CENTENAIRE DE LA SOCIÉTÉ GÉOLOGIQUE DE BELGIQUE
GÉOLOGIE DES DOMAINES CRISTALLINS, LIÈGE, 1974, 301-321

THE MINERAL POTENTIAL OF GRANULITE TERRANES AND OTHER HIGHLY METAMORPHOSED SEGMENTS OF THE EARTH'S CRUST

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ABSTRACT

Physical and chemical adjustments of sulphide and oxide base metal deposits during high grade metamorphism are sufficiently restricted in magnitude to encourage vigorous exploration for economic ore bodies in granulite and other highly metamorphosed terranes. Many of these terranes are relics of highly mineralized Archaean basement and cover rocks, and other granulites are within Precambrian mobile belts which cut Archaean cratons and have been modified considerably from mantle-derived emanations.

The relationship between the tectonic and metamorphic setting of these terranes and irregularities of the mantle-crust interface appear to favour development of a range of ores, such as Ni and Cu. The economic significance of zones of retrogression within these terranes is postulated. A wide range of gems, ornamental and industrial minerals is a feature of these terranes. Gold mineralization is uncommon.

A review of the mineral potential of the deep zones of the earth must be limited to those portions of the deep crust which are likely to come within economic reach of mankind within the foreseeable future.

Most of the rocks discussed in this review have suffered one or more phases of granulite facies metamorphism or are igneous bodies emplaced within the deep crust.

THE INFLUENCE OF METAMORPHISM ON MINERAL DEPOSITS

One of the main reasons that rocks of the deep crust have generally been overlooked as prospects for ore search is the widespread belief that metamorphism (especially high grade metamorphism) tends to expel or disperse sulphides.

In view of an inadequate and erroneous view of the effect of metamorphism on ore bodies, a brief summary of the more important principles is set out. More detailed treatments of some aspects of this subject are given by McDonald (1967), Vokes (1969), Mookherjee (1970) and Sangster (1971).

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(1) Contact metamorphism

Although contact metamorphic conditions commonly produce spectacular but very localized external and mineralogical modifications of ore bodies, very little migration of material has been recorded, unless major metasomatism is also clearly related to the contact metamorphism.

(2) Dynamic metamorphism

In zones of intense shearing, schistose and gneissose frabrics normally develop and mylonites are common. The more ductile sulphides such as chalcopyrite are commonly mobilized into local regions of low pressure within shear zones or into tension gashes within the enclosing rocks.

(3) Regional metamorphism

The most profound modifications of ore bodies and "protore" are brought about by regional metamorphism. The grain size of sulphides and oxides greatly increases, thus causing upgrading of some very fine grained sulphide or oxide-bearing rocks into ore which can be metallurgically treated.

Although mobilization of sulphides is more pronounced under regional than dynamic metamorphism, the maximum movement of sulphides seems to be no more than a few tens of metres.

Chemical, rather than physical, movement of components of ore bodies is normally much more profound. A well documented effect is the conversion of pyrite to pyrrhotite and the consequent release of S from pyrite, and the scavenging effect of S on Cu, Zn, Ni, Fe, etc., on protores or country rocks elsewhere in the region. Recent isotopic work is showing that some fluids, especially connate and meteoric waters, are capable of being convectionally cycled during regional metamorphism, and these may modify sulphide-bearing rocks in such a way that new ore bodies can be produced. These effects are readily seen within the vicinity of high level plutons, especially within porous volcanic piles. Comparable convectional phenomena may be expected in deeper zones, although the effect of lower porosity and permeability would need to be taken into account.

CONCEPTS PERTINENT TO CONCENTRATION OF METALS AND OTHER SUBSTANCES OF ECONOMIC INTEREST

In this section of the paper several concepts are discussed which have a bearing on the economic potential of terranes of highly metamorphosed rocks. Following this section the application of some of the concepts is considered for Australian granulite terranes.

(1) Abnormal geothermal gradients

There is a concensus of opinion that in early Precambrian times the earth's crust was much thinner and geothermal gradients much steeper than during Phanerozoic times. Thus most shields now display broad regions of Archaean rocks and Lower Proterozoic rocks which have suffered high grade thermal metamorphism on a regional scale. Yet this has been brought about without the development of the pronounced linear features so well developed in Barrovian metamorphic belts. In later geological times this "regional thermal metamorphism" is more normally found near the contacts of large mafic intrusions.

The effect of this "regional thermal metamorphism" on mineralization is thought to be small except in zones where it is associated with much mantle-derived volatile components.

(2) Domes and ridges on the mantle

Some major positive gravity anomalies of the shields coincide with highly metamorphosed rocks, especially those of granulite facies (e.g. Pikwitonei subprovince of Canada, and the Fraser Range, Western Australia). Although some of the gravity anomalies may undoubtedly be ascribed to the somewhat higher density of the granulites compared with normal shield rocks, I postulate that many of these granulite terranes are underlain by mantle domes or ridges. The mode of transfer by heat from mantle into the crust immediately above the mantle protuberance is of fundamental importance not only to general metamorphic theory, but is of particular interest to the subject of this paper. If a hydrous medium is the medium for heat transfer, what substances other than "water" are also transferred into the crust from mantle cupolas or ridges?

(3) Emanations from the mantle

Sites for the earliest cupolas and mantle convection cells may have been dictated by primitive impact scars, for it seems highly likely that meteorite impacts caused major irregularities in composition and structure of the early mantle (Green, 1972). As topographic irregularities developed at the crust-mantle interface, it is probable that emanations produced during degassing of the interior of the earth would become largely concentrated in such gravity-favoured positions.

The economic potential of such positions becomes apparent when the mineralizing role of degassing products such as CO_2, H_2O, F, Cl, CH_4, NH_3, H_2S and related volatiles is considered. Not only may these products introduce new metallic substances into crust from the mantle: they may also cause major transfer metals to higher crustal levels, either by virtue of their intrinsic chemical nature, or by virtue of acting as vehicles of massive heat transfer from the mantle and deep crust.

(4) Major sutures or lineaments within shields

These structures may be the expression of several types of tectonic phenomena, and each has its own economic significance.

Most province boundaries are zones of major mantle and crustal disturbance, and as such are favourable zones for mineral deposits of various types.

