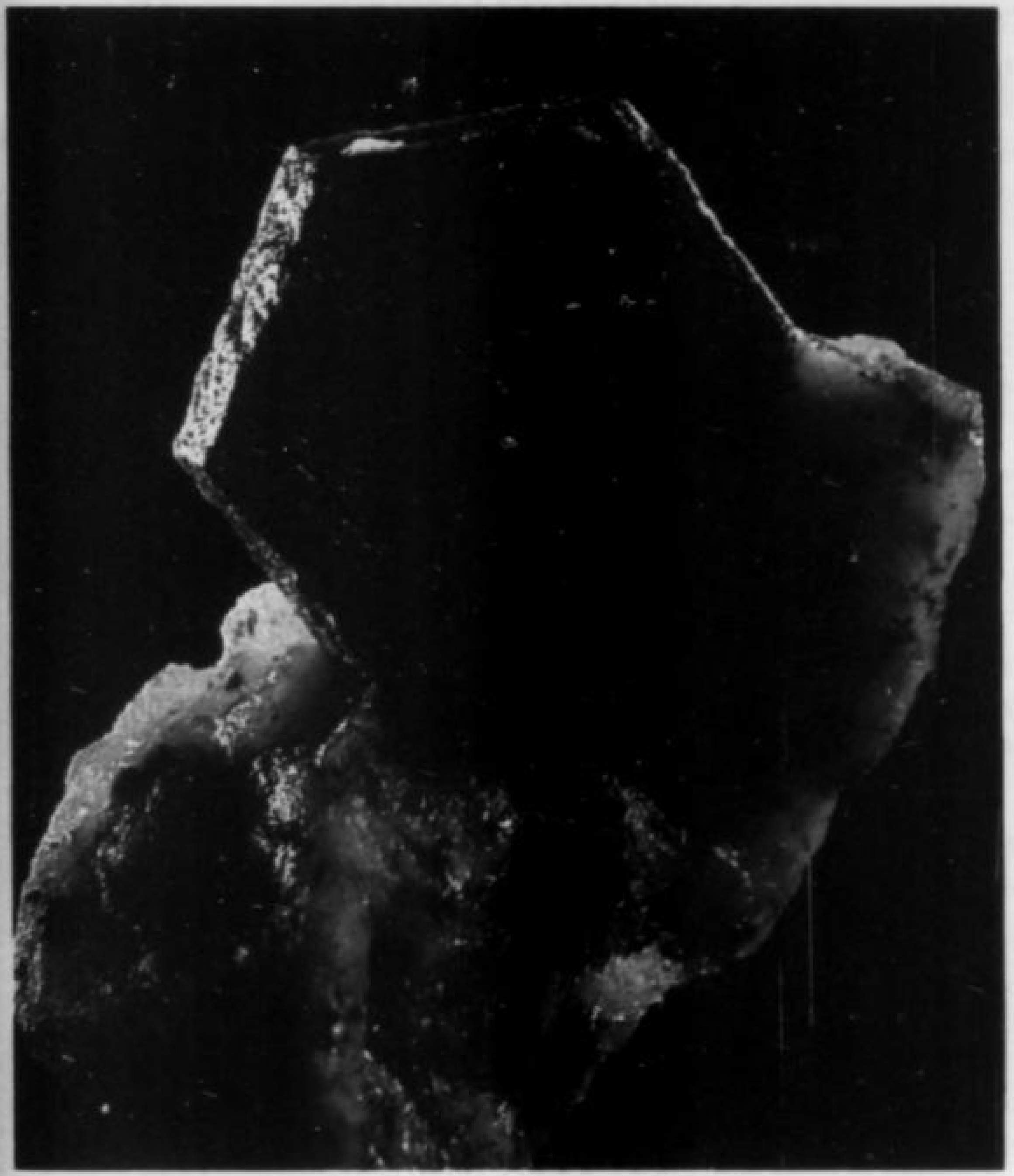


Figure 6. Ruby crystal, 2.2 cm, on matrix, from the eastern Harts Range, Northern Territory. Brian Shelton collection. This is one of the best crystals from Australia's only significant ruby deposit.

Figure 7. Kambaldite crystals to 1 mm, from Kambalda, Western Australia. Museum of Victoria collection. Kambaldite is perhaps the most attractive of a number of new secondary nickel-bearing minerals described in the past 15 years.

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THE MOUNT ISA-CLONCURRY MINERAL FIELD

Northwestern Queensland

●

Robert Sielecki
42 Hex Street, Tottenham
Victoria, 3012, Australia

The Mount Isa-Cloncurry mineral field is one of Australia's most important metallogenic provinces, with world class deposits of copper, lead, zinc and silver and smaller deposits of uranium, gold and other minerals. Much of the mining in this field has occurred in the oxidized zone resulting in a wide range of spectacular and rare minerals. The district includes type localities for two minerals, stillwellite and the recently described copper-aluminum phosphate, sieleckiite.

INTRODUCTION

The Mount Isa-Cloncurry mineral field is a north-northwesterly trending belt of Precambrian rocks in northwestern Queensland. The belt is approximately 500 km long with an average width of 120 km.

The topography is rugged with steep rocky hills rising 100 to 200 meters above the surrounding plains. Average elevation of the area is between 300 and 500 meters above sea level.

Although lying within the tropics, the area is semi-desert with summer temperatures frequently exceeding 40°C and an average annual rainfall varying from 275 mm in the south to 500 mm in the north. Cloncurry has recorded Australia's highest official temperature of 53.1°C (McWhirter, 1985). Winters are short with rare mild frosts.

Vegetation is typical of a semi-arid environment. Trees (mainly eucalyptus) are scattered, with low scrub (mainly acacia and ti-tree) and needle-sharp spinifex grass dominating.

Air, road and rail access to Mount Isa is excellent but travel within the area is often difficult and hazardous owing to the rugged topography and extreme heat. Waterholes are few and far between and more than a few prospectors (and mineral collectors) have perished after becoming stranded or lost. Road maps of the area are unreliable, so a little local knowledge and a keen bush sense are indispensable when visiting some of the more remote mines. Fortunately, many of the local "gougers" are only too happy to draw very accurate "mud maps" (even to the extent of marking in individual trees!) which to the author's surprise have never failed.

The principal town in the area is the city of Mount Isa with a population of 27,000, supported mainly by the large Mount Isa mine. The city of Mount Isa is listed in the *Guinness Book of Records* (McWhirter, 1985) as being the largest city (in area) in the world, encompassing an incredible 40,978^2 km, due to the town of Camooweal (188 km west) falling within the city limits.

There are literally hundreds of mines scattered throughout the field, with countless mineralized outcrops. Few of the mines are in operation today, due to generally low metal prices and high mining costs. Mining in the area has utilized both underground and open-cut mining methods, with much of the mining occurring in the oxidized zone. As a result some superb secondary copper, lead, zinc, silver and cobalt minerals have been found.

Very little recent work has been published on the mineralogy of the area. The purpose of this paper is to describe some of the most important crystal-producing mines in the field, with an emphasis on the Mount Isa mine.

HISTORY

The first white explorers to traverse the Mount Isa-Cloncurry mineral field were Burke and Wills in 1860–1861 (Carter *et al.*, 1961). They were leading an ill-fated expedition to cross the continent from south to north and succeeded in reaching the mangrove swamps of the Gulf of Carpentaria just north of the mineral province. On the return journey, however, they reached a point where they had previously left men and supplies only to find that their support team had left earlier that day thinking they had already perished. The two explorers soon succumbed to the unforgiving land.

Not long after the Burke and Wills expedition, Ernest Henry and Roger Sheaffe made the first of several visits to the area in search of new pastoral country. They finally returned in 1867 to become the first white settlers in the area.[1] They set up their camp at Fort Con-

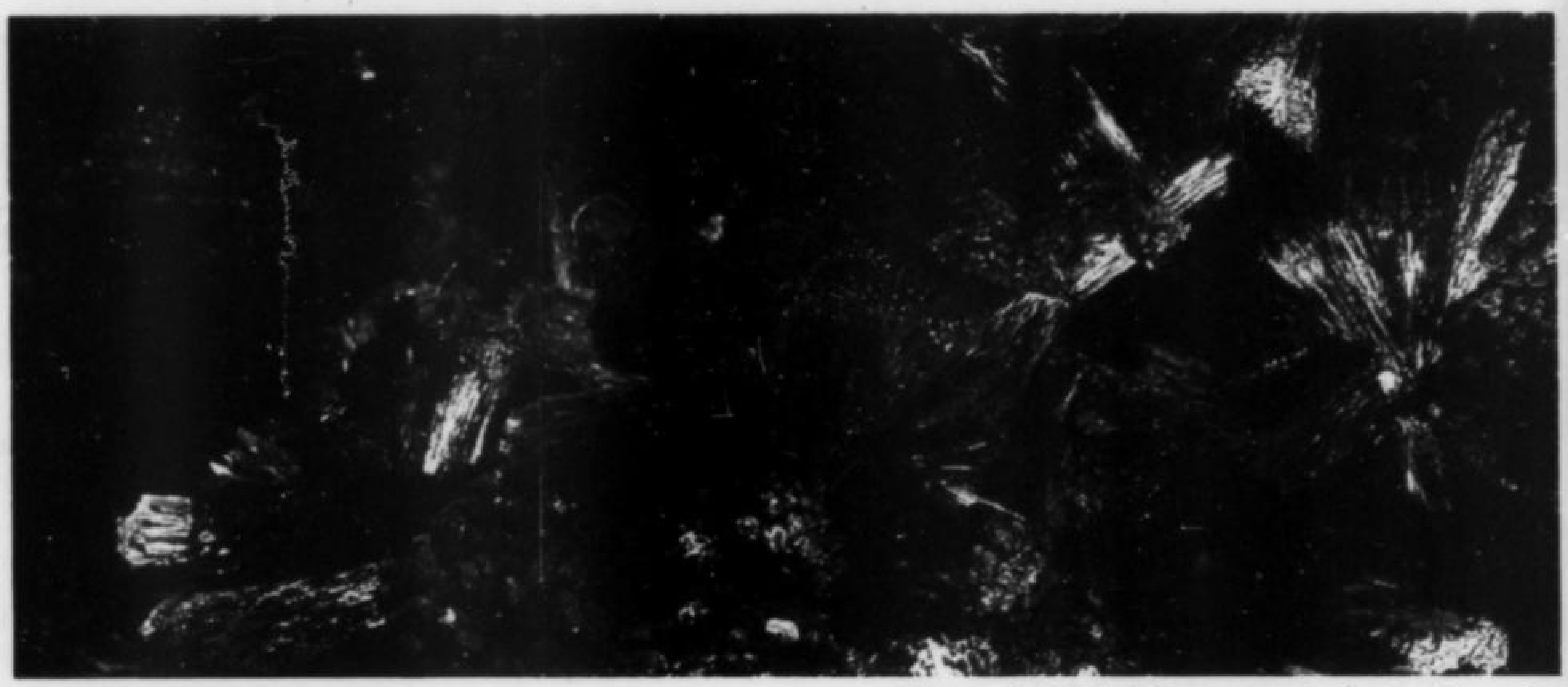

Figure 1. **Malachite sprays to 8 mm from the Black Rock open cut, Mount Isa mine. Museum of Victoria collection; photo by Frank Coffa.**

Figure 2. **Pseudomalachite crystals to 1 mm, on chrysocolla from the Mount Glorious mine. Museum of Victoria collection; photo by Frank Coffa.**

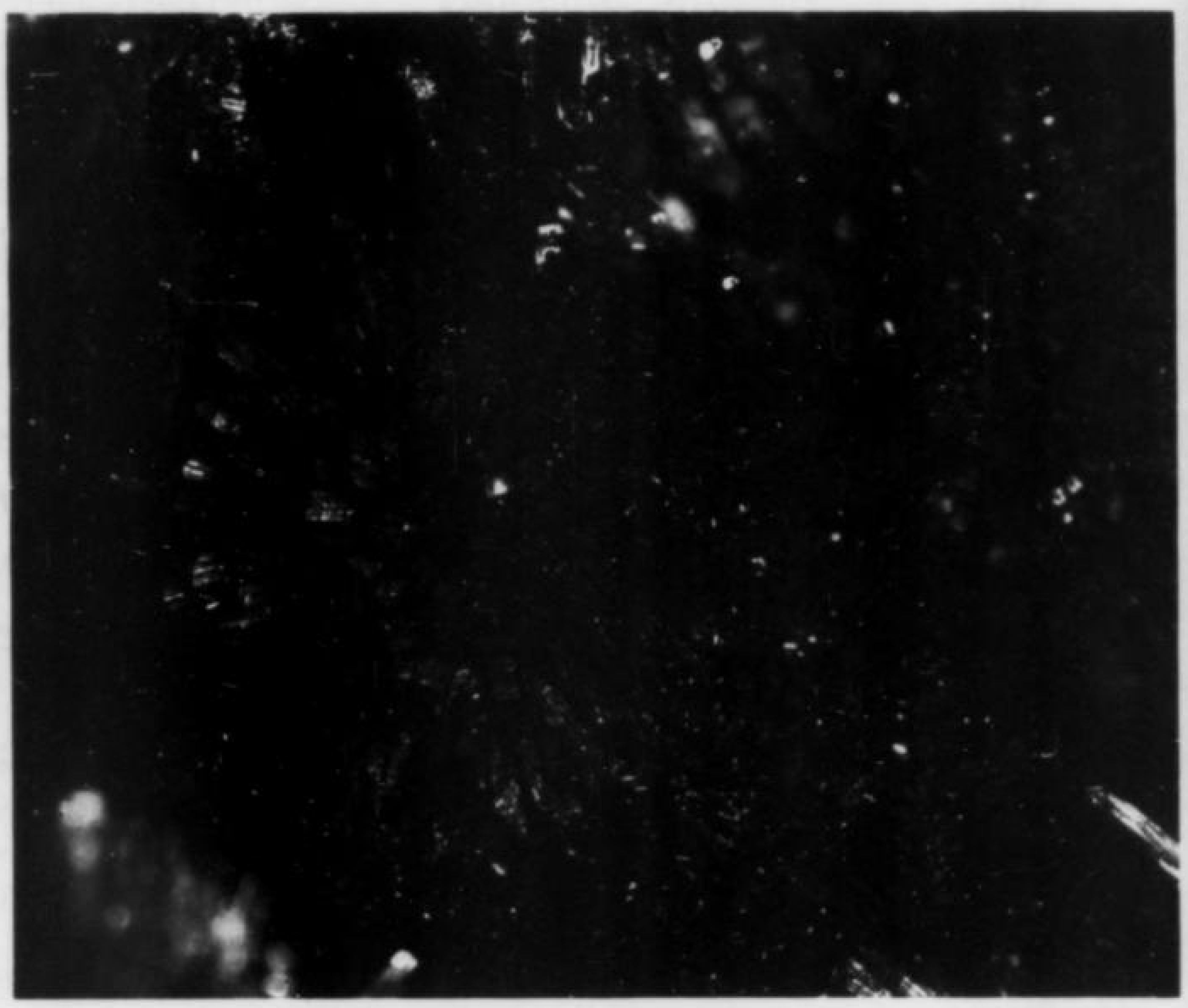

Figure 3. **Erythrite rosettes to 5 mm from the Mount Cobalt mine. Museum of Victoria collection; photo by Frank Coffa.**

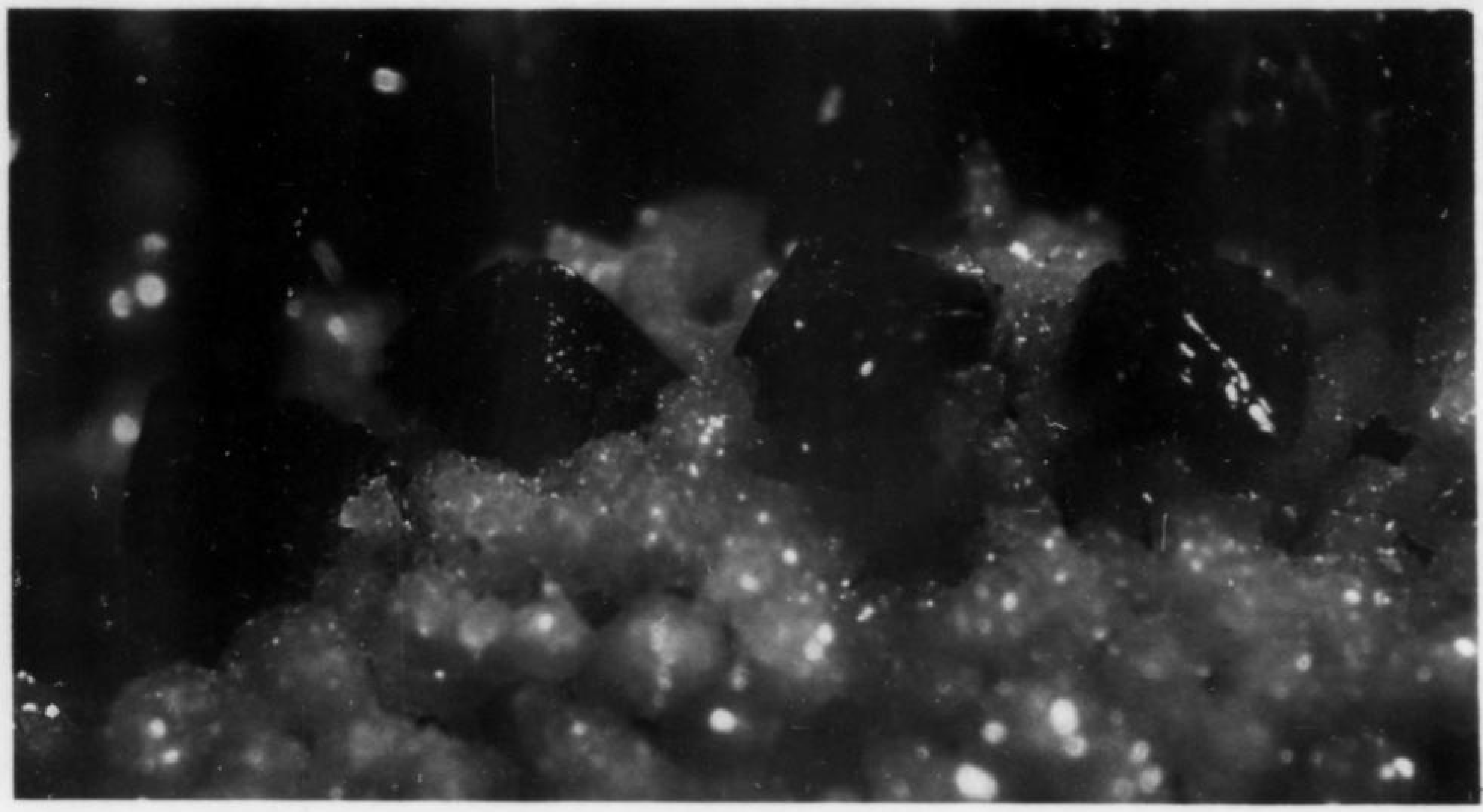

Figure 4. **Libethenite crystals to 1 mm, on turquoise from the Mount Oxide mine. Author's collection; photo by Frank Coffa.**

Figure 5. **Acicular cuprite in a cavity about 1.3 cm across, from the Black Rock open cut, Mount Isa mine. Museum of Victoria collection; photo by Frank Coffa.**

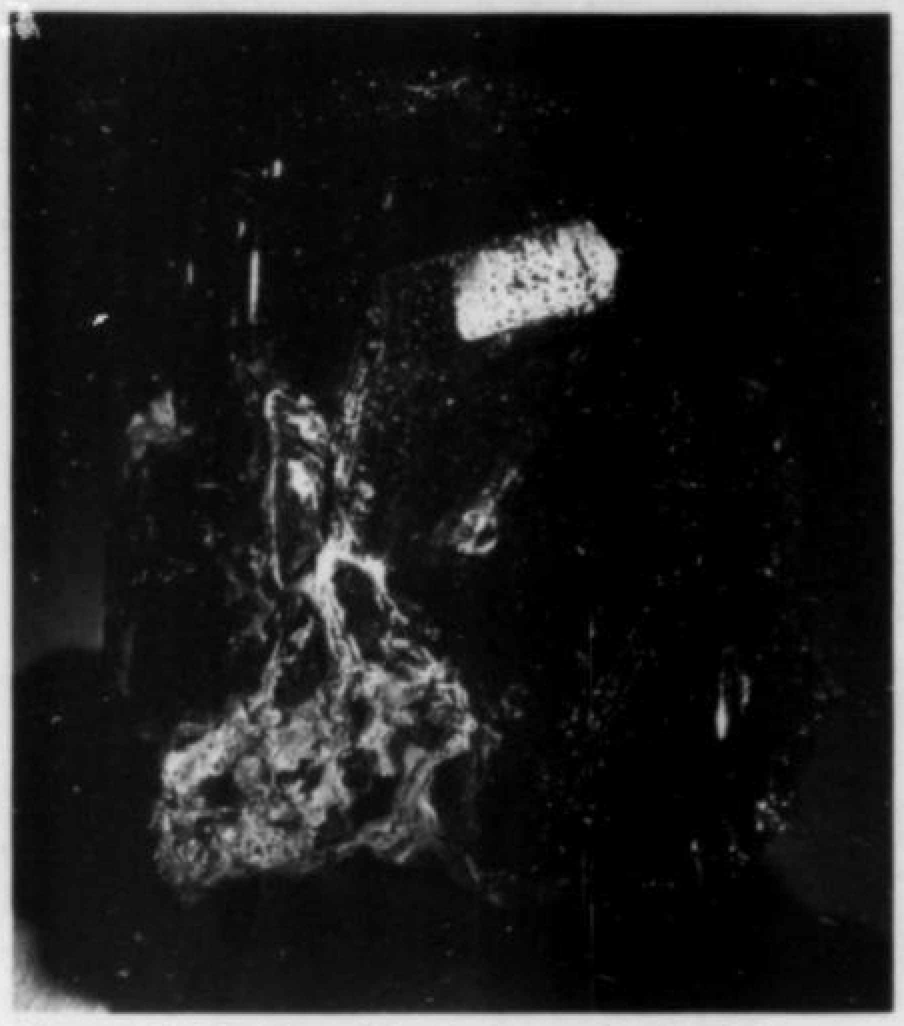

Figure 6. **Barite with chalcopyrite inclusions from the Black Rock open cut, Mount Isa mine. The specimen is 10 cm tall. Museum of Victoria collection; photo by Frank Coffa.**

