A Contact Metamorphic Axinite Paragenesis at London Bridge, Near Queanbeyan, N.S.W.

T. G. Vallance

Department of Geology and Geophysics, University of Sydney

Abstract — Axinite occurs with epidote, tremolite and calcite (all of which have been analysed) in a narrow band within a group of calcareous shales and limestones, now typically epidote-amphibole-(enstatite) hornfelses and calcite marbles, near an intrusive quartz-feldspar porphyry. The axinite is richer in Mg (4.20% MgO) than others recorded and its low refringence (a 1.659; γ 1.668) extends the known range for this mineral. The assemblage axinite-epidote-tremolite-calcite is shown to be a characteristic product derived from calcareous shales and marls in the albite-epidote hornfels facies where small amounts of boron are available.

Introduction

A natural arch of limestone, known locally as London Bridge, crosses Burra Creek, a tributary of the Queanbeyan River, at a place some 2½ miles NW of Burra and 11 miles SSW of Queanbeyan. The area was mapped by J. J. Veevers (1951) while an Honours student in the University of Sydney and Dr. Veevers has kindly given permission for use to be made of his thesis in the preparation of these geological notes. Near London Bridge a sequence of non-calcareous subgreywacke sandstones and shales, some six to eight thousand feet thick, overlie unconformably Ordovician low-grade schists and phyllites. Above the sandstones and shales, the Silurian succession is marked by lenticular beds of limestone (the arch occurs in one of these) associated with calcareous subgreywackes, siltstones and marly shales. This calcareous sequence has a maximum thickness of 1,500 feet and, on palaeontological evidence gathered by Veevers, the London Bridge limestone is of Wenlock age. Intrusive quartz-feldspar porphyry bodies are apparently associated with a thick pile of acid volcanic rocks which lies above the limestones. At London Bridge acid material has invaded and locally metamorphosed the calcareous rocks. It is in an exogenous contact zone thus formed that axinite occurs.

Veevers has, in fact, recognized two porphyry bodies intruding the calcareous sequence. The Keewong Foliated Quartz Porphyry has a roughly concordant relation with the country rocks but details are now obscured as a result of post-consolidational deformative action. This intrusion extends well beyond the confines of the London Bridge area but its precise limits are not known. The London Bridge Massive Quartz Porphyry is, on the other hand, largely restricted to the outcrop area of the Silurian calcareous rocks near London Bridge and occurs as isolated small bodies, irregular in outline, often discordant with the sediments. It has locally invaded the Keewong body and appears to have escaped extreme deformation. A zone of contact-altered sediments, variable in surface width from about 50 feet to more than 500 feet, outcrops along the eastern margin of the Keewong porphyry. The massive porphyry is closely associated with hornfelses WSW and SW of London Bridge but elsewhere in the vicinity it occurs with limestones outside the recognized contact zone. Field evidence indicates that the main thermal influence was connected with the larger Keewong body. In this case there seems to have been little assimilation of country rocks by the porphyry but, on the other hand, a distinct zone of contaminated material was observed by Veevers within the London Bridge porphyry. This latter endogenous facies is local and patchy in its distribution; some contacts against calcareous sediments display few signs of such mutual reaction.

Petrography

Keewong Foliated Quartz Porphyry

This body consists typically of bluish-grey material forming prominent "tombstone" outcrops, determined by the ubiquitous crude foliation. Small phenocrysts (ca. 2 mm diam.) of quartz and feldspar occur in a fine-grained matrix. All gradations exist locally from types with dominant quartz to others with a pre-
ponderance of feldspar phenocrysts. Microscopically, the quartz phenocrysts are strongly embayed and all display undulose extinction. Many are shattered and pass into crudely aligned aggregates of small grains. Patches of granular calcite and quartz commonly lie in the foliation planes adjacent to relic phenocrysts. Sodic oligoclase ($\text{An}_{15-20}$) is the typical phenocryst feldspar. Its high 2V and positive sign suggest low-temperature adjustment. Many grains are twinned (with albite law commonest, Carlsbad and pericline less abundant) and all are clouded with fine inclusions — white mica and carbonate alone being recognizable visually. Post-consolidational action has led to the fracturing of many feldspar phenocrysts with the development of irregular aggregates. Some phenocrysts, not so intensely fractured, are traversed by bands about 0.2 mm wide of fine feebly pleochroic pale greenish mica flakes arranged roughly in accord with the crude foliation in the adjacent groundmass regardless of the orientation of the bands. The groundmass of the porphyry now consists chiefly of fine granular quartz, white mica and chlorite with a little calcite and opaque material (apparently haematite/limonite after magnetite and/or pyrite). Most of the original biotite has been shredded and replaced by pale chlorite. The high content of white mica in parts of the groundmass suggests the former presence of alkali feldspar but unaltered relics are extremely rare.

