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METAMORPHIC CONDITIONS IN A PART OF THE HALIBURTON HIGHLANDS OF ONTARIO

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Metamorphism in the Haliburton Highlands is of Miyashiro's low pressure, intermediate type. Physico-chemical conditions ranged from 3.5 to 7 kilobars total pressure and 580 to 700 °C.

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The Grenville province is the easternmost portion of the Canadian Shield. Except for a comparatively small area in central Ontario (Lumbers 1967) it is a region of an almost uniformly high grade of metamorphism, that in the Haliburton Highlands and its environs, is generally taken to be of the almandine-amphibolite facies.

The implications of this particular facies label insofar as it applies to the Haliburton Highlands is examined in the first half of this paper. The last half constitutes an attempt to deduce metamorphic conditions in this region by use of a load-pressure (P_{load}) – temperature (T) grid. The determination of physico-chemical conditions by this and other means is without doubt an important objective of geochemistry, and the use of a grid stems ultimately from Bowen (1940). However, a major drawback to Bowen's scheme is that it depends upon the delimitation of pressure-temperature fields by use of bounding univariant reactions, and the number of truly univariant reactions that are useful in a petrogenetic sense is severely limited. In fact, in the realm of crustal petrogenesis, the petrologist may find that the only usable univariant reactions are those between Al_2SiO_5 polymorphs. Even here there is some evidence that the reactions are not strictly univariant (Althaus 1969, Zen 1969). Certainly, dehydration and decarbonation reactions, being divariant in systems open to H_2O and CO_2 respectively, will be less useful than Bowen thought.

Although such difficulties inhibit the construction of a petrogenetic grid for the general case, a specific grid, applicable to a particular metamorphic area, can in many cases be set up by a judicious choice of mineralogical reactions. Such a choice is dictated by the mineralogy of the rocks studied, and it leads to a petrogenetic grid tailored to a specific problem—in Wyllie's (1964) phrase 'a metamorphic grid'.