(a) NARROW MOUNTAIN CHAINS

Some province boundaries, such as the Ural Mountains, are marked by a major mountain range (or by the roots of a deeply eroded mountain range) and may have resulted from the collision of two crustal plates. The Urals is a highly mineralized belt.

(b) SUTURES ASSOCIATED WITH A NARROW BELT OF INTRACRATONIC SEDIMENTS AND DEEP CRUSTAL TECTONIC SLICES

An example of this type of suture is the junction between the Superior and Churchill provinces in Manitoba, Canada. It is marked by a narrow belt containing intracratonic shallow-water Precambrian sediments, tectonic slices of granulites, gneisses and ultramafic bodies. Major nickel deposits are mined at Thompson, Manibridge and elsewhere. This suture has been variously interpreted as resulting from collision between the two provinces, or from a graben-like tensional zone within a more extensive proto-Superior province.

The Red Sea, an intracratonic tension zone with its associated volcanic rocks, metalliferous hot brines and sediments, is thought by some to be the beginning of a province suture. Others see the Red Sea either as the beginning of a mid-oceanic ridge, and others as an arrested (aborted) cratonic rupture, as with the Great African Rift Zones. Owing to the thinner crust in Archaean times, similar phenomena may have been more common, and the associated mantle and deep crustal disturbances may have been more profound and of greater significance for mineralization than the present day Red Sea.

(c) POTASH-RICH MOBILE BELTS

The Limpopo Belt is one of several "mobile belts" found in Africa, Australia and elsewhere. It is a linear zone composed of highly metamorphosed rocks set between the low grade Archaean cratons of Rhodesia and South Africa. For many years geologists have assumed that such belts are the exposed roots of ancient mountain chains. Although some mobile belts may have such an origin, it is becoming increasingly clear that these mobile belts were belts of unusually high heat flow and metasomatism, and other genetic models may be more appropriate.

The Limpopo Belt comprises portions of the Archaean basement rocks of the craton as well as "cover" or "supra-crustal" Archaean sediments and volcanic rocks. The belt appears to have developed about one or more deep-seated Archaean faults which dismembered a primitive Rhodesian-South African cratonic block. Shallow-water sedimentation associated with some volcanism took place in the linear zone. Later in Archaean times, a high thermal flux and abundant K-metasomatism metamorphosed both the basement and cover rocks to high amphibolite and granulite facies.

Syngenetic iron sulphides are common in the metamorphosed supracrustal rocks, and recent exploration has revealed nickel deposits among the high grade basement mafic rocks and gneisses in the extension of the Limpopo Belt westward into Botswana. The prolific copper mines at Messina in the South African sector are set within the high grade gneisses. The mineralization, although post-Precambrian in age, seems to me to have some carbonatitic affinities for it is related in time to a string of carbonatites "on line" to the east. The copper may have been derived from re-working of Archaean cupriferous protores. On the other hand, Messina is close to the intersection of a gravity ridge within the Limpopo Belt and the major gravity ridge which extends along the Great Dyke of Rhodesia soutward into South Africa through the Bushveld Complex and still further south through Vredefort and other domal structures of major mantle significance. Thus the location of the copper mineralization at Messina may owe much to post-Precambrian volatiles (especially CO_2 and F) which emanated from a mantle cupola and which retrogressed the weakly cupriferous Archaean granulites and gneisses.

Potash metasomatism is abundant throughout the Limpopo Belt, and may be an important factor in removing gold from the highly metamorphosed relics of the (normally) gold-bearing greenstone belts of the adjoining low grade Archaean cratons (see section on "Gold," p. 309).

(5) Zones of retrogression within highly metamorphosed terranes

Major faults are common within all highly metamorphosed terranes.

(a) SHALLOW NORMAL FAULTS

Shallow normal faults with open breccia zones are commonly of relatively recent age. These may modify the tenor of primary mineralization in deep-seated rocks, for these fault zones may serve as a porous zone for circulation of post-Precambrian meteoric waters or warm connate or subartesian waters from overlying sediments. Some metals may thus be leached from the enclosing high grade rocks during their retrogression by the waters with which the host rocks are out of equilibrium. Thus ancient metals may become part of "hydrothermal veins" whose age may be very much younger than the host rocks and their protores.

(b) SHEAR ZONES OF VARIOUS TYPES, INCLUDING SOLES OF NAPPES

By far the most common faults are those with shear components. These cause major textural and mineralogical changes, producing chlorite, mica or hornblende schists from granulites and high temperature mafic-ultramafic bodies.

It is normally assumed that retrogression involves addition of water to the high grade rocks, but in many cases there is little change in the major element content. In other cases the addition of water has been accompanied by large scale replacement of original elements in the high grade rocks. This may be due to the fact that the addition of halogens (notably Cl or F) to H_2O greatly increases its capacity to transport many of the base metals (e.g. Cu). In such circumstances new metallic components of economic potential may become fixed within the schist zone. Although the source of these new metals may be the mantle, it is probable that much of the metals can be leached from deeper portions of the fault or related faults.

An example of this mechanism has been described from Australia (Wilson, 1969*c*, p. 43). There a sulphur-rich scapolite (up to 5.10 % SO_3) is a major mineral in some mafic granulites. The scapolite is not secondary, but is isofacial with hypersthene and the other mafic granulite minerals. It is postulated that during retrogression of a scapolite-bearing mafic granulite to an actinolite-albite schist abundant sulphur would be liberated from the scapolite, for it cannot be accommodated in the albite lattice. At the same time much of the Cu in the pyroxenes (commonly in the range 400-200 ppm Cu in hypersthene) would be liberated and become available for redistribution elsewhere, for the actinolite (or micas or chlorites) do not normally retain such high levels of Cu.

On an earlier occasion, I noted that "In the vicinity of the Fraser Fault Zone in Western Australia sulphur-rich scapolites of the pyroxene granulites have been broken down to secondary plagioclase, and the copper-bearing pyroxenes to amphibole and chlorite. The result is the development of small quantities of chalcopyrite (first recognized by finding malachite stains in outcrop) in appropriate down-graded rocks in the fault zone. The scapolite contains 3.00 percent SO_3 and 2.32 percent CO_2" (Wilson, 1969*c*, p. 43).