**London Bridge Massive Quartz Porphyry**

This is characteristically porphyritic in quartz, feldspar and, less often, biotite. Quartz phenocrysts up to 4 mm in diameter tend to be euhedral where not resorbed. Compared with the strained phenocrysts in the main (Keewong) porphyry the quartz here is relatively untouched by deformation though some exhibits undulose extinction. The feldspar phenocrysts, typically subhedral and as much as 3 mm across, are extensively altered to clays. Some appear to be oligoclase, others are too altered to allow of sure identification. A few biotite phenocrysts (3 mm) occur but most of the biotite, which never seems to exceed 10% of the rock, appears as small flakes in the base. Much of it is altered to green chlorite but where original mica has been preserved it is strongly pleochroic from light yellow to dark green. Apart from minor opaque phases, biotite represents the sole primary dark mineral. The fine-grained groundmass contains quartz and subordinate altered feldspar as well as scattered biotite. Some examples show micrographic quartz-feldspar intergrowths in the groundmass.

Where the London Bridge porphyry has assimilated calcareous sediments it acquires a distinctive character. Addition of material is marked first by the development of small amounts of greenish actinolite. With more lime the amphibole content is enhanced and aggregates of epidote granules appear — especially in the feldspars. As actinolite and epidote become more prominent the quartz content declines. Very little quartz appears in the most modified types of porphyry which consist largely of epidote and amphibole, in roughly equal proportions, and feldspar. The remains of feldspar phenocrysts in such rocks are ragged and carry minute inclusions as well as clusters of epidote granules. Between the inclusions the feldspar ($\text{An}_{8-10}$) is clear and unzoned. Small amounts of untwinned clear granular albite occur interstitially in the groundmass. As well as being included in feldspar, epidote is scattered throughout as aggregates of anhedral grains of variable size (up to 0.5 mm). The larger grains are slightly pleochroic from colourless to pale yellow with $2V_\chi \approx 80^\circ$ and $\gamma - \alpha \approx 0.038$. The amphibole appears as subhedral units, up to 1 mm long and with ragged margins, or as bundles of fibres in subradiating groups or, again, in fine decussate patches. Typically the amphibole has $Z^\chi = 21^\circ$; $2V_\chi \approx 70^\circ$; $X =$ colourless to pale dirty yellow, $Y =$ yellowish green, $Z =$ light bluish green. Small brownish granules of accessory sphene are found throughout the groundmass but biotite, the typical dark mineral of the normal porphyry, does not appear in the contaminated facies.

**Exogenous Contact Rocks**

The main contact zone associated with the Keewong porphyry is marked by fine-grained green or yellowish-green calc-silicate hornfelses. Some display signs of bedding but most are fairly massive. Purer limestone bands have been recrystallized to fine marble. The calc-silicate rocks appear to have resisted deformation more effectively than the adjacent porphyry. Some dislocation occurred in the hornfelses but within the country rocks mechanical action was more pronounced in the marbles and along the marble-calc-silicate hornfels boundaries. Throughout most of the
contact zone there is a notable uniformity of mineral assemblages developed in rocks of similar composition. The calc-silicate rocks consist principally of tremolite/actinolite and epidote or these phases with diopsidic pyroxene. Calcite is not usually abundant and quartz rarely exceeds the status of an accessory mineral. The dominant phases are arranged irregularly with discrete patches rich in amphibole and others of epidote or diopside. Amphibole is normally present in decussate groups with some individuals as much as 0.5 mm in length though most are finer. In some cases where pyroxene is present amphibole has formed overgrowths the c-axes of which lie coincident with those of the host pyroxene. The amphibole of the hornfelses is weakly pleochroic from colourless to pale green and has $\gamma = 1.642$, $2V_x \approx 80^\circ$, $Z^c = 22^\circ$. Yellowish amphibole adjacent to occasional scattered and altered pyrite (?) grains probably owes its colour to staining. Epidote in the hornfelses is granular and nearly colourless with $2V_x \approx 85^\circ$, $\gamma - \alpha \approx 0.038$. Grains of nearly colourless pyroxene ($2V_x \approx 60^\circ$), where present, attain a maximum size of 0.4 mm but like the other phases are usually finer. The marbles need not be described in detail. Typically, they are granoblastic calcite rocks in some of which calcite grains show dimensional preferred orientation; some carry accessory amphibole and/or epidote.