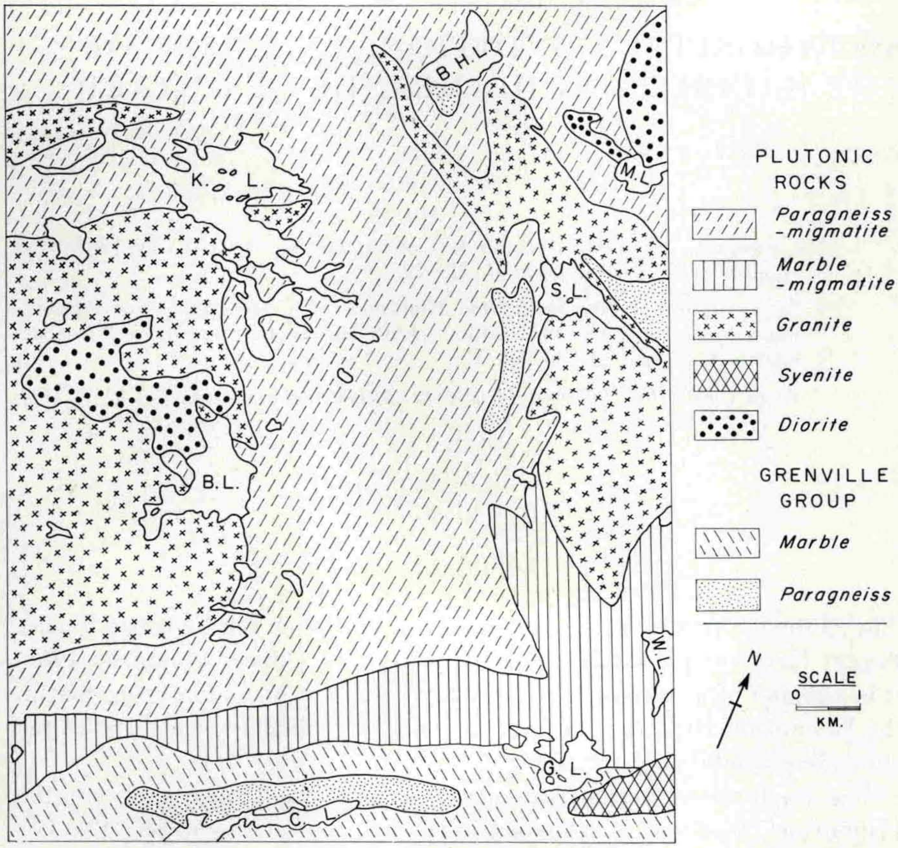


Fig. 1. Precambrian Geology of part of Glamorgan township. Geology by H. S. Armstrong and Ward Chesworth. The abbreviations are as follows: B.H.L. = Blue Hawk Lake, K.L. = Koshlong Lake, M.L. = Minniecock Lake, S.L. = Stormy Lake, B.L. = Bark Lake, W.L. = Wolf Lake, G.L. = Gooderham Lake, C.L. = Contau Lake.

Geological setting of Glamorgan township

Glamorgan township, in the Haliburton Highlands, is about 150 miles north of Toronto. The area studied (Fig. 1) is underlain by Precambrian rocks of the Grenville province. An approximate time scale is shown in Table 1.

Rocks of the Grenville group (Wynne-Edwards 1967) represented here include marble, paragneiss, amphibolite and quartzite. Granite of three contrasted compositions (Chesworth 1968) pervasively veins these rocks to form the migmatitic complex referred to by Adams & Barlow (1910) as the Glamorgan batholith.

The metamorphic grade is stated by Armstrong & Gittins (in press) to be of the almandine-amphibolite facies. In order to examine this characterization, it is worthwhile to consider some of the characteristics of the amphibolite facies in general.

Table 1. Precambrian (Proterozoic) time scale for the Haliburton Highlands, Ontario.

Age in m.y.	Dominant events
900	Post-metamorphic intrusions (pegmatite and diabase)
1000 – 1200	Metamorphism with formation of granite, pegmatite and migmatite
1200 – 1300	Pre-metamorphic intrusions (nepheline syenite, gabbro, diorite)
1300 – 1400	Grenville group sedimentary and volcanic rocks laid down

The amphibolite facies

The mineral facies concept has on the whole been a powerful aid to the study of metamorphic rocks. However, individual facies are not unambiguously defined (see Lambert 1965), and in the case of the amphibolite facies this fact becomes obvious on examining the boundaries of the facies at low and high grades.

The low-grade boundary is marked by Eskola (1939) with the breakdown of epidote and the appearance of plagioclase and hornblende existing together. Ramberg's (1952) boundary is an isograd along which epidote coexists with a plagioclase of composition An_{30} Ab_{70}. In real terms these two boundaries may not be significantly different if Ramberg's (1952, p. 51) epidote-plagioclase phase diagram is to be believed, but in any case it is probably more sensible to recognize that the low grade boundary is transitional in nature, a point made clearly by Turner (1968, pp. 303 ff).

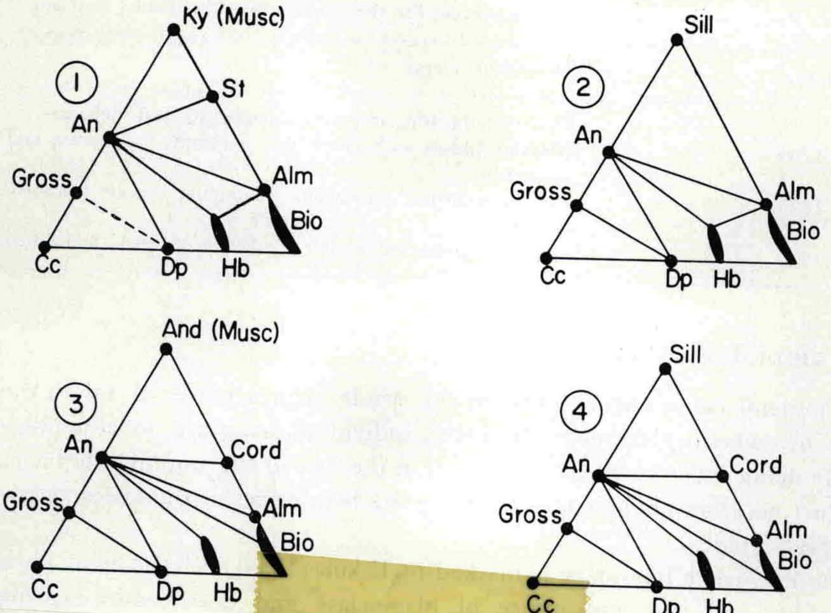
The high grade boundary of the amphibolite facies is not so much ambiguous as meaningless for all practical purposes. Eskola (1939) marked this upper limit by the breakdown of all hydrous phases – a breakdown that could be marked by such reactions as