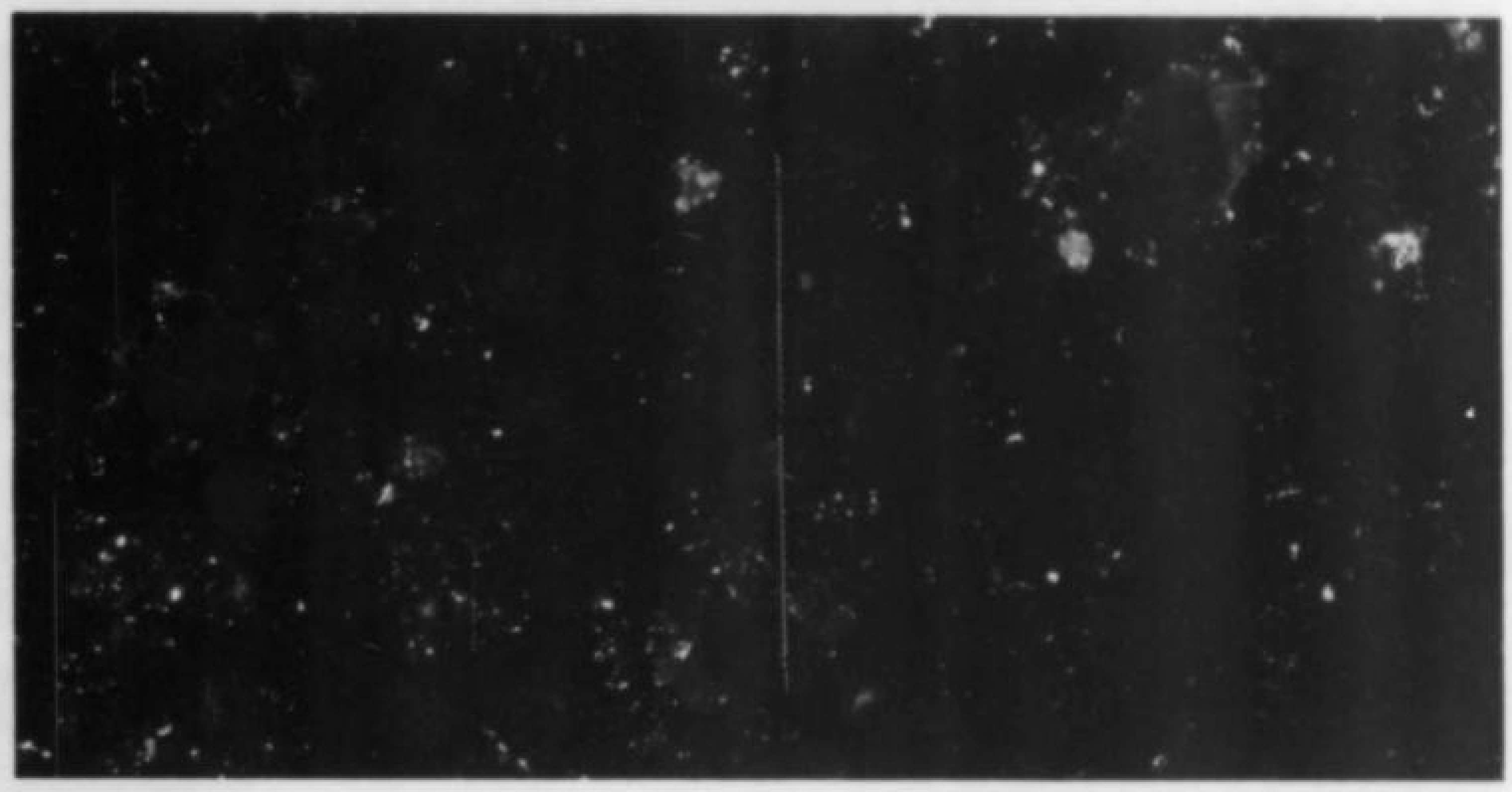

Figure 7. **Sieleckiite globules to 0.2 mm on green libethenite and white variscite from the Mount Oxide mine. Author's collection; photo by Frank Coffa.**

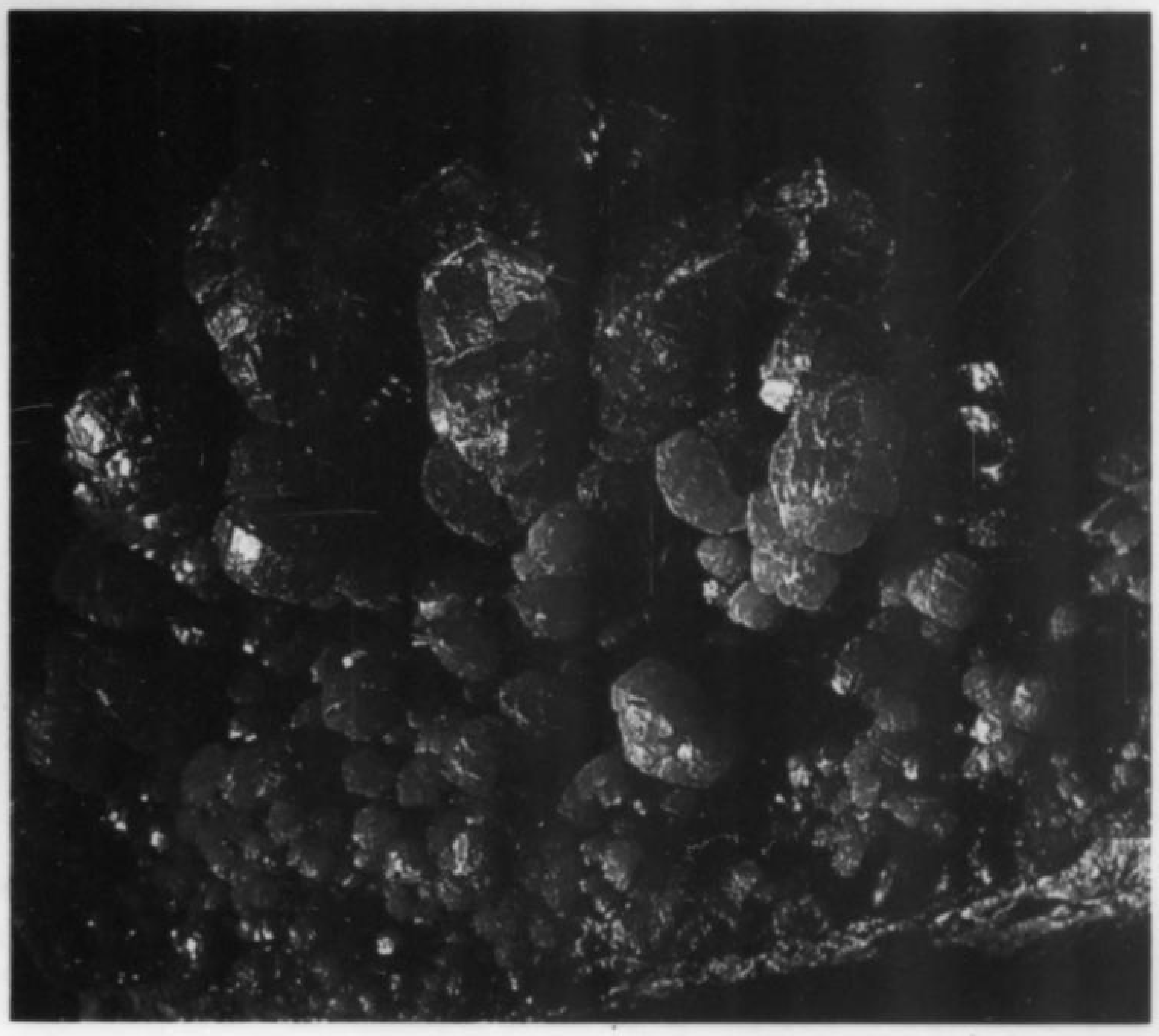

Figure 8. **Pyromorphite crystal group, about 3 cm as shown, from the Black Star open cut, Mount Isa mine. Melbourne University collection; photo by Frank Coffa.**

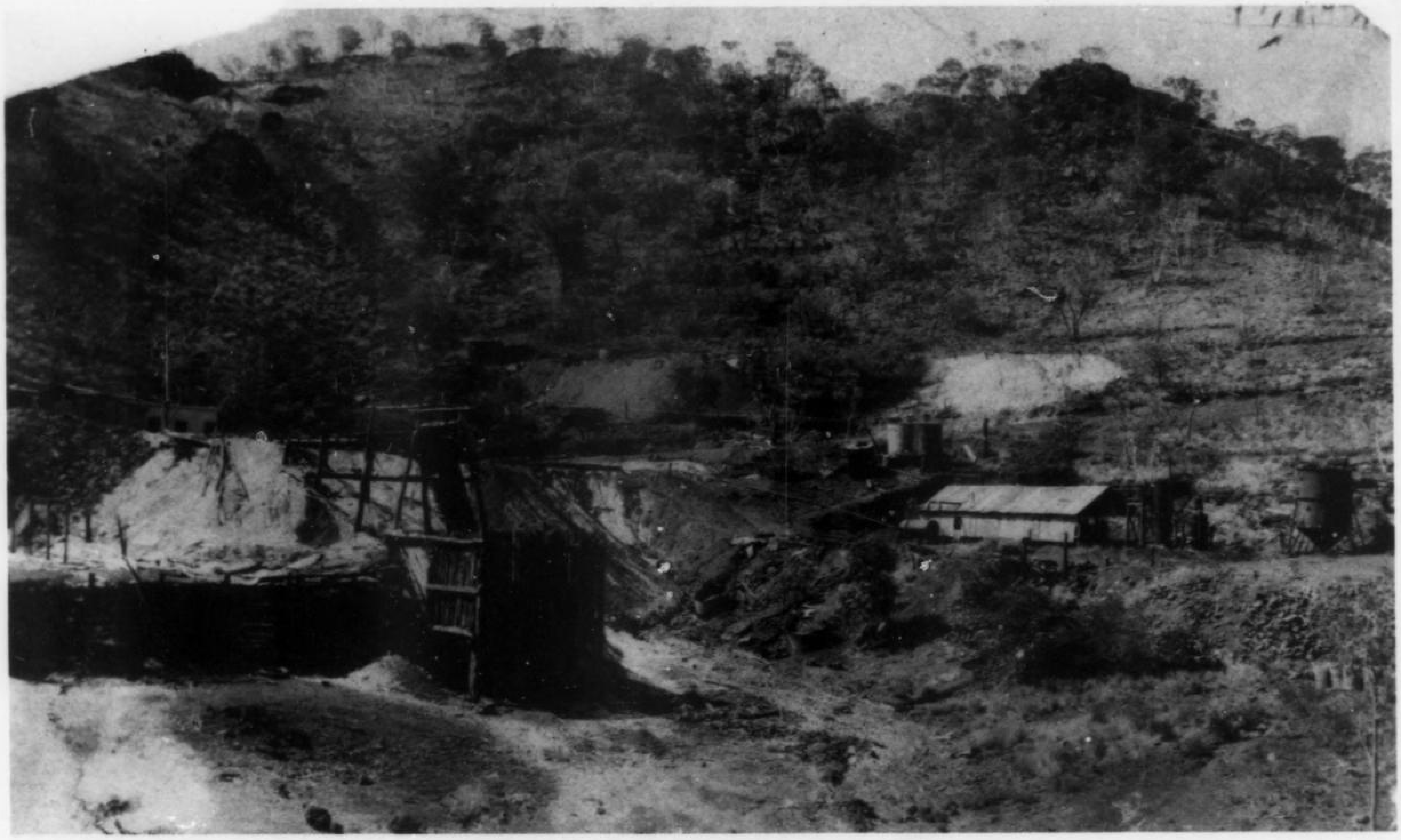

Figure 9. **The Mount Oxide mine, ca. 1920. Photo courtesy of Mount Isa Mines Ltd.**

stantine on the Cloncurry River. At this time Henry discovered the Great Australia copper deposit, thus giving birth to the settlement of Cloncurry (Dunstan, 1913). The first real influx of population came late in 1867 when gold was discovered at nearby Top Camp. The gold rush peaked in 1872 (Brooks, 1982) and was only short-lived.

Apart from the natural hazards, the settlers also feared the large number of aborigines in the area. The most fearsome tribe were the Kalkadoons; several white settlers had been killed by them, and numerous cattle stolen. However Ernest Henry befriended the aborigines, and they helped him find several copper deposits including Argylla (later renamed the Blockade) and Mount Oxide (Carter *et al.*, 1961). These two deposits are discussed later.

Up until 1910 the white population in the district rarely exceeded 500, but by 1918 the official estimate was 7795 (Carter *et al.*, 1961).

The first regular passenger service to the field was a coach service to Cloncurry from the east coast begun in 1884 by Cobb & Co. In 1908 a railway line from Townsville (on the east coast) to Cloncurry was completed, this event initiating a great period of expansion. The line was later extended to various mining centers within the field. An airmail service was begun in 1922 and Australia's first flying doctor base was established in Cloncurry in 1928. At last the effects of remoteness were being appreciably lessened. Even today, despite a daily air service, the area still suffers from its extreme isolation, lying some 1847 kilometers by road from the nearest major Australian city—Brisbane.

Between 1867 and the present, many townships have grown and died in the district along with the mines that spawned them. Numerous relics can still be found throughout the field.

During their epic journey to the gulf, Burke and Wills made a note

Figure 10. **Shrinkage stoping in the Black Rock area, Mount Isa, in 1932. Photo courtesy Mount Isa Mines Ltd.**

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[1] The nearby Gregory Downs homestead and the township of Burketown were settled in 1865 but these lie just outside the mineral field.

***Figure 11*. The Racecourse outcrop, scene of the earliest mining at Mount Isa, 1923–1924. Photo courtesy Mount Isa Mines Ltd.**

of the mineralized appearance of some of the rocks of the district. McKinley led a search for Burke and Wills in 1861 and noticed a specimen of rock containing copper (Carter *et al.*, 1961). These were the first indications of the metalliferous wealth of the district.

Even though it was copper which first brought attention to the mineral wealth of northwest Queensland, it was gold which accounted for most of the activity between 1867 and 1900. Gold was first reported from Sunday Gully in the Bower Bird area in 1867, and later in the year from Top Camp, south of Cloncurry. The largest nugget reported weighed 336 ounces, from Chinaman's Flat in the Top Camp area (Birch, 1987). The Chinese were undoubtedly the most successful in mining the alluvial gold. Most of the gold in the field was alluvial, with reef gold being the exception. The Cloncurry district was declared a "goldfield" in 1889 and a "mineral field" in 1899. Overall the field has never ranked as a major producer of gold, however some significant discoveries have been made recently which may in time change the status of the field.

With the coming of the railway and increasing copper prices in the early 1900's, copper became the most important metal in the province. Between 1900 and 1930 the largest copper producers were Mount Elliott and Duchess, each producing about 25,000 tons of copper metal. Both mines were prospected in the 1890's.

The Mount Cobalt deposit (see later) was discovered in 1919 and produced 766 tons of cobalt between 1921 and 1934 (Carter *et al.*, 1961).

The Mount Isa deposit was discovered in 1923, and large scale production began in 1931 (Mount Isa Mines Ltd., 1977). This changed the emphasis of mining in the district to silver-lead-zinc until 1943, when copper stocks became low due to World War II. Since then copper and silver-lead-zinc have vied for importance.

In 1954 a new phase of mining was entered in the field with the discovery of the Mary Kathleen uranium deposit. Mining began in 1956 and continued until 1963 when interest in uranium languished. Mining commenced again in 1978 and ended in1982 when ore reserves were depleted (Brooks, 1982). Much of the town of Mary Kathleen and the mining equipment was subsequently moved to a historical park in Cloncurry for preservation.

In 1948 a new silver-lead-zinc body was intersected 20 km north of Mount Isa (Mathias *et al.*, 1973). This deposit is now being developed as the Hilton mine by Mount Isa Mines Ltd., and began trial production in 1987. Already some attractive microcrystals of stephanite and pyrargyrite have emerged. Present indications are that the deposit is of similar size to the Mount Isa silver-lead-zinc orebodies, so the Mount Isa-Cloncurry mineral field looks as though it may have quite a long future.

GEOLOGY

The Mount Isa-Cloncurry mineral field occurs in a belt of north-northwesterly trending Precambrian rocks variably known as the Mount Isa geosyncline (Brown *et al.*, 1968; Mathias and Clark, 1975), or the Mount Isa inlier (Blake *et al.*, 1986). The area has been divided into three tectonic provinces known as the Western Succession, the

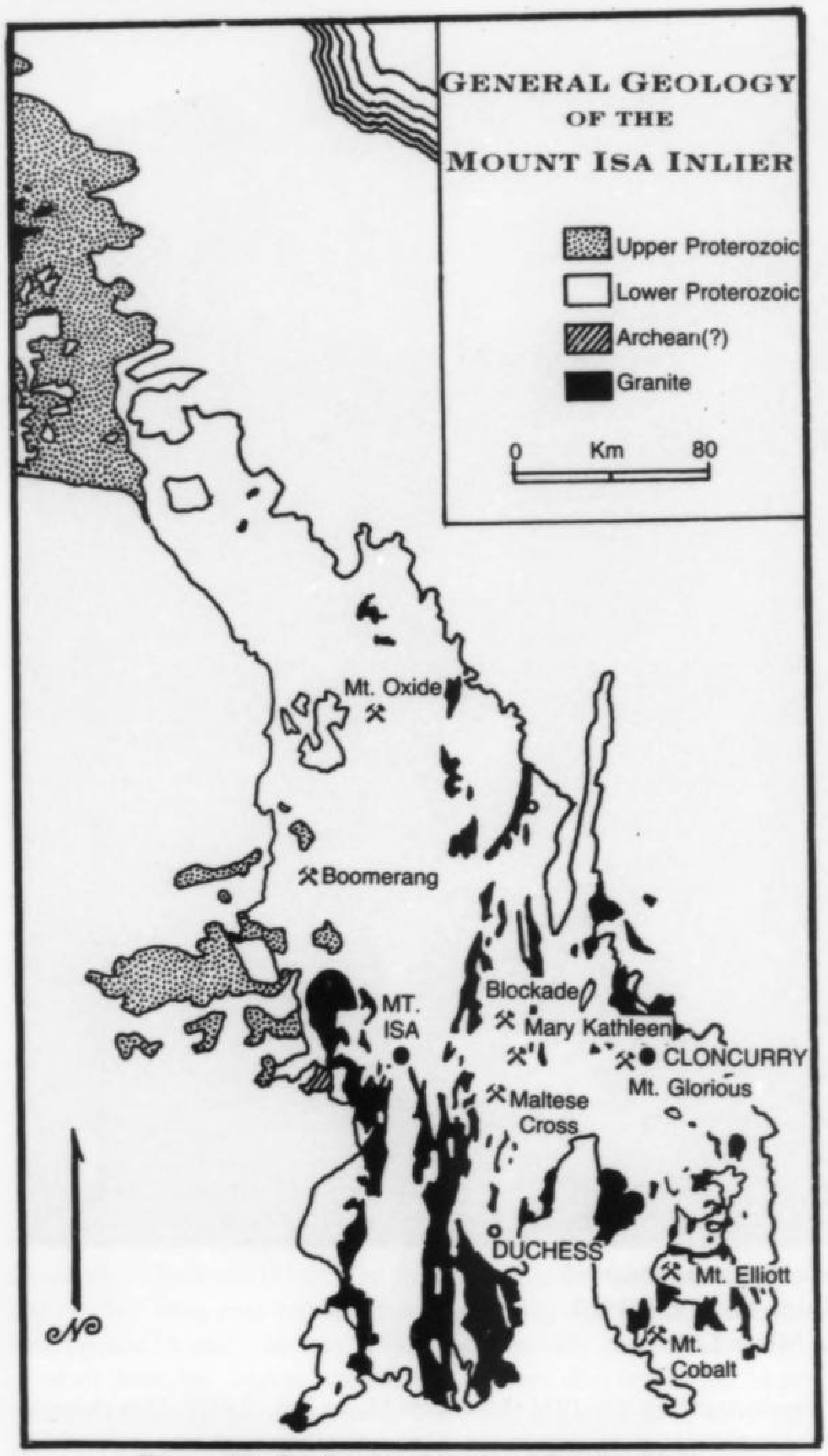

Figure 12. **Geology and major mine locations in the Mount Isa-Cloncurry area (adapted from Carter *et al.*, 1961).**

Tectonic Welt and the Eastern Succession (Taylor and Scott, 1982).

The economically important Western succession is further subdivided into the Lawn Hill platform and the Leichhardt River fault trough. The rocks in this succession are of lower to middle Proterozoic age. The Tectonic welt represents an uplifted block of lower Proterozoic basement rocks known as the Leichhardt metamorphics, these being extensively intruded by the Kalkadoon Granites of similar age. The Eastern succession is represented by lower Proterozoic rocks.