Whereas the contact zone as a whole is characterized by amphibole-epidote or amphibole-epidote-diopside hornfelses and calcite marbles, two variant metamorphic types are developed locally. Of these, that consisting of axinite-epidote-calcite-tremolite outcrops as a concordant band some 10-15 feet wide and 350 feet long within the calc-silicate rocks about ½ mile SW of London Bridge. The band lies some 100 feet from the Keewong porphyry and about this same distance from an outcrop of the massive porphyry. However, it is not clear whether the London Bridge porphyry has more than an accidental association with either the gossans or the axinite rock. The gossanous material, unlike the massive calc-silicate rocks, is marked by strong dimensional preferred orientation of amphibole which occurs as subhedral to euhedral individuals up to 1 mm in length. It is typically clear and colourless and apparently iron-poor despite its present association with abundant iron oxides. In places, amphibole rods are bent or fractured but generally post-crystallization deformation was not severe. Most of the haematite/limonite appears in fine granular aggregates or in dark red-brown earthy patches surrounding amphibole. Larger granules of translucent haematite afford poor uniaxial figures. That part, at least, of the iron oxide material replaced pyrite (?) is suggested by patches with square outlines in the dark parts of the gossans. Little attention has been devoted to these rocks but it seems unlikely that they are isochemical products. Accession of iron, as sulphide (?), probably post-dated the iron-poor amphibole which may have formed, originally with calcite, in a tremolitic tremolite. The zones, now gossanous, apparently suffered some deformation before the formation of pyrite (?) and its subsequent alteration and probably also before the advent of the London Bridge porphyry.

The axinite-bearing rocks tend to be coarser-grained and more obviously heterogeneous than the typical calc-silicate rocks. Again, calcite is generally more abundant in the axinite rocks. In outcrop and hand specimen they are marked by irregular bands and patches. Patches rich in calcite (practically calcite marble), some several inches across, are often lens-shaped and follow roughly a crude foliation. This foliation is even more marked locally by narrow bands rich in amphibole. Pale brown patches, rich in axinite and epidote, tend to be isolated by the calcite- and amphibole-rich parts. Despite the crude foliation, the axinite-epidote patches appear to be massive.

In addition to axinite, calcite, epidote and tremolite which, in varying proportions, constitute the bulk of these rocks, brownish granular sphene is a minor accessory; accessory quartz occurs rarely. The axinite is colourless in thin section and usually forms subhedral units up to about 4 mm across though grainsize is highly variable. The coars-
est material is confined to axinite-rich patches; finer axinite (and epidote) appears where calcite is more abundant. Where axinite is common the crystals tend to be broadly elongate but euhedral outlines are rare because of the clustered growth. Some are poikiloblastic with inclusions of calcite while others carry bladed crystals of epidote. However, many of the axinite porphyroblasts are free from included material. As a rule, cleavages parallel to (100) are most prominent and {011} cleavages less well-defined; cleavages or partings parallel to (110) and (001) have been recognized but these are usually poorly-defined and discontinuous. Twinning is rarely evident but a few crystals show broadly lamellar twinning with composition plane apparently near {011}. Fine lamellar banding, somewhat like twin banding in appearance, occurs in some axinites but careful examination shows this can pass from one grain to its neighbour, regardless of crystallographic orientation. These bands may be curved within a single axinite crystal and where this feature is seen the host displays undulose extinction. Presumably the banding was related to deformative action. Evidence of deformation is commonest in the larger axinites some of which have been twisted and fractured, the fractures usually being filled with granular calcite (Figure 1). Unlike the larger axinites, small elongate wedge-ended crystals of axinite occur disseminated in calcite. These smaller crystals often have ragged boundaries against calcite in contrast to the sharp margins characteristic of the clustered axinite. Optical and chemical data for the axinite are listed in Table 1.