Hornblende=pyroxenes+water

Biotite=almandine+orthoclase+hypersthene+water

taken from Turner & Verhoogen (1960, p. 557). The absolute, upper stability limit for these hydrous phases would pertain to a condition in which equilibrium partial pressure of water is equal to load pressure ($PE_{H_2O}=P_s$), a condition under which biotite and hornblende could be expected to remain stable beyond the point where melting and magmatic processes become dominant in the crust of the earth. Even though the condition $PE_{H_2O}=P_s$ is unlikely to be encountered in an environment of regional metamorphism (a point recognized by Francis 1956, in his tentative metamorphic grid) it is still questionable whether at depth there exists a temperature high enough, or PE_{H_2O} low enough, for all hydrous phases to break down before the onset of melting. Certainly it appears that the assemblages of Eskola's (1939) granulite facies are not found except in the presence of hydrous phases (see for example the short review in Hsu 1955).

Further confusion arises with the various internal subdivisions that have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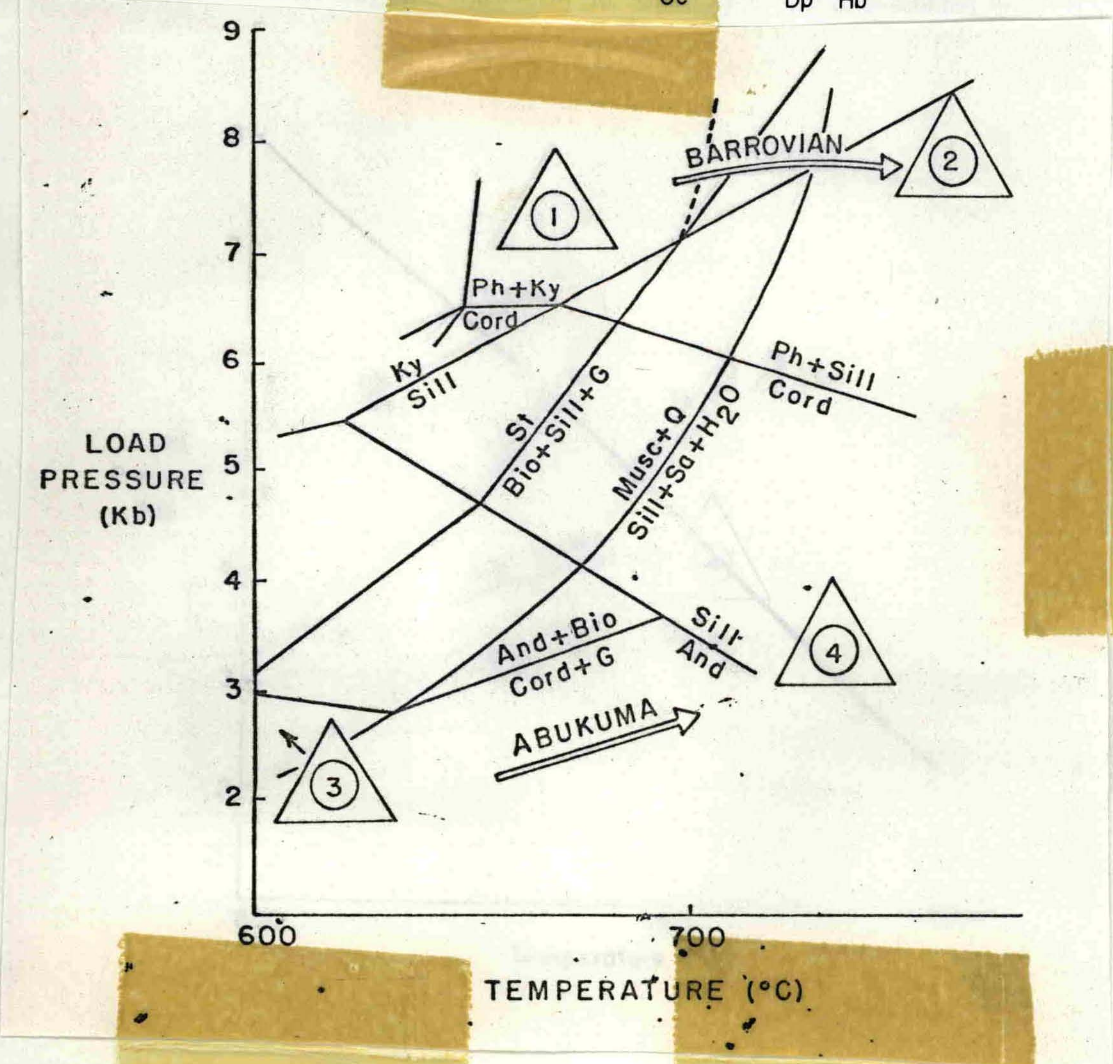
LOAD PRESSURE (Kb)
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BARROVIAN
2
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Cord
Ky
Sill
St
Bio+Sill+G
Musc+Q
Sill+Sa+H2O
Ph+Sill
Cord
Sill
And
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And+Bio
Cord+G
ABUKUMA
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600
700
TEMPERATURE (°C)