Similar high-sulphur scapolites have been recorded by Lovering and White (1964) from the xenolithic blocks of granulite from explosive basaltic pipes in Eastern Australia. This indicates that portions of the deep crust must contain very large amounts of sulphur tied up in the scapolite structure. Thus retrogression of portions of the deep crust should liberal vast quantities of sulphur.

There are other sources of sulphur. Pyritic sediments abound in Precambrian sediments and igneous rocks. Metamorphism of pyrite (FeS_2) to pyrrhotite ($Fe_n S_{n+1}$) liberates sulphur. Naldrett (1966) has pointed out how nickel sulphides may be formed by the process of sulphurization whereby sulphur scavenges nickel from retrogressed ultramafic rocks.

The efficiency of a trace of sulphur as a scavenging agent has recently been emphasized by experimental work by MacRae and Kullerud (1972) and MacRae (1974). Almandine garnet has been converted to magnesian cordierite by addition of S to water. Conversion to cordierite did not take place in the absence of S. MacRae and Kullerud (1972) state that "Our experiments at 700 °C and 1 Kb confining pressure conclusively confirm that Fe is readily removed from almandine garnet by a sulphur-containing aqueous solution. Presumably, the results may be extrapolated somewhat to temperatures and pressures above and below the limits of our experiments. We note that proportionately *very small amounts of sulphur are required to break down the garnet*" (emphasis mine).

Another mechanism for ore formation during retrogression has been described by Ewers (1972). The uptake of nickel into the lattice of pyrrhotite was studied experimentally in the temperature range 200 °C to 760 °C. Nickel from both aqueous solutions (nickel chloride, conc. 3 M) and salt melts diffuses rapidly into the sulphide lattice with an accompanying release of iron into the solution or melt. Ewers points out that "pyrrhotite of any origin whether primary or derived by desulphurization of pyrite must be considered a potential sink for any nickel that is available in a mobile form."

This is particularly interesting for our present study, because pyrrhotite is more abundant than pyrite in granulites and deepseated mafic and ultramafic intrusives. During retrogression of nickeliferous rocks (such as occurs during conversion of peridotites to serpentinite or chlorite schists) some nickel is released, for serpentinites normally contain less nickel than the rocks from which they have been formed. Ewers points out that "such nickel, at the temperatures at which serpentinization occurs, will be absorbed by available pyrrhotite. In the presence of plentiful sulphide the result would be a pentlandite-pyrrhotite association; if sulphide is rare, nickel displaces iron, and millerite or heazlewoodite results, depending on temperature."

These experiments are only some of many that lead us to conclude that in zones of retrogression of highly metamorphosed rocks there is scope for discovery of sulphide ores of metals such as Ni and Cu, and probably several other base metals. Sulphur, chlorine, water and other volatiles may be derived either from metamorphic modification of crustal rocks, or may be mantle-derived.

The porosity and permeability of the crustal rocks both within and without zones of shearing will be major factors in controlling the amount of metals that can be scavenged from the rocks, and at what locations the chemical parameters would enable redeposition to take place.

(6) Camouflaged metals

During metamorphism of rocks to granulite facies some metals do not appear in a form readily recognized. In an earlier paper I gave an example of how beryllium can be camouflaged (Wilson, 1969*c*, p. 43): "Beryl is unstable within the granulite facies facies (although beryl-bearing pegmatites, characteristic of amphibolite or lower facies, may be found cutting rocks of any metamorphic terrane). Chrysoberyl ($BeAl_2O_4$) seems to tolerate higher metamorphic grades than beryl ($Be_3Al_2Si_6O_{18}$). However, the rare beryllium mineral taaffeite ($Al_4Mg\,[Be, Fe]\,O_8$) has been found in the granulite terrane of the Musgrave Block, central Australia (Hudson, Wilson and Threadgold, 1967). The taaffeite contains 5.50 % BeO. It is a dull pale olive-green fine-grained tabular mineral which could be mistaken for chloritoid in handspecimen. Beryllium has also been found as a significant constituent (0.7 % BeO) in sapphirine coexisting with taaffeite, thus showing that a valuable metallic element can easily be camouflaged in granulites (Wilson and Hudson, 1967)."

Another metal that may not be easily recognized in highly metamorphosed rocks in *zinc*. It may occur as a major constituent of the dull grey or green spinellid, gahnite, or the black spinellid, franklinite; or as the zinc silicate, willemite; or as the mixed oxide, zincian hoegbomite.

In some localities, one or more of these minerals has been found to be sufficiently abundant to be considered a potential zinc ore, especially as metallurgical processes may soon be developed to extract the zinc from refractory ores of this type.

THE REGIONAL AND TECTONIC SETTING OF AUSTRALIAN GRANULITE TERRANES (1) AND THEIR ECONOMIC POTENTIAL

Figure 1 shows that there are several regions in Australia wherein granulites are found. The geochemical characteristics and tectonic setting of these granulites vary greatly. The origin of the Archaean granulite terrane, and some of the better known belts of Proterozoic granulites, are discussed with a view to considering their economic potential.

(1) Archaean (2) granulite terranes

Southwestern Australia is typical of several shield regions in other continents. Irregular patches of hypersthene-bearing mafic and felsic granulites, ranging in

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(1) The term "granulite terrane" is used in the sense of a region in which rocks of granulite facies are found. This usage implies that these may be either dominant in the terrane or occur as relics or patches set within regions dominated by rocks of amphibolite or other metamorphic facies.

(2) The term Archaean implies an age of at least 2 400 million years.