Epidote (see also Table 1) associated with axinite is colourless or slightly yellow-brown and at most feebly pleochroic. It occurs both as euhedral bladed crystals elongated (a few as much as 3 mm) in b or as rather ragged smaller porphyroblasts and grains. The largest individuals are developed with the coarsest axinite and, like the latter, these epidotes may be twisted and display undulose extinction. Crystalloblastic relations between epidote and calcite are variable. In places calcite seems to be euhedral against epidote; more commonly the reverse holds. Epidote is usually euhedral against axinite.

The amphibole is always finely fibrous, no larger units such as appear in the normal calc-silicate hornfelses being found in the axinite rocks. Even fairly uniform patches of amphibole as much as 0.5 mm across and 5 mm long seem to consist of bundles of parallel fibres. Most of the amphibole occurs in smaller groups which are commonly twisted round epidote or axinite crystals. Bundles of fibres may be enclosed in the associated phases—especially in the granular calcite. Pale green in hand specimen, the amphibole is colourless to faintly yellow in thin section and barely pleochroic. Further details are given in Table 1.

The irregular distribution of granular cal-

![Fig. 1](image-url)
cite has been noted. It varies from a predominating position in the patches and bands which are essentially calcite marble to the status of a minor constituent in the silicate-rich parts of the axinite rocks. Notable contrasts in fabric are related to the calcite content. Some marble patches consist of aggregates of grains showing strong preferred dimensional orientation. Rarely, coarse grains, 5 mm or more in diameter and markedly twinned with lamellae bent, are embedded in these granular patches. It seems likely that the present fabric of the marble patches resulted from recrystallization induced by deformation after the development of the axinite-epidote-calcite-tremolite assemblage. This recrystallization, the results of which seem so evident in the calcite-rich material, must have involved changes in grain-shape only for there are no signs of chemical alteration of any of the phases present.

The association axinite-epidote-calcite-tremolite locally in the exogenous zone at London Bridge appears to be contemporaneous with the epidote-tremolite and epidote-tremolite-diopside hornfelses and calcite marbles. Certainly all of these metamorphic products have been influenced to some extent by deformation which apparently ante-dated the massive porphyry. No high grade of thermal metamorphism was attained within the aureole and the assemblages of the calc-silicate hornfelses are typical of the albite-epidote hornfels facies. The occasional appearance of diopside suggests a higher-temperature subfacies.

Table 1
Chemical and Physical Data for the Constituents of an Axinite-bearing Hornfels, London Bridge, N.S.W.
(Univ. Syd. spec. 18103). Anal: T.G.V.

<table>
<thead>
<tr>
<th></th>
<th>Axinite</th>
<th>Epidote</th>
<th>Tremolite</th>
<th>Calcite</th>
</tr>
</thead>
<tbody>
<tr>
<td>SiO₂</td>
<td>42.39</td>
<td>37.90</td>
<td>55.03</td>
<td></td>
</tr>
<tr>
<td>Al₂O₃</td>
<td>17.10</td>
<td>24.19</td>
<td>2.04</td>
<td></td>
</tr>
<tr>
<td>Fe₂O₃</td>
<td>1.68</td>
<td>10.74</td>
<td>1.54</td>
<td></td>
</tr>
<tr>
<td>FeO</td>
<td>5.18</td>
<td>0.32</td>
<td>5.96</td>
<td></td>
</tr>
<tr>
<td>MgO</td>
<td>5.21</td>
<td>0.57</td>
<td>17.46</td>
<td></td>
</tr>
<tr>
<td>MnO</td>
<td>1.38</td>
<td>tr.</td>
<td>nt. fd.</td>
<td></td>
</tr>
<tr>
<td>CaO</td>
<td>20.13</td>
<td>23.69</td>
<td>13.44</td>
<td></td>
</tr>
<tr>
<td>Na₂O</td>
<td>0.06</td>
<td>0.05</td>
<td>0.17</td>
<td></td>
</tr>
<tr>
<td>K₂O</td>
<td>0.03</td>
<td>0.04</td>
<td>0.08</td>
<td></td>
</tr>
<tr>
<td>H₂O⁻</td>
<td>1.67</td>
<td>1.86</td>
<td>1.99</td>
<td></td>
</tr>
<tr>
<td>H₂O⁺</td>
<td>0.31</td>
<td>0.55</td>
<td>0.32</td>
<td></td>
</tr>
<tr>
<td>B₂O₃</td>
<td>5.52</td>
<td>23.69</td>
<td>13.44</td>
<td></td>
</tr>
<tr>
<td>CO₂</td>
<td>43.94</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Total 99.83 99.89 99.93 99.91