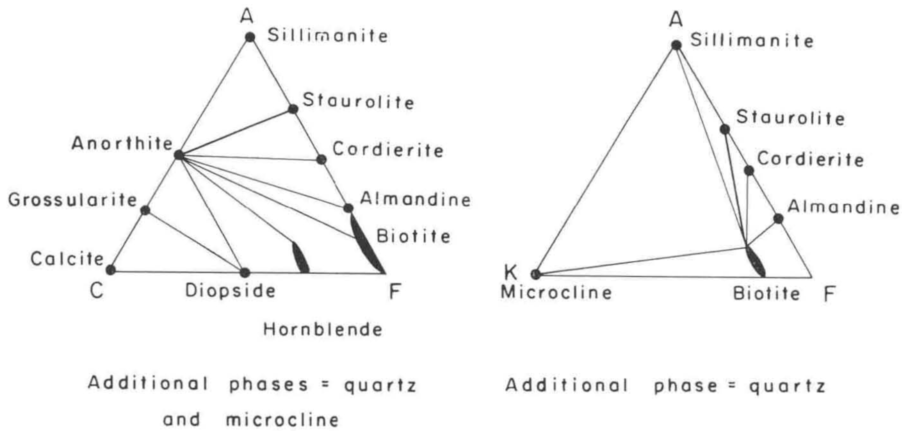

Fig. 3. ACF and AKF diagrams showing the principle assemblages in rocks of the area.

