Sediments, Ores, and Metamorphism: New Aspects

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MINERALOGICAL ASPECTS OF ORES

Sediments, ores, and metamorphism: new aspects

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[Plate 1]

Recent years have witnessed the discovery of new large stratabound deposits of base metals, tungsten and uranium, as well as intensified research efforts in the investigation of known occurrences. Three problems are of particular interest: (1) The response of stratabound metal concentrations to varying degrees of metamorphism, and the limits of 'survival' of their geometrical and compositional parameters, (2) the distribution of manganese in the ore environment of sulphide deposits, and (3) the participation of elements not traditionally associated with the sedimentary cycle, such as tungsten, in the formation of stratabound deposits.

The northwestern Cape Province, S. Africa, has been selected for an initial study of these aspects because of its wealth in large and economically significant base metal concentrations. These occur in volcano-sedimentary successions of probable Kheis age (2600 Ma) which have been metamorphosed during the 1200 Ma Kibaran orogeny. Metamorphism was of amphibolite facies grade (600–700 °C, 3–4.5 kbar) in the east (deposits of Aggeneys and Gamsberg) and of granulite facies grade (800–1000 °C, 6–8 kbar) in the west (deposits of the O'okiep Copper District, including the Wolfram Schist).

In amphibolite facies terrain, the stratabound nature of orebodies is generally well preserved, although complicated by several phases of folding. Electron probe analyses reveal high MnO-contents in silicates of the ore environment (garnets 20 %, pyroxene 5 %, stilpnomelane 11 %). These findings correlate with recent data from the Broken Hill, N.S.W. deposits (Stanton 1976) and from the Red Sea (Cronan *et al.* 1976). Their potential value lies both in the fields of ore genesis and of exploration geochemistry.

Major concentrations of copper ore in transgressive 'noritoids' are limited to the granulite facies terrain of the O'okiep Copper District. Their isotopic, geochemical and petrological parameters favour crustal rather than mantle origin. A source bed model deriving the noritoids by partial melting of Cu-bearing members of the stratigraphic sequence, is thus proposed.

Small tungsten deposits have in the past been mined in the granulite facies terrains of Namaqualand: concordant quartz–ferberite veins occur in the 'Wolfram Schist' and have previously been interpreted as hydrothermal and pegmatitic. Their distinct limitation to a specific stratigraphic horizon as well as new quantitative data on the age and grade of metamorphism in the area suggested a review of this genetic concept. The recent discovery of stratabound tungsten mineralization in Austria, Norway and Rhodesia, and the recognition of the sedimentary origin of the Sundong, S. Korea, deposit further stimulated these considerations. The Namaqualand tungsten deposits are thus interpreted as the product of granulite-facies metamorphism of sedimentary scheelite concentrations.

These investigations necessitate the combination of many geoscientific disciplines, including field work, structural geology, geophysics, petrology, isotopic studies, geochemistry, ore microscopy and experimental mineralogy, here termed 'the comprehensive geoscience approach'. This clearly requires team work; the author has had the privilege of closely cooperating with groups led by Professor T. N. Clifford (Witwatersrand University) and Mr J. Marais (O'okiep Copper Company Limited).

1. Introduction

The recent evolution of certain concepts in economic geology shows some remarkable features. Until the beginning of the 1950s, the formation of ore deposits was, to a very considerable extent, attributed to magmatic and associated hydrothermal processes. It was largely European workers who first started to challenge the dominance of this conceptual model. The frequent temporal and spatial association of sedimentary rocks and ores raised the question whether both might be products of the same process.

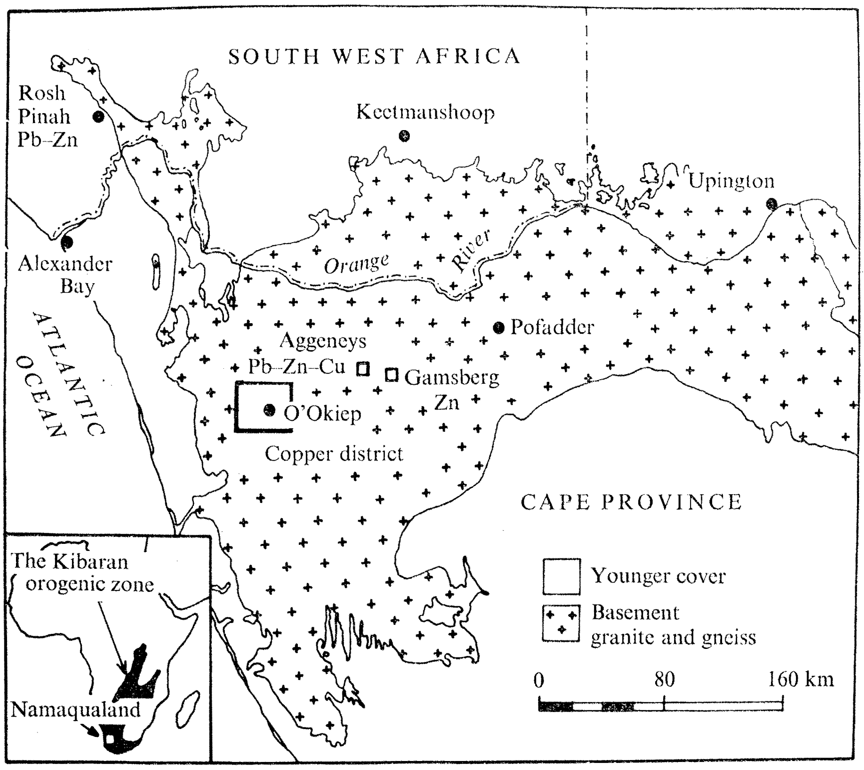

Figure 1. Location map of major base metal deposits, northwestern Cape Province.

Fifteen years later, by the end of the 1960s, the significance of sedimentary processes for the economic concentration particularly of base metals had become widely accepted and well consolidated. The remarkable advances of oil geology had contributed an increased understanding of the mobility and movement of solutions in and through porous media. Experimental mineralogists had quantified the physicochemical conditions of the transport of metals in solutions; one of the most remarkable results of these researches was the recognition of the importance of low-temperature environments for ore deposition. A great number of ore deposits had clearly formed as integral parts of the evolution of sedimentary basins, with metals supplied by the continental crust, by submarine volcanicity or by thermal convection systems in rocks of the sea-bed. Oceanographic and geochemical work, particularly in the North Atlantic and in the Red Sea, contributed significantly to these developments.

Not many sedimentary successions have, however, remained undisturbed since deposition; most of them have been incorporated into mobile belts and exposed to varying degrees of metamorphism. Recent years have been characterized by a growing realization of the importance of an adequate understanding of metamorphic processes for ore genesis and exploration. This takes us to the third step in the recent evolution of ore geology – the attempt to see through the veil of metamorphism, to establish its physicochemical parameters and to deduce those of the original sedimentary environment. The challenge which has emerged here is very likely going to occupy economic geologists throughout the last quarter of this, and right into the twenty-first century. Fortunately, they will be able to rely on the wealth of new data provided by experimental mineralogy and petrology: a quantitative approach to the response of, for instance, a stratabound base metal deposit to granulite-facies metamorphism is now possible. It was this kind of consideration which prompted the investigation, preliminary results of which are presented in this paper. For two reasons, the Northwestern Cape Province (see figure 1) was considered particularly attractive and promising: (1) Intensive exploration has succeeded in delineating some of the Western World's largest base metal concentrations in the area – first public announcements of ore reserves were made in 1973. (2) The eastern part (Bushmanland) had been exposed to amphibolite facies metamorphism, the western part (Namaqualand) to granulite facies metamorphism. Stratabound mineralization (Pb, Zn, Cu, W) occurs in both parts.

Table 1. Major base metal deposits, northwestern cape province

(Ages given as 2600/1200 refer to rocks attributed to the 2600 Ma Kheis system which have been metamorphosed 1213 ± 22 Ma ago)

	metals %			reserves	age	metamorphic
deposit	Cu	Pb	Zn	Mt	Ma	grade
Prieska	1.7	—	3.8	47	1250	amphibolite
Aggeneys:						
Black Mountain	0.8	2.6	0.6	80	2600/1200	amphibolite
Broken Hill	0.4	4.0	2.3	62	„	„
Big Syn	—	1.2	2.9	?	„	„
Gamsberg	—	0.6	7.4	95	2600/1200	amphibolite
O'okiep	1.6	—	—	25	1200	granulite
Rosh Pinah (SWA)	0–0.8	0.5–6.0	2–18	? (prod. 0.5 p.a.)	720	greenschist

2. Bushmanland: base metal ores in amphibolite facies terrain

New discoveries include the Gamsberg area (one major zinc deposit, 90 Mt, 7.4 % Zn, 0.6 % Pb) and, 30 km to the west, the Aggeneys area (so far, two major deposits: Broken Hill and Black Mountain, and a third, Big Syn, in the stage of exploration); total published reserves (G.S.S.A. 1975) exceed 200 Mt. Ore grades are summarized in table 1. The geology of the region is dominated by a volcano-sedimentary sequence consisting of quartzites, iron formation, schists, gneiss and amphibolites. These rocks form part of the 1200 Ma Kibaran mobile belt which extends through Botswana and Zambia as far as Uganda (figure 1). Three phases of folding with three major axial directions have resulted in a complex pattern of interrelated synclines and anticlines. Abundant sand cover in the Bushmanland plateau (average elevation, 900 m a.s.) does not facilitate structural correlation between the well-exposed 'Inselbergs' to which known mineralization is linked.