Most of the major stratigraphic groups contain economic mineralization, especially the Mount Isa and McNamara groups. These two groups, which are between 4 and 6 km thick, may be correlated and are host to major dolomitic and pyritic shale-hosted silver-lead-zinc deposits.

In terms of the tectonic evolution of the region (Derrick, 1982), the Mount Isa and McNamara groups represent a marked change to quiet-water sedimentation following an extended period of widespread and thick deposition of epicontinental clastics, conglomerates, orthoquartzites and carbonates with intervals of substantial basaltic and lesser acidic volcanism.

Within the Eastern succession and the Tectonic welt most of the strata have been subjected to at least two periods of orogenic deformation. The Western succession of the Mount Isa inlier has experienced at least three major periods of deformation between 1670 and 1480 m.y. ago (Swager, 1985), resulting in complex structural overprinting (Bell, 1983).

The Western succession rocks are generally metamorphosed to greenschist facies whereas those in the Tectonic welt and Eastern succession often reach amphibolite facies. Contact metamorphism around granitic rocks is locally well developed and calc-silicate rocks are common. Metasomatism is particularly well developed in the Corella Formation to the east where minerals such as scapolite (euhedral crystals reaching 20 cm) are common.

Granitic rocks are widespread throughout the region, with the most important events occurring around 1680 m.y. ago with the intrusion of the Sybella and Weberra Granites. Tholeiitic dikes are also common.

Mineralization

Northwestern Queensland has, for a long time, been one of Australia's most important metal-producing districts. Significant deposits of copper, lead, zinc, silver, uranium, gold, cobalt, cadmium, rare earths, manganese and beryllium occur here.

Silver-Lead-Zinc

Silver-lead-zinc deposits are most common in the Mount Isa and McNamara groups. The Mount Isa and Hilton deposits occur in the Urquhart Shale within the Mount Isa group. The Lady Loretta deposit occurs in the Paradise Creek formation within the McNamara group and will soon be producing ore. Smaller silver-lead-zinc deposits occur in the Eastern succession. All of the major deposits are thought to be stratiform and largely syngenetic. Two small but extremely rich epigenetic silver deposits occur in the region. The Silver Phantom deposit consists of chlorargyrite and native silver in a barite and limonitic jasper gangue, whereas the deposit near O'Brien's Soak consists of naumannite, native silver, chlorargyrite and calcite in a narrow fissure in amphibolite (Carter *et al.*, 1961).

Cadmium

Cadmium occurs associated with sphalerite in the Mount Isa deposit.

Copper

Copper deposits occur throughout the field and are generally associated with structural features such as faults, with many of the important copper deposits occurring along north to northwest-trending shear zones. The major Mount Isa copper deposit is associated with transgressive silica-dolomite formed during a major deformation event (Perkins, 1984). Most of the deposits are recognized as being epigenetic. An arid climate with an irregular seasonal rainfall (such as in the Mount Isa-Cloncurry district) facilitates the development of extensive oxidation zones. These processes of oxidation and supergene enrichment can increase the grade over hypogene ore several fold. Such processes have been responsible for the formation of hundreds of small, high-grade secondary copper deposits in the area.

Uranium and Rare Earths

There are numerous small epigenetic uranium deposits scattered through the earlier sequences of the Mount Isa inlier, but only the Mary Kathleen deposit is of major economic significance. The major uranium ore mineral in the district is uraninite, although davidite and brannerite are commonly associated with pegmatites in the central part of the region. Individual subhedral davidite crystals up to 7 cm long have been reported (Carter *et al.*, 1961). With the exception of the Milo deposit, secondary uranium minerals are uncommon. The main ore mineral at the Milo deposit is coarse grained metatorbernite, with platy crystals frequently reaching 5 mm. The rare earth minerals allanite and stillwellite occur in abundance at Mary Kathleen.

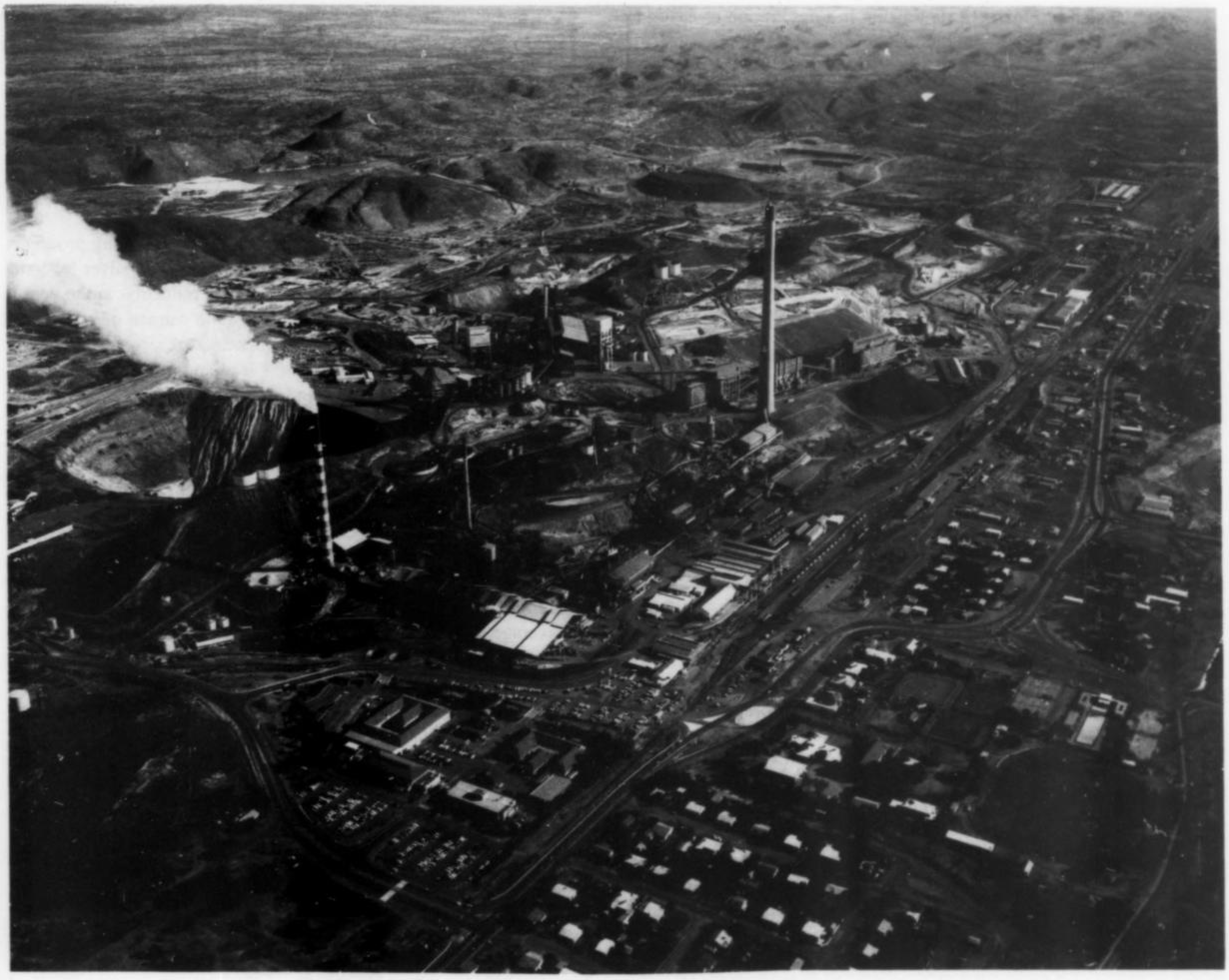

Figure 13. **The Mount Isa mine, 1984. Photo courtesy Mount Isa Mines Ltd.**

Gold

Gold is associated with many copper deposits throughout the stratigraphic sequence but is generally of low grade. The grades tend to be highest south and east of Cloncurry, e.g., the Mount Elliott copper-gold deposit, which averaged 6 grams/tonne gold (Carter *et al.*, 1961). In the Soldiers Cap group medium-grade deposits occur associated with ferruginous sediments and ironstones. Reef gold occurs in isolated deposits (e.g., Gilded Rose reefs) while alluvial gold deposits near Cloncurry were important in the early history of the mineral field. The alluvial gold is often associated with native bismuth and bismuthinite.

Cobalt

Cobalt mineralization generally occurs as small deposits of cobaltite in a narrow meridional belt from Kajabbi in the north to Mount Cobalt in the south. The deposits are generally shear controlled, although the origin of the cobalt is uncertain. The important Mount Cobalt deposit occurs in a shear zone within sediments of the Kuridala formation (Carter *et al.*, 1961).

Manganese

Manganese occurs most commonly in a north-south belt between Cloncurry and Mount Cobalt. The most important deposits occur in the Marimo slate within the Mary Kathleen group. The manganese (along with iron and quartz) was deposited within strike faults and shear zones, with subsequent weathering forming prominent ridges of manganese and iron oxides and quartz. The ore generally consists of massive, mixed manganese oxides, although pyrolusite is common, with sharp lustrous crystals commonly exceeding 3 mm in vugs up to 15 cm across. Some hausmannite has also been reported.

Beryllium

Beryllium occurs as beryl in the pegmatites of the Mica Creek area, immediately southwest of Mount Isa. These pegmatites have formed in mica schists and amphibolites along the margin of the Sybella Granite. Large beryl crystals exceeding 1 m long have been reported (Brooks and Shipway, 1960) but good gem-quality material is unknown. Some well crystallized, but poor gem-quality aquamarines have been found. Associated minerals include quartz, feldspar, coarse books of muscovite and biotite, and rare bertrandite. Less closely associated minerals include euhedral tantalite-columbite crystals up to 10 cm across and prismatic schorl crystals up to 30 cm long, with doubly terminated crystals reaching 10 cm in the surrounding mica schists.

There are literally hundreds of mines in the Mount Isa-Cloncurry field, some of which have from time to time yielded display-quality mineral specimens. Some of the more important specimen-producing mines are shown in Figure 12. Following is a description of each of these mines, along with a brief summary of several others.

MOUNT ISA MINE

Introduction

The Mount Isa mine is located on Mount Isa at latitude 20°44′S, longitude 139°29′E. It lies within a small range of hills on the vast, semi-arid plains of Australia at an elevation of 380 m above mean sea level. The mine is one of the world's great base metal mines.

Though not well known for its mineral specimens, it has over the years continued to produce small quantities of top-quality specimens of copper, cuprite, barite, pyromorphite and more recently voltaite and roemerite.

History

The discovery of silver-lead-zinc at Mount Isa was made in February, 1923, by the prospector John Campbell Miles. Although looking for gold and copper, he sent an unfamiliar looking sample of heavy gossanous ore to Cloncurry for assaying, and was surprised when the assays returned yielding very high lead values. Shortly after, he began small-scale mining of the surface lode, little realizing the vast wealth that lay beneath his feet.

Mount Isa Mines Limited was formed as a company in 1924, largely through the efforts of W. H. Corbould who was also influential in forming Mount Elliott Ltd., the first major mining and smelting company in the field.

Large-scale development of the mine began in 1927 when Russo-Asiatic Consolidated Limited bought a controlling interest in the company. Two years later, Mining Trust of London took over all the interests of Russo-Asiatic. In 1930, American Smelting and Refining Company (ASARCO) bought an interest in Mining Trust Limited and thus Mount Isa Mines Limited, an interest which has endured to this day.

Mining, milling and smelting of the oxidized lead and silver ores began in May, 1931. These oxidized ores were depleted in zinc and it wasn't until 1935 when mining of the primary sulfide ore began that zinc concentrate was first produced. Apart from an interruption between 1943–1946, mining of primary silver-lead-zinc ores has continued to this day. Mining of carbonate ores has also continued periodically to this day, these mostly being used as a flux in the smelting of primary sulfide ores. The Black Star open cut is a major source of such carbonates, and has also yielded some spectacular lead, zinc and silver minerals.

Copper was first found near Mount Isa in 1920 at Native Bee. At Mount Isa itself, major copper ore was first detected in 1927, when an exploratory drill hole in the Black Rock area intersected 12 m of secondary ore grading 17% copper.

By 1943 copper reserves had increased considerably and, with the advent of a copper shortage during World War II, the decision was made to concentrate on copper mining. The conversion to copper smelting on such short notice necessitated a scavenger hunt for abandoned smelting equipment around the Cloncurry area, even though the smelters here had been abandoned for more than 20 years. After the war both copper and silver-lead-zinc were being extracted concurrently. In 1954, the 1100 orebody[2]—the largest single orebody in the Mount Isa lodes—was discovered, with reserves estimated at 200 million tonnes grading 3.3% copper.

Of particular interest to mineral collectors is the Black Rock copper deposit which forms the oxidized portions of the 500 copper orebody. The mineralization was first intersected in 1927 but it wasn't until the late 1950's that the extensive nature of the copper orebody was realized. Although some mining of the lode had begun years earlier, most of the mining of the Black Rock open cut occurred between 1957 to 1965. As the open cut expanded it became necessary to move many buildings including the general office. Mining ceased in 1965, with the walls of the open cut needing to be stabilized because subsidence threatened to undermine the new mine office!

One of the more bizarre proposals put forth at this time was to use a nuclear explosion to create a ready-made open cut which could then be expanded by conventional mining methods. This idea was quickly shelved.

Since its first year of production in 1931, when mining proceeded at an annual rate of approximately 660,000 tonnes of silver-lead-zinc ore, the mining rate has steadily increased. Production in the year to June 30th, 1986, amounted to 5.38 million tonnes of copper ore grading 3.3% copper and 4.59 million tonnes of silver-lead-zinc ore grading 145 grams/tonne silver, 5.4% lead and 6.5% zinc.

The aforementioned history and production figures were gleaned primarily from Carter *et al.* (1961), Buchanan *et al.* (1983), Mount Isa Mines Limited (1977), Smith (1975), Blainey (1970), and Mount Isa Mines Limited (1986).

Geology

The Mount Isa deposit consists of two groups of orebodies, the copper orebodies and the silver-lead-zinc orebodies.. The two groups, closely related spatially but perhaps not genetically, extend over a strike length of 4.5 km, a width of 1 km and a depth of 1.6 km, with an average dip of 65° to the west. The orebodies are almost entirely confined to the Urquhart Shale member of the Mount Isa group.

The Urquhart Shale has been subdivided into: (1) an essentially stratabound silica-dolomite which hosts the copper orebodies and which consists of partly brecciated and recrystallized dolomite and/or siliceous shale fragments and crystalline dolomite and quartz; (2) pyritic, tuff-bearing shale hosting all the stratiform silver-lead-zinc orebodies and (3) non-mineralized tuffaceous, carbonaceous dolomitic shale and siltstone.

A number of thin but persistent microcline-rich tuffaceous beds occur throughout the Urquhart Shale and these have been conveniently used as marker horizons.

In the Mount Isa mine area the steeply dipping Urquhart shale is truncated at depth by a complex fault contact with older greenstones correlated with the Eastern Creek volcanics (Perkins, 1984).

There are eight major copper orebodies and numerous silver-lead-zinc orebodies at Mount Isa. The copper orebodies occur close to, but separate from, the silver-lead-zinc orebodies. This observation has led to much debate over the years regarding the genesis of the two groups of orebodies. The first published geological interpretation was that of E. C. Saint Smith (1923) who suggested that granite intrusion resulted in replacement of nearby strata. Since that time a number of origins have been proposed, for example:

Epigenetic Ag-Pb-Zn and Cu (Grondijs and Schouten, 1937)
Syngenetic Ag-Pb-Zn and Cu (Stanton, 1962)
Syngenetic Ag-Pb-Zn and diagenetic Cu (Mathias and Clark, 1975)
Syngenetic Ag-Pb-Zn and epigenetic Cu (Murray, 1961; Smith and Walker, 1972)

The most popular theory being expounded these days is for syngenetic or early diagenetic silver-lead-zinc and epigenetic copper. The silver-lead-zinc orebodies are generally thought to have formed about 1670 m.y. ago in a saline, shallow-water environment, possibly a fault-bounded lake complex (Neudert and Russell, 1981). Modern-day analoges for such a system occur in East Africa and the Dead Sea.

The driving force behind this first mineralizing event is still in doubt,although Gulson *et al.* (1983) have suggested the formation of the rift and a high geothermal gradient setting up a large convection cell. Meteoric waters circulating around this cell scavenged silver, lead and zinc from the underlying rocks and rose to the surface along faults, whereby the metals were deposited either as chemical sediments

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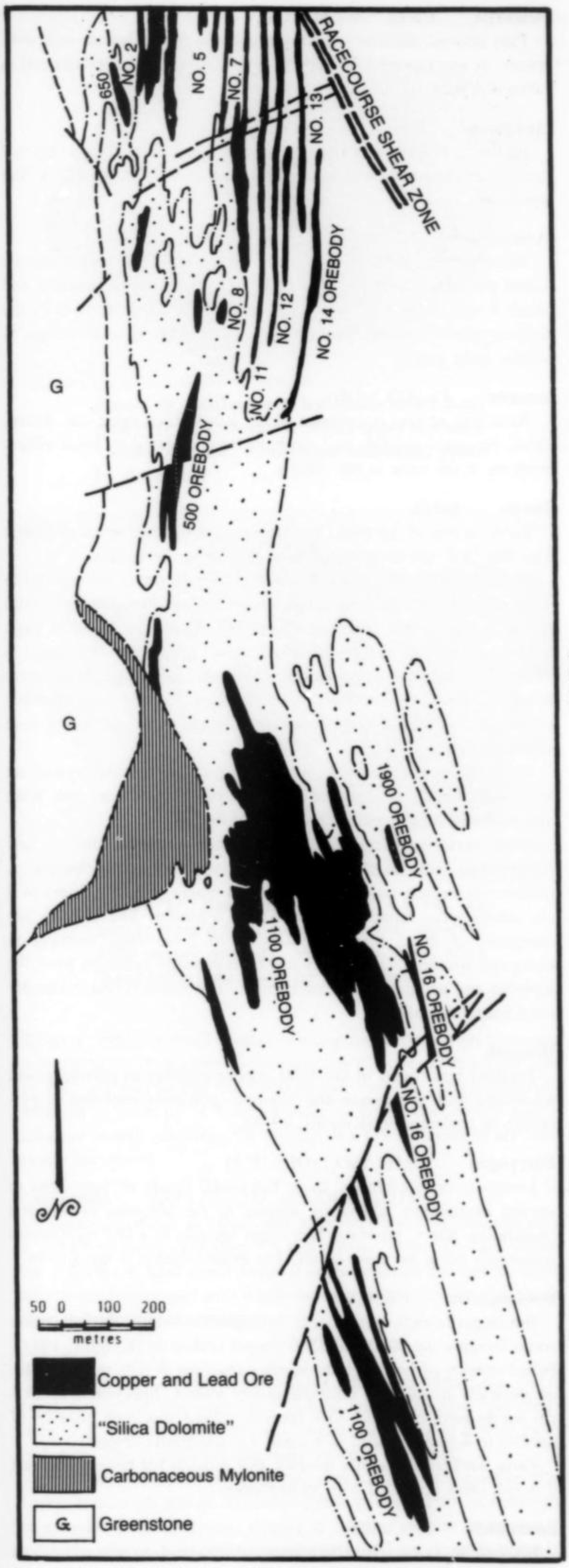
[2] Named by measuring the distance from the hangingwall of the main formation to the orebody itself—i.e., 1100 feet.



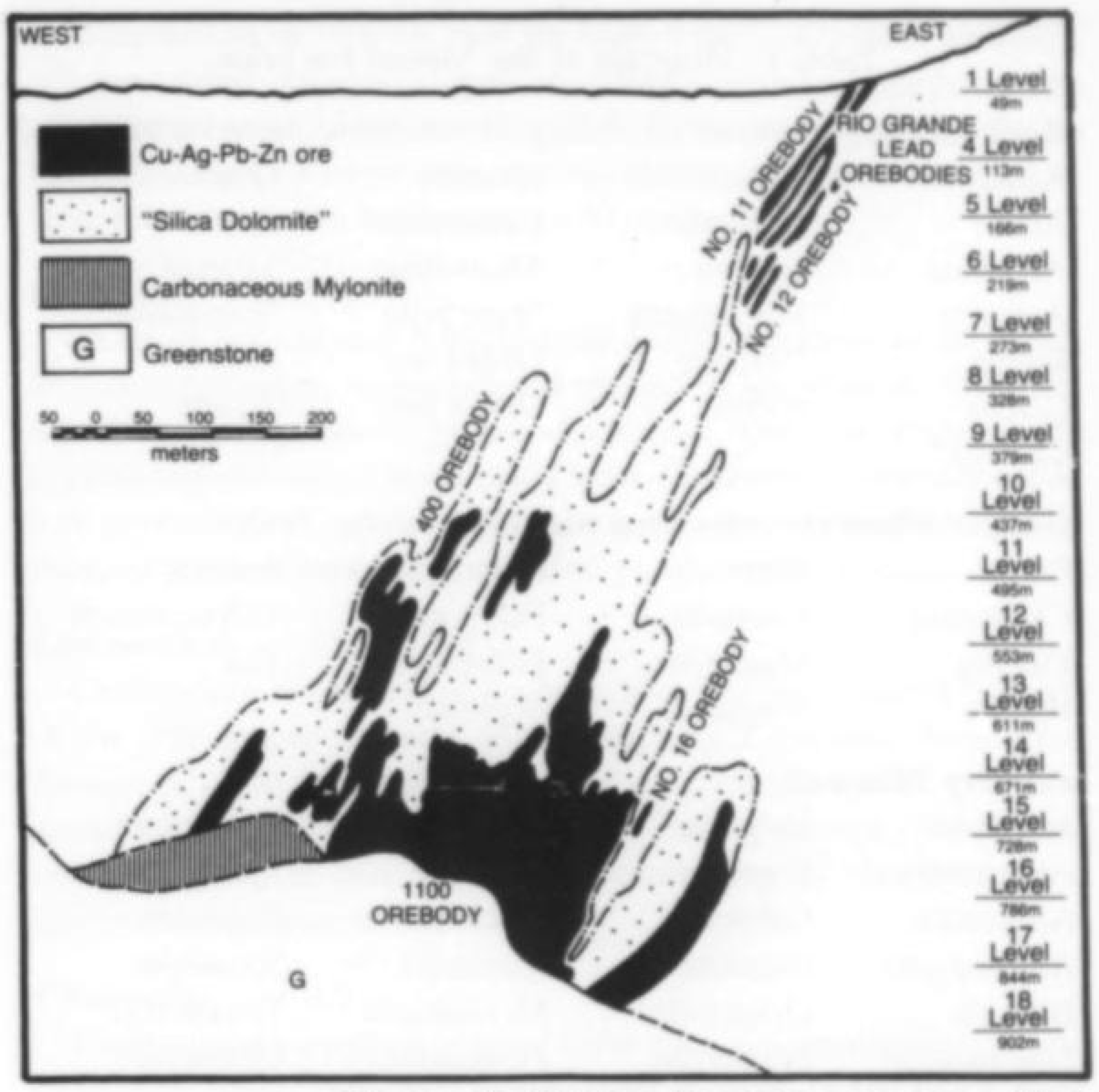


***Figure 15.* Mount Isa mine, cross section through the southern area (after Mount Isa Mines Ltd., 1983).**

***Figure 14.* Mount Isa mine, No. 15 level (728 meters below the surface (after Mount Isa Mines Ltd., 1977).**

at the basin floor/water interface or diagenetically within the sediments. An alternative heat source for this convection cell may be the intrusion of the Sybella Granite around 1680 m.y. ago (Derrick, 1982).