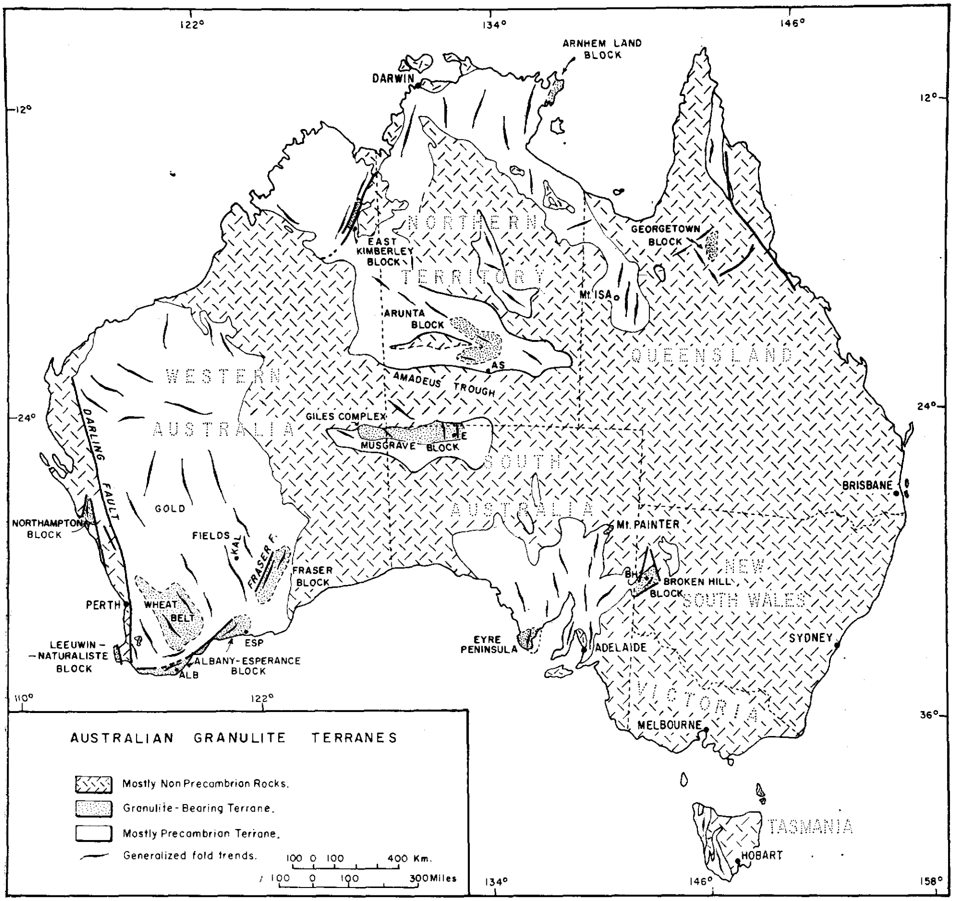

FIG. 1. — *Granulite terranes of Australia. The Wheat Belt granulites are Archaean, whereas all other granulites yield Proterozoic ages by Rb/Sr. KAL, Kalgoorlie; ALB, Albany; ESP, Esperance; E, Ernabella; AS, Alice Springs; BH, Broken Hill.*

size from a few square metres to several square kilometres, are widespread within the highly deformed biotite or hornblende granites and gneisses which make up the major part of the region (Wilson, 1969*b*).

There are at least two main modes of origin of these granulites:

(a) METAMORPHISM OF KEELS OF "POST-BASEMENT" TROUGHS

Many of the granulites appear to be the keels of synclinoria or other relics of folds now enclosed in granitic material. Some of the synclinoria are relics of basins or troughs in which Archaean lavas, tuffs and jaspilites were deposited. Other granulites are relics of small layered, mafic-ultramafic igneous intrusions and dykes.

(b) RECRYSTALLIZATION OF THE BASEMENT ITSELF

In several parts of southwestern Australia the basement gneisses themselves appear to have suffered a superimposed granulite facies metamorphism. For example, in the vicinity of Lake Grace and in the Bruce Rock-Narambeen region many of the felsic rocks of the polymetamorphosed basement are hypersthene-bearing (see fig. 2, Wilson, 1969*b*). At Dingo Rock, 16 km east-north-east of Lake Grace, the felsic rocks of the basement show a contorted gneissose and migmatitic character on weathered surfaces and as such cannot easily be distinguished from the normal biotite gneisses of the shield. However, the fresh rock shows no obvious banding, and is greasy dark bluish-grey or greenish grey which is the typical appearance of the Indian "acid charnockites."

It is not clear whether or not the recrystallization of the basement was due to dehydration of the basement during its depression beneath a post-basement sedimentary trough.

On the other hand, the charnockitic character may have been imprinted without a marked increase in temperature, for an increase in the proportion of CO_2 would decrease the H_2O component of the total fluid pressure, thus tending to replace hydrous by anhydrous minerals (Touret, 1970). This may be an explanation for the charnockitic character of some of the gneisses of Madagascar where I suspect metamorphism of nearby carbonate rocks has considerably increased the CO_2 component of total fluid pressure.

"Another cause of a superimposed granulite imprint on the basement complex may be dependent on a regional increase in temperature without being related to superimposed geosynclinal troughs. This has been noted in India (Pichamuthu, 1965). There the granulites occur in the south near Bangalore and as one proceeds northwards along the tectonic trend of the gneisses and the rocks of the Dharwar 'System' the grade of metamorphism is found to decrease first towards the amphibolite and then to greenschist facies. This may be explained simply by the hypothesis that in South India we are looking at a deeper portion of the crust which has been exposed by erosion as the 'slab' of Peninsular India has been tilted downwards to the north. In India the isograds are said to cut across both basement and the Dharwar geosynclinal rocks.

"In the Archaean of Western Australia a similar pattern seems to be emerging. The granulites of the Dangin region give way along the strike to the northnorthwest to amphibolites and greenschists in the Bolgart region and Wongan Hills. A preliminary delineation of the Archaean granulites shows that few occur north of a line from Burracoppin to Toodyay. This 'isograd' cuts across the regional northwesterly trend, and may indicate a regional tilt northwards and downwards of this portion of southwestern Australia." (Wilson, 1969*b*.)

The economic potential

As the Archaean granulite terrane is thought to consist of the more highly metamorphosed equivalents of the greenstone and granitic belts of the Goldfields regions of the shield, one might expect to find a comparable mineral potential in the granulite terrane.

The deposits to be most expected in Archaean terranes are those containing gold, nickel-copper, and copper-zinc. *Gold* is very rare where granulite metamorphic conditions have prevailed, and such gold mineralization that does occur appears to be related to post-granulite igneous phenomena.

Other shields such as India and Africa display a similar falling away of gold with increase in grade of metamorphism. Thus we may conclude that highly metamorphosed rocks are not favourable hosts for gold mineralization, for gold appears to have been driven off during early stages of metamorphism. The same effect of metamorphism on gold-bearing host rocks has been noted in Canada (Weber and Stephenson, 1973).