Calculated Formulae:
32(O.OH.F) 13(O.OH.F) 24(O.OH.F) 6(O)

Physical Characters:

<p>| | | | | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>x</td>
<td>-1.659</td>
<td>1.722</td>
<td>1.610</td>
<td>1.487</td>
</tr>
<tr>
<td>β</td>
<td>1.665</td>
<td>1.736</td>
<td>1.632</td>
<td>1.660</td>
</tr>
<tr>
<td>γ</td>
<td>1.668</td>
<td>1.749</td>
<td>1.632</td>
<td>1.660</td>
</tr>
<tr>
<td>2V₉</td>
<td>76°</td>
<td>81°</td>
<td>75°</td>
<td>18°</td>
</tr>
<tr>
<td>Z₉</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>D</td>
<td>3.19</td>
<td>3.31</td>
<td>2.99</td>
<td>2.70</td>
</tr>
</tbody>
</table>
Chemical Discussion

All four phases present in the axinite-bearing hornfels have been separated and analysed. In each case there is reasonable agreement between the calculated and appropriate ideal formulae. Observed physical characters of the epidote accord with those of similar compositions quoted by Deer, Howie and Zussman (1962). Refractive indices of the amphibole are somewhat lower than might be predicted from these authors' compilation but it should be noted that fluorine was not determined because of the limited amount of sample. The deficiency in the (OH)− group of the calculated formula may be due to the presence of fluorine. Compositionally the amphibole falls within the range of tremolites accepted by Deer, Howie and Zussman (1963): its Al2O3 content is not exceptional for tremolites. Despite its association with phases carrying varying amounts of Fe2+, Mg and Mn, the carbonate is pure CaCO3. The analysed axinite is notable for its high Mg content—higher, in fact, than any previously recorded—and for this reason, as well as its apparent rarity in Australia, will be considered in more detail than the other phases.

In connection with the high MgO value quoted for the axinite it may be mentioned that estimations of FeO, MgO, MnO and CaO were duplicated to check initial results. Despite addition of bromine water to separate Mn with the "R3O8" hydroxides it was found that measurable amounts of Mn remained in the filtrates after precipitation with ammonia. Both calcium and magnesium estimations had to be corrected for co-precipitated Mn salts. As a final check, total MnO was determined in a separate portion. The magnesian character of this mineral from London Bridge was noted by Vevers (1951) though its identity with axinite was not recognized at the time. Vevers recorded the following composition: SiO2 47.66, Al2O3 15.85, Fe2O3 3.49, FeO 4.87, MgO 4.03, MnO 1.41, CaO 20.18, P2O5 1.09, TiO2 0.10, total 98.68. Apart from the high SiO2, which is clearly erroneous due to the undetected presence of boron, there is a general resemblance between this analysis and that given in Table 1.