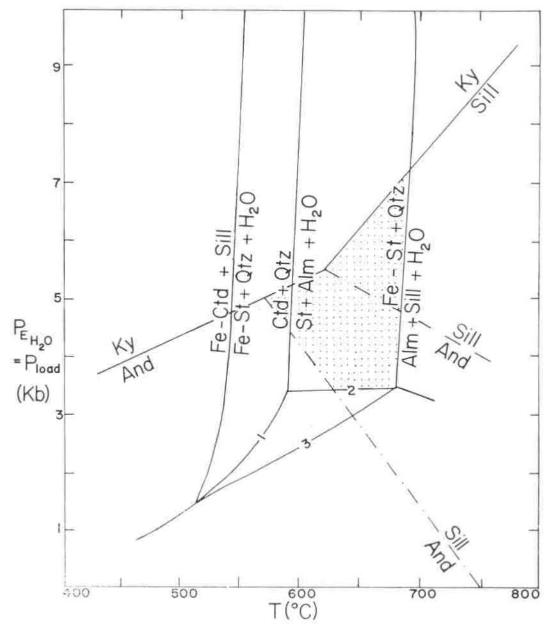

Fig. 4. A metamorphic grid for part of the Haliburton Highlands of Ontario. The maximum spread of conditions of formation is represented by the dotted area. Reactions 1, 2 and 3 are respectively reactions VI, VII and II of Richardson (1968). Sources for the other curves will be found in the text.

been proposed. Fyfe, Turner & Verhoogen (1958) originally erected three subfacies of what they called the almandine-amphibolite facies based in large measure on the work of Francis, who took much of his data from the classical Barrovian zones. Later, Turner & Verhoogen (1960) added a fourth subfacies that does not fit well with the other three, possibly because

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Fig. 2. Metamorphic assemblages from the Scottish Highlands and the Abukuma Plateau superimposed on the PT grid of Hess (1969). 1 and 2 are respectively the kyanite-muscovite-quartz subfacies and the sillimanite-almandine subfacies, in the Barrovian zones (Fyfe et al. 1958). 3 and 4 are found respectively in zones B and C at Abukuma (Miyashiro 1958).

Table 2. Mineral assemblages found in Glamorgan township.

Rock type	Characteristic mineral assemblage
Basic igneous	Hornblende-plagioclase-augite (± biotite, ± scapolite, ± calcite) Hornblende-scapolite-augite-calcite
Granitic (including granitic bands in migmatite)	Quartz-microcline-plagioclase-biotite-magnetite (± muscovite in some late stage veins) Quartz-microcline-plagioclase-biotite-hornblende-magnetite Quartz-microcline-plagioclase-magnetite
Non-granitic bands in migmatite	Quartz-plagioclase-biotite-hornblende-microcline-magnetite (± sillimanite)
Paragneiss	Quartz-plagioclase-biotite (± magnetite) Quartz-plagioclase-biotite-hornblende-microcline-magnetite Quartz-plagioclase-biotite-microcline-almandine (± epidote, ± cordierite)
Pelitic	Sillimanite-almandine-biotite-quartz-plagioclase (± hornblende ± staurolite)
Marble and skarn	Calcite-diopside-tremolite Calcite-diopside-scapolite Calcite-diopside-phlogopite Calcite-diopside-spinel Calcite-diopside-hornblende Calcite-diopside-grossularite Calcite-diopside-grossularite-plagioclase-epidote
Calc-silicate rock	Diopside-tremolite Diopside-tremolite-scapolite Diopside-scapolite

as the authors recognized, it is 'believed to have formed at lower pressures' (p. 545). In other words (and to use Miyashiro's, 1961, term), two distinct *facies series* are here placed together, all under the umbrella of the almandine-amphibolite facies.

Miyashiro (1961) in fact, was one of the first petrologists to dispute the idea that the almandine-amphibolite facies had any universal applicability. He recognized that low pressure environments (for example, Abukuma) gave rise to a set of mineral assemblages of amphibolite facies type, distinctly different from amphibolite facies assemblages found in higher pressure series such as the Barrovian.

Miyashiro's work suggests that it may be possible to divide the amphibolite facies into subfacies by means of pressure-dependent mineralogical changes, and relations between the Al_2SiO_5 polymorphs could be particularly useful in this respect. For example, the amphibolite facies defined by Eskola (1939) as that one in which plagioclase and hornblende coexist, could be divided into andalusite- sillimanite-, and kyanite-subfacies in a sequence from low to high pressure. One obvious shortcoming of a simplistic scheme of this kind arises from the fact that transitions between the Al_2SiO_5

polymorphs are not simply pressure-dependent so that further mineralogical information is necessary to label say, the sillimanite-subfacies as being formed at a *higher pressure* (and not just a higher temperature) than the andalusite-subfacies. In this respect, Miyashiro's (1961) recognition that staurolite characterizes certain Barrovian rocks whereas cordierite is found at Abukuma, is particularly useful.