The reason for this may lie in the fact that the solubility of gold in alkali-chloride brines is very greatly increased with increase in temperature, and that a high concentration of potassium seems to facilitate the solubility (Henley, 1972; Fyfe and Henley, 1973). Granulite and other high grade terranes are commonly flushed with brines rich in K, CO_2, Cl and F. Although the relative role of each of these components is unknown, it is clear that gold which has been leached from granulites presumably has been deposited elsewhere in a low temperature environment.

Nickel is commonly found in granulite terranes, not only within silicate minerals but also as the sulphide pentlandite. McCall (1972), however, in reviewing the nickel sulphide ultramafic rocks of the Western Australian Archaean, suggested that ultramafic rocks of the granulite terranes were deep seated, and thus their economic potential should not be confused with that of the nickel-rich sub-volcanic and volcanic ultramafic rocks of the Goldfields region. He believes that the deep levels of erosion have stripped off the most likely sites for rich nickel deposits. My own work, however, shows that some ultramafic flows, interlayered with banded iron formations, have still been preserved in the Archaean granulite terrane of Western Australia, and thus the depth of erosion may not be as detrimental to exploration for nickel as McCall suggests (Wilson, 1958, 1971).

Copper-Zinc

Recent discoveries of "strata bound" copper and zinc sulphides in granulites from the Arunta Block of central Australia show that the granulite metamorphic conditions were not too severe to disperse these sulphides. Moreover, the very large concordant layers of silver-lead-zinc sulphides among the granulites and gneisses of Broken Hill shows that we may expect to find sulphides of many of the base metals within granulite terranes.

The Kidd Creek (Canada) type of copper-zinc deposit and similar sulphide deposits related to acid and intermediate volcanic rocks are being found in the low grade Archaean belts of Australia. The search for these deposits should also be pursued within the high grade terranes in the expectation that primary sulphides should not migrate far from the site of orignial deposition. Indeed, the high grade metamorphic process should serve to convert complex ores into coarse rocks, and may cause some structurally controlled segregation of copper from zinc. This should facilitate treatment, and may even upgrade parts of an ore body sufficiently to enable its economic development.

(2) Proterozoic granulite terranes

Figure 1 shows that all granulites, other than those of the Wheat Belt in southwestern Australia, yield Proterozoic ages by Rb/Sr methods. It is probable, however, that future techniques will uncover an Archaean history for some of the rocks.

The belts of Proterozoic granulites show a wide range of tectonic and geochemical features. A summary of those features most likely to be pertinent to the economic appraisal of Proterozoic granulites is given in this paper. For this purpose reference will be made to only some of the Australian belts. The belts chosen are:

(a) the belt which engirdles the Archaean block in southwestern Australia;

(b) the granulites of central Australia: the Musgrave Block and the Arunta Block;

(c) the Willyama Block (or "Broken Hill Block") in eastern Australia.

Petrological and other details on these and other belts may be found in other papers (e.g. Wilson, 1960, 1968, 1969*b*).

(a) THE PROTEROZOIC GRANULITE BELTS OF SOUTHWESTERN AUSTRALIA

The Archaean block of southwestern Australia is engirdled for about 1 900 km on the west, south and southeast with a narrow, discontinuous belt of granulites, all of which yield Proterozoic Rb/Sr ages which range from about 650 m.yr. to about 1 370 m.yr. This shows that the belt has suffered a series of high grade metamorphic episodes, each of which has developed rocks and structures of markedly different economic potential.

The belt which yields the oldest granulite ages (~1 370 m.yr.) is the *Fraser Block*. This is separated from the Archaean rocks to the west by the Fraser Fault Zone which is marked by an extensive mylonite zone and an intense gravity anomaly. The Bouguer anomaly which has been traced for at least 250 km, has a gradient of 12.5 mgal/km and consists of a positive gravity ridge over the western portions of the range (+30 mgal) and a gravity trough (down to −100 mgal) immediately to the west of the fault zone.

The Fraser Block is composed mainly of mafic pyroxene granulites, many of which were derived from tholeiitic basalts (many were vesicular, and some were pillowed—Wilson, 1969*d*) and gabbros (Wilson, 1969*a*). Felsic and mafic garnet-bearing granulites are important in the west, and felsic granulites and narrow anorthosite layers are dominant in some regions east of the Fraser Range.

In the central region of the Fraser Block there is an important metamorphic phenomenon. During their conversion to granulites (~1 330 m.yr. ago; Arriens and Lambert, 1969), the mafic rocks were strongly folded. However, notwithstanding the presence of folds and lineation, the preferred orientation of the mafic granulites has been destroyed during a regional annealing. This is presumed to have taken place (about 1 210 m.yr. ago; Wilson, 1969*a*, p. 4) as a result of a substantial rise of basic magma corresponding to a major mantle rupture which gave rise to the large positive gravity anomaly.

The granulites take on a more rigidly banded appearance, become garnetiferous (pyrope-almandine) and eventually give way to retrogressed zones and mylonites as the Fraser Fault Zone is approached. The economic potential of some of these rocks has been outlined by Wilson (1969*d*). New data are now available, and several small highly metamorphosed ultramafic bodies (non-outcropping), some of which carry sub-economic nickel and copper, have recently been found close to the fault zone. Several of the tectonic and petrological features of the Fraser Block are similar to those of the nickel belt of the Thompson region of Manitoba.

The Albany-Esperance Block extends along the south coast of Western

Australia and appears to have been welded to Archaean rocks to the north. The block appears to have been the site of a Proterozoic orogenic belt that cut across the primitive Archaean shield, the southern extension of which lies off the present coast of the continent and is probably to be found in Antarctica.

The gneisses and granulites are more felsic and many seem to have been greywackes. Mafic granulites mostly occur as narrow layers in the felsic gneisses and granulites and are likely to be highly deformed small basic intrusions and occasional flows. The block includes several large bodies of "acid charnockite," remarkably like those of Madras (India). At Albany these rocks are cut by the Albany granite which was emplaced 1 000 m.yr. ago (Turek and Stephenson, 1967). It is possible that these charnockitic masses are metamorphosed basement which were caught up in the Proterozoic mobile belt. The granulites on the other hand, are thought to be similar in age ($\sim$1 350 m.yr.) to the mafic granulites of the Fraser Block.

The economic potential of this block has been largely ignored. Some base metal deposits (Cu-Ni) may be expected near the generally obscured junction between the block and the Archaean Craton. Particularly favourable mantle disturbances can be expected near the western extremity of the belt where it is cut off by the huge Darling Fault, for in this region the westerly-trending belt suddenly swings to the north-west and next appears to the west of the Perth Basin in the Leeuwin-Naturaliste Block.