Gamsberg mountain rises about 200 m above the plateau. The main members of the stratigraphic succession which have tentatively been correlated with the 2600 Ma. Kheis group are shown on the geological sketch map (figure 2). Particularly informative as regards the original environment of deposition is the presence of iron formation, of two generations of amphibolite in the upper part of the succession, and of a baryte later several metres in thickness which can be traced over hundreds of metres in outcrop in the western part of the mountain, where it overlies magnetite–haematite quartzite. Calc–silicate rocks (skarns) and marbles are less widespread; they are also found in association with sphalerite ore. Typical samples of drillcore include banded sphalerite–galena skarns, and large (> 2 cm) cordierite crystals in a matrix of massive sphalerite. An impressive gossan covers the outcropping portions of ore-bearing strata. A detailed survey of Gamsberg geology has been given by Rozendaal (1976). All the above rocks have been exposed to amphibolite facies metamorphism (600–700 °C, 3–4.5 kbar†);

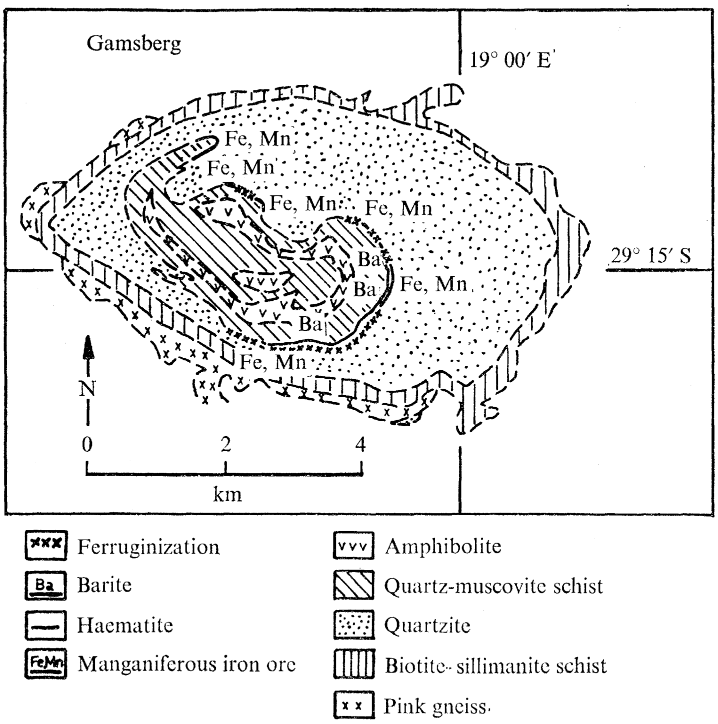

FIGURE 2. Geological sketch map of the Gamsberg zinc deposit (after G.S.S.A. excursion guide, 1975).

DESCRIPTION OF PLATE 1

FIGURE 3. Graphite flakes (various intensities of grey due to reflexion pleochroism) in sphalerite (grey). Pyrrhotite (white) and gangue (black). Reflected light, oil immersion. Gamsberg Zinc Deposit.

FIGURE 4. Magnetite (medium grey) oxidized to haematite (light grey, 'martitization') following cubic crystallographic directions. There are also some large grains of haematite. Note absence of ilmenite or spinel lamellae in magnetite. Gangue is black. Reflected light, oil immersion. Gamsberg Zinc Deposit.

FIGURE 6. Copper mineralization in noritoid: chalcopyrite (white, large grains) and bornite (light grey), following cleavage cracks in silicates (black). Note rounded, zoned grains of zircon (medium grey), the smallest of which is enclosed in phlogopite (black). (Reflected light: oil immersion; Rietberg Copper Mine.)

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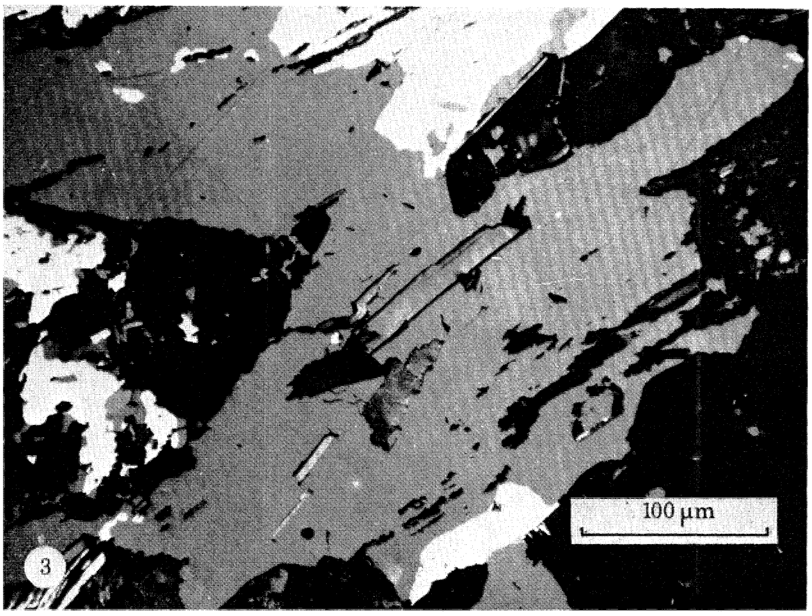
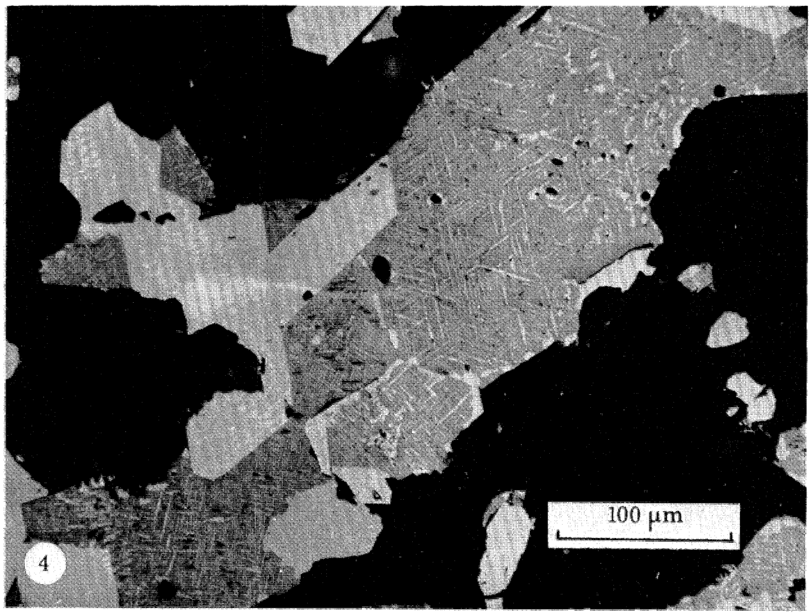
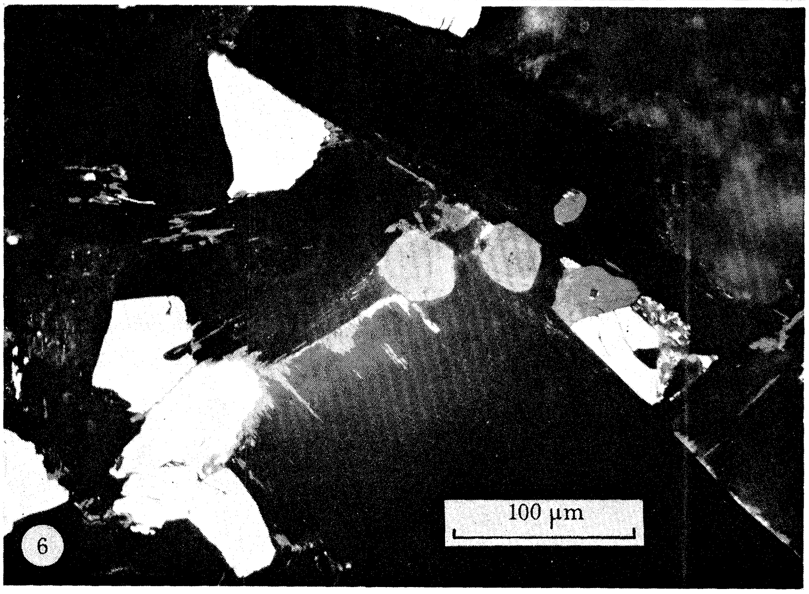
† 1 kbar = 10^8 Pa.







FIGURES 3, 4 AND 6. For description see opposite.

they represent the equivalents of a succession of argillaceous to arenaceous (and, to a smaller extent, calcareous) sediments, submarine lavas, ironstones, baryte layers and metalliferous muds.

Gamsberg ore consists largely of sphalerite, magnetite, pyrite and pyrrhotite; galena occurs in minor amounts (0.6 % Pb on average); chalcopyrite is an accessory constituent. Recrystallization has affected the entire sulphide association, resulting in a comparatively coarse-grained ore, but without obliterating some of the original sedimentary textures. Sedimentary S-planes are frequently occupied by graphite flakes (figure 3, plate 1). Magnetite has been exposed to varying degrees of martitization (figure 4, plate 1).