Milton, Hildebrand and Sherwood (1953) have shown that axinites exhibit a four-fold variability in composition—the variables being Ca, Fe2+, Mn2+, and Mg. The formula \( \Pi (CaFeMn)_{3}Al_{2}BSi_{4}O_{16} \) given by these authors recognizes the fact that the Ca content is not fixed as had been accepted following the work of Schaller (1911). They indicate that while up to two atomic positions in the \((CaFeMn)_{3}\) group may be occupied by Mn (tinzenite = magnanovan axinite) the majority of analysed axinites approach the case in which two positions are taken by Ca with the remaining place shared largely between Fe and Mn. The variety of axinite called severinite by Barsanov (1951) and for which the ideal formula is given as Mn3Al2BSi14O15(OH) in fact shows much less Mn/Ca substitution than tinzenite (cf. Serduchenko and Pavlov, 1962). No undoubted cases with Ca = 3 are known; some old analyses list high CaO but the reliability of these is doubtful. Milton et al. recognize some substitution of Mg for Ca/Fe/Mn but clearly regard this as minor. A similar view is expressed by Deer, Howie and Zussman (1962, vol. I, p. 324).

Considering the difference in radii between Ca2+ (1.06 Å) and Mg2+ (0.78 Å) it is unlikely that a complete series through to axinites of the type \((CaMg)_{2}\) analogous to \((CaMg)_{3}\) in magnanovan axinite will be found. Even the most iron-rich axinites known do not quite reach the case \((Ca_{2}Fe)_{1}\). From published information it is clear that Mg-substitution in axinite is less extensive than the variability among Ca, Fe and Mn but the present data serve to widen the observed compositional limits. Only one other axinite with comparable Mg content seems to have been recorded. This has 4-13% MgO and is associated with prehnite in a diabase from Silbach, Westphalia (Steinwachs, 1929). Both this and the London Bridge material approximate the case \((Ca_{2}Mg_{0.5}(FeMn)_{0.5})\). These and other analysed axinites with \((Ca_{2}(FeMnMg)_{1})\) are plotted in Figure 2 to illustrate variability in the common Ca2 axinites. Only examples with the number of Ca atoms per formula unit within the limits 1.9-2.1 have been used in this diagram though some analyses which fulfil this requirement were rejected because the calculated formulæ suggest analytical error or impurity (the commonest defect is excessive Fe3+). A notable feature of the group plotted is that whereas several axinites approach \((Ca_{2}Mn)_{1}\) no instances of \((Ca_{2}Fe)_{1}\) or \((Ca_{2}Mg)_{1}\) axinites are known. Furthermore there is not a simple reciprocal relation between Fe2+ and Mn2+ in the series. The most magnaniferous are practically Mg-free but increase in Fe is usually accompanied by increase in Mg.

Specific gravity and refractive indices of
the London Bridge material are low compared with those of other \((\text{Ca}_2(\text{FeMnMg})_1)\) axinites. The refractive indices are, in fact, outside the range previously noted for this mineral and one is drawn to correlate low refringence with high Mg content. Efforts made in the past to connect chemical and physical characters in axinite achieved only limited success. Thus Gädeke (1938) and Harada (1939) attempted to relate refringence and specific gravity to MnO content and claimed evidence of a decline in the intermediate refractive index with increasing MnO. In these studies it was assumed that variations in physical properties are due to changes in the Fe/Mn ratio. Collation of all available data on analysed \((\text{Ca}_2(\text{FeMnMg})_1)\) axinites suggests that these authors’ conclusions are of doubtful value. When refractive indices are plotted against the proportion of Mn in the FeMnMg group there is found to be an apparent slight increase in refringence towards the Mn-rich end. But we have seen that the more Mn-poor axinites are richer in Mg as well as Fe. It is also worth noting that the refractive indices determined by Gädeke for his Mn-poor examples are distinctly higher than those recorded by others for axinites of similar compositions. The present writer believes, on the evidence available, that mutual substitution of Mn\(^{2+}\) and Fe\(^{2+}\) causes little change in physical properties. One would expect a \((\text{Ca}_2\text{Fe}_1)\) axinite, if found, to have only slightly higher refringence and specific gravity than the analogous \((\text{Ca}_2\text{Mn}_1)\) type. On the other hand, the Mg content appears to be of great significance in reducing specific gravity and refractive indices. As one example, if we assume as an approximation that the unit cell volume is constant throughout the group \((\text{Ca}_2\text{Fe}_1)-(\text{Ca}_2\text{Mn}_1)-(\text{Ca}_2\text{Mg}_1)\), the calculated specific gravities based on cell dimensions given by Ito and Takeuchi (1952) are, respectively, of the order 3·33(5), 3·33(0) and 3·15. While the present sample has a lower observed specific gravity (3·19) than the calculated value (3·23) for this composition, the agreement is better (obs. 3·22; calc. 3·23) for Steinwachs’ material. It is unfortunate that Steinwachs did not record refractive indices but extrapolation from available data suggests a value for \(\gamma\) about
ACF diagram for the albite-epidote hornfels facies, with calculated compositions of calc-silicate hornfelses (o) and axinite-bearing rocks (+) plotted as well as the analysed phases (x) from one of the latter. The joins to axinite are dashed to signify that axinite strictly does not fall on the ACF plane.