The second major mineralizing event produced the copper orebodies and, according to Swager (1985), may have occurred 180 m.y. after the formation of the silver-lead-zinc orebodies. The currently accepted model being advocated by workers such as Perkins (1984) and Swager (1985) involves syntectonic introduction of quartz, and dissolution and reprecipitation of dolomite forming the silica-dolomite host rock. Continued deformation resulted in further fracturing and brecciation. Finally copper-rich solutions were introduced into the silica-dolomite resulting in chalcopyrite mineralization, largely through replacement of dolomite. The source of these metamorphic mineralizing solutions is still in question. It is not yet known if the formation of the Mount Isa copper deposit is a unique event in the region or if it represents a single part of a regional mineralization event resulting in the formation of the many hundreds of copper deposits in the area.

Later oxidation, leaching and secondary enrichment have affected the Mount Isa orebodies to varying extents. Nearly complete oxidation extends to an average depth of 50–60 meters below the surface while the zone of secondary enrichment is confined to within 20 meters of the base of complete oxidation. The most striking effect of oxidation is seen in the 500 copper orebody where, because of a major series of late-stage, near-vertical faults (S39—U51 fault system), complete oxidation reaches 200 meters and major leaching reaches 800 meters.

Minerals

A total of 118 species have been confirmed from the Mount Isa mine. Table 1 lists these species according to their most common mode of occurrence, with some minerals really falling into more than one category. Most of the post-mining minerals would also have formed as supergene minerals prior to mining.

Most of the minerals described below have been positively identified by modern analytical techniques such as XRD and SEM. Those which have been identified by optical means only are so indicated. Only the more significant species are described.

Table 1. **Minerals of the Mount Isa mine.**

Rock-forming Minerals (including metamorphic alteration minerals)

Actinolite
Albite
Andesine
Ankerite
Biotite
Calcite
Chlorite*
Clinozoisite
Dolomite
Epidote
Fluorapatite
Graphite
Halite
Ilmenite
Leucoxene*
Microcline
Muscovite
Oligoclase
Orthoclase
Quartz
Rutile
Titanite
Tourmaline*
Zircon
Zoisite

Gangue Minerals (associated with mineralizing fluids)

Barite
Cacoxenite
Fluorite
Huntite
Illite
Kaolinite
Magnesite
Magnetite
Montmorillonite
Palygorskite
Phlogopite
Sepiolite
Siderite
Stilpnomelane
Talc

Primary Minerals

Acanthite
Allargentum
Alloclasite
Arsenopyrite
Bismuth
Boulangerite
Bournonite
Chalcopyrite
Cobaltite
Costibite
Cubanite
Digenite
Dyscrasite
Freibergite
Galena
Gold
Gudmundite
Lillianite
Mackinawite
Marcasite
Meneghinite
Pentlandite
Polybasite
Proustite
Pyrargyrite
Pyrite
Pyrrhotite
Sphalerite
Tetrahedrite
Ullmannite
Willyamite

Secondary Minerals

Anglesite
Aragonite
Azurite
Cerussite
Chalcocite
Chlorargyrite
Chrysocolla
Copper
Coronadite
Covellite
Cuprite
Delafossite
Goethite
Gypsum
Hematite
Hemimorphite
Hydrocerussite
Leadhillite
Lepidocrocite
Malachite
Massicot
Mimetite
Phosgenite
Psilomelane*
Pyrolusite
Pyromorphite
Rosasite
Silver
Smithsonite
Sulfur
Tenorite

Post-mining Minerals

Botryogen
Chalcanthite
Coquimbite
Dietrichite
Epsomite
Ferricopiapite
Halotrichite
Hexahydrite
Jarosite
Kieserite*
Kornelite
Melanterite
Pickeringite
Rhomboclase
Roemerite
Voltaite

*Mineral group (species yet to be determined).

Acanthite Ag_2S

Acanthite occurs as microscopic inclusions in the silver-lead-zinc ores, where it forms from the decomposition of earlier silver sulfosalts.

Allargentum $Ag_{1-x}Sb_x$

Minute grains of allargentum have been found in silver-antimony rich veins occurring in the outer silica-dolomite envelopes of the 3000 and 3500 copper orebodies (Knights, 1984).

Alloclasite (Co,Fe)AsS

Alloclasite occurs sparingly as silver-white, doubly terminated, prismatic crystals averaging 0.015 mm. It is associated with cobaltite in the copper orebodies (Croxford 1974)

Anglesite $PbSO_4$

Anglesite is moderately common in the lower oxidized portions of the silver-lead-zinc orebodies. White to colorless prismatic crystals to 3 mm were recently found associated with hemimorphite in the Black Star open cut. The mineral commonly occurs as concentric rings formed around galena residuals.

Ankerite $Ca(Fe^{+2},Mg,Mn)(CO_3)_2$

Fine grained ankerite occurs sparingly in the carbonate-rich sediments. It was reported by Bennett (1965) as an accessory mineral in silica-dolomite.

Aragonite $CaCO_3$

Radiating clusters of colorless, prismatic aragonite crystals up to 7 mm in length occur on dolomite and magnesite from the Black Star open cut.

Arsenopyrite FeAsS

Arsenopyrite occurs in minor amounts in both the copper and the silver-lead-zinc orebodies. The crystals are commonly euhedral and reach 4 mm (Blanchard and Hall, 1942). The cobalt content of the arsenopyrite is variable; Croxford (1974) reported up to 10 weight % within some grains.

Azurite $Cu_3(CO_3)_2(OH)_2$

Azurite is of rare occurrence in the Black Rock open cut. Sharp, thick, prismatic crystals to 2 cm have been reported by local miners working at the mine in the 1960's.

Barite $BaSO_4$

Barite is one of the more spectacular minerals occurring at Mount Isa. The best specimens come from the copper orebodies.

Beautiful, golden brown, flattened tabular to prismatic crystals to 4 cm occur associated with native copper (often altered to malachite) within a honeycomb siliceous sinter. The sinter was found in large masses on 4 level within the Black Rock open cut. The barite is clouded by native copper inclusions. Plates exceeding 30 cm were found but few have survived. Some large, golden brown, prismatic crystals to 10 cm with copper, chalcopyrite and pyrite inclusions were also found.

Occasional yellow-brown, blocky prismatic to tabular crystals up to 10 cm in length, some doubly terminated, have emerged from various fault zones within the copper orebodies.

Some attractive barite clusters have been found in sepiolite and palygorskite fault fill from within the silver-lead-zinc orebodies. A notable occurrence was on 16D sublevel where yellow clusters to 3 cm across were found enclosed within sepiolite. The clusters are composed of thick, bladed crystals up to 2 cm long, forming as elongated rosettes. The miners use high-pressure hoses to blast the sepiolite and palygorskite in such faults. The result is that it literally rains barite crystals.

Bismuth Bi

Bismuth was found in the 1100 copper orebody as minute grains associated with ullmannite and lillianite, generally enclosed in pyrrhotite or chalcopyrite (Knights, 1975).

Botryogen $MgFe^{+3}(SO_4)_2(OH)\cdot 7H_2O$

Lustrous, orange-brown, thick botryoidal crusts of botryogen to several centimeters across are housed in the Museum of Victoria (Australia). Short, prismatic botryogen crystals to a few millimeters commonly occur on these crusts. The exact location is not known.

Boulangerite $Pb_5Sb_4S_{11}$

Boulangerite-rich veins occur infrequently within the alteration zones fringing the 3000 and 3500 copper orebodies (Knights, 1984). Felted masses of boulangerite needles reaching 8 mm in length are occasionally found on a dolomite-quartz matrix. Specimens up to 3 cm across have emerged. One recently mined specimen consists of needles to 4 mm included in a clear, 1.6-cm quartz crystal.

Early workers frequently mistook this mineral for jamesonite, and it is still often confused with meneghinite.

Bournonite $PbCuSbS_3$

Bournonite occurs sparingly associated with boulangerite and galena

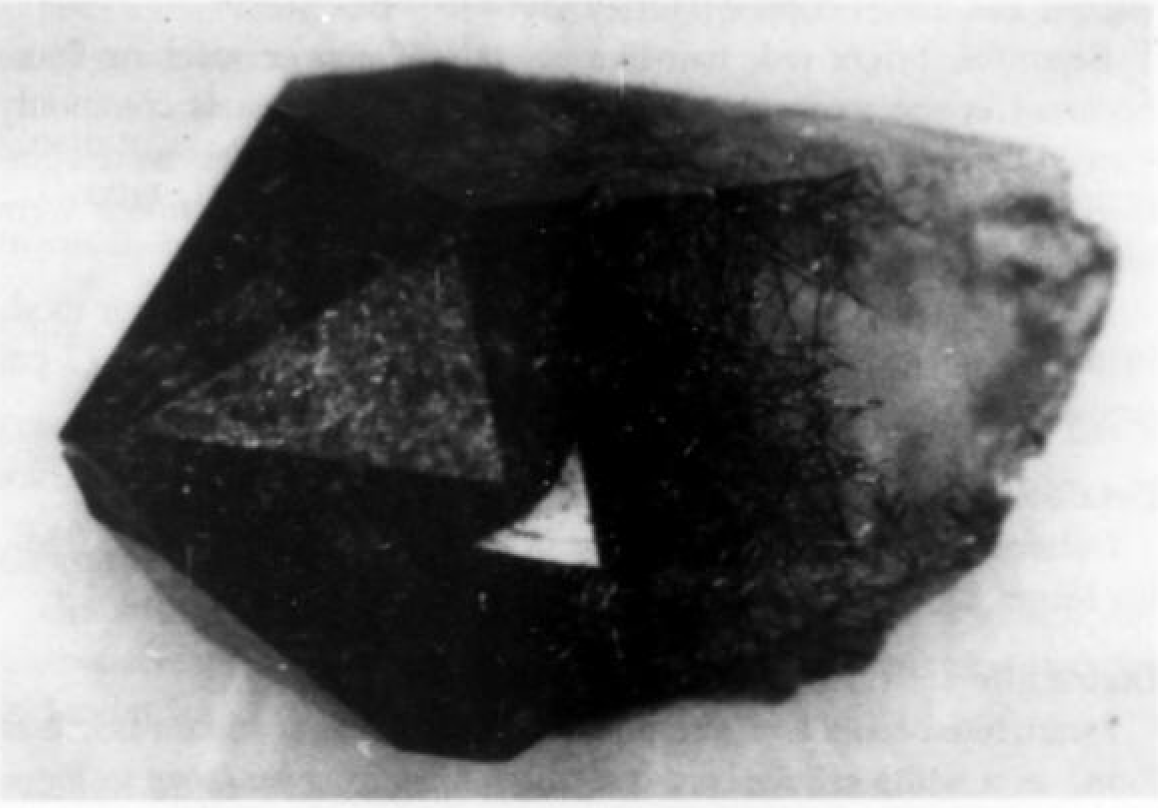


Figure 16. **Boulangerite inclusions in a 1.6-cm quartz crystal, from the 3000 copper orebody, Mount Isa mine. Anonymous collection; photo by the author.**

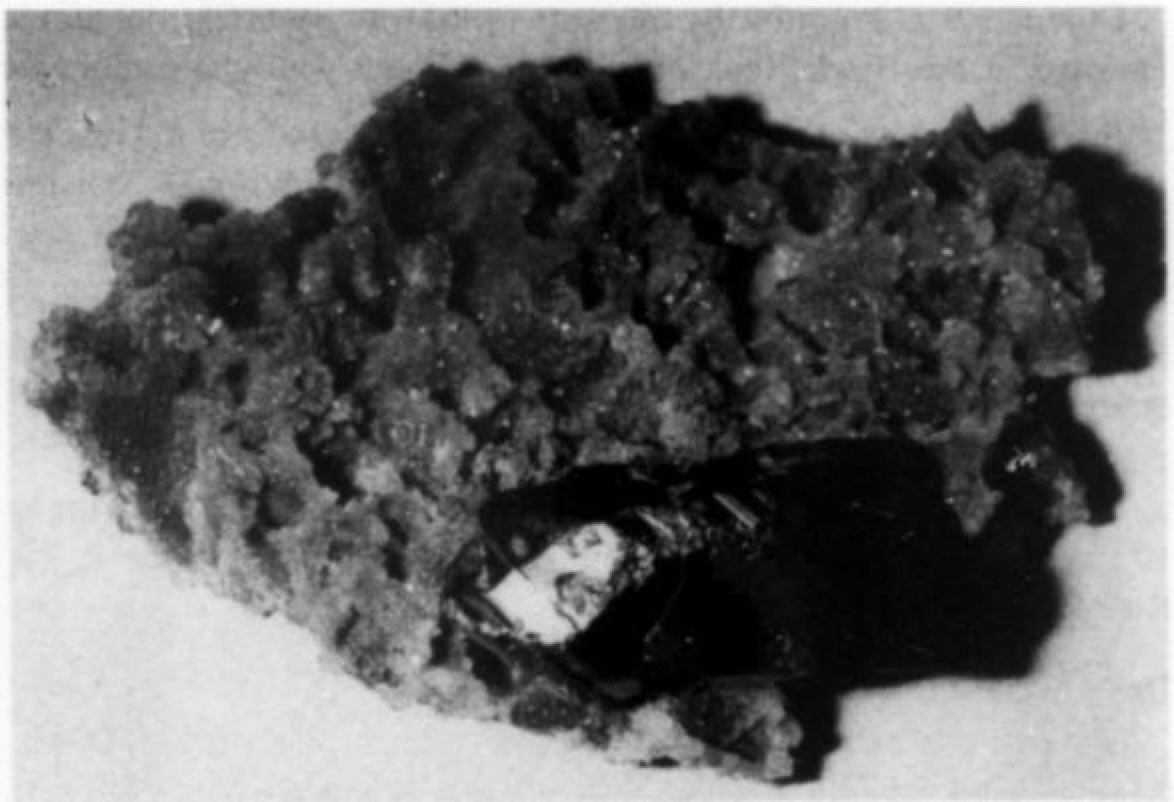


Figure 17. **Bournonite crystal, 4.5 cm, on quartz from a fault zone on the 18C sublevel, 1900 copper orebody, Mount Isa mine. Mick Toole collection; photo by the author.**

(Knights, 1982). A small number of exceptional crystals have emerged over the years. A notable occurrence was discovered in a fault zone on 18C sublevel within the 1900 copper orebody. Sharp, flattened prismatic crystals up to 5 cm or more in length occur on a quartz-dolomite matrix. Chalcopyrite crystals to a few millimeters are commonly associated.

Cacoxenite $(Fe^{+3},Al)_{25}(PO_4)_{17}O_6(OH)_{12}\cdot 17H_2O$

Cacoxenite occurs as radial tufts of brownish yellow, acicular crystals; the tufts rarely exceeding 0.5 mm across. A rare mineral at Mount Isa, it occurs in fault zones where it coats dolomite and quartz. Some attractive micromounts arise where the cacoxenite tufts occur on small, clear, euhedral quartz crystals.

Calcite $CaCO_3$

Although only a minor rock-forming mineral at Mount Isa, calcite veins throughout the mine have yielded many attractive specimens. Individual crystals reach 20 cm or more and occur in a wide range of habits. The crystals are generally white or colorless.

"Nail head" calcites are often found in palygorskite/sepiolite-filled faults, some with minute iridescent pyrite pyritohedrons covering the terminations. Some crystals display an unusual scepter formation.

Thick, tabular, hexagonal crystals reaching 5 cm occur in plates up to 25 cm across on 19 level, near the base of the 1100 copper orebody.

Large, white, irregular shaped "dog-tooth" crystals resembling ice-cream cones were found in a fault zone in the 1900 copper orebody. Individual crystals commonly reached 20 cm and often occurred in randomly intergrown clusters up to 50 cm across.

Cerussite $PbCO_3$

Cerussite is a common mineral in the oxidized portions of the silver-lead-zinc orebodies, however good specimens are unusual. The most significant occurrence is in the Black Star open cut where single crystals and reticulated twins reach 1 cm. Cerussite is often associated with pyromorphite, sometimes forming an attractive frosted mass of interlocking crystals coating euhedral pyromorphite crystals.

Chalcanthite $CuSO_4\cdot 5H_2O$

Chalcanthite has occasionally been found in the oxidized portions of the 500 copper orebody. Fibers reaching 2 cm have been seen. Stalactites up to 8 cm high composed of granular crystals are occasionally found. Although listed as a post-mining mineral, chalcanthite has been noted in fresh drill cores, confirming its occurrence as a legitimate supergene product.

Chalcocite Cu_2S

Chalcocite is a common mineral in the zone of secondary enrichment (transition zone), especially in the lower portions of the Black Rock open cut where it is associated with pyrite and native copper (Smith, 1975). It is often seen to replace pyrite and is generally sooty in appearance. Specimen-quality crystals are unknown.

Chalcopyrite $CuFeS_2$

Chalcopyrite is a major ore mineral associated with pyrite, pyrrhotite, cobaltite, dolomite and quartz. Although not common, good quality crystals occur in dolomite and quartz-lined veins within the copper orebodies. Sphenoidal crystals reaching 7 mm, perched on curved dolomite rhombohedra up to 8 mm across, have recently emerged from the 1900 copper orebody. Plates up to 20 cm across have been collected. The chalcopyrite crystals are often intergrown to form aggregates up to 1 cm across. Clear quartz crystals to 1 cm are a common associate.

Chlorargyrite AgCl

Chlorargyrite occurs in small amounts with native silver between the 25 m and 50 m levels (Clark, 1968). Gloryholing of the Black Star orebodies in the mid-1900's unearthed a number of specimens. Surviving specimens have invariably been labeled "embolite," so further work is needed to confirm the identity of these.

Chrysocolla $(Cu,Al)_2H_2Si_2O_5(OH)_4\cdot nH_2O$

Chrysocolla is abundant near the top of the oxidation zone at the Black Rock open cut where it is associated with malachite (Smith, 1975). Attractive specimens are rare.

Cobaltite CoAsS

Cobaltite is a relatively common mineral in the copper orebodies. It occurs as 0.05-mm crystals associated with pyrite; as overgrowths to 0.3 mm on octahedral pyrite from within quartz veins; and as an infilling in fractures disrupting coarse grained pyrite (Croxford, 1974).

Copper Cu

Copper is common in the lower portions of the oxidized zone where it is most commonly associated with chalcocite and cuprite. It is often seen altering to malachite. The best specimens came from the 500 copper orebody, including the Black Rock open cut.

Up to 150 kg of worm-like, intricately entangled native wire copper occurred along a fault on 5 level, just below the limits of the Black Rock open cut. Arborescent copper occurred in jasper breccia 90 m below the surface at Black Rock (Blanchard and Hall, 1942). Individual crystals in these specimens may reach 1 cm. Leaf forms of copper were also common here. Masses of dendritic copper weighing many tons were common in the Black Rock ores and the crushing unit at Mount Isa was often jammed by these large, malleable masses.

Delicate, spongy, dendritic masses of malachite after copper in specimens up to 10 cm across have been preserved. Native copper often occurs as inclusions in barite crystals found at Black Rock.

Coquimbite $Fe_2^{+3}(SO_4)_3\cdot 9H_2O$

A minor occurrence of coquimbite was found in a leached zone within pyritic sediments on 10 level, near the R62 shaft. The mineral is a delicate, pale lavender color under incandescent light, but pale grey under fluorescent light or sunlight. It is mostly granular, but often forms as aggregates of subparallel platy hexagonal crystals. It is also known as perfect, single, tabular hexagonal crystals to 0.5 x 1 mm and as platy hexagonal crystals to 0.3 x 2 mm.