TABLE 2. MINOR ELEMENTS IN ORE MINERALS FROM GAMSBERG ZINC DEPOSIT

%	Mn	Mg	Co	Ni
ilmenite OX	1.5	0.2	—	—
ilmenite OZ	1.6	—	—	—
magnetite 915	1.5	—	—	—
pyrrhotite	—	—	< 0.05	0.1
pyrite	—	—	< 0.05	< 0.05
sphalerite	7.1	(10.8 Fe)	—	—

Preliminary geochemical investigations of ore minerals from the Gamsberg deposits (table 2) have revealed certain characteristic features; pyrite and pyrrhotite carry only trace amounts (< 0.05 %) of cobalt and nickel; titanium, vanadium and chromium are all but lacking in magnetite. On the other hand there are comparatively high values of manganese (1.5 %) in magnetite and ilmenite. Sphalerite contains up to 7.1 % Mn and 10.8 % Fe. The significance of these findings will be discussed later.

TABLE 3. ELECTRON-PROBE ANALYSES OF SILICATES FROM THE ORE ENVIRONMENT OF STRATABOUND SULPHIDE DEPOSIT, NORTHWESTERN CAPE PROVINCE

(PX, pyroxene, HBL, hornblende, GNT, garnet, STILP, stilpnomelane)

	PX 150	PX 235	HBL OX	GNT 235	GNT 150	STILP. 150
SiO_2	51.1	51.0	42.6	37.3	37.0	46.9
TiO_2	—	—	1.2	0.1	—	—
Al_2O_3	0.6	0.4	11.8	17.5	21.1	5.1
FeO	13.9	16.1	17.6	13.6	19.5	22.1
MgO	8.5	7.0	9.7	0.5	1.9	4.7
MnO	3.7	4.7	0.3	19.8	11.3	11.0
CaO	23.0	21.3	12.1	11.6	10.1	—
K_2O	—	—	0.7	—	—	4.2
Na_2O	—	—	1.3	—	—	0.3
H_2O	—	—	2.1	—	—	5.4
total	100.8	100.4	99.4	100.4	100.9	99.7

Electron probe analyses of minerals from the ore environment of these deposits have also been performed; some results are summarized in tables 3 and 4. The presence of stilpnomelane, well known as a major constituent of the silicate–iron formations of the Lake Superior region, has been recognized in the course of the present investigation. Although frequently described from, and attributed to, lower-grade metamorphic facies, stilpnomelane also occurs in association with garnet, muscovite and chlorite in the Kanto Mountains, Japan (Miyashiro & Seki

1958). Whether its presence in the Gamsberg metasediments is due to post-tectonic recrystallization as reported from the Otago schists (Deer, Howie & Zussman 1971, vol. 3), will be clarified in due course. It is, however, interesting to note that out of 13 stilpnomelane analyses compiled by the latter authors, only one gives MnO-values exceeding 3.08 % – and that is of parsettensite from Val d'Err, Graubünden. A detailed survey of the mineral chemistry of the Gamsberg ore environment will appear elsewhere (Rozendaal & Stumpfl, in preparation).

Table 4. Electron-probe analyses of garnets from the ore environment of stratabound sulphide deposits

	NW Cape 235	NW Cape 150	NW Cape 067	Broken Hill,† NSW		Harlech,‡ Wales
				A	B	
SiO_2	37.3	37.0	36.7	—	—	36.1
TiO_2	0.1	—	—	—	—	—
Al_2O_3	17.5	21.1	21.1	—	—	17.5
FeO	13.6	19.5	6.3	> 30	10–20	15.6
MnO	19.8	11.3	23.1	~ 5	12–20	21.1
MgO	0.5	1.9	2.1	—	—	—
CaO	11.6	10.1	10.6	—	—	5.0
total	100.4	100.9	99.9	—	—	100.0 (incl. 4.7 % Fe_2O_3)

† Stanton 1976. ‡ Mohr 1956 (calc. comp.).

These observations assist in establishing the original environment of deposition of ores and country rocks. The most prominent feature appears to be the manganese content which is not limited to a specific member of the mineral association: pyroxenes carry up to 4.7 % MnO, stilpnomelane up to 11 %, and garnets up to 20 %. These data obviously suggest a distinct geochemical trend which is far from accidental, and which has recently (1976) been well documented by Stanton: a thorough study of the ore environment at Broken Hill, New South Wales showed that the Mn-content of garnets in the country rock increases from 5 to 24 % as one approaches the centre of a given occurrence of banded iron formation. Stanton concludes that, at Broken Hill, N.S.W., 'higher levels of manganese and base metal traces appear to characterize iron-rich sedimentary rocks close to ore position'. More detailed investigations of the Broken Hill, Cape Province, and Gamsberg deposits may well supply statistical backing for these emerging similarities.

Stratabound, although non-economic, pyrite concentrations occur in the Cambrian succession of the Harlech Dome, North Wales. Mohr succeeded, as far back as 1956, in obtaining analyses of fine-grained garnet from an adjoining chlorite–garnet rock. He determined MnO colorimetrically, measured the refractive index and calculated the composition of the garnet, which shows a remarkably high MnO-content (table 4).

Limited data only have so far been published on the geology of the Aggeneys deposits (G.S.S.A. 1975). Stratabound mineralization has been located in three areas within a several 100 m thick sequence consisting of red gneiss, quartzites, grunerite-bearing magnetite–amphibolites, magnetite–quartzite and biotite schists. These include the large deposits of Black Mountain, Broken Hill and Big Syn (table 1). Many ore lenses outcrop at surface and are presently (1976) being developed by adits. In addition to lenses of massive sulphides, base metal values also occur in magnetite quartzite and magnetite–amphibolite. One of the major problems presently being investigated is the stratigraphic correlation between the deposits of the Aggeneys area; this is complicated by a tectonic style determined, as at Gamsberg, by three major phases of folding. Structural geology thus plays a significant rôle in these endeavours.

A large-scale look at the compositional parameters of Bushmanland ores reveals a distinct geochemical trend; copper values decrease steadily (table 1) as one proceeds eastwards from the westernmost orebody, Black Mountain, through Broken Hill to Gamsberg. Pronounced variations in major metal concentrations within single, and between different, stratabound ore deposits in mobile belts are well documented: the Middle Devonian ore bodies of Meggen (60 Mt., 10 % Zn, 1.3 % Pb) and Rammelsberg ('rich ore', 22 Mt., 19 % Zn, 9 % Pb, 1 % Cu) both occur in shale-type lithologies of the Variscan mobile belt (Krebs 1976). Baryte is an integral constituent of the ore environment at Meggen, where it surrounds the sulphide body (15 Mt., 96 % $BaSO_4$). At Rammelsberg, it constitutes 22 % of the rich ore and also forms a separate ore type, 'grey ore' (0.2 Mt., 85 % $BaSO_4$). Recent work by Dornsiepen (1976) has shown that manganese contents in hanging-wall shales at Meggen increase as one moves from the centre towards the periphery of the orebody.

In polished sections, Aggeneys ores show a high degree of recrystallization: coarse grained sulphide aggregates with grain size exceeding 5 mm are widespread. Magnetite, sphalerite, pyrite, galena and pyrrhotite are major constituents.

Sphalerite frequently contains characteristic lamellae and inclusions of chalcopyrite. Electron probe analysis of magnetite from Broken Hill shows absence of titanium and chromium but manganese values ranging from 1.0 to 2.5 %. Sphalerite from the same deposit contains 8.8–9.3 % Fe, 4.6 % Mn and 0.2 % Cd. Although these data must, at present, be considered preliminary, there emerge distinct similarities between sulphide compositions in the Gamsberg and Aggeneys areas: in particular the lack of Ti and Cr in magnetite and the pre-eminence of manganese, and the very low Ni and Co values in Fe-sulphides should be mentioned. Stanton's (1976) comprehensive work on the Banded Iron Formation (B.I.F.) at Broken Hill, N.S.W., has shown that TiO_2 in magnetite is 'virtually undetectable'.

A good example of present-day ore deposition which is relevant to our considerations has been described by Cronan *et al.* (1976) from the Atlantis II Deep of the Red Sea. There is a distinct fractionation between Fe and Mn; manganese and some minor elements may precipitate as far as 10 km away from the Deep. The authors underline the potential significance of their findings in geochemical exploration for submarine hydrothermal ore bodies. Data from sulphide deposits in volcano-sedimentary sequences in mobile belts (Variscan, Caledonian, Kibaran) do, however, suggest that the method may well be extended to include metamorphic deposits – as long as they formed on the seafloor with metal supply from hydrothermal 'vents' A good example for the possibilities in this field is given by Stanton (1976); at Broken Hill, N.S.W., the amount of manganese in the iron formation might be related to the proximity of significant sulphide.

At this juncture the question may be asked whether we must deduce a Red-Sea type environment of deposition for the Bushmanland deposits and, even more disturbing, whether this part of the Kibaran mobile belt, at some time in the past, constituted a zone of Continental separation as the Red Sea does now. At this stage, any attempt to answer that question on a sound quantitative basis would be premature. There can be little doubt, however, that the vast amount of new data which is imminent as a by-product of the development of these mega-deposits, will also make a contribution to our understanding of Precambrian plate tectonics.

