ON THE GENETIC AND STRUCTURAL RELATIONS BETWEEN CONTACT METAMORPHIC MINERALIZATION AND A HYDROTHERMAL VEIN AT WALANG, N.S.W.

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With Plate III and one Text-figure.

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Abstract.
The extraction, in its entirety, of a small quartz-scheelite-galena vein wholly contained within contact metamorphosed limestone near Bathurst, N.S.W., has facilitated a close study of the vein and its terminations. Structural and mineralogical features commencing with contact metamorphism and concluding with the flow of hydrothermal solutions are discussed.

Introduction.
A small deposit of scheelite recently discovered about a mile north-east of the village of Walang, 15 miles east of Bathurst, furnishes an interesting study of the genetic and structural relations between contact metamorphism and the formation of hydrothermal fissure veins.

The requisite degree of surface erosion, together with mining operations, has completely bared the extremity of a shear fissure vein and portion of a contact metamorphic zone within which the vein was wholly contained. An opportunity was thus afforded to study, in detail, the structure and origin of the vein, its downward passage into the contact zone, and the mineralogical changes that occurred from the contact-zone to the vein over a distance of less than 40 feet. As C. S. Ross states, "small size and compact relations are often an advantage and facilitate study" (U.S.G.S. Prof. Paper 179, 1935).

Some Previous References.
That ore deposits of contact metamorphic or metasomatic origin formed under favourable structural conditions tend to develop outwards from centres of metamorphism is clearly indicated by the numerous examples of pipes, lenses, veins and segregations associated with metamorphic aureoles. Most of the references to contact metamorphic veins, however, appear to be contained in early literature.

The deposition of ore minerals often takes place late in the metamorphic sequence, though there are instances of the mergence or telescoping of metasomatic ore with the products of other processes which normally operate earlier or later than the period of ore formation.

The tungsten deposits of Oreana, Nevada, regarded by Kerr (1930) as unique, are of the nature of scheelite-bearing pegmatites within a sill-like mass of epidiorite, lying above a thick bed of limestone which is penetrated at depth by granite. The pegmatites, composed of oligoclase, albite, quartz, beryl and scheelite, with traces of garnet and epidote, are connected to the underlying
limestone by narrow channels containing small amounts of scheelite. Kerr considers that these deposits disclose a direct link between processes of contact metamorphism and the development of pegmatites.

An even closer relationship between contact metamorphism and the injection of pegmatitic fluids is indicated by the "pegmatites" of Gold Hill, Utah (Butler, 1920; Nolan, 1935), where pipe-like ore bodies occur along intersecting joints within contact metamorphosed limestone and cordierite hornfels. The pipes contain grossular, epidote, calcite, quartz, orthoclase and actinolite with scheelite and chalcopyrite.

Fissuring, with flow at elevated metamorphic grade, is indicated by the presence of wollastonite with garnet, quartz, sphalerite and chalcopyrite at Zacatecas, Mexico (Bergeat, 1909), where fissures commence in calc-silicate rock and pass outwards into unaltered limestone. Wollastonite also occurs with sulphides in some of the veins of Tepezala, Mexico (Wandke and Moore, 1935).

Diopside accompanies garnet, vesuvianite, fluorite, calcite, quartz and scheelite in veins at Pine Creek near Bishop, California (Hess and Larsen, 1921). Associated with these ore bodies, within the same contact zone, are numerous quartz lenses rich in scheelite alone.

At Haitcha, New Mexico, veins of galena, pyrite, sphalerite and calcite with garnet traverse metamorphosed limestone containing disseminated sulphides. According to Lindgren et al. (1910) some of the deposits of this region "appear to form connecting links between contact metamorphism and vein deposits".

Sphalerite, galena, chalcopyrite and pyrite occur along a fracture in metamorphosed limestone in the Santa Maria Range of Verlardena, Mexico (Spurr and Garretty, 1908). In other parts of the same district veins containing sphalerite and galena with quartz, calcite and garnet are wholly contained within metamorphosed limestone.

Hedenbergite-andradite veins with iron oxides and copper sulphides in the Oslo region (Goldschmidt, 1911) follow fault-planes in the skarn for considerable distances away from the centre of metamorphism.

At Campiglia Marittima, Italy (Beck, 1905; Knopf, 1942), the galena veins contain manganiferous pyroxene, ilvaite, epidote, calcite, quartz and fluorite and appear to be related to a nearby bed of metamorphosed limestone. Because of the prominence of hydrous silicates the veins were classified as hydrothermal.