It is possible to put tentative values on pressures of formation of the amphibolite facies rocks from the Scottish Highlands and the Abukuma plateau, by taking the mineralogical assemblages from these two areas (Fig. 2) and superimposing them on Hess's (1969) grid. Hess himself concluded that the Abukuma rocks must have formed at total pressures below 3 kilobars to place them outside the field of stability of staurolite. Similarly the assemblages of the Barrovian amphibolite facies can be placed on Hess's grid at total pressures above 6.5 kilobars.This leads to the schematic arrangement shown in Fig. 2, a framework that will prove useful in discussing the metamorphism of the Haliburton area.

Mineral facies in Glamorgan township

The mineral assemblages found in this part of the Haliburton Highlands are shown in Table 2. Those assemblages that can be plotted on the usual ACF and AKF diagrams are shown in Fig. 3. A comparison of Fig. 3 with Fig. 2 indicates the obvious similarities that exist between the Glamorgan rocks and both Barrovian and Abukuma assemblages. For example, staurolite *and* cordierite are found in Glamorgan township. In fact these two minerals are observed in other parts of the Grenville province in Ontario (e.g. Lal & Moorhouse 1969, Shaw 1962).

A reasonable inference from the similarity of Glamorgan rocks with what Miyashiro (1961) calls andalusite-sillimanite, and kyanite-sillimanite types of metamorphism, is that the Canadian occurrence forms part of a low pressure intermediate facies series. Added support for this conclusion is provided by the fact that andalusite (Lumbers 1967) as well as sillimanite and kyanite (Best 1966) occur in adjacent parts of the Grenville province, and Miyashiro (1961) has suggested that the occurrence of all three Al_2SiO_5 polymorphs is diagnostic of low pressure intermediate type metamorphism.

Physical conditions of metamorphism

In order to place limits on conditions of formation of the Glamorgan rocks, the following field observations prove useful.

(a) Sillimanite occurs in the scarce pelitic rocks of the region, and also in some of the non-granitic bands in migmatite.
(b) Staurolite occurs in some of the pelitic rocks.
(c) Cordierite is found in some of the paragneisses.

Conditions of formation that could give rise to the appearance of these three important index minerals can be estimated by reference to an internally consistent body of experimental work due to Richardson and coworkers (Fig. 4). Within the stippled area of the diagram, sillimanite, staurolite and cordierite may all form. In other words, the stippled area represents limiting metamorphic conditions for the Glamorgan rocks. By inspection, the limits prove to be 4.5 to 7 kilobars total pressure, and (in round figures) 600 to 700 °C.

Discussion

In any exercise such as the foregoing, choice of experimental curves is obviously critical. In the case of staurolite and cordierite, no problem of choice arises, since Richardson's (1968) study is the only one to delimit clearly the field of mutual stability of the two minerals. However, with sillimanite almost an embarassment of choice exists. The work of Richardson et al. (1969) was used here because of its compatibility with Richardson's other work. Furthermore, it is consistent with Newton's reversals of the kyanite-sillimanite (1966b) and the kyanite-andalusite (1966a) reactions. The biggest problem arises with the sillimanite-andalusite boundary, which is an approximation at best. By comparison with other work (notably Weill 1966, Althaus 1967) it appears possible that the boundary may have been placed at too high a temperature. However, if we take the estimated uncertainty in the location of the triple point (Richardson et al. 1969), we can drawn an extreme, lower temperature sillimanite-andalusite curve consistent with Weill and Althaus. This curve would be approximately as shown by the lower dotted line in Fig. 4.