3. Namaqualand: base metal deposits in granulite facies terrain

Mineralized volcano-sedimentary successions of probable Kheis age (2600 Ma) continue to the west into Namaqualand, a region of higher (granulite facies) metamorphic grade. Joubert (1971) attributed this situation to the presence of a regional thermal dome in central Namaqualand. Proceeding further west, towards the Atlantic we pass again through rocks of amphibolite facies, which finally, near the coast, changes to greenschist facies. In the course of further considerations in this section we should remain aware of one remarkable feature: it is only in the area of granulite facies metamorphism that we find economic copper concentrations in transgressive pipes and lenses of so-called 'noritoids' – rocks of basic to intermediate composition which are spatially linked to 'steep structures', short-wavelength, high-amplitude folds which occur on a linear pattern throughout an area of more than 2000 km². Figure 5 illustrates a typical cross-section through a cupriferous noritoid body, which typically contains 0.2–3 Mt of ore. The noritoids have, for some time, formed the economic basis of the O'okiep Copper District. Published reserves presently amount to 25 Mt of ore grading 1.7 % Cu on average.

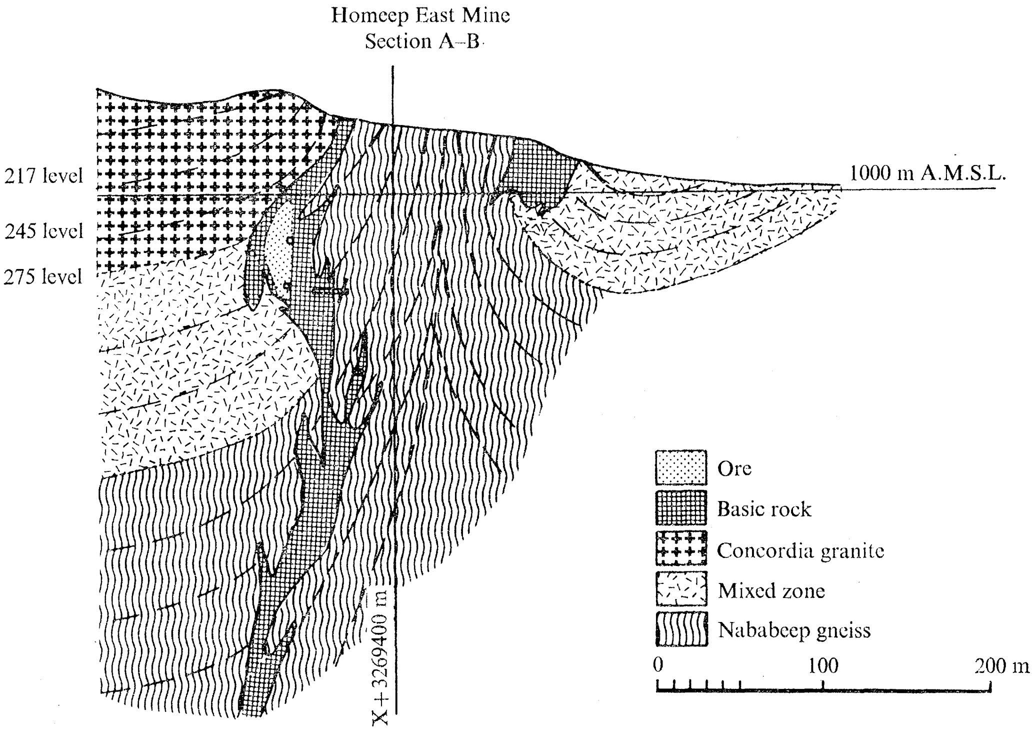


Figure 5. Geological section through Homeep East Mine, Namaqualand. This is a typical example of the setting of a cupriferous noritoid associated with a 'steep structure' (dotted lines). (From OCC Excursion Guide, XVI Geokongres, 1975.)

The noritoids show a remarkable preference for two major members of the 3000 m stratigraphic sequence: Concordia granite and gneiss, and Nababeep gneiss. Other important members include quartzites, as well as layers of two-pyroxene granulites and gneisses. In terms of rock chemistry, many noritoids consist of an older, Fe-rich phase and a younger, Mg-rich phase – an unusual intrusive order. Economic mineralization is confined to the latter type.

Electron probe analyses have shown that phlogopite, and not biotite, is the dominant species of mica. The widespread occurrence, in noritoids, of rounded zircons (figure 6, plate 1) is also of interest. The geology of the area has been discussed by Marais *et al.* (1976), Lombaard & Schreuder (1976) and Genis *et al.* (1976), the petrology and geochronology by Clifford *et al.* (1975*a*, *b*), and aspects of economic geology and genesis by Stumpfl *et al.* (1976). Our discussion will be limited to data relevant to the response of sedimentary ore environments to metamorphism. This includes the problem of the origin of noritoids.

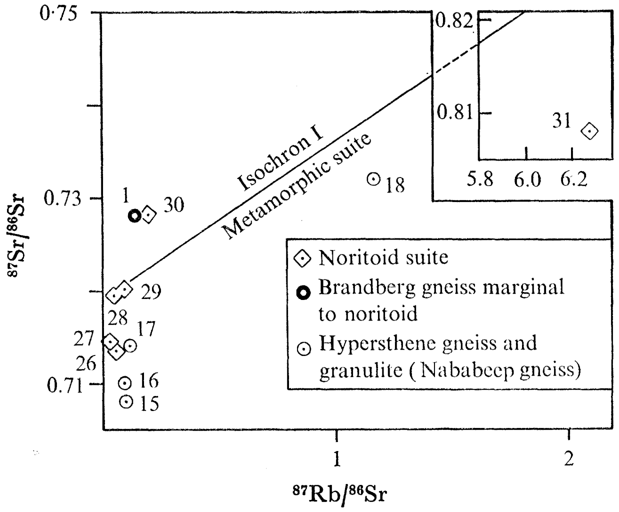


FIGURE 7. Rubidium and strontium isotopic ratios for numbered samples of the Noritoid Suite, the Nababeep Gneiss, and the chloritized Brandberg Gneiss, in relation to the isochron I yielded by acidic metamorphic rocks (from Clifford *et al.* 1975*a*).

At first glance, one would tend to interpret these rocks as basic intrusives: they are transgressive, they show magmatic textures, they have been emplaced after the 1213 ± 22 Ma peak of Kibaran metamorphism. Isotopic and trace element analyses (Clifford *et al.* 1975*a*) reveal, however, average initial $^{87}Sr/^{86}Sr$ ratios (R_0-values) of 0.718 (figure 7) which cannot be reconciled with direct mantle derivation. Crustal contamination is ruled out by low K and Rb values of 0.5 % and 20 parts/10^6, respectively. Mantle-derived basic rocks have R_0-values of about 0.703, granite-type crustal rocks contain 3–5 % K and 200–300 parts Rb/10^6. On the other hand, R_0-values as well as K- and Rb-contents are similar to those of hypersthene-bearing gneisses and granulites from the metamorphic country rock.

Pyroxene and plagioclase compositions from noritoids have been determined by electron probe; they are plotted in figure 8. For comparison, data from two-pyroxene granulites of the Namaqualand stratigraphic sequence, from massif-type anorthosites, and from the Skaergaard and Stillwater complexes have also been included. This reveals a certain 'consanguinity' of the respective minerals from noritoids and from granulites, but distinct differences from compositions from basic igneous complexes. These data do not encourage an interpretation of the cupriferous noritoids as mantle-derived basic rocks. They rather raise the question 'whence the noritoids?' The only alternative to mantle derivation being crustal derivation, we have to consider possible mechanisms. Could the noritoids represent mobilized basic members of the stratigraphic sequence? What conditions would be required to facilitate such mobilization?

This problem had to be settled before further steps towards resolving the argument could be taken. Field evidence in Namaqualand reveals the widespread occurrence of migmatites of granitic composition, suggesting that temperatures facilitating partial melting had been reached during the 1213 ± 22 Ma peak of metamorphism. Laboratory evidence, however, was required to quantify the condition of metamorphism. A layer of sapphirine–cordierite–phlogopite–enstatite rock occurs within the stratigraphic sequence; microprobe analyses show that the enstatite contains 7.1 % Al_2O_3. Correlation of these and other findings with recent results of experimental work suggest temperatures of 800 °C–1000 °C and pressures of 6–8 kbar (figure 9; Clifford *et al.* 1975 *a*, *b*). Yoder & Tilley (1962) have shown that rocks of olivine–tholeiite composition may start partial melting in the presence of water at 825 °C and 5 kbar. Some of the two-pyroxene gneisses in Namaqualand have, in fact, compositions approximating olivine–tholeiite. The data summarized above tend to favour a 'source bed' origin for the noritoids rather than a derivation from the mantle.