Narrow quartz veins containing scheelite and minor amounts of pyroxene, actinolite, andradite, biotite, epidote, zoisite, calcite, sphene, pyrite and chalcopyrite transgress the bedding of the scheelite-bearing skarn at King Island, Australia (Edwards et al., 1956). The following sequence of events has been established: (1) Contact metamorphism of calcareous beds; (2) metasomatism yielding scheelite-bearing skarn; (3) formation of veins, confined to the area of metasomatism.

The ore bodies of the Wilson Consolidated Mine, Utah (Nolan, 1935), afford an example of epimetamorphic mineralization; scheelite, gold and bismuthinite occurring in lenses within calc-silicate rock bordered by sandstone. Hess and Larsen (1921) have described similar deposits at Golconda, Nevada, where quartz and scheelite form irregular patches and lenses in scheelite-bearing "tactite".

At various localities around the Berggiesshübel bathylith in Saxony (Beck, 1905), where it invades Silurian limestones and tuffs, as at Nenntmannsdorf, veins of magnetite and haematite with small amounts of chalcopyrite and bornite pass outwards through the contact zone into unaltered limestone. The contact metamorphosed limestone carries iron oxides and sulphides of metasomatic origin. According to Beck, a second generation of sulphide-bearing veinlets
which are confined to the contact zone "seem to have been formed as primary veins during the metamorphic process, since they occasionally carry garnet".

Two sets of veins have been recognized at the Yavapai mine at Clifton-Morenci, Arizona (Emmons et al., 1913). The more prominent set contains magnetite and sulphides, has contact metamorphosed limestone walls, and is believed to be connected directly to intrusive porphyry at depth; the second set carries the same ore minerals and is wholly contained within the contact rock. Emmons (1913) notes that "the mineralogical trend of the hydrothermal processes at Morenci undoubtedly connects it in some way with contact metamorphism".

Text-fig. 1.—Block diagram illustrating the occurrence of scheelite at Walang, near Bathurst, N.S.W. (Lower diagram is an enlargement of portion of upper diagram.) Note.—In Legend, Calc-silicate Rock should have Limestone hatching.

**Geology of the Walang Area.**

(a) *Stratigraphy and Structure.*

The greater part of the Walang area consists of Upper Silurian slates, phyllites, sheared andesitic tuffs and impure limestone in association with strata of an argillaceous-calcareous nature. Intensely sheared dykes of diabase occur in places. Low-grade regional metamorphism appears to have been followed by the intrusion of small stocks of lamprophyre and dykes of felsite. The Silurian strata strike N.N.W.-S.S.E. and, in the region of mineralization, dip toward the north-east at 60° to 75°.

Remnants of Upper Devonian quartzites, shales and conglomerates form steep, heavily-wooded ranges rising 250 feet above the otherwise undulating
surface. The Devonian sediments strike due north-south and rest with strong unconformity upon the eroded surface of the Silurian. Kanimblan tectonics folded the Devonian rocks and facilitated large-scale igneous intrusion.

In general the geological pattern at Walang differs very little from that of other Siluro-Devonian areas in central-eastern New South Wales.

(b) Igneous Intrusion.

The main igneous rock of the area is a coarse-grained, sphene-bearing, biotite granite of the "Hartley" type (Joplin, 1931). This granite (Text-fig. 1) may be continuous at no great depth with the large Bathurst bathylith, which is exposed a few miles to the west.

The granite is veined by narrow pegmatites of simple mineralogy and by equally narrow veins of aplite of similar composition. Possibly related to the granite is a small intrusion of quartz-orthoclase porphyry which has suffered strong deuteric alteration.

CONTACT METAMORPHISM.

Contact metamorphism, to a greater or less degree, is discernible for a distance of some 500 yards from the visible margin of the granite. The phyllites and the limestone lens exhibit more pronounced thermal metamorphism than the associated rocks.

The phyllites have been changed to cordierite-hornfelses, some of which contain narrow bands of quartzite developed by either metamorphic diffusion or the metamorphism of intercalated layers of sandstone. In places there is a rapid change in the size of the cordierite porphyroblasts from 2 mm. to 7 or 8 mm., presumably reflecting particle-size variation in the original sediment. Two varieties of cordierite-hornfels may be distinguished in thin section. The coarse-grained rock contains large ill-defined patches of distinctly pleochroic cordierite containing a host of inclusions of quartz and sericite; these two minerals, together with scattered magnetite, make up the remainder of the rock. Where the sericite is in larger flakes (muscovite), a decussate texture is exhibited. The absence of biotite is an interesting and unusual feature of this rock. In the finer-grained hornfels the cordierite is smaller, non-pleochroic and contains fewer inclusions, quartz, biotite and accessory magnetite being the other constituents. The cordierite grains in some of the outcrops display a lineation inherited from the original bedding of the sediments, and strikes and dips have been obtained locally from this crystal alignment.