Coquimbite was reported by Blanchard (1968) to be fairly common as a rose-pink to tan-yellow mineral transitional between pyrite and copiapite. The present scarcity of coquimbite at Mount Isa may suggest that this material was in fact roemerite.

Coronadite $Pb(Mn^{+4},Mn^{+2})_8O_{16}$

Coronadite occurs as a fine grained coating on various secondary minerals within the Black Star open cut (Taylor and Scott, 1982). It is also found in gossanous outcrops at Mount Isa.

Costibite (or Paracostibite) CoSbS

Costibite was tentatively identified by Knights (1984) as irregular grains to 0.02 mm associated with boulangerite and an ullmannite to cobaltian ullmannite series of minerals. It occurs in the outer silica-dolomite envelope of the 3000 and 3500 copper orebodies. Further work is needed to differentiate between costibite and paracostibite.

Covellite CuS

Covellite is commonly associated with chalcocite in the transition zone of the 500 copper orebody (Bennett, 1965). Display quality specimens are unknown.

Cubanite $CuFe_2S_3$

Cubanite was of minor occurrence in the 1100 copper orebody. It most commonly occurs as parallel lamellae to 0.4 mm associated with pyrrhotite and chalcopyrite (Knights, 1975).

Figure 18. **Deep red cuprite crystals to 6 mm, from the Black Rock open cut, Mount Isa mine. Mount Isa Mines Ltd. collection; photo by the author.**

Cuprite Cu_2O

Top-quality specimens of cuprite (especially the acicular habit) have come from the lower reaches of the Black Rock open cut. Here a 10-meter zone at the base of oxidation was composed predominantly of cuprite and native copper (Hurley, 1964).

Beautiful, bright red, hair-like crystals of cuprite reaching 2 cm occurred in specimens up to 25 cm across. The crystals commonly formed densely packed felted masses but isolated crystals were common in cavities within the limonitic matrix. Larger specimens were undoubtedly mined but have not survived.

Fine, deep red cubes up to 6 mm on edge, some with minor modifications, occur with black "psilomelane" in specimens up to 17 cm across.

Delafossite $Cu^{+1}Fe^{+3}O_2$

Delafossite is of rare occurrence in the Black Rock open cut (Mt. Isa Mines Ltd.).

Dietrichite $(Zn,Fe^{+2},Mn)Al_2(SO_4)_4\cdot 22H_2O$

Dietrichite occurs as a rare post-mining mineral at Mount Isa. It is found as a white efflorescent mineral similar in appearance to halotrichite. The mineral quickly breaks down to a fine powder upon exposure to the surface environment (Mary Kathleen Park Museum specimen).

Digenite Cu_9S_5

Digenite was reported by Bennett (1965) as occurring in minor amounts at the Black Rock open cut associated with chalcocite and covellite.

Dolomite $CaMg(CO_3)_2$

Dolomite is a major rock-forming mineral at Mount Isa. The only well crystallized specimens are plates up to 20 cm of white, curved rhombohedral crystals to 8 mm across, sometimes associated with quartz and chalcopyrite crystals. These commonly occur in faults, especially in the copper orebodies.

Lustrous, white to pink stalactites and columns of dolomite up to 10 cm long occur in vugs within massive dolomite-magnesite in the Black Star open cut.

Dyscrasite Ag_3Sb

Dyscrasite has been reported as prismatic crystals up to 0.004 x 0.007 mm included in galena from the Black Star orebodies (Stillwell and Edwards, 1945).

Epsomite $MgSO_4\cdot 7H_2O$

Epsomite is a common post-mining mineral in the mine workings, especially in the upper levels, occurring as white efflorescences, crusts and stalactites.

Ferricopiapite $Fe^{+3}Fe_4^{+3}(SO_4)_6O(OH)\cdot 20H_2O$

Ferricopiapite is a locally common, post-mining mineral in pyrite-rich zones. It occurs as transparent to translucent, bright yellow, platy crystals reaching 1 mm in length, often as loosely aggregated masses on other sulfates such as roemerite, voltaite, and halotrichite. It also occurs as granular masses of darker citrine-yellow grains of indeterminate crystal form. A particularly striking occurrence was described by Sielecki (1985) from an exposure on 4 level in the V60 south drive.

Fluorite CaF_2

Fluorite is rare at Mount Isa, although beautiful, translucent purple cubes up to 8 mm across are occasionally found. The fluorite generally occurs in dolomite veins within the silver-lead-zinc orebodies.

Freibergite $(Ag,Cu,Fe)_{12}(Sb,As)_4S_{13}$

Freibergite is the major silver-bearing mineral at Mount Isa. Riley (1974) has calculated the silver content in Mount Isa freibergite to range from 18.5–42.5 weight %. It occurs as irregular grains up to 0.2 mm across included in galena.

Galena PbS

Galena is a major ore mineral at Mount Isa, associated with sphalerite, freibergite, pyrite and pyrrhotite. It is generally fine grained, although Blanchard and Hall (1942) report galena cubes up to 2.5 cm on edge occurring in quartz veins.

Goethite αFeO(OH)

Goethite is common in gossans at Mount Isa; Hurley (1964) refers to small, brown, radiating clusters of acicular goethite crystals.

Gold (Au,Ag)

Gold is of rare occurrence in the 1100 orebody. It occurs as microscopic inclusions in coarse grained, fractured pyrite, and has a variable silver content (Knights, 1975).

Graphite C

Graphite is a common mineralformed along slickensides at the mine. Carbonaceous material is disseminated through many of the rock types at Mount Isa.

Gudmundite FeSbS

Gudmundite occurs sparingly associated with boulangerite, bournonite, galena and arsenopyrite in silica-dolomite fringing the 3500 copper orebody. Irregularly shaped grains rarely exceed 0.2 mm. Gudmundite is sometimes seen replacing sprays of stilpnomelane (Knights, 1982).

Gypsum $CaSO_4{\cdot}2H_2O$

Gypsum has been observed as both a supergene and a post-mining mineral. Gypsum-filled veins occur throughout the mine, although crystals in such cases are rare. Clear, prismatic crystals up to 5 cm in length, of post-mining origin, occur on fine grained sulfides from 19C sublevel in the 1100 copper orebody. Small, clear, acicular crystals to a few millimeters occur associated with carbonates in the Black Star open cut.

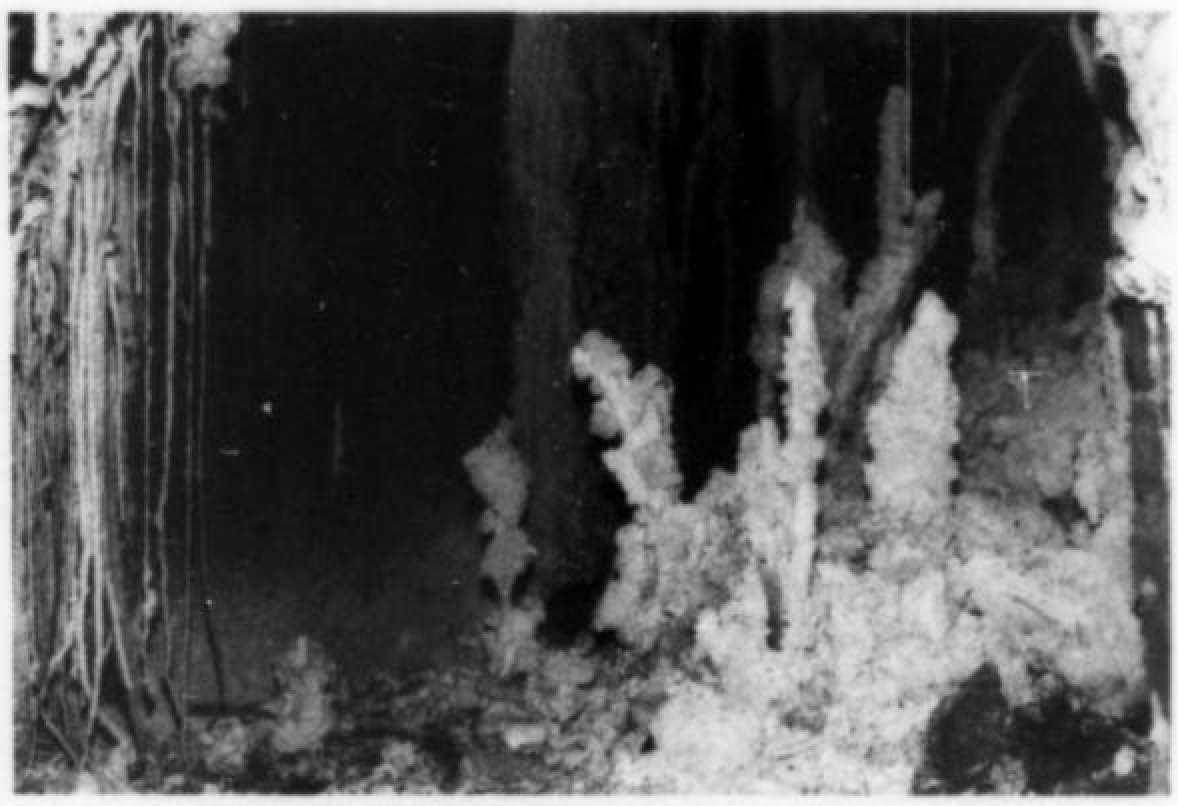


Figure 19. **Post-mining growths of sulfate minerals on 4 level, Mount Isa mine. The filaments at left are about 1.5 meters long. Photo by the author.**

Halotrichite $Fe^{+2}Al_2(SO_4)_4{\cdot}22H_2O$

Halotrichite is a locally common, post-mining mineral at Mount Isa. It occurs in oxidized, pyrite-rich zones, sometimes with other sulfates; it generally forms in the upper levels and near poorly ventilated shafts at deeper levels. It is most common on 4 level where it forms in large masses of silky, white, flexible fibers up to several centimeters in length, and as "ramshorn" aggregates of yellowish white fibers up to 30 cm long. Upon exposure to fresh, circulating air, the halotrichite dehydrates to white, brittle fibers.

Hematite αFe_2O_3

Minor, fine grained hematite occurs in the gossanous rocks at the Black Star open cut. It also occurs sparingly in veins and fractures throughout the mine.

Hemimorphite $Zn_4Si_2O_7(OH)_2{\cdot}H_2O$

Hemimorphite is a rare mineral at Mount Isa owing to a depletion of zinc from the oxidized zone. It occurs as clear, bladed crystals up to 3 mm in length associated with anglesite and cerussite from the Black Star open cut. It is also found here as attractive, colorless to white, sheaf-like aggregates to a few millimeters associated with rosasite.

Hexahydrite $MgSO_4{\cdot}6H_2O$

Hexahydrite has been found on 4 level as a massive, pale green encrustation of post-mining origin.

Huntite $CaMg_3(CO_3)_4$

Huntite forms in small patches with dolomite, magnesite and siderite at the Black Star open cut. White, compact, chalky masses up to 20 cm across have been found.

Hydrocerussite $Pb_3(CO_3)_2(OH)_2$

Hydrocerussite is reported to be widely dispersed throughout the lower 30 meters of the oxidized zone, where it occurs associated with leadhillite (Blanchard and Hall, 1942). No surviving specimens could be found for confirmatory analyses.

Jarosite $KFe_3^{+3}(SO_4)_2(OH)_6$

Khaki-brown, earthy patches of jarosite up to 1 cm across coat voltaite, halotrichite and ferricopiapite exposures on 4 and 10 levels. The patches are composed of minute, hexagonal scales up to 0.1 mm across. It also occurs with other secondary minerals in the Black Star open cut (Taylor and Scott, 1982).

Kaolinite $Al_2Si_2O_5(OH)_4$

A moderately common alteration mineral at Mount Isa, kaolinite is particularly common in the Black Rock open cut where bands up to 10 cm thick envelop chalcocite bodies (Hurley, 1964).

Kieserite Group $M^{+2}SO_4{\cdot}H_2O$

Pale, brownish yellow aggregates of poorly formed kieserite-like crystals up to 0.2 mm across are occasionally seen on coquimbite in a leached zone near the R62 shaft on 10 level. The exact species has not been determined, however, considering that iron-rich phases seem to dominate the sulfate species at Mount Isa, the mineral may prove to be szomolnokite.

Kornelite $Fe_2^{+3}(SO_4)_3{\cdot}7H_2O$

Violet, silky kornelite tufts and crusts with a radial fibrous structure have been described by Blanchard (1968) as occurring in the sulfate-rich zones at Mount Isa (optical identification only).

Leadhillite $Pb_4(SO_4)(CO_3)_2(OH)_2$

Leadhillite occurs with hydrocerussite in the lower 30 meters of the oxidized zone, although it tends to occur more toward the base of oxidation (Blanchard and Hall, 1942). No surviving specimens could be found.

Lepidocrocite γFeO(OH)

Lepidocrocite occurs with goethite in massive limonite gossans at the Black Rock open cut (Hurley, 1964).

Lillianite $Pb_3Bi_2S_6$

Lillianite occurs as microscopic grains nearly always associated with native bismuth and ullmannite, all enclosed in pyrrhotite or chalcopyrite. Knights (1975) described this assemblage from the 1100 copper orebody but it has since been found in several other copper lodes at Mount Isa.

Mackinawite $(Fe,Ni)_9S_8$

Mackinawite has been tentatively identified by Knights (1975) as microscopic inclusions in chalcopyrite from within the copper orebodies. SEM work has revealed a mineral with a mackinawite composition but the structure has yet to be determined.

Magnesite $MgCO_3$

Magnesite is locally common in carbonaceous mylonite of the contact zone between the basement greenschist and the overlying ore horizons (Knights, 1975). Magnesite patches occur with dolomite, siderite and huntite in the Black Star open cut.

Magnetite $Fe^{+2}Fe_2^{+3}O_4$

Magnetite is a fine grained accessory mineral in the basement greenschists (Mathias and Clark, 1975). It also occurs as disseminated grains within the silver-lead-zinc orebodies.

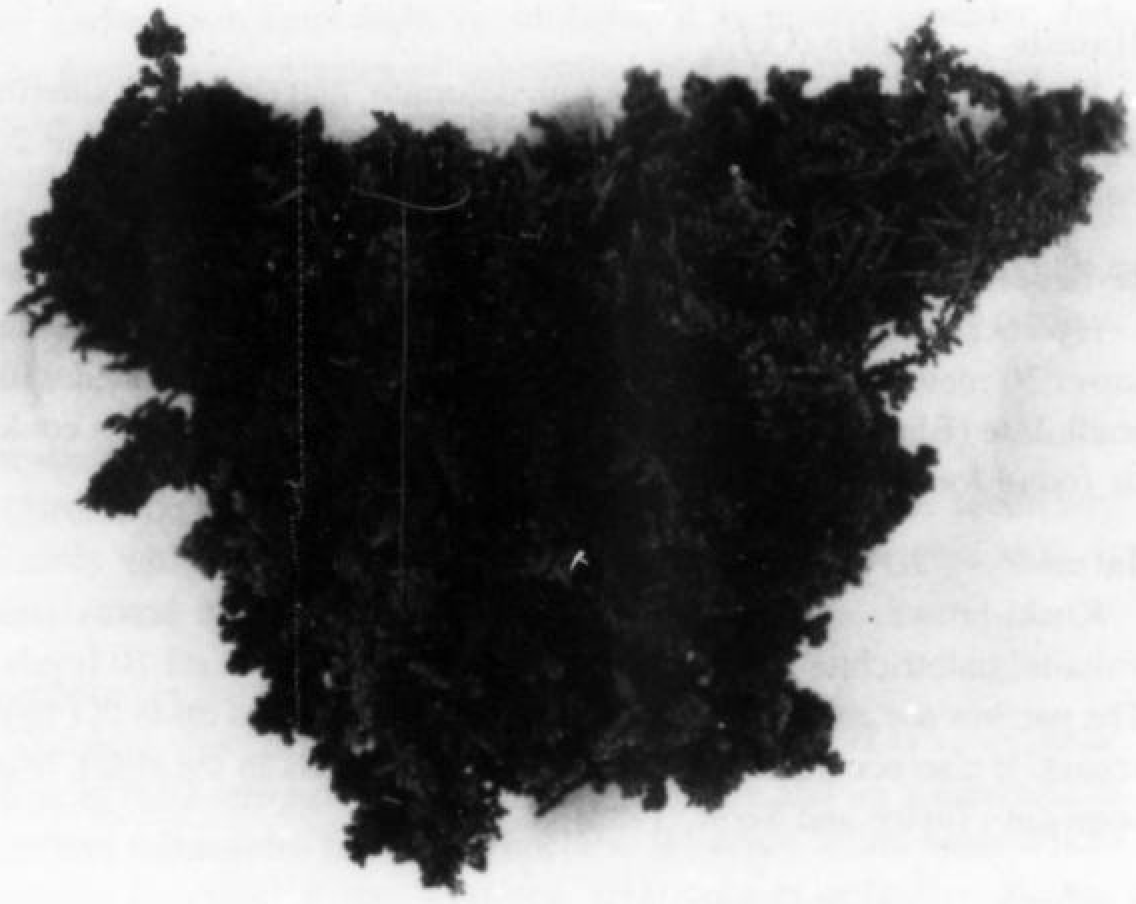


Figure 20. **Malachite replacing dendritic copper, 8 cm across, from the Black Star open cut, Mount Isa mine. Author's collection and photo.**

Malachite $Cu_2(CO_3)(OH)_2$

Malachite is a common mineral in the Black Rock open cut but scarce elsewhere. Blanchard (1968) reports an interesting occurrence, found in 1934, on 3 level in the 500 copper orebody (prior to open cutting). Here, thick crystals of arborescent malachite (presumably after native copper) occurred in a fold zone measuring 4 x 9 meters.

Marcasite FeS_2

Marcasite occurs in minor amounts in both the copper and silver-lead-zinc orebodies and as laths and spearpoint crystals in barren shale. It has also been reported as a supergene mineral forming mutilated spearpoint crystals up to 10 cm long, occurring along bedding planes within the oxidized zone (Blanchard and Hall, 1942).

Massicot PbO

Rarely observed patches of massicot have been noted (optically identified) in the Black Star outcrops (Blanchard and Hall, 1942).

Melanterite $Fe^{+2}SO_4 \cdot 7H_2O$

Found with other sulfates on 4 level, melanterite occurs as an irregularly shaped, massive, transparent salt with vitreous luster and a greenish blue tinge.

Meneghinite $Pb_{13}CuSb_7S_{24}$

Meneghinite is of similar appearance and occurrence to boulangerite, a mineral with which it is often confused (Riley, 1971). It occurs as needle-shaped crystals in veins from the alteration zones fringing the 3000 and 3500 copper orebodies.

Mimetite $Pb_5(AsO_4)_3Cl$

Earthy mimetite occurred sparingly in the Black Star outcrops (Blanchard and Hall, 1942).

Muscovite $KAl_2(Si_3Al)O_{10}(OH,F)_2$

Muscovite is a very common mineral throughout the mine sequence, especially as the fine grained variety, sericite.

Palygorskite $(Mg,Al)_2Si_4O_{10}(OH) \cdot 4H_2O$

Thick masses of bluish grey palygorskite commonly fill faults at Mount Isa. These masses become pliable when wet. The palygorskite often contains spectacular crystals of barite, calcite and pyrite. The mineral is easily confused with sepiolite.

Pentlandite $(Fe,Ni)_9S_8$

Pentlandite has been reported as microscopic grains associated with chalcopyrite and pyrrhotite in the copper ores (Blanchard and Hall, 1940). The mineral also occurs rarely in the basement greenstones.

Phlogopite $KMg_3Si_3AlO_{10}(F,OH)_2$

Phlogopite is a locally common mineral in the mine sequence; it is the dominant mineral in the "phlogopite beds" which occur near the footwall of the silver-lead-zinc orebodies.

Phosgenite $Pb_2(CO_3)Cl_2$

Phosgenite was present in minor amounts with orange pyromorphite in the oxidized zone of the Black Star orebodies (Blanchard and Hall, 1942).

Pickeringite $MgAl_2(SO_4)_4 \cdot 22H_2O$

Pickeringite has been widely reported as occurring in oxidizing zones throughout the mine. All of the specimens so far collected by the author have proved to be halotrichite.

Polybasite $(Ag,Cu)_{16}Sb_2S_{11}$

Polybasite is a rare mineral at Mount Isa; it occurs as a hypogene mineral associated with galena and other silver sulfosalts in the silver-lead-zinc orebodies. It also occurs rarely as a supergene mineral with proustite, pyrargyrite, native silver and chlorargyrite in the transition zone of the Black Star orebodies (optically identified, Blanchard and Hall, 1942).

Proustite Ag_3AsS_3

Like polybasite, proustite occurs rarely with galena and other silver sulfosalts in the silver-lead-zinc orebodies, and with other supergene silver minerals in the transition zone of the Black Star orebodies (Blanchard and Hall, 1942).

"Psilomelane" unidentified massive manganese oxides

Unidentified, black manganese oxides occur in the oxidized zone at Mount Isa. They often form an attractive, black (sometimes botryoidal) background for crystals of pyromorphite, cuprite, etc.

Pyrargyrite Ag_3SbS_3

Like proustite and polybasite, pyrargyrite occurs as both a hypogene and supergene mineral at Mount Isa. Blanchard and Hall (1942) indicate that pyrargyrite is the more common supergene mineral and that polybasite is the more common hypogene mineral.

Pyrite FeS_2

Pyrite is an extremely common mineral at Mount Isa, occurring in the copper and silver-lead-zinc orebodies and the enclosing sediments. The pyrite is generally fine grained and framboidal but well formed crystals also occur. Cubes up to 1 cm on edge occur in the basement greenschist near the contact with the 1100 copper orebody (Knights, 1975). Cubes 2–8 mm across, loosely clustered in spherical aggregates up to 10 cm across, occur in palygorskite/sepiolite filled faults within the copper orebodies.