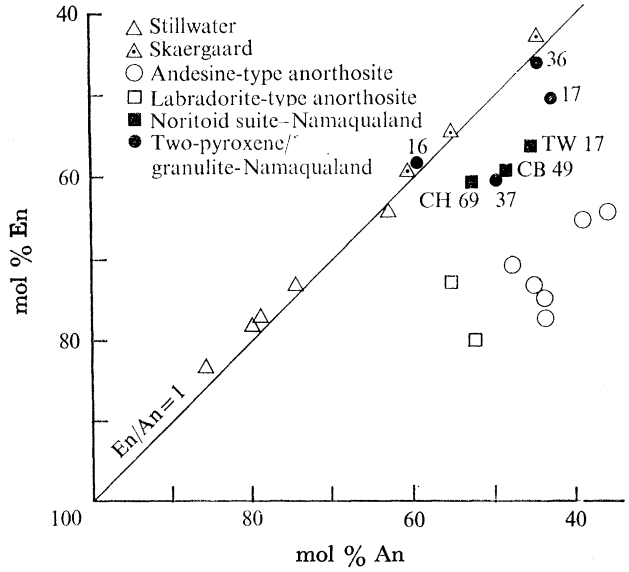


FIGURE 8. Plots of electron probe analyses of plagioclases and hypersthenes in noritoids from Namaqualand compared with those in pyroxene granulites in the country rock metamorphic suite, and in massif-type anorthosites and the Stillwater & Skaergaard igneous complexes (from Stumpfl *et al.* 1976).

And here we may return briefly to one aspect of the distribution of noritoids mentioned initially: noritoids are limited to the area of granulite facies metamorphism. Only under the very high temperatures and pressures reached did partial melting occur not only of significant volumes of granitic composition but also of comparatively small volumes of basaltic composition. We can thus interpret the cupriferous noritoids of Namaqualand as representing one facet of the response of a volcano-sedimentary, base-metal-bearing succession to granulite facies metamorphism.

The concept outlined above should, however, not be accepted without further questioning. Are there, within the granulite-facies terrain of Namaqualand, relics of these supposed source beds which have escaped mobilization? Until very recently, the answer would have been ambiguous. Now, however, we have had the opportunity to study a cordierite–hypersthene–magnetite rock from the Nababeep Mine which carries 5 % copper, mainly as bornite and chalcopyrite. Petrological and ore-microscopic evidence cannot be reconciled with postmetamorphic introduction of this rock and its copper content. Further east, at the large Carolusberg Mine, rafts of galena–sphalerite-bearing schist have been intersected in new drill holes (Marais, personal communication, 1976). Recent exploration has shown that base-metal bearing schists can be traced further east towards Bushmanland.

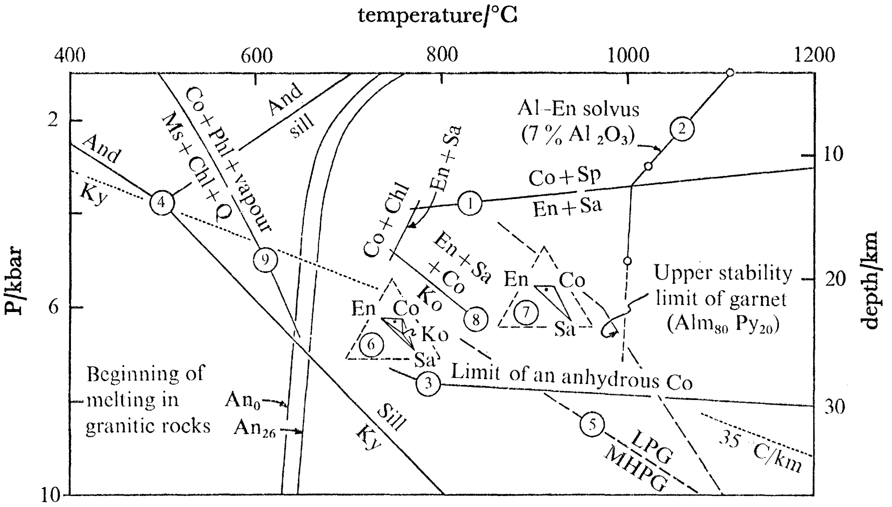


Figure 9. Some experimental data relevant to the discussion of metamorphism in the Nababeep district, Namaqualand (from Clifford *et al.* 1975*a*).

Summarizing the above observations, stratabound mineralization emerges as an integral part of the stratigraphic succession in the southern extension of the 1200 Ma Kibaran mobile belt throughout Bushmanland and Namaqualand. It is only in the latter region that high-grade metamorphism (800–1000 °C, 6–8 kbar) has resulted in mobilization of much of the ore-bearing strata; these have then been emplaced as noritoids into favourable structural 'habitats'. Relics of stratabound mineralization are present, but economically insignificant.

Cu–Pb–Zn mineralization is, however, not the only ore-type to occur in the region. Interesting, albeit at present uneconomic, concentrations of tungsten are also found; they will be discussed in the next section.

4. STRATABOUND TUNGSTEN MINERALIZATION

(*a*) *Namaqualand*

In addition to the economically important copper ores, small occurrences of tungsten ores have been mined in the high-grade metamorphic terrain of Namaqualand. Following the discovery of wolframite at Narrap in 1938, seven small mines have been developed, the largest of which was the Near West mine near Nababeep. Operations continued until 1949; by that time, about 1800 t of concentrates had been produced from ores averaging 1 % WO$_3$ (Söhnge 1950).

Tungsten ore occurs as concordant quartz–ferberite veins in the 130 m thick Wolfram Schist, preferentially in the lower part of the Concordia granite gneiss and near the contact to the Nababeep gneiss (figure 10). Outcrops of the Wolfram Schist can be followed intermittently over a distance of almost 40 km in strike, from Spektakel west of Nababeep to Concordia in the east.

Major constituents of the Wolfram Schist are quartz, plagioclase, garnet, biotite, cordierite and sillimanite. Ferberite is the major ore mineral, accompanied by minor amounts of chalcopyrite, pyrite, scheelite, and molybdenite. Microprobe analyses of garnet and cordierite are given in table 5. The low spessartite content of the garnet is in marked contrast to the high-Mn garnets from two-pyroxene gneisses in Namaqualand and from the ore environment of Bushmanland base metal deposits.

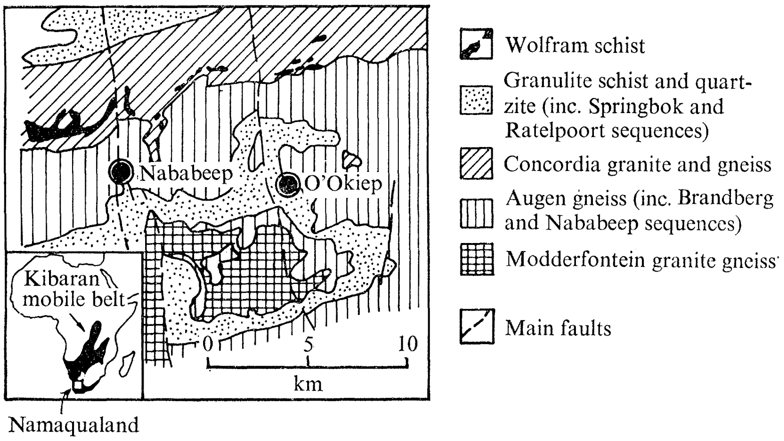


FIGURE 10. Distribution of Wolfram Schist in the O'okiep Copper District (simplified from Benedict *et al.* 1964).

TABLE 5. MICROPROBE ANALYSIS OF GARNET AND MICA FROM THE WOLFRAM SCHIST

	GNT 7	GNT 12	MIC 4	MIC 11
SiO_2	38.3	38.0	37.8	38.0
TiO_2	—	—	4.2	4.3
Al_2O_3	20.4	20.7	15.4	15.2
FeO	30.1	29.9	13.9	13.6
MgO	7.3	7.3	14.5	14.9
MnO	2.4	2.5	—	—
CaO	0.9	0.9	—	—
K_2O	—	—	11.9	12.0
H_2O	—	—	1.8	1.7
total	99.4	99.3	99.5	99.7

At first glance, the mode of occurrence of ferberite, in quartz veins, would fit the accepted pattern of high-temperature hydrothermal veins in granitic terrain. It accords well with the attitudes prevailing at the time that the only report on a Namaqualand tungsten mine (Söhnge 1950) ascribes mineralization to the intrusion of 'Archean formations by a pre-Cambrian granite which was the source of the tungsten-bearing solutions' (p. 931). Although it is suggested that the Wolfram Schist has been derived, by metamorphism, from shale, the sillimanite-rich layers from kaolinic clay, and the augite–amphibole schist from dolomitic marl, the ore is not viewed as part of the original sedimentary succession: 'Analysis of the detailed structure in the Nababeep Near West mine shows how pre-existing folds and fractures have guided the ascending vein-forming fluid and localized the formation of ore-shoots' (p. 940).

Beyond the local context, these observations serve to illustrate some very pertinent aspects of the evolution of genetic concepts in ore geology. The setting of ferberite veins in the Wolfram Schist stimulates further thought: first, they are concordant; second, outcrops of the host rock occur as a distinct stratabound horizon and can be followed over 40 km along the regional strike.

What geological factors could account for what clearly is an example of stratabound distribution of quartz–ferberite veins? Certainly, high-grade metamorphism should be considered. In the preceding section, we have assembled quantitative data for the temperatures and pressures which obtained during the peak of the regional metamorphism 1213 ± 22 Ma ago. We have also seen evidence for partial melting of copper-bearing strata of basaltic composition.

There is, therefore, no need to assume that the tungsten content of the Wolfram Schist has always been present as ferberite in quartz veins. Recent years have seen the discovery of stratabound tungsten mineralization (albeit largely as scheelite) in a variety of different geological environments, and it is necessary to briefly consider these occurrences before returning to the Wolfram Schist.