1.64 for \((\text{Ca}_2\text{Mg}_1)\) axinites if such are found to exist.

No bulk analyses of contact rocks at London Bridge have been made but a rough idea of the rock compositions has been obtained by calculation using modes and assuming mineral compositions and specific gravity values are of the same order throughout. Thus the common calc-silicate rocks appear to have the compositions of calcareous shales. Though the amphibole of these hornfelses may be a little richer in iron than that found with axinite, calculations suggest the hornfelses carry 5-10% by weight MgO. From the calc-silicate rocks there is a gradation to pure CaCO₃ rocks and as the sediments outside the contact aureole appear to be of similar chemical character (calcareous shales, marls, limestones) it is reasonable to regard the hornfelses lacking axinite as essentially isochemical products. The seeming absence of dolomite from the vicinity leads one to consider the Mg present in the epidote-amphibole hornfelses as derived from the clay fraction of the calcareous shales. Calculated compositions of the axinite-bearing hornfelses (Figure 3) fall within the range of the other contact rocks—except for the obvious presence of boron. The axinite rocks appear to have been derived largely from marly limestones but can scarcely be isochemical products. While the case for boron accumulation is clear it might also be argued that Mn has been concentrated in the axinitic rocks though it would be unwise to assume that epidote and amphibole occurring without axinite are lacking in Mn.

The source of boron at London Bridge is not obvious. Restriction of axinite to a narrow zone within the aureole might have been due to local access of boron from the Keewong porphyry but neither tourmaline nor any other boric phase has been noticed in the porphyry while the observed mineral replacements in the intrusion cannot be assumed to result from magmatic volatile attack. The alternative view, concentration of boron from the marine sedimentary rocks, is equally lacking in proof. Geochemical work overseas suggests that boron is rarely abundant in lime-
AXINITE PARAGENESIS

Table 2

<table>
<thead>
<tr>
<th>London Bridge, N.S.W.</th>
<th>Ontario</th>
</tr>
</thead>
<tbody>
<tr>
<td>axinite</td>
<td>epidote</td>
</tr>
<tr>
<td>Fe²⁺</td>
<td>0.37</td>
</tr>
<tr>
<td>Fe²⁺ + Mg + Mn</td>
<td></td>
</tr>
<tr>
<td>Mg</td>
<td>0.53</td>
</tr>
<tr>
<td>Fe²⁺ + Mg + Mn</td>
<td></td>
</tr>
<tr>
<td>Mn</td>
<td>0.10</td>
</tr>
<tr>
<td>Fe²⁺ + Mg + Mn</td>
<td></td>
</tr>
<tr>
<td>Al</td>
<td>0.94</td>
</tr>
<tr>
<td>Al + Fe³⁺</td>
<td></td>
</tr>
</tbody>
</table>

*Alvi only.

As no other analyses of undoubtedly coexisting axinite, epidote and/or amphibole have been noted. An epidote from Porcupine, Ontario, studied by Bruce and Greenland (1924) is claimed to be similar to epidote occurring with an axinite analysed by Walker and Parsons (1925); as a matter of interest the appropriate ratios are listed in Table 2. Axinites and epidotes from Bourg d’Oisans, Dauphiny, have been analysed and described in the literature but the present writer is unaware of the mode of occurrence. Using homogenization of liquid-gas inclusions as a temperature indicator, Koltun, Liakhov and Pismur (1961) claim the Dauphiny axinite formed at temperatures below 200°C, so it may not have developed with epidote.