Pyrite also occurs as iridescent, purplish pyritohedra averaging 0.1 mm across, coating the pyramidal terminations of trigonal calcite crystals—these being particularly well developed on 19C sublevel within the 1100 copper orebody.

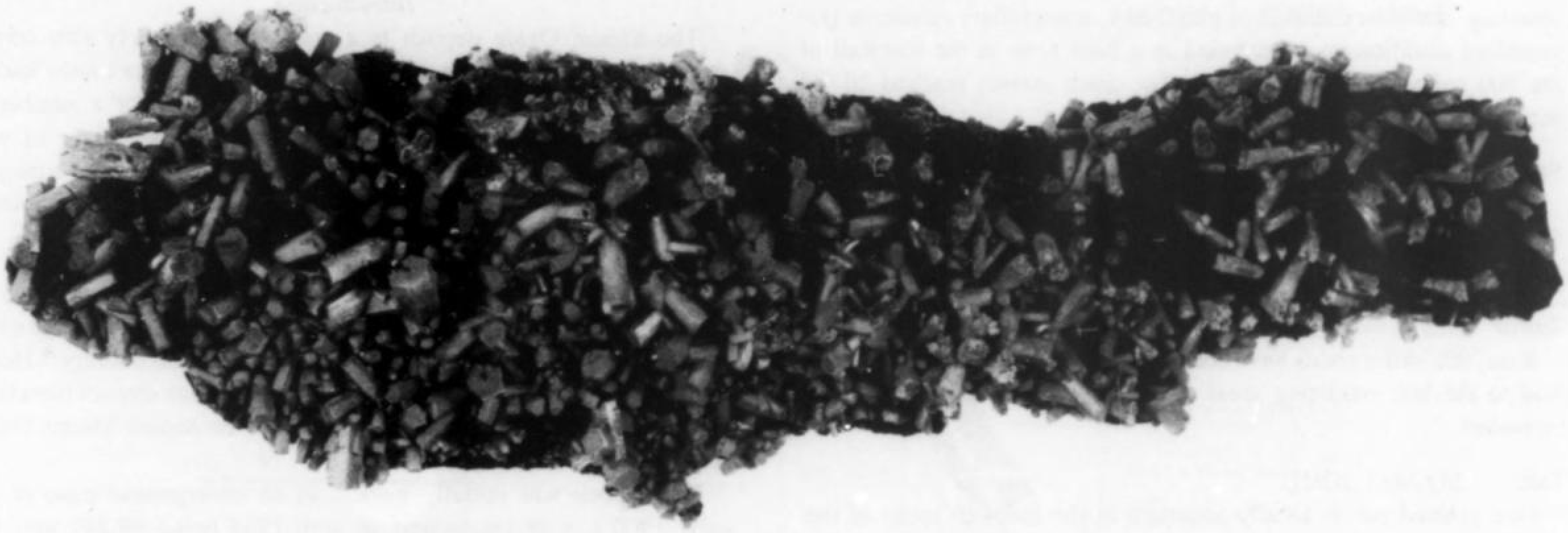


***Figure 21.* Yellow-green pyromorphite crystals on matrix, 26 cm across, from the Black Star open cut, Mount Isa mine. Author's collection and photo.**

Pyrolusite MnO_2

Pyrolusite occurs sparingly in the oxidized zone, often as small spherical aggregates.

Pyromorphite $Pb_5(PO_4)_3Cl$

One of the most spectacular minerals at Mount Isa, pyromorphite occurs profusely in parts of the oxidized portions of the Black Star orebodies. It occurs in a variety of colors including white, gray, yellow, green, brown and orange, and in a wide variety of habits ranging from thin tablets to barrel-shaped crystals to acicular needles. The most commonly associated mineral is cerussite.

The Black Star open cut continues to produce attractive specimens of pyromorphite. Here, fractures reaching several meters across are lined with green pyromorphite crystals—often reaching (and occasionally exceeding) 1 cm in length. The crystals usually have a dull luster but are still very attractive. One notable occurrence is characterized by lustrous, green, multiple crystals, often club-headed with cavernous terminations, reaching 1.7 cm in length.

The best specimens were mined in the mid 1900's. Blanchard and Hall (1942) describe botryoidal, lustrous, deep orange groups of pyromorphite (sometimes with phosgenite) occurring often for 7 to 9 meters along open fissures down to a depth of 45 meters. These fissures were commonly visible in the workings above 1 level, in the Black Star orebodies. Unfortunately, only a few of these specimens have survived.

Pyrrhotite $Fe_{1-x}S$

Pyrrhotite is a very common mineral in both the copper and silver-lead-zinc orebodies. It is generally fine grained, but well formed crystals are occasionally seen. Tabular to bladed crystals up to 2 cm on edge occur in shale adjacent to the silica dolomite rock. Crystals up to 10 cm across have been observed in the Black Star, No. 1 lode, silver-lead-zinc orebody (Blanchard, 1968). Hexagonal plates up to 3 mm across occur in some quartz-dolomite veins.

Quartz SiO_2

Quartz is a ubiquitous rock-forming mineral at Mount Isa; it occasionally occurs as clear, well formed crystals in faults. The crystals are generally small although thick, colorless to milky crystals reaching 20 cm in length are occasionally found (e.g., on the 20E sublevel, 1100 copper orebody).

Rhomboclase $HFe^{+3}(SO_4)_2 \cdot 4H_2O$

Rhomboclase occurs as a white, gray or pale yellow mineral with other sulfates at Mount Isa (optically identified, Blanchard, 1968).

Roemerite $Fe^{+2}Fe_2^{+3}(SO_4)_4 \cdot 14H_2O$

Roemerite is an uncommon mineral at Mount Isa, although one notable occurrence in the V60 south drive on 4 level was described by Sielecki (1985). Here, transparent to translucent, tabular to blocky, vitreous, red-brown crystals commonly reach 1 mm across and occasionally reach 4 mm. Some of the larger crystals appear to be multiple growths with stepped terminations. The mineral also occurs as red-brown to pale pink, sugary masses of anhedral to euhedral crystals, such masses reaching 2 meters across and 30 cm in thickness. Occasional radiating clusters of tabular roemerite crystals have been noted. The roemerite is often associated with ferricopiapite and minor voltaite and halotrichite.

Rosasite $(Cu,Zn)_2(CO_3)(OH)_2$

Rosasite occurs sparingly in the Black Star open cut. Attractive blue-green spherules of acicular crystals occur scattered on a limonitic jasper matrix. The spherules reach 1 mm across, and are sometimes found as inclusions in hemimorphite.

Sepiolite $Mg_4Si_6O_{15}(OH)_2 \cdot 6H_2O$

Similar in appearance and occurrence to palygorskite, masses of bluish-grey sepiolite commonly fill faults at Mount Isa. Barite, calcite and pyrite crystals frequently occur within the sepiolite.

Siderite $Fe^{+2}CO_3$

Siderite occurs sparingly in the Black Star open cut, associated with dolomite and magnesite. It also occurs as an accessory mineral in leached pyritic shales.

Silver Ag

Native silver was quite common in the enriched transition zone of the Black Star silver-lead-zinc orebodies, between 27 and 45 meters in depth. It often occurred profusely in leaf and wire forms associated with chlorargyrite (Blanchard and Hall, 1942). Very few specimens have survived.

Smithsonite $ZnCO_3$

Smithsonite is an uncommon mineral at Mount Isa owing to the depletion of zinc from the oxidized zone. Nonetheless, isolated patches of smithsonite do occur in the oxidized portions of the Black Star orebodies (Blanchard and Hall, 1942). Specimen-quality material is rare.

Sphalerite $(Zn,Fe)S$

Sphalerite is a major ore-forming mineral at Mount Isa. Attractive specimens are rare although crystals up to 9 mm across have been reported from quartz-dolomite veins (Blanchard and Hall, 1942). Interesting, secondary masses of gray-black, mammillary sphalerite (resembling cauliflower) were found in a fault zone in the footwall of the 500 copper orebody at Mount Isa. Such masses reached 20 cm across.

Stilpnomelane $K(Fe^{+2},Fe^{+3},Al)_{10}Si_{12}O_{30}(OH)_{12}$

Stilpnomelane occurs in moderate amounts in isolated beds to the footwall of several of the copper orebodies. It is generally fine grained, although laths occasionally reach 2 mm (Knights, 1975).

Sulfur S

Rare, thin sulfur crusts have been observed coating vent walls which lead to the hot, oxidizing areas of the Black Rock and Black Star orebodies.

Talc $Mg_3Si_4O_{10}(OH)_2$

Fine grained talc is locally abundant in the footwall rocks of the copper orebodies. The talc is commonly associated with pyrrhotite (Knights, 1975). It often occurs as small rhombs replacing dolomite (Clark, 1968).

Tenorite CuO

Tenorite was a minor ore mineral in the Black Rock open cut. It occurred in a massive form most closely associated with cuprite and malachite (Smith, 1975).

Tetrahedrite $(Cu,Fe)_{12}Sb_4S_{13}$

The occurrence of tetrahedrite at Mount Isa is similar to that of freibergite. The two minerals form a solid solution series with both species being confirmed at Mount Isa (Riley, 1974). Much of the tetrahedrite reported in the early literature is in fact freibergite. The tetrahedrite occurs as grains up to 0.2 mm across included in galena.

Ullmannite NiSbS

Ullmannite and cobaltian ullmannite occur as microscopic grains in and around the copper orebodies. They generally occur in association with lillianite and bismuth enclosed in pyrrhotite or chalcopyrite (Knights, 1984).

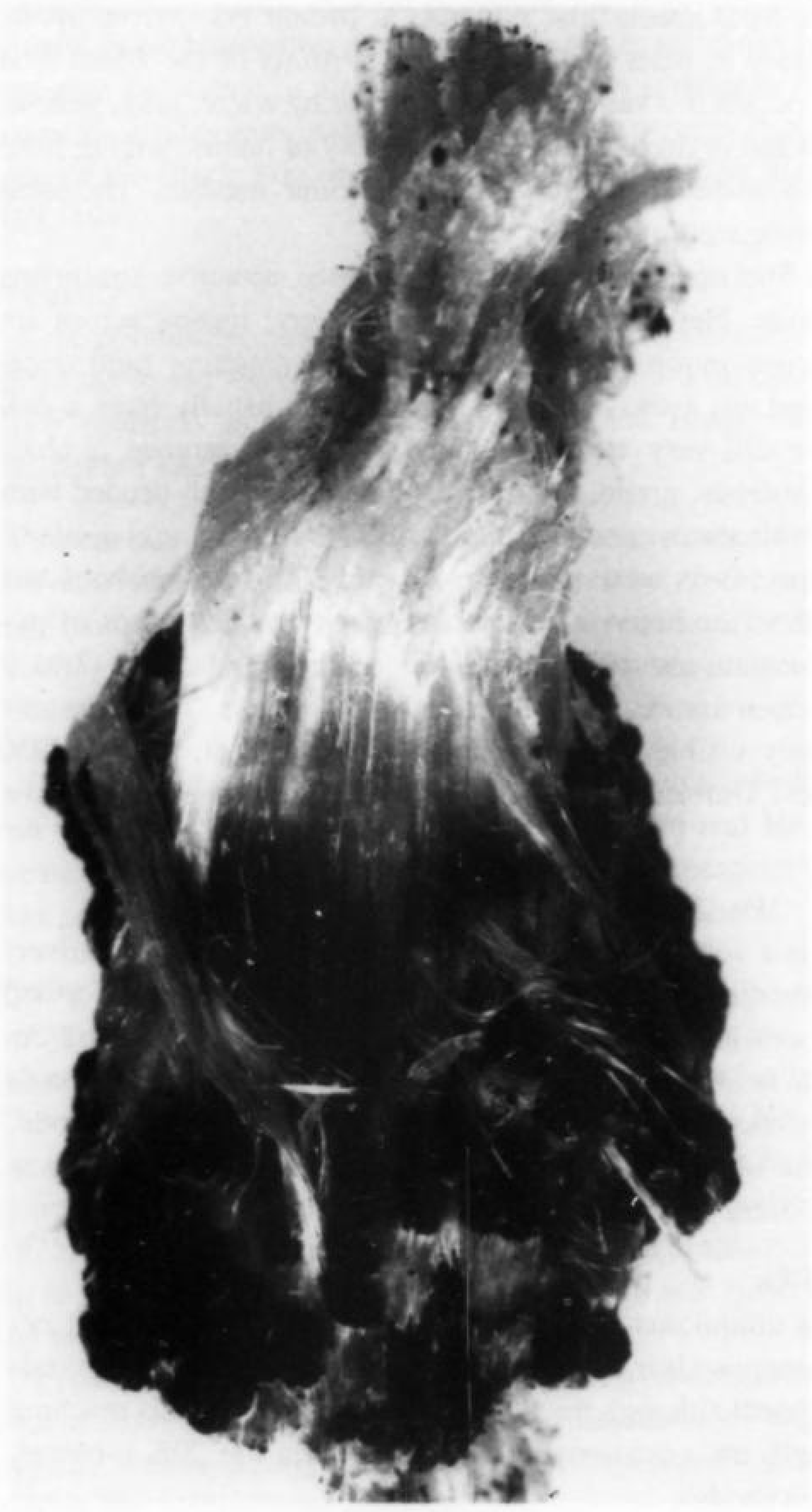


***Figure 22*. Black voltaite crystals with silky white to pale blue-green halotrichite from the V60 South drive, 4 level, Mount Isa mine; 8 cm tall. Author's collection and photo.**

Voltaite $K_2Fe_5^{+2}Fe_4^{+3}(SO_4)_{12}\cdot 18H_2O$

Superb crystals of voltaite occur in a leached pyritic zone in the V60 south drive on 4 level (Sielecki, 1985). Vitreous, black (sometimes with an olive-green tinge), modified, octahedral crystals often reach 6 mm and occasionally 9 mm across. Perfect octahedra reach 3 mm and near-perfect cubes reach 1 mm across. The most striking specimens occur where black voltaite crystals occur among lustrous, white halotrichite fibers. Specimens up to 20 cm across have been preserved. Roemerite, ferricopiapite and melanterite also occur with the voltaite. Flattened rosette-shaped intergrowths of voltaite reaching 1 cm in diameter are common.

A second occurrence of voltaite is on 10 level, near the R62 shaft. Here the voltaite occurs as flattened rosettes up to 1 cm across associated with coquimbite and halotrichite.

Willyamite (?) (Co,Ni)SbS

Willyamite, a rare mineral at Mount Isa, occurs with ullmannite and costibite (?) in boulangerite-rich veins enclosed in pyrrhotite or chalcopyrite. The major occurrence to date is in the outer silica-dolomite envelope of the 3000 and 3500 copper orebodies (Knights, 1984). Work is still going on to distinguish between willyamite and cobaltian ullmannite.

MOUNT OXIDE MINE

Introduction

The Mount Oxide deposit is a small but extremely rich copper deposit located 150 km north of Mount Isa. Collectors have known about attractive brochantite and atacamite crystals for a number of years. Recently, a zone containing an unusual assemblage of well crystallized copper and aluminum phosphates was found. An attractive new mineral species, sieleckiite, has been identified in this assemblage.

History

The Mount Oxide copper deposit was shown to Ernest Henry in February, 1882. Toby, a member of the Waggaboonga aboriginal tribe, had told Henry that "copper plenty sit down longa his country." Henry set out with Toby to see this country and, after many days of traveling, reached the copper-stained hill that was to be named Mount Oxide (Blainey, 1970).

The deposit was initially worked as an underground mine in the early 1900's, with production up until 1958 being 48,249 tons averaging 21% copper and a little more than 30 grams per ton silver (Carter *et al.*, 1961). Leaching operations took place during 1962–1968 and recommenced for a brief period in 1979 when a large open cut was developed. It was during this latter mining episode that the phosphate minerals were exposed.

Geology

The Mount Oxide deposit occurs along a northeast-trending shear zone within weakly metamorphosed sandy shales of the lower Proterozoic Gunpowder Creek Formation (Carter *et al.*, 1961). The orebody dips to the southeast at 60°. All of the production to date has come from the zone of oxidation and secondary enrichment, with massive,

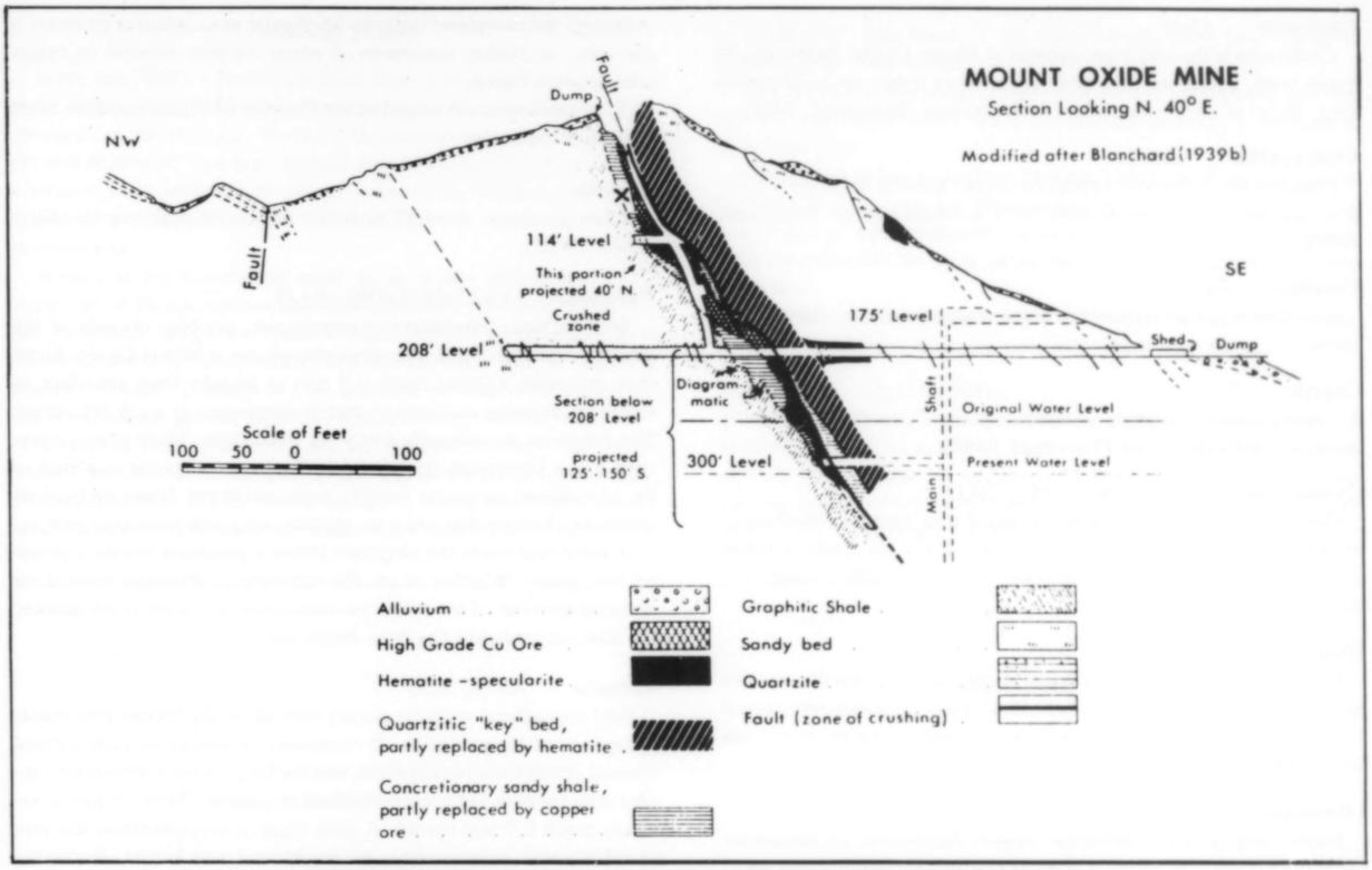


Figure 23. **Cross section through the main workings of the Mount Oxide mine (from Blanchard *et al.*, 1968). The southeast portion of the hill has now been removed by open cutting. Phosphate assemblage found at "x."**

supergene chalcocite being the dominant copper mineral. Quartz constitutes the major gangue mineral while a massive hematite body occurs on the hanging wall of the lode.

Minerals

An unusual phosphate assemblage consisting of turquoise, variscite, libethenite, pseudomalachite, and a new hydrous copper aluminum phosphate species was recently found by the author at Mount Oxide. It came from a bench in the northwest corner of the open cut, approximately 20 meters below the former surface. Most of the minerals are relatively common in this part of the open cut. The new mineral, sieleckiite, was found in only one boulder on this bench, but there is little doubt that it originated from nearby. The paragenetic sequence of phosphate crystallization is shown below. *Table 2* shows the vertical distribution of the copper minerals at Mount Oxide.

Atacamite $Cu_2Cl(OH)_3$

Atacamite was a common mineral during the early mining period but few specimens have been found in recent times. It occurs as blocky prismatic, blackish green crystals up to several millimeters in length. A number of attractive cabinet specimens were preserved but these rarely appear on the market.

Azurite $Cu_3(CO_3)_2(OH)_2$

Small, bladed, prismatic crystals up to 6 mm in length occur in abundance along fractures in a silicified shale. Azurite crystals up to 1 mm across are occasionally seen speared by malachite needles, such specimens forming attractive micromounts.

Bornite Cu_5FeS_4

Bornite occurs sparingly with chalcocite near the 90 meter level (Blanchard, 1968).