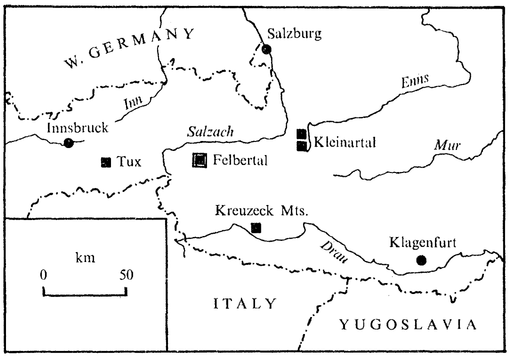


FIGURE 11. Major scheelite occurrences in Austria. Felbertal is, at present, the only economic deposit.

(*b*) *The Eastern Alps*

Intensive exploration for scheelite in the Eastern Alps was prompted by Maucher's new concepts (1965) regarding the genetic connections of Lower Palaeozoic submarine volcanism and the formation of Sb–W–Hg deposits. Within a few years, spectacular results had been achieved, culminating in the discovery of the Felbertal orebody (Höll 1969). This contains 20 Mt scheelite ore, and is presently (1976) approaching production. Minor scheelite concentrations occur extensively in the Eastern Alps; most of them are distinctly stratabound and linked to volcano-sedimentary successions of Lower Palaeozoic age. The area between Kleinarltal and Felbertal in the Province of Salzburg (an east–west distance of about 60 km) is particularly rich in scheelite (figure 11). The Felbertal orebody has been delineated over 2500 m in strike. It is linked to a volcano-sedimentary sequence (Habach-Serie) within the 'Schist Cover' (Schieferhülle) of the Tauern Mountains. Höll & Maucher (1972) describe the orebodies as 'scheelite-bearing varieties of the surrounding, finegrained quartzitic country rocks'. The deposits at Kleinarltal are linked to slightly siliceous dolomites and graphitic limestones with well-preserved sedimentary textures. Metamorphism did not exceed greenschist–amphibolite facies conditions.

At Tux mine, southeast of Innsbruck, scheelite occurs preferentially in black schists in the footwall of an economic, dolomite-bearing magnesite deposit of Lower Palaeozoic age. Höll (1971) stresses the close association of many alpine scheelite deposits with basic (submarine) effusive rocks.

(*c*) *Norway*

Stratabound tungsten deposits have recently been reported from Norway. In the Bindal area of Northern Norway (figure 12) scheelite-bearing reaction skarns are present within a sequence of Caledonian supracrustal rocks comprising amphibolite-facies gneisses, micaschists and marbles (Skaarup 1974). Two particular types of skarn, diopside skarns and garnet–schlieren diopside skarns, carry significant tungsten concentrations; they are widely linked to the marble–gneiss contact zones. It is important to note that 'scheelite is restricted to certain levels in the hornblende–biotite gneiss or to skarns formed by replacement of this gneiss' (p. 305).

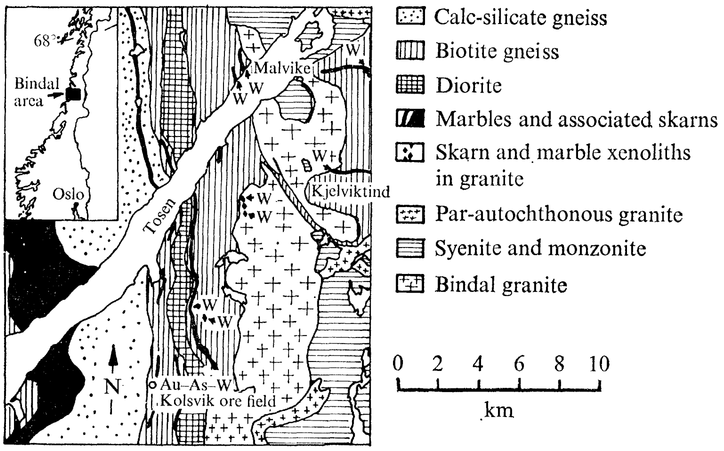


Figure 12. Geological sketch map of the Bindal area, N. Norway (modified after Skaarup 1974).

Table 6. Major ore minerals, host rock, metamorphic grade and age of some stratabound tungsten deposits

deposit	mineral	host rock	metamorphic grade	age / Ma
Felbertal, Austria	scheelite	volcano-sedimentary	almandite–greenschist	400–500
Kleinarltal, Austria	scheelite	carbonate rock in phyllites	almandite–greenschist	400–500
Kreuzeck Mts., Austria	scheelite–stibnite	graphitic schist in metavolcanics	greenschist	400–500
Bindal, N. Norway	scheelite	hornblende–biotite–gneiss and reaction skarns	amphibolite	500
O'okiep District, S. Africa	ferberite	quartz veins in gneiss	granulite	1200
Örsdalen, S. Norway	ferberite and scheelite	cordierite–garnet–schist	granulite	1480
Bulawayan Formn., Rhodesia	scheelite	carbonate rock	greenschist–amphibolite	2900

The migmatitic gneiss complex of Örsdalen, Rogaland, S. Norway contains a series of graphite-bearing amphibolite layers. The area has been affected by granulite–facies metamorphism 1480 Ma ago (Urban 1971). One of the above amphibolite layers carries concordant quartz veins with ferberite and scheelite; single grains exceed 1 cm in diameter. Molybdenite is also widespread and occurs preferentially with biotite-, garnet-, amphibole- and graphite-rich portions of amphibolite; it has not been found in quartz veins.

Scheelite cores in ferberite have frequently been observed and suggest partial replacement of scheelite by ferberite. Of significance for our considerations is the fact that scheelite was the pre-existing tungsten mineral. Tungsten was originally deposited with a sequence of alternating effusive rocks and sediments. Later, these have been exposed to granulite-facies metamorphism. There are distinct geological and mineralogical similarities with the occurrences in the Wolfram Schist of Namaqualand. The Örsdalen deposits have previously been interpreted as products of four phases of mineralization (Heier 1955): one pneumatolytic and two late hydrothermal stages, followed by large-scale calcium metasomatism which resulted in the alteration of wolframite to scheelite.

Further pertinent examples of stratabound tungsten mineralization include the producing Sandong mine, Korea (So 1968; Wiendl 1968) and various occurrences in Rhodesia.

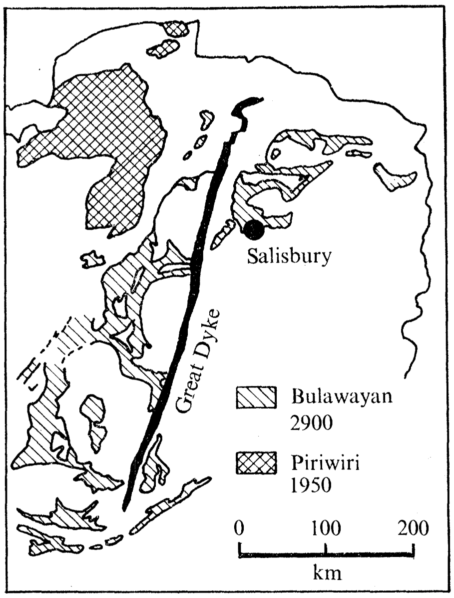


Figure 13. The Bulawayan and Piriwiri systems in Rhodesia. Both contain stratabound tungsten mineralization (simplified after Cunningham *et al.* 1973).

(*d*) *South Korea*

The Sandong mine is situated about 100 km south of the 38th parallel; scheelite production is mainly from one of six concordant layers of garnet (or hornblende)–diopside–epidote skarn within sediments of the Cambro–Ordovician Myobong series. Within these units, scheelite is preferentially associated with quartz and biotite. The ore contains on average 1.5–2 % WO_3. There are no igneous rocks in the area.

(*e*) *Rhodesia*

In Rhodesia, tungsten mineralization occurs over thousands of square kilometres within the 1950 Ma Piriwiri and the 2900 Ma Bulawayan systems (Cunningham *et al.* 1971, figure 13). Within the Bulawayan system, metamorphism has attained greenschist or amphibolite facies grade. Three different ore facies can be distinguished, including scheelite skarns and garnet–vesuvianite–epidote rocks with scheelite within ultramafic metavolcanic schists. Scheelite and wolframite mineralization within the Piriwiri system (argillaceous and aranaceous sediments with intercalations of basic lava) occurs as dissemination pegmatoids and quartz veins.

The fabrics of tungsten ores from both systems are similar to those described from deposits in the Eastern Alps.