The limestone is exposed for a distance of 300 yards, and possibly continues for a further 200 yards beneath thick soil cover to the margin of the granite. It thins out to the north-west, has an exposed vertical extent of about 75 feet, and is bordered on the south by cordierite-hornfels and on the north by calcareous argillites.

The metamorphic minerals of this limestone lens are disposed both in bands, where their distribution is related either to slight compositional changes in the original sediment, or to metamorphic diffusion, and in composite masses. Wollastonite up to two inches in length, greenish diopside, grossular crystals up to half an inch across, and granular calcite are conspicuous.

Thin sections of composite masses taken from a small wollastonite quarry less than 300 yards from the granite outerop show an unusual mineral assemblage consisting of diopside, grossular, wollastonite, calcite and quartz (Plate III, Fig. 1). Wollastonite is preferentially distributed along cleavage-planes in the calcite and often completely replaces that mineral. Euhedral crystals of grossular
as small as 1 mm. occur embedded in quartz or as lenticular patches of larger subhedral crystals showing segmental twinning and weak anisotropism. Granular patches and minute euhedral crystals of diopside are scattered along the quartz-calcite grain boundaries, whence they gradually spread outwards. The calcite is apparently magnesium-bearing, as indicated by the profuse development of granular diopside along many of the calcite-quartz grain boundaries. Quartz, ranging in size up to 0.5 mm., is spread throughout the rock; its junction with calcite generally results in the formation of wollastonite, but there are instances of sharp non-reactive boundaries where quartz and calcite are in juxtaposition.

The percentage mineral distribution within the composite portions is as follows: wollastonite, 20%; diopside, 30%; grossular, 10%; calcite, 25%; quartz, 10%; epidote, 5% or less.

Within 100 yards to the south of the wollastonite quarry the composition of the calc-silicate rock changes, for wollastonite is no longer present and the garnet shows evidence of substantial replacement by epidote, quartz and sericite. Diopside is still a principal constituent and tremolite appears in places, together with quartz, calcite and epidote.

Where the rock contains pieces of scheelite over an inch in size, the proportions of the various silicates again change. Tremolite, ferriferous in part, then becomes the major component either as confused fibrous aggregates or as larger (up to 1 mm.) subhedral grains. Diopside, next in abundance, occurs as granular aggregates and small euhedral crystals. Quartz, with mutual boundaries against other mineral grains or as narrow (0.25 mm.) replacement veinlets, is accompanied by minor amounts of calcite (Plate III, Fig. 2). Locally, however, calcite is conspicuous megascopically in association with large areas of epidote. The percentage mineral composition of this rock (omitting scheelite) is as follows: tremolite, 40%; diopside, 30%; quartz, 15%; calcite, 5%; epidote, 5%; chloritized biotite, 5%. Small fragments of argillite incorporated in the rock have been converted to very fine-grained cordierite-hornfels.

An interesting feature of the lower-grade calc-silicate rock is the presence of small (up to 1 mm.) elliptical patches (Plate III, Fig. 3), sometimes bordered by tremolite, epidote and calcite. These patches represent cavities filled with quartz which shows extreme undulose extinction as though its entry and subsequent crystallization had been resisted by the enclosing rock. Minute grains of epidote and a mineral believed to be scheelite are occasionally included within the quartz fillings. Narrow zones of silicification (Plate III, Fig. 3) from 0.5 to 1 mm. wide, traverse parts of the rock, especially in the vicinity of the quartz-filled cavities, and it certainly appears that quartz has been introduced into the rock during the closing stages of metamorphism.

**MINERALIZATION.**

The appearance of tremolite with much epidote and additive quartz indicates a fall in temperature, a movement away from conditions of predominantly dry metamorphism and the imminence of a stage of hydrothermal activity.

Several pieces of tungsten ore were collected at the surface and from a small prospecting pit in this vicinity. One of these consisted of calc-silicate rock rich in epidote, including a coarse-bladed patch five inches across within which was a mass of scheelite some six square inches in area. It appeared that the scheelite had truncated part of the epidote aggregate indicating a sequence: (1) calc-silicate rock, with fine-grained epidote; (2) epidote, possibly of a later generation than that in (1) above; (3) scheelite.