Throughout the felsic granulites flakes of graphite and layers of sillimanite are common. The possibility of syngenetic Pb-Zn deposits (of Broken Hill type) may be expected. In regions where basic granulites are more plentiful, metamorphosed stratiform Cu-Zn should be sought.

The *Leeuwin-Naturaliste Block* is cut off from the main shield area by the Darling Fault and the Perth Basin. The granulites have been so intensely deformed that in many places rigid layering has developed of the type commonly found near deep-seated fault zones such as the Fraser Fault.

The age of metamorphism is confusing. Rb/Sr techniques yield only 650 m.yr. (Compston and Arriens, 1968). It is presumed that the granulites of this block were derived by polymetamorphism of Proterozoic rocks and possible slices of Archaean basement that form part of the complex Proterozoic mobile belt that engirdles the Archaean nucleus.

No minerals of economic significance have been found within the block, although its erosion has produced the very large deposits of chromium-free ilmenite, zircon and monazite which are being mined on nearby ancient and modern beaches.

The *Northampton Block* is separated from the main body of the Archaean shield by the Darling Fault and the Perth Basin. Many of the rocks are cordierite-bearing felsic granulites of greywacke composition; there are also some mafic pyroxene granulites and sillimanite-graphite quartzites. During a late phase of metamorphism (minimum age of pegmatites is 1 000 m.yr.; Wilson *et al.*, 1960), the granulite-gneiss complex and its minor intrusive granites have suffered a metamorphism which appears to have essentially thermal. Most of the rocks were converted to a coarse hornfels, original linear fabric was largely obliterated and garnet developed in many rocks.

The block has base metal potential, for the rocks represent a wedge of sediments and related minor igneous rocks of a type similar in composition and metamorphic grade to those which enclose the Broken Hill Pb-Zn deposits in the Willyama Block.

(b) THE GRANULITES OF CENTRAL AUSTRALIA

The granulites of the Musgrave and Arunta Blocks cover extensive areas, and exhibit many structural and geochemical features of economic interest.

In the *Musgrave Block* Proterozoic sediments and mafic igneous rocks have been converted to granulites of medium to low pressure types. Although many of the felsic granulites have a greywacke composition, it is likely that acid volcanism has made an important contribution to the sedimentary pile. Calcareous sediments are rare.

The granulite facies metamorphism in the western portion of the block took place about 1 600 m.yr. ago (Gray and Oversby, 1972) whereas in the central and eastern portions the granulites yield ages of about 1 350 m.yr. (Arriens and Lambert, 1969). Large intrusive bodies of acidic charnockite (Wilson, 1960) intruded the granulites about 1 120 m.yr. ago, and several layered basic intrusions (the Giles Complex) were emplaced about the same time and exhibit granulite features, especially at their margins (Arriens and Lambert, 1969; Nesbitt *et al.*, 1970).

South of the Mann Range and elsewhere in the block there are large bodies of anorthosite. These are commonly highly granulated and recrystallized.

Lateritic nickel occurs above peridotites within the Giles Complex. Low oxygen and sulphur fugacities and the deep-seated nature of the intrusions have enabled Cr and Ni to be incorporated in the silicates and have precluded significant deposits of chromite and nickel sulphides (Nesbitt *et al.*, 1970). Platinoids have not been recorded.

Small ultramafic bodies with sub-economic nickel have recently been found near Kenmore Park in the eastern Musgrave Range.

The widespread presence of S-rich scapolites in the Musgrave granulites implies a high S content of the fluids with which many of the granulite mineral assemblages were equilibrated. Stratiform base metal sulphide deposits could be expected among the metasedimentary granulites of the Musgrave Block.

The Precambrian *Arunta Block* lies to the north of the Amadeus Basin, an intracratonic basin containing a great thickness of sediments ranging from Upper Proterozoic to Devonian. Recent work has shown that during the Carboniferous, large slices of granulites and amphibolites have been thrust from the north over the sediments of the northern margin of the basin. Many portions of the granulites have been completely retrogressed to mica and chlorite schists, whereas other portions still retain small relics of granulite (Forman and Shaw, 1973).

The first granulite facies metamorphism took place at 1 850 m.yr. (Iyer *et al.*, in press), and resulted in cordierite-hypersthene assemblages in many felsic rocks in the Strangways Range (where the granulites have been best studied). Preliminary Rb/Sr work is showing that some of the mafic relics in the granulites may be Archaean.

A subsequent granulite facies metamorphism, during which sapphirine was developed in certain highly aluminous rocks, occurred about 1 440 m.yr. ago (Hudson and Wilson, 1966; Iyer *et al.*, in press; Woodford *et al.*, in press).

The granulites contain some sub-economic conformable deposits of Cu, Pb and Zn associated with graphite-bearing aluminous and calcareous granulites, and some of the impure marbles and calcsilicate granulites contain some small deposits of Cu and Pb.

Small anorthosites and layered mafic bodies and many small mafic intrusions have been recognized. Several large magnetic anomalies lying beneath the desert sands near some of these mafic bodies may indicate other hidden mafic bodies or zones of possible Cu or Ni mineralization.

The stratigraphy and metamorphic history of the Arunta Block is very complex. The oldest gneisses and granulites contain irregular masses of mafic and ultramafic rock, and may represent Archaean basement. A Lower Proterozoic sedimentary succession contains many carbonate rocks and argillites metamorphosed (at 1 850 m.yr.) to granulite or to the amphibolite facies. A presumed unconformity between these sediments ("cover rocks") and the older basement rocks has been olbiterated during the deformation of the whole terrane. The base metal potential of the cover rocks and of the presumed rocks in the vicinity of the unconformity has not been tested.

Several very large Bouguer gravity anomalies (both positive and negative) traverse or flank the Arunta Block. These show the irregular mantle-crust relationships in the region. Kimberlite has not yet been recognized, but several carbonatites (rich in magnetite, apatite and zircon, but lacking Cu) have been found (Crohn and Gellatly, 1968). Fluorine-rich phlogopite has been mined in a mafic pegmatoid similar to some of those mined in the Madagascar granulite terranes.