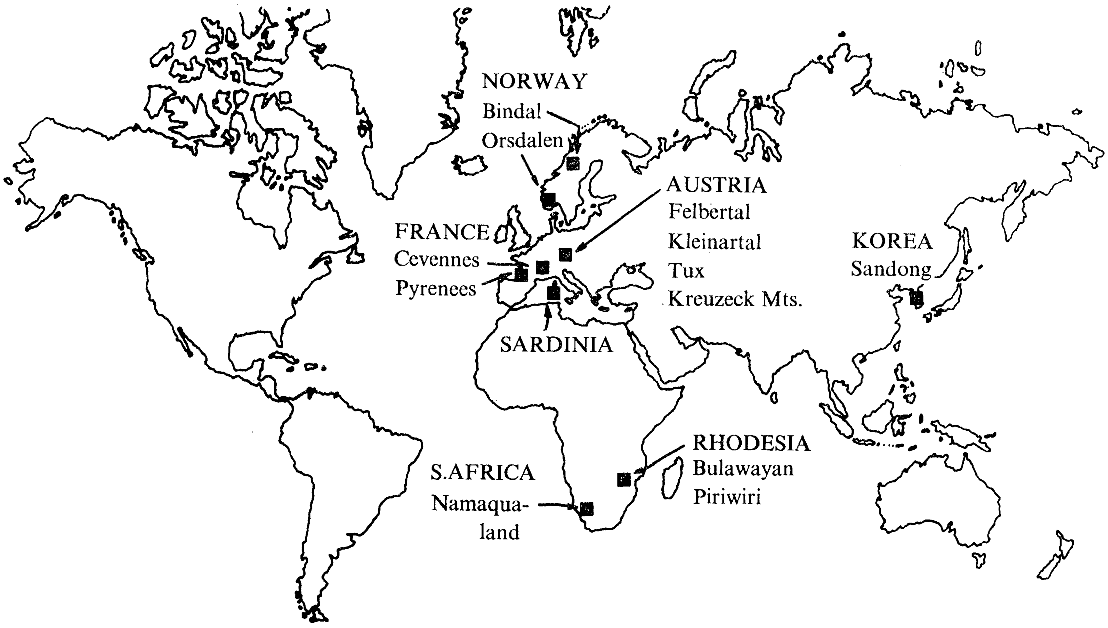


Figure 14. Sketch map showing distribution of some stratabound tungsten deposits.

(*f*) *Some genetic aspects*

Recent evidence from world-wide occurrences (figure 14) shows that tungsten can be deposited by volcano-sedimentary processes, resulting in stratabound concentrations. These frequently also contain minor amounts of base metal sulphides, suggesting potential links to base metal deposits of similar origin. Sedimentary textures are well preserved in many stratabound tungsten deposits and apparently 'survive' metamorphism up to amphibolite grade. Higher (granulite facies) metamorphism results in changes in texture and mineralogical constitution of the orebodies. The development of concordant quartz–ferberite veins is a case in point. Quantitative data on the conditions of metamorphism in high-grade tungsten-bearing rocks have, so far, become available only from Namaqualand. The Wolfram Schist and its quartz–ferberite veins are thus interpreted as the metamorphic equivalent of an original volcano-sedimentary scheelite concentration.

5. Summary and conclusions

(1) Results obtained in the course of a continuing investigation of the response of stratabound ore deposits to amphibolite and granulite facies metamorphism have shed new light on certain aspects of ore genesis. Work carried out so far has largely been concentrated on the north-western Cape Province, S. Africa. The area contains some of the largest base metal deposits of the Western World within a volcano-sedimentary sequence of probable Kheis age (2600 Ma). This has been exposed to varying degrees of metamorphism at the peak of the 1200 Ma Kibaran orogeny.

(2) The combination of various geoscientific methods (the 'comprehensive geoscience approach') has proved advantageous for dealing with the complex problems involved. Field investigations, structural geology, petrology, isotopic studies, geochemistry, ore microscopy and experimental mineralogy have all contributed significant results. The microprobe has been invaluable for several aspects of the work.

(3) In amphibolite facies terrain, the geometrical and compositional parameters of stratabound base metal deposits are well preserved, in spite of changes in mineralogy and texture. The ore environment is characterised by paragneisses, micaschists, skarns, quartzites, amphibolites and iron formation. Conglomerates and baryte layers are important locally. This sequence is interpreted as the metamorphic equivalent of argillaceous, calcareous and arenaceous sediments, ironstones, submarine lavas and metalliferous muds.

(4) Manganese is a significant constituent of the ore environment. Microprobe analyses show garnets to contain up to 20 % MnO, and stilpnomelanes 11 % MnO. These data correlate well with recent findings from other stratabound Precambrian deposits (Broken Hill, New South Wales: Stanton 1976) and from ore deposits *in statu nascendi* in the Red Sea: Cronan *et al.* (1976) have described manganese haloes of up to 10 km radius around submarine centres of mineralization in the area of the Atlantis II Deep. It is hoped that further work will help to establish the possible plate tectonics setting of the NW Cape deposits.

(5) Magnetite, sphalerite, chalcopyrite, pyrite, galena and pyrrhotite are the major opaque constituents of deposits in the amphibolite facies (eastern) part of the area. Magnetite is free of ilmenite or spinel lamellae, and carries very low (0.05 %) Ti- and Cr-values, but up to 2 % MnO. Sphalerite is rich in MnO (up to 7 %) and FeO (up to 11 %). Pyrrhotite and pyrite contain minor amounts of Co and Ni (0.1 %). Graphite is widespread and tends to be arranged parallel to sedimentary S-planes.

(6) In granulite facies terrain, stratabound sulphide mineralization has been preserved as rafts and layers of limited extent only. These include galena–sphalerite-bearing schists and cupriferous cordierite–hypersthene rocks. The major type of economic mineralization in this (western) part of the area, however, occurs as transgressive lens- and pipe-shaped bodies of copper-bearing noritoids – rocks of igneous texture and intermediate to basic composition.

(7) The noritoids have been emplaced following the peak of 1213 ± 22 Ma granulite facies metamorphism. Isotopic (average $R_0 = 0.718$) and geochemical data (0.5 % K, 20 parts Rb/10^6) do not support a concept of mantle derivation or of crustal contamination of mantle material. They rather suggest crustal derivation; some petrological evidence points in the same direction. The noritoids are thus interpreted as mobilized portions of cupriferous horizons within the volcano-sedimentary sequence.

(8) These considerations necessitated a quantitative approach to temperatures and pressures which obtained during the peak of granulite facies metamorphism. Field evidence reveals widespread migmatization of granitic rocks in the area. Microprobe analyses of silicates from several indicator rocks, paragenetic studies and recent data from experimental mineralogy show that temperatures of 800–1000 °C and pressures of 6–8 kbar have been reached. This is considered sufficient for partial melting of intermediate to basic members of the stratigraphic sequence.

(9) Stratabound tungsten mineralization also occurs in granulite facies terrain in the northwestern Cape Province. Several small occurrences of ferberite–quartz veins have been mined in the past. They are linked to one specific member of the succession, the Wolfram Schist.

The veins are concordant and can be followed in outcrop intermittently over a distance of 40 km in strike. The Wolfram Schist carries low-MnO garnets (almandine$_{67}$pyrope$_{25}$) and phlogopitic mica with up to 5 % TiO_2, in addition to quartz, microcline and cordierite. Minor ore minerals are chalcopyrite, scheelite, pyrite, molybdenite and sphalerite. The distinct stratabound nature of the mineralization, as well as the quantitative data now available on age and grade of metamorphism in the area suggested a reconsideration of the origin of these deposits which has previously been ascribed to hydrothermal and pegmatitic solutions.

(10) This aspect received further stimulus from the recent discovery of economic tungsten mineralization in the Eastern Alps, which is distinctly stratabound, and from new work on similar deposits, including quartz–ferberite veins in granulite facies terrain, in Norway and Rhodesia. These observations further underline the significance of submarine volcanism and sedimentation for the distribution of metalliferous deposits in metamorphic terrains of the north-western Cape Province. Similarities with other major ore fields, such as Broken Hill, New South Wales, are emerging and will receive increased attention in the future.

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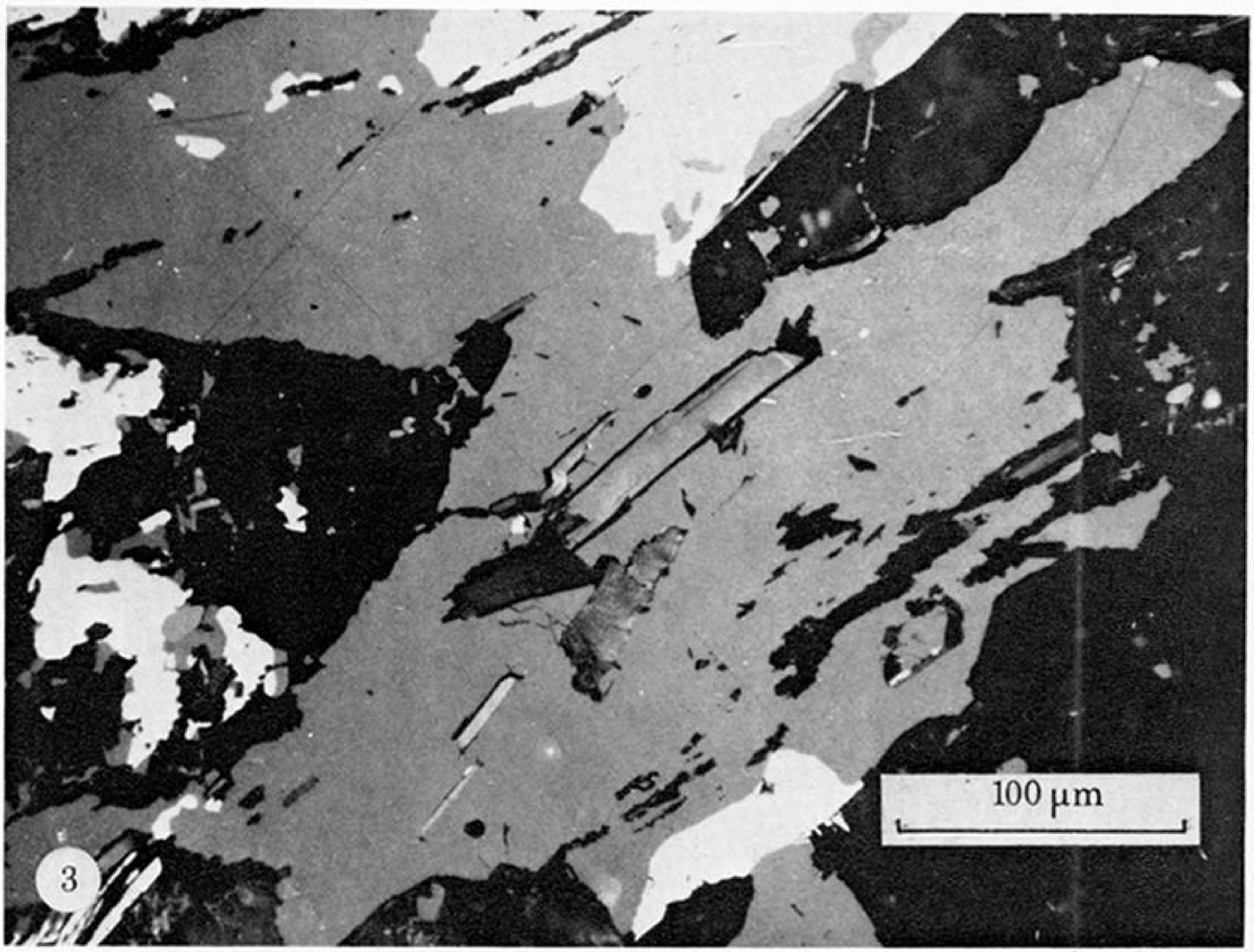