Small grains of pyrrhotite and larger (up to half an inch) patches of galena occur in this part of the contact zone. The galena is a totally additive product...
(Pb and S), but the iron of the pyrrhotite, which occurs principally in the hornfels fragments, may have been derived by reaction between magmatic H₂S and biotite. It would appear that the scheelite was formed by reaction between tungsten-bearing fluids expelled from the granite at depth and small patches of calcite that remained in excess of the requirements of metamorphism. Occasional patches of calcite still persist in the rock.

**VEIN FORMATION.**

At the point shown in Text-figure 1 an outcropping quartz vein dipped into the contact zone at 3° to 5° to the north. The vein was nine to ten inches in maximum thickness, tapered at either side, and was moulded on to the wall rock with strongly slickensided margins. The length of the remaining portion of the vein was 25 feet and its outcrop width six feet.

**Table 1.**

Trace Element Comparison of Galena and Scheelite from Contact Rock and Quartz Vein Respectively.

<table>
<thead>
<tr>
<th>Element</th>
<th>Scheelite from Contact Rock (Per cent.)</th>
<th>Scheelite from Quartz Vein (Per cent.)</th>
<th>Galena from Contact Rock (Per cent.)</th>
<th>Galena from Quartz Vein (Per cent.)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fe</td>
<td>0·01–0·1</td>
<td>0·01–0·1</td>
<td>0·15–1·5</td>
<td>0·03–0·3</td>
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<tr>
<td>Mg</td>
<td>0·01–0·1</td>
<td>0·01–0·1</td>
<td>0·05–0·5</td>
<td>0·01–0·1</td>
</tr>
<tr>
<td>Ca</td>
<td></td>
<td></td>
<td>0·3–3</td>
<td>0·03–0·3</td>
</tr>
<tr>
<td>Al</td>
<td>0·01–0·1</td>
<td>0·003–0·03</td>
<td>0·002–0·02</td>
<td>0·003–0·03</td>
</tr>
<tr>
<td>Ti</td>
<td></td>
<td></td>
<td>0·01</td>
<td>0·03–0·3</td>
</tr>
<tr>
<td>As</td>
<td></td>
<td></td>
<td>0·01–0·1</td>
<td>0·01–0·1</td>
</tr>
<tr>
<td>Sb</td>
<td></td>
<td></td>
<td>0·1–1</td>
<td>0·1</td>
</tr>
<tr>
<td>Bi</td>
<td></td>
<td></td>
<td>0·003–0·03</td>
<td>0·003–0·03</td>
</tr>
<tr>
<td>Sn</td>
<td>0·0015–0·015</td>
<td>0·0003–0·003</td>
<td>&gt;0·1</td>
<td>&lt;0·1</td>
</tr>
<tr>
<td>Ag</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Pb</td>
<td>0·003–0·03</td>
<td>0·003–0·03</td>
<td></td>
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<tr>
<td>Yt</td>
<td>0·03–0·3</td>
<td>0·03–0·3</td>
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<td></td>
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<tr>
<td>Yb</td>
<td>0·03–0·3</td>
<td>0·03–0·3</td>
<td></td>
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</tbody>
</table>

The vein was followed in by means of a shallow drive and at a distance of 20 feet from the portal it turned towards the north-east and split into three veinlets each about half an inch wide and joined by a number of narrow feeders. Scheelite was visible right down to the ends of the feeders, which were wholly contained in calc-silicate rock. Numerous small grains of scheelite were present in the wall rock in the immediate vicinity of the feeding channels.

From a careful study of the vein, especially at its extremity, and of the distribution of scheelite in the adjacent contact rock, it can be stated with conviction that the vein originated within and was fed via the zone of metamorphism and metasomatism. The vein was not directly connected to the granite and dipped away from the granite margin at a very low angle (Text-fig. 1).

The greater part of the vein consisted of high-grade ore with scheelite crystals up to an inch long embedded in the vein-quartz (Plate III, Fig. 4). The scheelite was associated with minor amounts of galena. Thin-section study of the vein failed to reveal the presence of any gangue minerals other than quartz, metamorphic silicates being notably absent.

The mechanism of fissuring may be related to stresses induced by differential volume changes consequent upon metamorphism. It has been shown (Barrell, 1902) that metamorphism of shales to cordierite-hornfels causes volume reduction,
while the conversion of limestone to calc-silicate rock results in volume expansion (Maxwell and Verrall, 1953). It is significant in this regard that fracturing occurred at the junction of the cordierite-hornfels and the calc-silicate rock.

Trace Element Determination.