(c) THE WILLYAMA BLOCK (OR "THE BROKEN HILL BLOCK")

One of the world's greatest Ag-Pb-Zn deposits occurs at Broken Hill in cordierite and sillimanite gneisses and low-pressure mafic granulites. The host rocks of the mines yield a metamorphic age of about 1 700 m.yr. (Compston and Arriens, 1968). The Willyama Block, however, is a polymetamorphic region, and several distinct metamorphic episodes, ranging down to the Palaeozoic, have affected the block.

The economic significance of this block is that a great strata-bound sulphide deposit has survived several metamorphisms, including at least one phase of granulite facies. Individual layers of sulphides, which may be traced for hundreds of metres, retain their distinctive characteristics and metal ratios. Local migration of metals and "flowage" of some portions of the ore bodies into weaknesses within the enclosing gneisses is not uncommon.

Metamorphism has had a very beneficial effect on the ore for the original fine-grained sulphide sediments have been very coarsely recrystallized, thus facilitating metallurgical separation of the several sulphides. Rocks of equivalent composition and age at McArthur River in northern Australia cannot be mined at present, owing to the exceedingly fine-grained nature of the unmetamorphosed ore (Croxford and Jephcott, 1972).

REVIEW OF SPECIFIC METAL AND OTHER ECONOMIC PROSPECTS

In earlier sections some of the concepts pertinent to the discovery of metals and other materials of economic potential have been discussed in relation to special tectonic or geochemical settings. It remains to comment on specific substances such as the noble metals, base metals, minor elements, building materials, and gemstones.

(1) The noble metals

(a) GOLD

The view has already been expressed (p. 309) that gold is flushed from granulites and high grade gneisses.

(b) SILVER

As there is no evidence that Ag is expelled during high grade metamorphism from strata-bound Pb-Zn ore bodies at Broken Hill, some attention should also be paid to the metamorphosed equivalents of the acid volcanic rocks in which disseminated silver ores may be found.

(c) PLATINOIDS

The presence of the platinoids in high temperature rocks such as the Merensky Reef and the Great Dyke should encourage the search for platinoids in the metamorphosed layered basic bodies and peridotites which are so common in granulite terranes.

However, in many nickel ore bodies in igneous rocks the platinoids are commonly found concentrated in fluorine- or chlorine-rich phlogopite and apatite pegmatoid patches or apophyses. This suggests that the platinoids may be readily concentrated by certain volatile-rich magmatic fractions, especially as several of the platinoid minerals in the Merensky Reef are complex substances and contain low melting point elements such as Bi, Sb, As and Te. Thus the platinoids may be scavenged from ultramafic rocks during metamorphism by any one of several mobile elements. Although this process could explain the depletion of some metamorphosed nickel ore bodies of their platinoids, it also raises the possibility of finding platinoid deposits in geochemical traps "up structure" from Pt-depleted ultramafic rocks.

(2) The base metals

(a) SULPHIDES OF COPPER, LEAD, ZINC AND IRON

Mention has already been made of the fact that sulphides of *copper, lead, zinc and iron* are well known from granulite and other high grade terranes. In complex ore bodies Cu is commonly segregated during deformation. However, the degree to which segregation of the various sulphides takes place will depend on chemical as well as physical parameters.

A large range of possible environments for base metal ore deposition should be investigated within granulite terranes. The metamorphosed cover rocks on Archaean basement commonly exhibit the right environment for several types of strata-bound deposits. These could include metamorphosed equivalents of the Keweenawan Cu-bearing basalts. White Pine Cu-bearing black shales, Missouri-type Pb-Zn algal limestones, Sullivan or Mt Isa Ag-Pb-Zn sediments, Kidd Creek Cu-Zn volcanogenic precipitates, as well as a range of base metal deposits directly related to intrusive mafic and ultramafic bodies and acid volcanic rocks.

(b) OXIDES OF ZINC

The zinc spinellids, gahnite (ZnO ~ 30 %) and franklinite (ZnO ~ 23 %) and other zinc minerals in granulites have already been mentioned (p. 307). These minerals are abundant in some terranes (e.g. the "zinc lodes" at Broken Hill) but metallurgical processes are as yet unable extract the zinc profitably.

(c) OXIDES OF IRON AND TITANIUM

Other base metals such as *iron* and *titanium* are well represented in granulite terranes as oxides. Many fine-grained banded iron formations and other iron-bearing rocks have been coarsely recrystallized and converted into *magnetite* ores during high grade metamorphism in Canada, Australia and elsewhere. In the Adirondacks and Quebec, ilmenite, associated with anorthosites and related granulites, is mined.

In southwestern Australia *ilmenite sands* have been derived from the granulite terranes. The ilmenite is free from chromium, a deleterious element common in ilmenites derived from basalts. During the metamorphism of the original basic igneous rocks, the chromium impurities of the ilmenite have been removed and have become fixed in the pyroxenes of the granulites, and thus the chronium has become separated during subsequent erosion of the granulites and heavy mineral concentration on the coasts.

Although *rutile* is a common mineral in metamorphic rocks of several grades, it is an important titanium mineral in some granulites, especially those which have a high Mg/Fe ratio. Common specific host rocks are sillimanite quartzites, cordierite-bearing felsic granulites, phlogopite schists, sapphirine-bearing rocks, and corundum-bearing rocks. Pegmatoid patches within these rocks may be sufficiently rich in rutile to warrant mining. Heavy mineral concentrates in beaches adjoining terranes with a large proportion of suitable rocks may be unusually rich in rutile.

(d) NICKEL

The nickel prospects of some Australian granulite terranes have already been discussed (p. 310 and p. 311). During high grade metamorphism nickel seems to remain close to its place of original deposition. Suitable ultramafic and mafic host rocks abound in granulite terranes, and some ore bodies have been located.

The development of nickelliferous immiscible liquids from igneous intrusions is inhibited by low sulphur content at early stages of magma crystallization. However, processes such as sulphurization of consolidated ultramafic rocks, and other phenomena, may be effective in producing nickel sulphide ore bodies (p. 306).

Nickeliferous laterites in granulite terranes have been discovered, e.g., Wingellina, in the Musgrave Block, central Australia.

(e) VANADIUM

Magnetite from some anorthosites and from the upper zones of layered gabbros is normally vanadiferous, and vanadium does not seem to be mobile during high grade metamorphism.