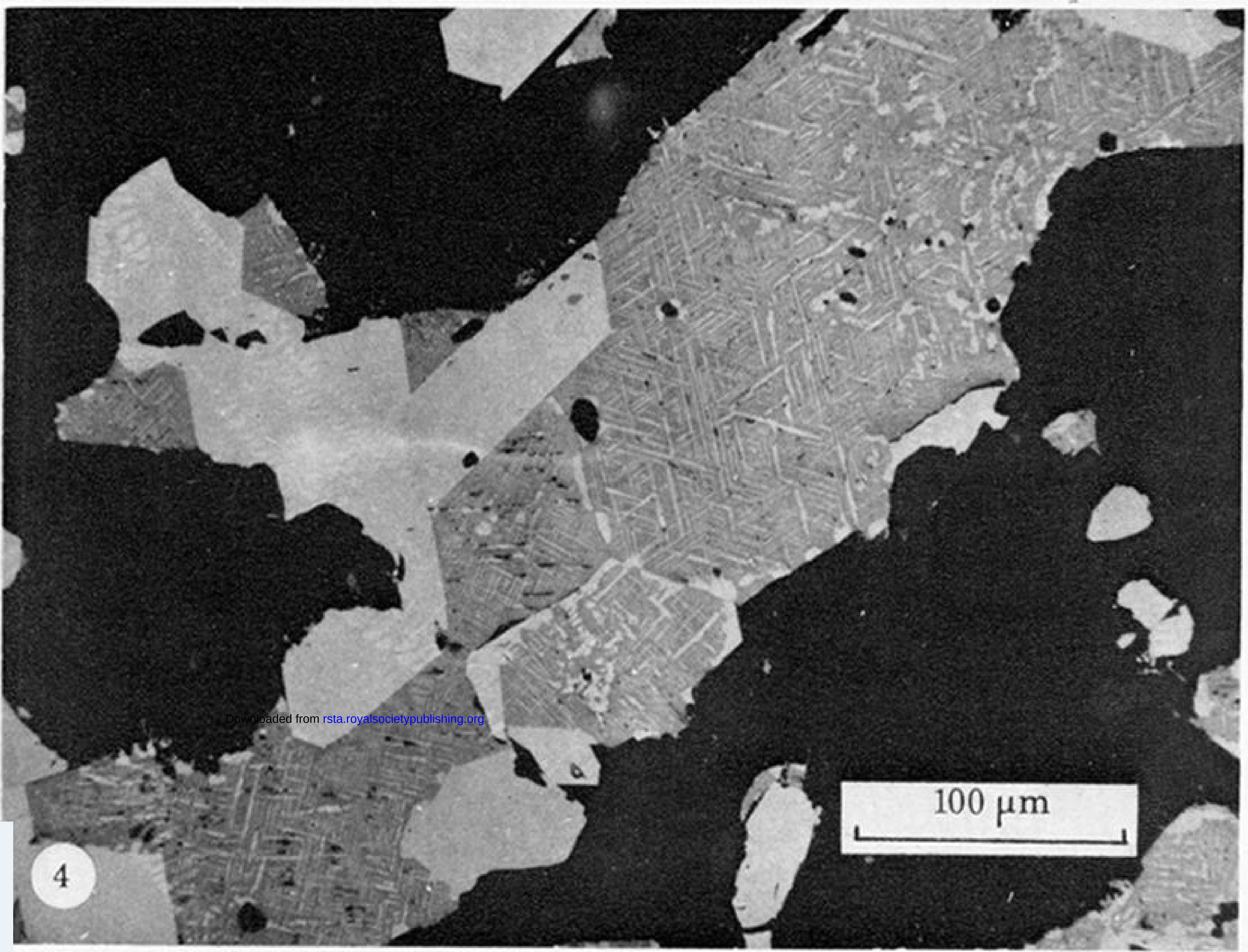

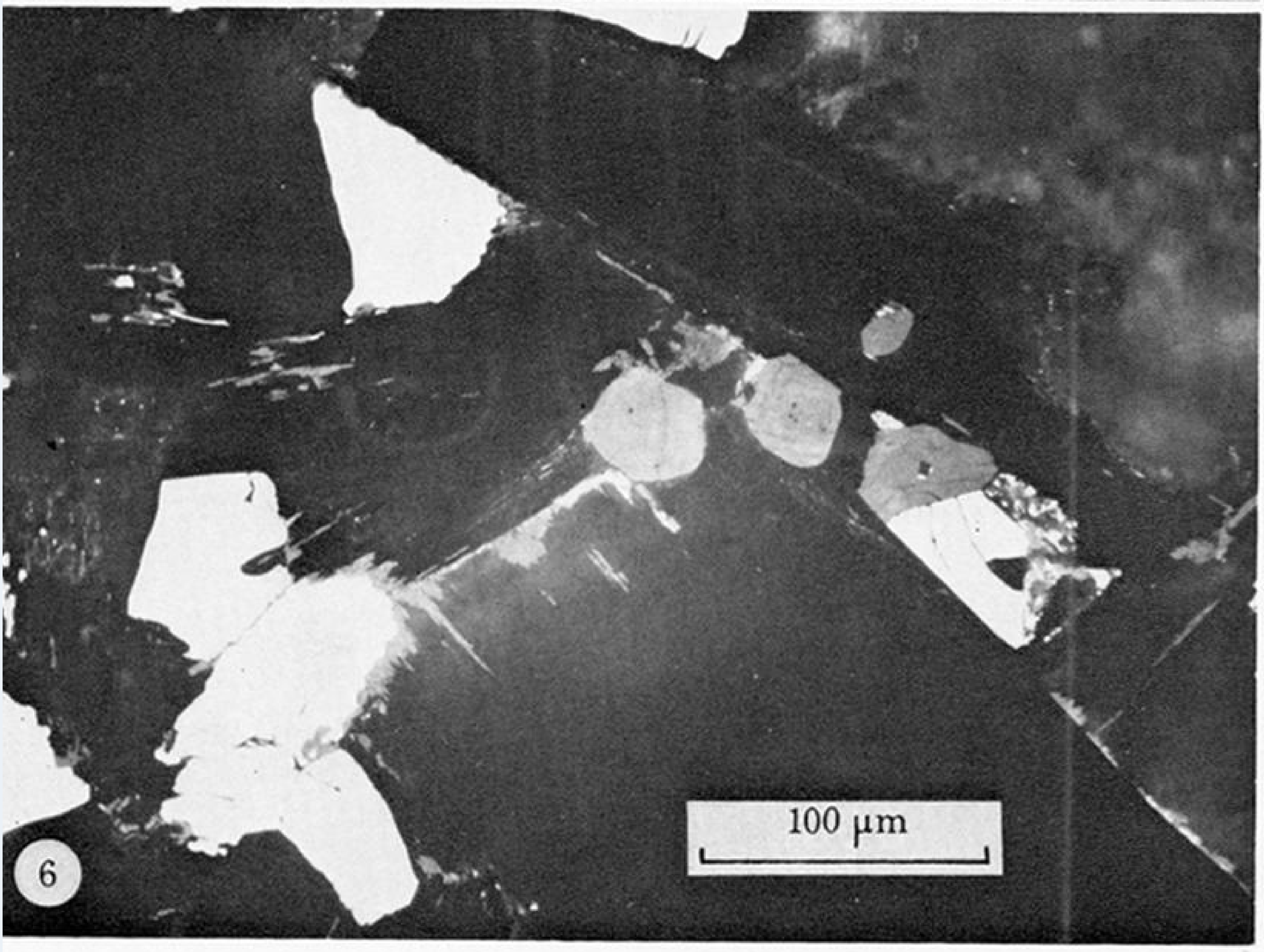

FIGURES 3, 4 AND 6. For description see opposite.