With the aid of a large quartz Hilger spectrograph, the trace element assemblages of galena and of scheelite from the contact rock were compared with those of the same minerals from the vein. In each instance some 20 trace elements were detected; only those considered significant* are listed on p. 52. Close agreement was obtained from the respective pairs of minerals. None of the trace elements present in galena or scheelite from one environment was missing from the corresponding mineral in the other, contrary to what might be expected had the vein minerals been formed other than in the contact zone.

Conclusions.

Two metamorphic grades may be identified within the limestone lens: grossular-diopside-wollastonite-quartz-calcite (omitting minor amounts of epidote) near the exposed granite and diopside-grossular-tremolite-quartz-calcite-epidote further away.

The intimate association of wollastonite with both quartz and calcite indicates that metamorphism ceased at a temperature little in excess of the quartz-calcite stability point. If Danielsson's (1950) thermodynamic assessment of the most likely temperature for the wollastonite reaction be applied to metamorphism at Walang, a temperature of the order of 550° C. is indicated (cf. Edwards et al., 1956).

Somewhat lower temperatures, in accordance with greater distance from the granite margin and the disappearance of wollastonite, may be postulated for the metamorphism in the vicinity of the scheelite mineralization.

The absence of metamorphic silicates in the quartz vein shows that contact metamorphism had been completed prior to the flow of aqueo-siliceous solutions into the fissure and points to a further fall in temperature, though perhaps only slight. A similar time-lag between metamorphism and scheelite mineralization has been noted at King Island.

The narrow bands of silicification in the scheelite-bearing contact rock (Plate III, Fig. 3) are interpreted as indicating the subsequent rise through the rocks of a hydrothermal "front". Whether the scheelite of the contact rock was formed by a gas-solid or a liquid-solid reaction is debatable. If by the former then aqueo-siliceous solutions must also have been available near the sites of reaction between expelled volatiles and excess calcite within the contact rock. At the moment of reaction some of the scheelite, as well as galena, was taken into solution (or suspension) and carried, via the narrow feeders, into the shear fissure under strictly hydrothermal conditions.

By virtue of its close proximity to a contact metasomatic source, the vein might well be classified as hypothermal, corresponding to the temperature range 300–500° C. of Lindgren's classification.

There seems to be a case for identifying three possible stages in the formation of ore deposits of contact metasomatic origin:

(1) Contact metamorphism-metasomatism, giving rise to more or less disseminated ore within the contact aureole at high temperatures.

* Dr. J. R. Butler (Imperial College). Personal communication.
(2) Early fissuring yielding contact metamorphic-metasomatic veins, containing metamorphic silicates of various grades as well as ore minerals, formed at slightly lower temperatures than (1) above.

(3) Late fissuring yielding hydrothermal veins of contact-metasomatic origin, like the vein at Walang, containing contact metasomatic ore minerals but no contact metamorphic silicates, and having hypothermal, mesothermal and perhaps epithermal mineral assemblages.

The temperature at which the vein minerals form would depend, inter alia, on the time lag between metamorphism and the ascent of metallizing agents, the stage in the metamorphic sequence at which fissuring, faulting, etc., occurred, and the distance travelled by the ore-bearing fluids from the focus of metamorphism.

In some respects the processes of mineralization attending contact metamorphism seem to recapitulate the ore-forming processes proceeding directly from an orthomagma.

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Mr. T. Mathews, of Bathurst, N.S.W., owner of the Walang lease, supplied the author with selected specimens during the working of the deposit. Thanks are due also to Professor F. J. Turner, of the University of California, who visited the area with the author in 1956, and Professor D. Williams, of the Imperial College, for reading the manuscript.

REFERENCES.

EXPLANATION OF PLATE III.

Fig. 1.—Calc-silicate rock containing granular diopside, calcite with wollastonite inclusions diagonal to cleavage, quartz (white) and a portion of a grossular grain (upper right). Note quartz abutting against calcite with non-reactive border. Nicols half crossed. × 25.

Fig. 2.—Calc-silicate rock containing diopside, tremolite, quartz and calcite in granoblastic arrangement with metasomatic scheelite (dark area on upper right). Crossed Nicols. × 25.

Fig. 3.—Fine-grained aggregate of diopside, tremolite, calcite, epidote and quartz with quartz-filled cavities and zones of fine-grained (additive) quartz (centre and right half of photo). Crossed Nicols. × 25.

Fig. 4.—Thin section of scheelite-bearing quartz vein. Upper right portion scheelite with quartz inclusions; lower left portion quartz. Crossed Nicols. × 25.
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