(f) CHROMIUM

In ultramafic magmas deficient in oxygen, chromium will not be precipitated as chromite but will enter the pyroxenes. Thus some deep-seated layered gabbro intrusions, such as the Giles Complex of the Musgrave Block of central Australia, contain no chromite deposits. However, in the Fiskenaesset region of western Greenland, there are abundant narrow layers of chromite in Archaean anorthosites, which together with intercalated hypersthene amphibolites and subsidiary pyroxenites and peridotites occur in the gneisses as horizons belonging to a folded and metamorphosed stratiform complex which has a maximum thickness of 2 km. The chromite horizons average 0.5 to 3 m in width and have an exposed length of at least 125 km. The Cr_2O_3 content (average about 33 %) is somewhat lower than that currently used in industry, but the very large reserves have stimulated interest (Ghisler and Windley, 1967).

Similar chromites are associated with Archaean anorthosites in the Limpopo Belt of South Africa and Rhodesia.

By analogy with the Merensky Reef of the Bushveld Complex a search for platinoids should be carried out in the layered series near the horizon where chromite is no longer found.

(3) Minor elements of economic interest

(a) BERYLLIUM

Mention has already been made of taaffeite, in which Be is camouflaged (p. 307).

(b) ZIRCONIUM

In addition to zircon sands produced from disintegration of granulites and gneisses, zircon and baddelyite (ZrO_2) may be plentiful in carbonatites which are common in high grade terranes.

(c) RARE EARTHS

Monazite and xenotime are phosphates of the rare earths, and are common in high grade terranes. Beaches in these regions commonly produce monazite (e.g. Travancore and southwestern Australia).

(d) THORIUM

Madagascar has produced much thorianite from phlogopite-diopside pyroxenites and other granulites. ThO_2 ranges from 55-89 % and UO_2 from 6 to 26 % (Noizet, 1969, III, 30). Monazite, a common mineral in granulites, contains a variable of ThO_2 (0-32 %, with 10 % ThO_2 common).

(e) GRAPHITE

Ceylon and Madagascar are famous for graphite mines. In both regions ancient carbonaceous sediments have suffered granulite facies metamorphism. The physical properties of graphite have permitted graphite to form dykes in the enclosing rocks during intense deformation.

The presence of minor flakes of graphite in felsic granulites may be taken as an indication of the presence of carbonaceous sediments, thus encouraging exploration for strata-bound base metals.

(f) PHOSPHORUS

Apatite, which contains about 42 % P_2O_5, is the only practical source of phosphorus from granulite terranes. It occurs in abundance in many carbonatites, and in some phlogopite schists which were formed in zones of P and F metasomatism in granulites. Apatite is also abundant in the upper zones of layered gabbro complexes, and remains during metamorphism of the host rocks.

(4) Industrial minerals and rocks

(a) PHLOGOPITE

Some pegmatites cutting ultramafic granulites and carbonate rocks contain high quality phlogopite, e.g. southern Madagascar, and Strangways Range, central Australia.

(b) VERMICULITE

Hydrogen metasomatism of phlogopite in pyroxenites and in carbonatites may produce large bodies of vermiculite (e.g. Young River, Western Australia; several carbonatites, Strangways Range, central Australia).

(c) MAGNESITE

Ultramafic bodies in granulite terranes commonly produce masses of high quality magnesite by surface weathering.

(d) TALC AND ASBESTOS

Zones of retrogression of peridotites and pryroxenites may produce talc and asbestos. The asbestos may be one of the three mineral species, chrysotile, amesite, or anthophyllite.

(e) SILLIMANITE

This mineral, which is coarsely crystalline, is sufficiently abundant in many aluminous granulites to warrant exploitation as a refractory mineral.

(f) KYANITE

Some high pressure granulites and eclogites contain kyanite. However, the most likely source of commercial kyanite is in zones of retrogression of aluminous granulites. Several such zones have recently been recognized in central Australia.

(g) CORUNDUM

This mineral may form from the desilication of felsic igneous or metasomatic bodies in contact with mafic or carbonate rocks. Metamorphism of bauxites (Coetzee, 1940) or other highly aluminous rocks is a major source of industrial corundum.

(h) GARNET

Abrasive garnet of high quality is available in the Adirondacks, Madagascar, and elsewhere.

(i) BUILDING STONES

Many rocks from granulite terranes are of economic importance as building or monumental stones. Examples are charnockite, khondalite and leptynite (Madras), anorthosite (Quebec, Norway, New York), various gneisses, granulites and migmatites and serpentinites (most terranes).

(5) Precious and semi-precious gemstones

Gravels from granulite terranes are commonly rich in gemstones of many types. Some of the minerals occur in pegmatites cutting the granulites, others are in concordant coarse pegmatoid patches which are isofacial with the granulites (most terranes). A large suite of minerals is derived from metamorphism and metasomatism of magnesio-calcareous and aluminous sediments (Sri Lanka [Ceylon]; Madagascar; central Australia). Others, such as zircon and apatite, are found within carbonatites (central Australia).

The following is a list of gemstones from granulite terranes. Other non-granulite minerals such as beryl, topaz and tourmaline may also be found in pegmatites cutting the granulite terranes.

Corundum (sapphire and ruby)
Spinel (especially red and blue)
Chrysoberyl (including varieties alexandrite and cymophane)
Taaffeeite
Kornerupine
Grandidierite
Sapphirine
Cordierite
Enstatite, Bronzite, Hypersthene (especially chatoyant varieties)
Diopside
Sillimanite
Kyanite
Labradorite
Sunstone, moonstone
Yellow orthoclase
Rhodonite
Scapolite
Garnet (pyrope, almandine pyrope and almandine)
Apatite
Zircon
Zoisite

CONCLUSIONS

It is clear that, although some metals such as gold and uranium are deficient, granulite and related highly metamorphosed terranes contain a great mineral potential.

The most important factor inhibiting vigorous exploitation of these terranes is that their stratigraphy, structure and geochemistry is considered by many exploration companies to be too difficult to elucidate. However, with the advances in petrology and tectonics, and with the rapid development of modern techniques such as the use of both radioactive and stable isotopes, new geophysical systems, remote sensing tools (such as the revolutionary "Air Trace" technique which can perform aerial base-metal "sniffing"), it is now possible for highly metamorphosed terranes to be explored with confidence.

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