Axinite in Contact Metamorphism

Despite the lack of chemical data on axinite parageneses the mineral is not especially rare in contact environments. Probably best known are the associations with andradite, hedenbergite, calcite and tremolite in the aureoles of the Dartmoor and Land’s End granites in SW England. In this region datolite is a rare associate in metamorphosed calcareous sediments while some recrystallized basic rocks carry axinite with amphibole and tourmaline (e.g. Reid, 1912; Harker, 1939; Deer, Howie and Zussman, 1962, vol. I, p. 307). Similar examples have been recognized elsewhere overseas. In a few localities, axinite occurs with the rare Ca-borosilicate danburite (e.g. Harada, 1939). Near Dundas, Tasmania, rocks containing some relic clinopyroxene with actinolite, axinite, calcite, datolite, danburite, quartz and Fe and Cu sulphides...
appear to be the product of contact pneumatolytic action by a granitic body (tourmaline-quartz porphyry) on pyroxenite (Twelvetrees and Petterd, 1899). Apart from the relic pyroxene, largely altered to amphibole, the complex assemblage appears to exist without obvious signs of mineral alteration. The occurrence points to the likelihood that the three borosilicates may coexist stably under certain conditions, the most obvious being the availability of sufficient boron. However, the metamorphic status of axinite parageneses must be interpreted with caution. Thus some axinite occurrences show disequilibrium characters and it is likely that the phases now coexisting represent mineral adjustments over a wide range of physical and chemical conditions (e.g. Mozgova, 1964). Indeed, of the borosilicates mentioned above, each has been recorded in metamorphic environments ranging from those of diagenetic character to others of fairly high grade.

Figure 4 serves to summarize some suggested compatibility relations in the albite-epidote hornfels facies where $B_2O_3$ exists as an extra component (borosilicates like serendibite and kornerupine with compositions which also fall in the tetrahedron A-C-F-$B_2O_3$ are excluded as they seem to be confined to high-grade environments). Probably similar relations hold in the hornblende hornfels facies with the significant differences confined to the ACF plane. Of the predicted 4-phase assemblages containing axinite and formed from impure limestones, marls and calcareous shales in low-grade contact zones—(1) axinite-calcite-epidote-tremolite, (2) axinite-calcite-datolite-epidote, (3) axinite-calcite-datolite-tremolite, (4) axinite-datolite-danburite-epidote, and (5) axinite-datolite-danburite-tremolite—only the first named is at all common. The reasons for this are probably two-fold, (a) among the rock-types mentioned, the commonest bulk compositions (ignoring boron) tend to fall within the ACF triangle rather than along the sides, and (b) boron concentrations in excess of a few percent by weight of the bulk seem to be distinctly rare. For similar reasons axinite-calcite-Ca garnet-Ca pyroxene is likely to be the most common of axinite associations derived from marls, etc., in the hornblende hornfels facies. Tourmaline will appear in these facies where Ca concentrations are lower, typically in hornfelses formed from argillaceous sediments or basic igneous rocks. Thus near the Moonbi Adamellite at Tintinhull, N.S.W., the assemblage blue tourmaline-axinite-actinolite/hornblende-epidote-(albite) occurs locally in small patches near veins in thermally meta-
morphosed spilitic rocks now consisting chiefly of albite and actinolite/hornblende (e.g. Univ. Sydney spec. 23304). At London Bridge where all the contact rocks are calcareous it seems clear that the axinite-bearing hornfelses are isofacial with the associated calc-silicate rocks and marbles.

References


View This Item Online: https://www.biodiversitylibrary.org/item/175277
DOI: https://doi.org/10.5962/p.360886
Permalink: https://www.biodiversitylibrary.org/partpdf/360886

Holding Institution
Smithsonian Libraries

Sponsored by
Biodiversity Heritage Library

Copyright & Reuse
Copyright Status: In Copyright. Digitized with the permission of the rights holder
Rights Holder: Royal Society of New South Wales
License: http://creativecommons.org/licenses/by-nc-sa/3.0/
Rights: https://www.biodiversitylibrary.org/permissions/

This document was created from content at the Biodiversity Heritage Library, the world's largest open access digital library for biodiversity literature and archives. Visit BHL at https://www.biodiversitylibrary.org.

This file was generated 27 June 2023 at 11:04 UTC