Brochantite $Cu_4(SO_4)(OH)_6$

Brochantite is a significant ore mineral at Mount Oxide. Large masses of brochantite were mined between the 20 and 35 meter levels (Blanchard, 1968). Thick seams of acicular brochantite crystals up to 5 mm in length can still be found in boulders strewn around the open cut. Short prismatic, glassy crystals up to 2 mm in length are also occasionally found.

Table 2. **Vertical zonation of copper minerals at the Mount Oxide deposit. (Based on Blanchard, 1968, and the author's 1986 mine visit.)**

Depth (m)	Major copper mineral	Lesser copper minerals*	Other minerals of interest
0–20	malachite	azurite, brochantite, atacamite, turquoise, libethenite, chalcocite, pseudomalachite, sieleckiite, cyanotrichite	hematite, variscite
20–25	brochantite	chalcocite, cuprite, tenorite, malachite, azurite, atacamite, turquoise, libethenite, pseudomalachite, sieleckiite, cyanotrichite	variscite, hematite
35–90	chalcocite	malachite, cuprite, bornite, covellite	
90–?		chalcopyrite, chalcocite	massive pyrite

*in approximate order of abundance

Chalcocite Cu_2S

Chalcocite is the major ore mineral at Mount Oxide. Below the 35 meter level, masses of chalcocite occurred in lenses up to 10 meters long. Veins of chalcocite persist to the surface (Blanchard, 1968).

Chalcopyrite $CuFeS_2$

Chalcopyrite is the only hypogene copper mineral at Mount Oxide. It occurs rarely below the 90 meter level in massive pyrite (Blanchard, 1968).

Covellite CuS

Covellite is of rare occurrence in the chalcocite bodies (Blanchard, 1968).

Cuprite Cu_2O

Cuprite occurs sparingly in seams up to 12 cm thick, generally associated with chalcocite (Blanchard, 1968).

Cyanotrichite $Cu_4Al_2(SO_4)(OH)_{12}\cdot 2H_2O$

One specimen of cyanotrichite was found with variscite, libethenite, pseudomalachite and sieleckiite. It occurs as a 1-cm patch of tufted masses of sky-blue, acicular crystals. Individual tufts average 1–2 mm across.

Hematite $\alpha\text{-}Fe_2O_3$

Hematite crystals commonly occur in open veins within the massive hematite body at Mount Oxide. Individual, platy crystals rarely exceed 1 mm but are often intergrown to form composite crystals up to 1 cm across. Occasional single platy crystals reach 5 mm across.

Libethenite $Cu_2(PO_4)(OH)$

Sharp, deep green, translucent, equant bipyramids of libethenite commonly reach 1 mm across. Larger multiple-growth crystals up to 4 mm across are common, while prismatic crystals up to 1 mm in length occur sparingly. The libethenite forms either as isolated crystals, crystal aggregates or fine grained druses. Matrix pieces up to 20 cm across with an 80% covering of libethenite have been collected. Turquoise, variscite and pseudomalachite are common associates. Libethenite crystals up to 1 mm across occur with sieleckiite (described below).

Malachite $Cu_2(CO_3)(OH)_2$

Malachite is a common mineral in the upper portions of the deposit. Acicular crystals rarely exceed a few millimeters, but attractive specimens occur where tufts of malachite are intergrown with azurite.

Pseudomalachite $Cu_5(PO_4)_2(OH)_4\cdot H_2O$

Pseudomalachite occurs as irregular stalactitic masses up to 2 mm high perched on libethenite. This habit rarely occurs in contact with any of the other phosphates. Spherules of pseudomalachite (?) up to 0.5 mm across are occasionally seen with variscite and turquoise.

Pyrite FeS_2

Massive pyrite is the dominant sulfide mineral below the 90 meter level (Blanchard, 1968).

Sieleckiite $Cu_3Al_4(PO_4)_2(OH)_{12}\cdot 2H_2O$

A new mineral species soon to be described occurs as vivid, deep sky-blue, translucent to opaque spherules up to 0.5 mm in diameter, with a compact, radial fibrous structure (Birch and Pring, 1988). The mineral occurs as isolated and intergrown spherules forming patches up to several centimeters across. It generally forms on turquoise, variscite and libethenite. Some libethenite crystals also occur perched on the new mineral. Cyanotrichite occurs on one specimen in close proximity to the new mineral.

The mineral was found in a narrow fracture within a medium-sized (one cubic meter) boulder of quartzite and shale. Approximately 10 specimens ranging from thumbnail to cabinet size were removed. Although the turquoise-variscite-libethenite association is common in the area, no further specimens of either the new mineral or cyanotrichite were found.

Type specimens are lodged in the Museum of Victoria and the South Australian Museum.

Tenorite CuO

Tenorite occurs in small amounts associated with cuprite (Blanchard, 1968).

Turquoise $CuAl_6(PO_4)_4(OH)_8\cdot 5H_2O$

Well formed, transparent to translucent, sky-blue crystals of turquoise occur associated with other phosphates at Mount Oxide. Short, thin, prismatic crystals reach 0.5 mm in length. They are often intergrown, forming coatings on matrix specimens up to 20 cm across. The turquoise occasionally forms on libethenite. More often, sharp, deep green libethenite crystals up to 2 mm across occur scattered on the crystallized turquoise matrix, such specimens being particularly attractive. Transparent variscite crystals are a common associate.

In some specimens the turquoise shows a gradation toward a greenish blue phase. Whether or not this represents a transition toward the iron end-member of the turquoise-chalcosiderite series is not known. No massive turquoise has been found here.

Variscite $AlPO_4\cdot 2H_2O$

Well crystallized variscite occurs with all of the copper phosphates recognized at Mount Oxide. It commonly occurs as an early-formed mineral in colorless, transparent, interlocking crystals displaying parallel orthorhombic (or pseudo-octahedral) prisms. These crystals commonly reach 0.5 mm across. A later stage of crystallization has produced isolated, orthorhombic prisms up to 1 mm across, displaying a random orientation. These crystals are sometimes perched on rosettes of intergrown libethenite crystals.

***Figure 24.* Suggested paragenetic sequence for the Mount Oxide phosphates. (The sulphate cyanotrichite, appears to be closely associated.)**

BOOMERANG MINE

Introduction

The Boomerang mine is a small copper mine located approximately 110 kilometers north-northwest of Mount Isa. The mine has produced some of Australia's finest azurite crystals.

Mining operations began in 1944 and have continued intermittently since. The mine, previously known as the Matlock or Mount Maggie mine, has produced several thousand tonnes of ore grading 5 to 8% copper. Both open cut and underground workings exist.

The deposit lies in a shear zone in the Paradise Creek Formation (Krosch and Sawers, 1974). The country rocks are shales and jaspers; the lode is contained in leached and silicified shales, jasper breccia and clays. The mineralization consists almost entirely of malachite and minor chrysocolla in the open cut, and malachite and azurite in the underground workings.

Collecting History

In the late 1960's a porous kaolinite-shale lode rock was intersected at the southeast end of 3 level. Spectacular clusters of azurite crystals abounded in the kaolinite. Much of this material was treated as copper ore and destroyed, however, toward the end of this mining period the operators were made aware of the value of these specimens. Consequently a moderate number of specimens was preserved and sold to collectors.

Mining at the Boomerang came to an abrupt halt around 1972, when one of the operators was shot dead at the mine under suspicious circumstances. Since that time a small number of collectors have ventured down the shaft and worked the kaolinitic lode in search of azurite crystals. Although not as abundant as they were during the initial discovery period, attractive specimens can still be found.

Collecting here is certainly not for the faint-hearted. The author visited the mine in 1985, and on one trip down the 40-meter shaft, encountered three deadly brown snakes. It seems that falling down a shaft merely tends to make the snake angry rather than killing it. The shaft is also full of 10–12 cm spiders, the workings are full of bats, and if all that weren't enough, the mine floor is alive with masses of cockroaches. The sight of sparkling azurite crystals, however, soon makes one forget the unpleasantries of the mine.

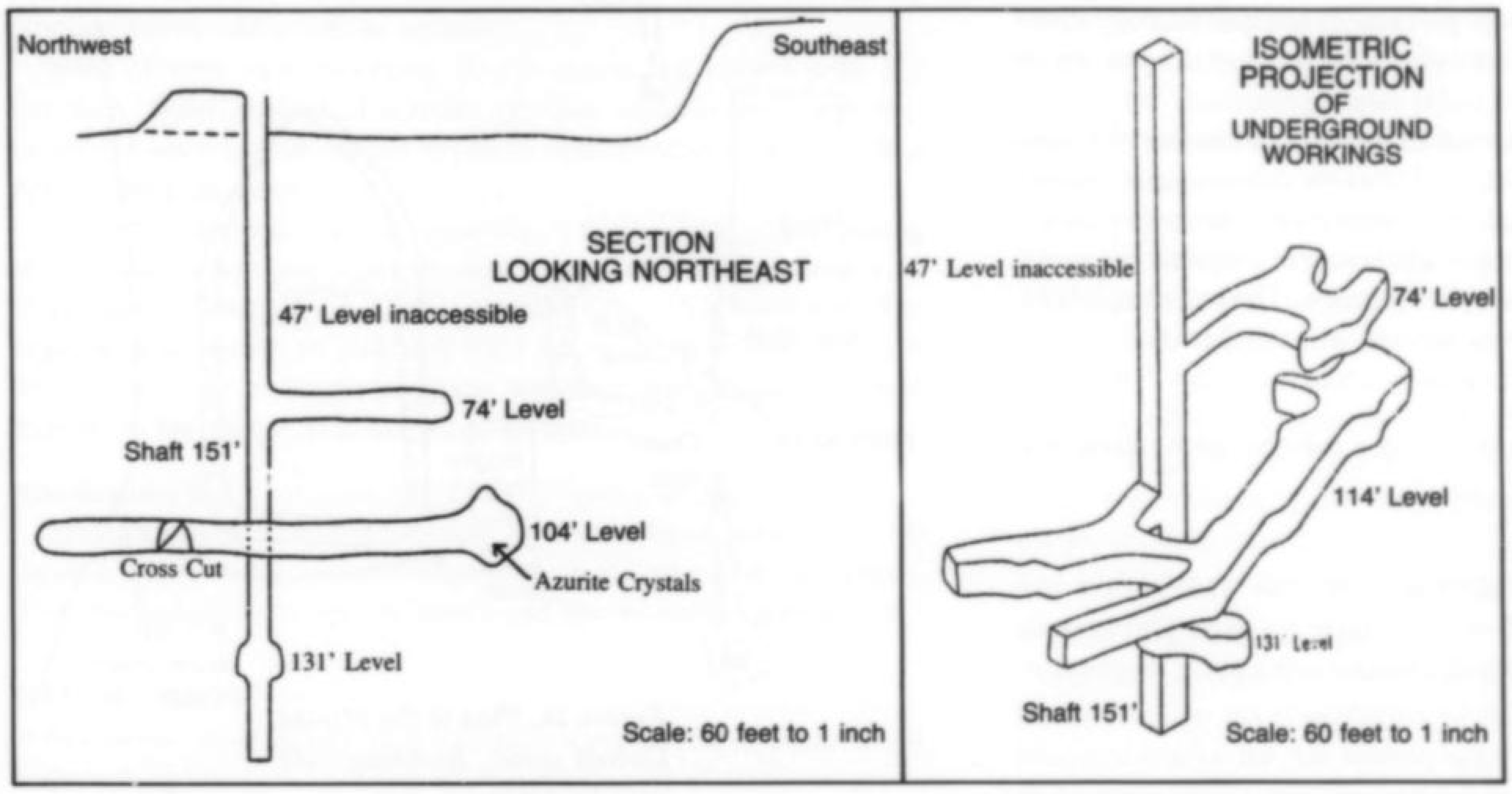


Figure 25. **Cross section and isometric projection of the underground workings of the Boomerang mine (from Krosch and Sawers, 1974).**

Minerals

The only minerals of interest to the collector are azurite and malachite.

Azurite $Cu_3(CO_3)_2(OH)_2$

Azurite occurs in a wide range of habits at the Boomerang mine. Individual pockets less than 30 cm across may contain several isolated clusters of azurite, each displaying a different habit. The color varies from light blue to blue-black and while the crystals are sometimes translucent, they are more commonly opaque. Small, siliceous fragments are often cemented onto the crystals. Some of the more prominent habits are discussed below.

(1) Individual prismatic crystals reaching 2 cm in length and multiple growth crystals reaching 8 cm in length are common. Such specimens are often highly lustrous and dark blue in color.

(2) Spherical aggregates or rosettes up to 10 cm in diameter are composed of 1 to 3 cm prismatic crystals. Fan and bow-tie shaped aggregates have also been found.

(3) Blocky, blue-black, 1 cm wide crystals have been found in clusters up to 5 cm across.

(4) Curved rhombohedral crystals in attractive miniature-sized clusters are sometimes found. Such crystals are generally a medium to dark blue color.

(5) Nodules of fine to medium grained, light to medium blue azurite reaching 20 cm across are often found.

(6) Veins of massive azurite reaching 1 cm in thickness are common. Only occasionally do such veins open up to produce well formed crystals.

Malachite is occasionally seen partially replacing azurite as pseudomorphs. Some very attractive specimens have been found.

Malachite $Cu_2(CO_3)(OH)_2$

Malachite was the major ore mineral at the Boomerang mine. It generally occurs as seams of earthy to fibrous malachite. Acicular crystals up to 3 mm are common. Malachite occurs selectively replacing individual crystals in azurite clusters. However such pseudomorphs are surprisingly uncommon at the Boomerang mine.

MOUNT GLORIOUS MINE

Introduction

The Mount Glorious mine is a small open cut copper mine situated 8 km east of Cloncurry. In June of 1985, this small gouger operation was visited by the author. Mining was taking place in the oxidized zone in a small, newly formed open cut. A quick look through the dumps and mine face revealed seams of world-class pseudomalachite and beautiful chrysocolla. Although the deposit was mined out very quickly by the operator, with no regard for specimen preservation, a number of unique specimens were saved.

The deposit was first claimed in the late 1960's but up until the recent open cutting, very little mining had taken place. The deposit lies in the Mary Kathleen group and consists of highly ferruginous, mineralized shale and quartzite located within a shear zone. A large quartz plug occurs in the core of the deposit. The best chrysocolla and some of the best pseudomalachite occur along fractures within the outer portions of the quartz plug. The center of the plug is devoid of mineralization.

A second, older and smaller open cut occurs 100 meters away from the first along the line of shear. Pseudomalachite is also common here but good specimens are more difficult to find.

Mineralization

Little can be said about the formation of the deposit other than that it is probably a shear-controlled epigenetic deposit. The role of the quartz plug is not known. No primary copper minerals are exposed, however the visible carbonates, oxides and phosphates almost certainly formed from the oxidation of copper sulfides. The abundance of the copper phosphate, pseudomalachite, remains enigmatic. Several other deposits in the district contain significant amounts of another copper phosphate, libethenite, but pseudomalachite is generally scarce.

Minerals

Azurite $Cu_3(CO_3)_2(OH)_2$

Azurite is occasionally found as massive seams up to 1 cm thick or as small prismatic crystals partially altered to malachite. Larger crystals are entirely replaced by malachite.

Chrysocolla $(Cu,Al)_2H_2Si_2O_5(OH)_4 \cdot nH_2O$

Chrysocolla was the major ore mineral at Mount Glorious. Seams up to 1 cm thick are common. Botryoidal chrysocolla occurs where the seams are not completely filled. The best development of this occurs in and adjacent to the outer portions of the quartz plug. Plates of beautiful, light blue, botryoidal chrysocolla up to 25 cm across have been found.

Thick rounded pseudomorphs (and coatings) of chrysocolla after tabular azurite crystals are common. Attractive cabinet-sized clusters with 1-cm pseudomorphed crystals have been found. Attractive spherical aggregates (rosettes) of malachite (after azurite) crystals are sometimes partially or wholly replaced by chrysocolla. The individual short, prismatic crystals in these clusters average 2–4 mm across.

Cuprite Cu_2O

Of minor importance, cuprite occurs in a massive form intergrown with tenorite.

Libethenite $Cu_2(PO_4)(OH)$

Libethenite is a rare mineral at Mount Glorious. One pocket was found containing numerous 0.2-mm prismatic crystals. The crystals are sometimes clustered around small limonite (after pyrite?) spherules averaging 2 mm across.

Malachite $Cu_2(CO_3)(OH)_2$

Malachite is a common mineral but specimen-quality material is confined to pseudomorphs after azurite. The pseudomorphous crystals display a prismatic to tabular habit and reach 2 cm across. Spherical aggregates (rosettes) of malachite after azurite are common. The rosettes average 3 cm across and are composed of short, prismatic crystals averaging 3 mm across.

Pseudomalachite $Cu_5(PO_4)_2(OH)_4 \cdot H_2O$

Pseudomalachite is a common mineral at Mount Glorious. It occurs in a variety of habits and quite often occurs as display-quality specimens. The most striking specimens are plates of lustrous, opaque, blackish green, botryoidal and spherical pseudomalachite up to 15 cm across. Individual botryoids reach 1 cm across and isolated spherules reach 7 mm across. The interiors of these spherules and botryoids display concentric banding while the exteriors are composed of curved, flattened prismatic crystals in subparallel growth. The pseudomalachite often occurs on massive quartz and ferruginous sediments, but the most striking association occurs where the pseudomalachite occurs on light blue, botryoidal chrysocolla. Another common matrix is an earlier formed, bluish green pseudomalachite. This earlier pseudomalachite occurs as interlocking 2–4 mm platy crystals.

A second habit consists of platy, prismatic, bluish green, translucent to opaque crystals up to 3 mm in length, generally in subparallel growth. Aesthetic plates up to 8 cm across have been found. These crystals frequently have a thin coating of silica.

The third and most common habit found consists of irregular veins of pseudomalachite, composed of densely packed platy crystals and microcrystalline material.

Quartz SiO_2

Massive, colorless to white quartz is common. Well formed crystals exceeding 30 cm in length were extracted from pockets in the outer portions of the quartz plug.

Tenorite CuO

Of minor importance, tenorite occurs in a massive form intergrown with cuprite.

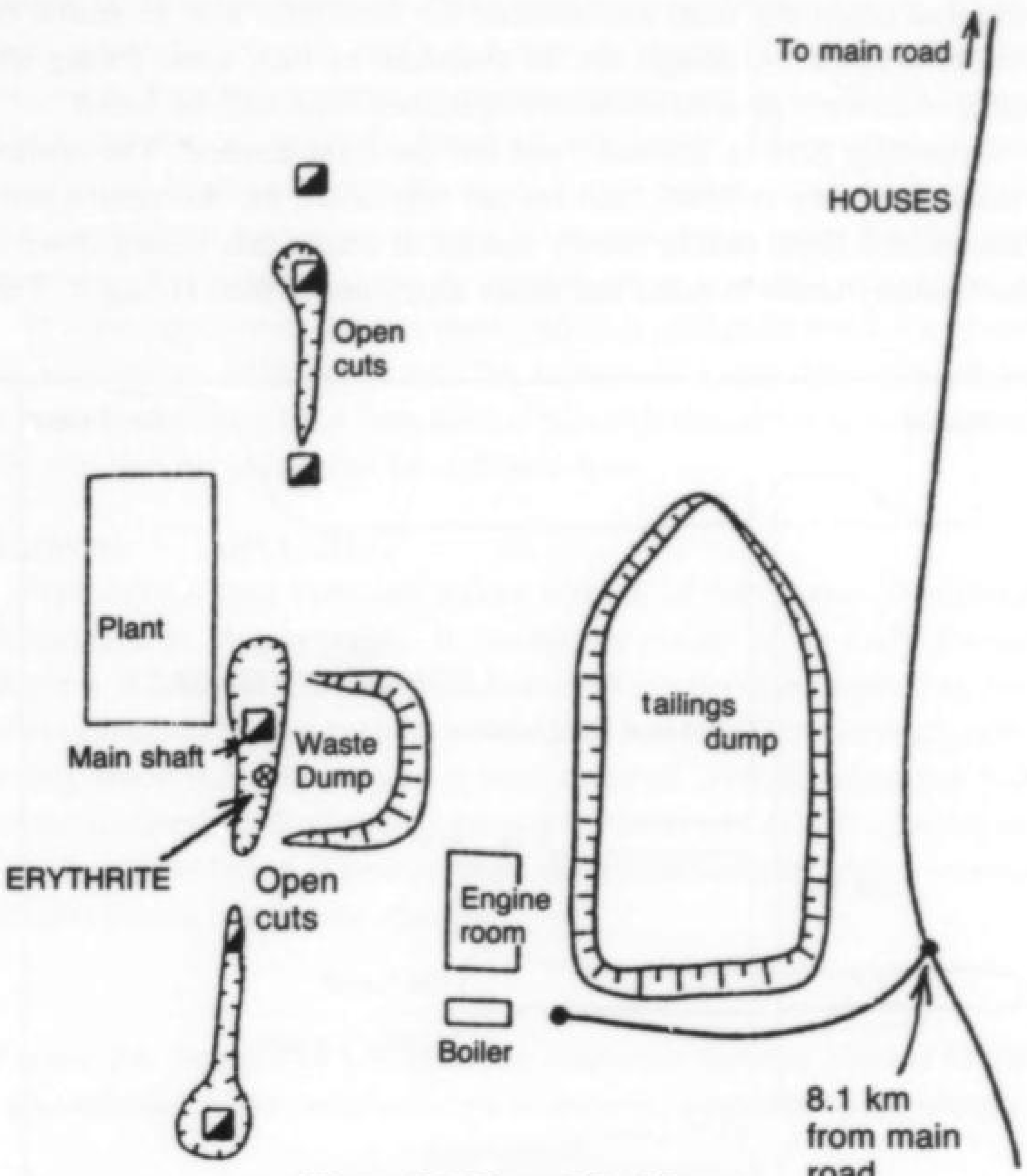


Figure 26. **Plan of the Mount Cobalt mine. Buildings are now in ruins.**

MOUNT COBALT MINE

Introduction

The Mount Cobalt mine is located approximately 140 km south of Cloncurry. For years it was Australia's only source of cobalt and is the only significant deposit in Australia to be mined primarily for cobalt. The deposit is exceptional in that erythrite constitutes a large part of the ore. Spectacular plates of acicular erythrite crystals occur in profusion and have been sought by collectors for years.

The mine has been abandoned for more than 50 years and most of the specimens seen in collections were mined by mineral collectors after the mine closed. Good quality material is now difficult to find.

The Mount Cobalt deposit occurs in a north-south trending shear along a contact between amphibolite and mica-quartz schists. The deposit lies in the Kuridala Formation (Carter *et al.*, 1961). The lode extends along strike for more than 300 meters, occurring as a steeply east-dipping, thin tabular body. The mineralization occurs in veins and fractures within the sheared mica-quartz schist and as disseminations within the amphibolite.

The workings consist of a series of shallow shafts and open cuts, with mining having occurred down to 65 meters (Carter *et al.*, 1961). Cobaltite extends below the 65 meter level but the grade is uneconomic. The open cuts have been expanded considerably over the last

50 years by collectors chasing the erythrite veins in search of well crystallized specimens.

Minerals

The major ore minerals at Mount Cobalt are cobaltite and erythrite. Skutterudite and sphaerocobaltite have also been reported but are unconfirmed. Smolianinovite has rarely been noted from Mount Cobalt but the author found it to be quite common during a recent mine visit. A number of other minerals occur at Mount Cobalt including malachite, chalcopyrite, pyrite, scheelite and metatorbernite. The major gangue minerals are quartz, calcite, biotite, muscovite and hornblende.

Cobaltite $CoAsS$

Cobaltite was the major ore mineral at Mount Cobalt. It occurs as well formed, cubic to pyritohedral crystals reaching 5 mm across. The crystals are always embedded in matrix.

Erythrite $Co_3(AsO_2)\cdot 8H_2O$

Erythrite was a significant ore mineral at Mount Cobalt. It occurs as an oxidation product of cobaltite, forming semi-continuous veins up to several centimeters thick. The erythrite is often seen coating smolianinovite and cobaltite crystals.

Slabs of wall rock exceeding 30 cm across and coated with 1–3 cm thick, felted masses of acicular erythrite crystals have been collected. In such specimens the erythrite crystals tend to be very thin and a light pink color.

The best individual crystals occur where there is only a thin coating of erythrite in an open vein. In such cases free-standing, deep pink to red-pink, flattened (on {010}), acicular crystals reach 1 cm. The crystals often occur in radiating tufts up to 2 cm across. Crystals exceeding 1 cm in length do occur but these are generally formed parallel to the matrix and are not as attractive.

Smolianinovite $(Co,Ni,Mg,Cu)_3(Fe^{+3},Al)_2(AsO_4)_4\cdot 11H_2O$

Smolianinovite is quite common in the oxidized portions of the deposit where it has pseudomorphically replaced cobaltite crystals. The smolianinovite is yellow-brown and has an earthy appearance.

OTHER MINES

Numerous other mines in the district have produced minerals of collector significance. A complete description of all these mines is not possible in a single article, however, a brief summary of some of the more notable mineral occurrences follows.

Mary Kathleen Mine

The Mary Kathleen mine exploits a rich uranium and rare earths deposit located midway between Mount Isa and Cloncurry. The deposit is the type locality for stillwellite $(Ce,La,Ca)BSiO_5$, which occurs as massive, resinous, brown masses up to fist-size. It is commonly associated with allanite, uraninite and various other rare earth minerals and occurs enclosed in garnet-diopside granulite.

The deposit also contains large masses of allanite including black, prismatic crystals up to several centimeters long enclosed in calcite veins.

Blockade Mine

The Blockade mine is an underground and open cut copper mine located 60 km east of Mount Isa. Attractive specimens of cuprite and botryoidal malachite are occasionally found. During a visit to the mine in 1986, the author discovered a zone rich in cornetite crystals. The zone was exposed in the north wall of the open cut and contained well formed, prismatic to equant cornetite crystals averaging 0.2 mm but reaching 1 mm in length. The smaller crystals tend to be a medium blue color and the larger crystals are dark blue. The crystals are sometimes intergrown and occasionally display a slight rounding of the edges. The cornetite occurs mostly on massive malachite.

A number of specimens were collected before a copper mining operation removed the entire zone. The deposit represents the first recorded occurrence of cornetite in Australia.

Mount Elliott Mine

The Mount Elliott mine is an underground copper mine located approximately 120 km south of Cloncurry. The mine is famous for its large, clear gypsum crystals. Thick, prismatic crystals reach one meter in length and frequently contain beautiful arborescent inclusions of native copper crystals. These specimens were mined in the early part of the century and the workings are now too unsafe to contemplate a collecting trip.

Maltese Cross Field

This locality is a favorite with the tourists. Staurolite twins in the form of "Maltese crosses" lie strewn across the countryside in the Cattle Creek area, approximately 50 km east of Mount Isa. It is now necessary to dig to find the better quality examples. The twins reach 2.5 cm across and have been weathered out of mica-staurolite schists. The author has seen such twins up to 4 cm across from an undisclosed locality in the Soldiers Gap area, south of Cloncurry.

CONCLUSIONS

Many of the mines in the district represent relatively small operations which were dependent upon good metal prices. Fortunately (for collectors) the fluctuating metal prices have resulted in many deposits being prematurely abandoned, leaving good specimens still to be found.

One cannot help but make a comparison between the Mount Isa-Cloncurry mineral field and the copper mining districts of Arizona. Although there are considerable differences in the geology, the mineralogy is remarkable similar. An important point is that the two areas share similar climates and consequently the respective oxidized zones show a similar development. Unlike the Arizona mining districts, the Mount Isa-Cloncurry mineral field has been the subject of comparatively little mineralogical study. Many species found in the Arizona copper deposits should also occur in the Mount Isa-Cloncurry deposits, and with time some of these specimens should come to light.

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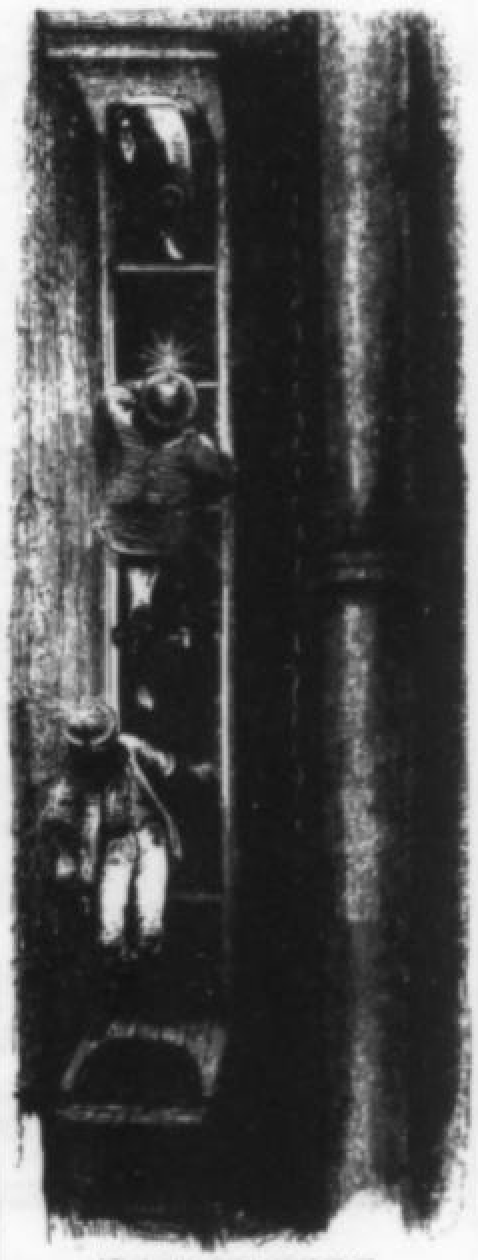

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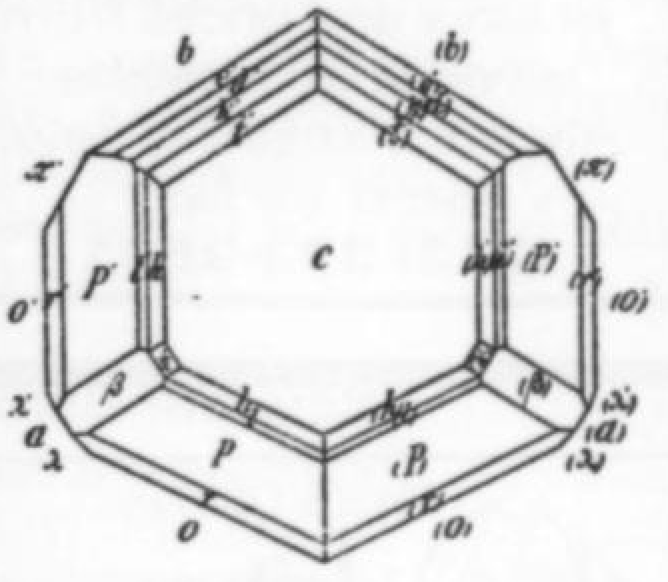

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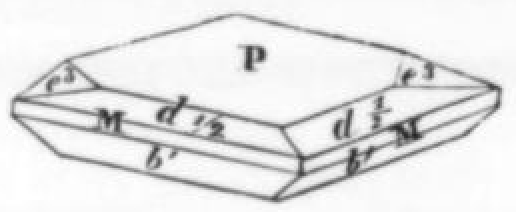

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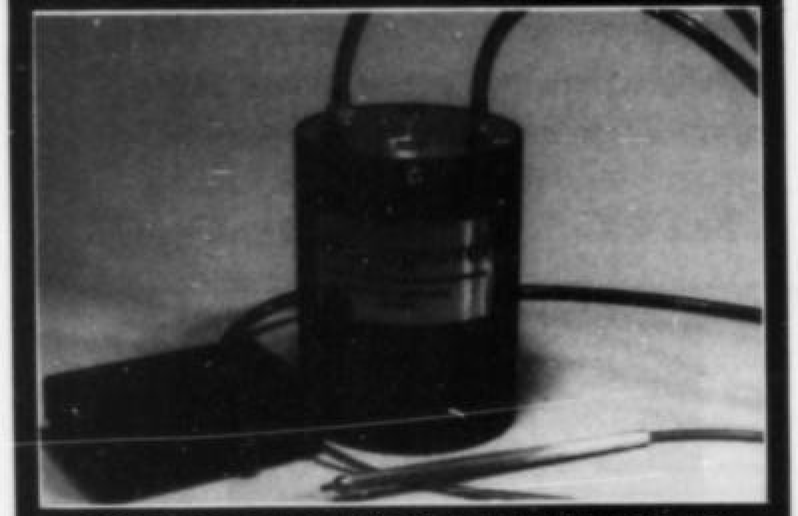

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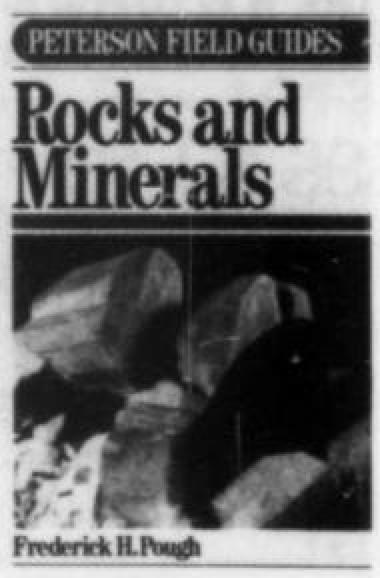

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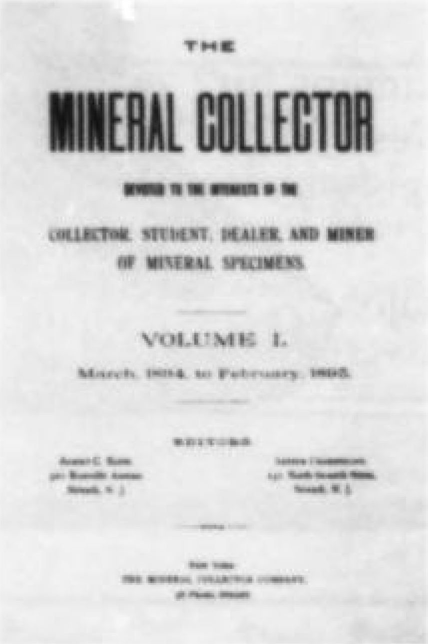

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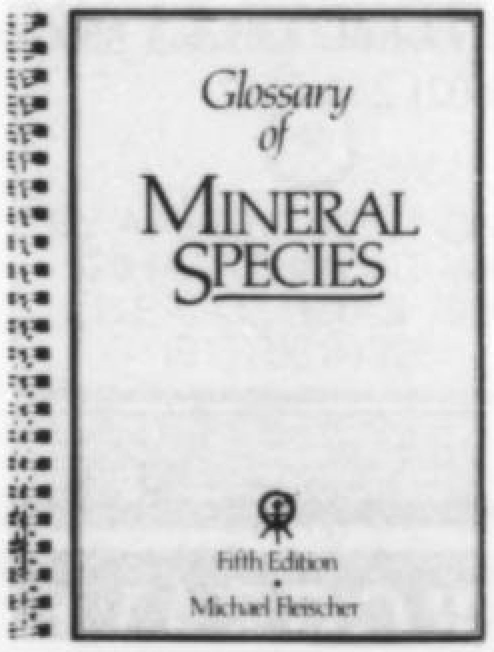

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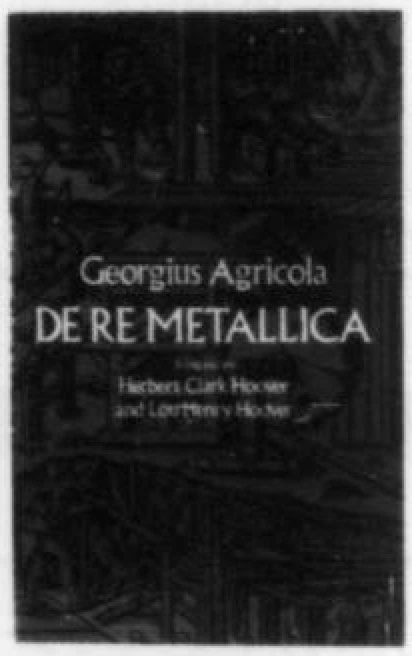

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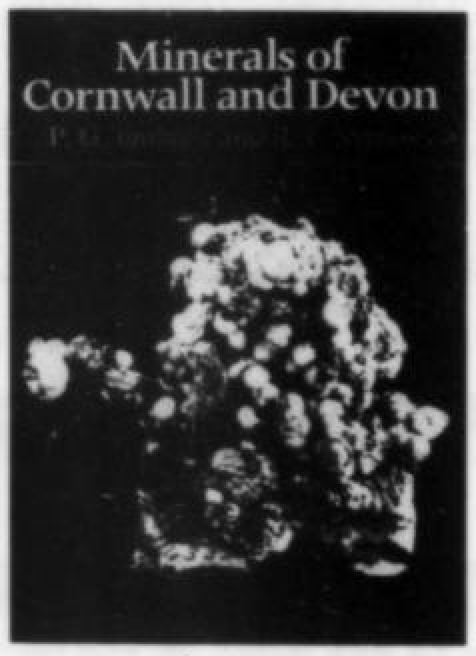

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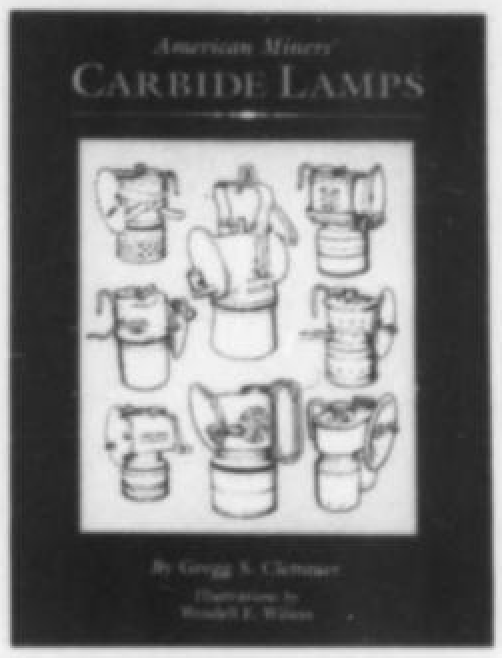

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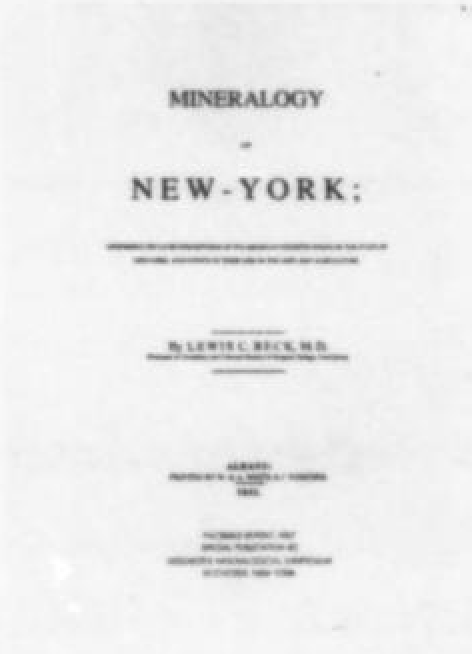

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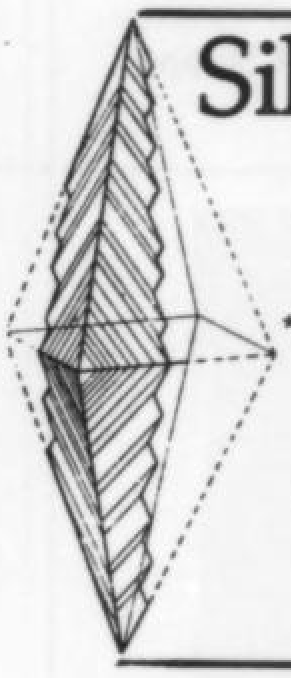

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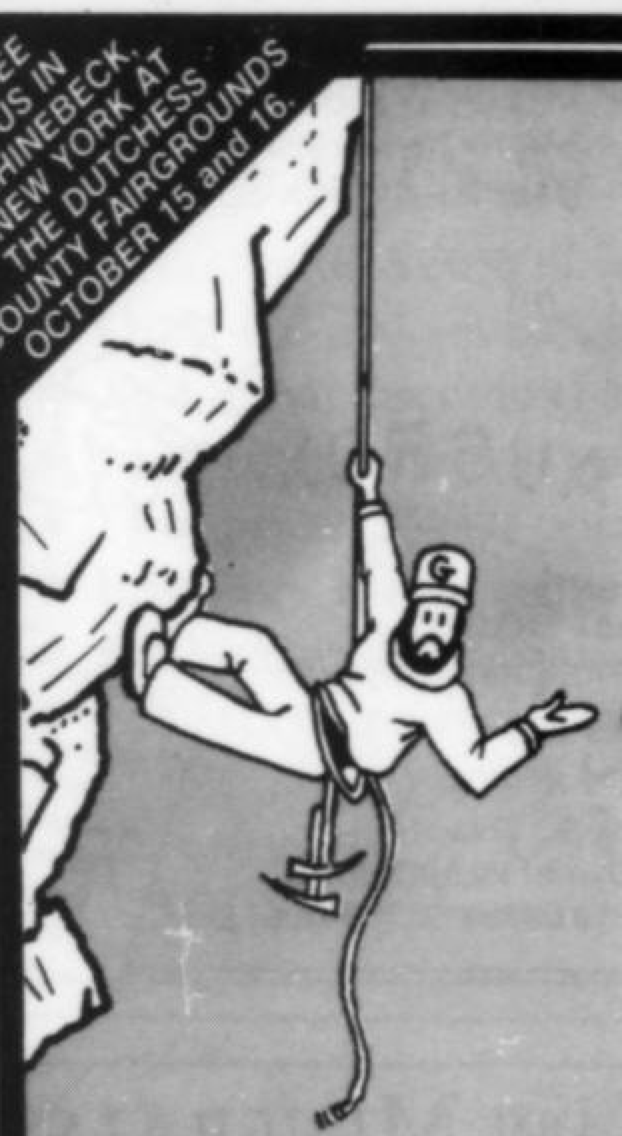

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1. *Title of publication:* Mineralogical Record
2. *Date of filing:* September 30, 1988
3. *Frequency of issue:* Bimonthly
   a. *Number of issues published annually:* Six.
   b. *Annual subscription price:* Twenty-seven dollars.
4. *Location of known office of publication:* 7413 N. Mowry Place, Tucson, Arizona 85741.
5. *Location of the headquarters or general business offices of the publishers:* 7413 N. Mowry Place, Tucson, Arizona 85741.
6. *Names and complete addresses of publisher, editor, and managing editor: Publisher:* Wendell Wilson, 4631 Paseo Tubutama, Tucson, AZ 85715. *Editor:* Wendell E. Wilson, 4631 Paseo Tubutama, Tucson, Arizona 85715. *Managing editor:* none.
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E. Total distribution	7103	7327
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