The temperature limits for the Glamorgan rocks now became 700 °C represented by the staurolite-quartz breakdown as before, and by the extreme triple point at about 580 °C. The upper pressure limit remains the same (7 kb.)—the intersection of the staurolite-quartz curve with the kyanite-sillimanite boundary. The lower pressure limit moves to 3.5 kb., the lowest pressure at which the Glamorgan assemblage staurolite-almandine-quartz is stable.

An important factor not yet explicitly considered is the equilibrium partial pressure of water (PE_{H_2O}). The reactions of Fig. 4 were determined under conditions where PE_{H_2O} was equal to P_{load}. Lowering PE_{H_2O} relative to P_{load} would have no effect on the solid-solid boundaries, but the staurolite-quartz reaction under such conditions could be expected to occur at lower temperatures than shown on Fig. 4. Thus 700 °C remains as an upper temperature limit for the metamorphism. In similar fashion the staurolite-almandine-quartz reaction will move down temperature in systems where PE_{H_2O} is less than P_{load}. This cannot result in a broadening of the pressure and temperature limits.

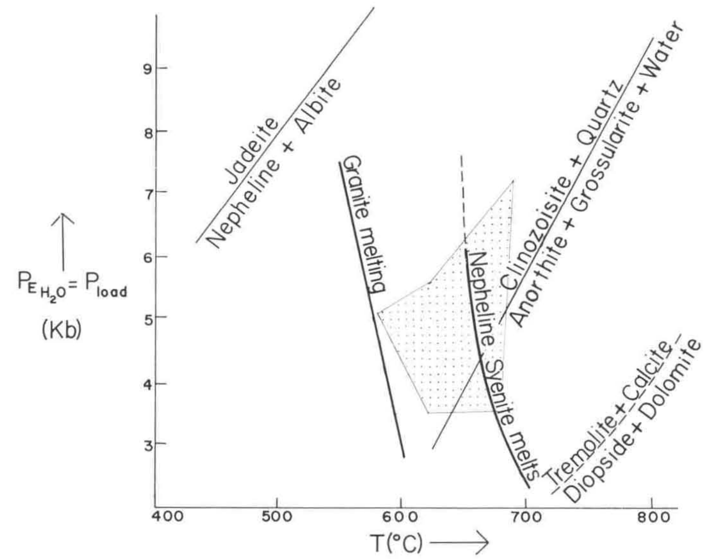

Fig. 5. Additional mineralogical equilibria pertinent to the Haliburton Highlands. The dotted area represents extremal conditions of formation for the Glamorgan rocks. Sources of reaction curves are as follows: Robertson et al. 1957 (Jadeite = Nepheline + Albite); Holdaway 1966 (Clinozoisite + Quartz = Anorthite + Grossularite + Water); Wyllie & Tuttle 1964 (minimum melting curve of granite in presence of Li_2O); Millhollen 1970 (minimum melting curve of nepheline syenite). The equilibrium Tremolite + Calcite = Diopside + Dolomite was calculated by the method of Turner 1967.

The effect of increasing the fugacity of oxygen to values greater than those appropriate to the QFM buffer used by Richardson will probably not increase the pressure-temperature limits of the field in which staurolite and cordierite may coexist (Richardson 1968, p. 485). The presence of MgO in staurolite will probably broaden this field (Richardson 1968, p. 484), but by an amount that is not as yet, predictable.

Some consequences of the proposed limits

The proposed limiting conditions of metamorphism for Glamorgan township have now been widened to 3.5 to 7 kilobars and 580 to 700 °C. If these are reasonable limits, certain predictions can be made by reference to other mineralogical equilibria (Fig. 5).

For example, clinozoisite may be used as a model for epidote, and Holdaway's (1966) breakdown curve for clinozoisite-quartz can be taken as an upper limit for this assemblage, since in the pressure range of interest here, it occurs at higher temperatures than either Newton's (1966c) version of the curve, or Merrin's (1962) curve for epidote- (33% iron component) quartz. From Fig. 5, it would appear likely, therefore, that epidote-quartz would be a stable assemblage in Glamorgan township. This is in fact, the case.

It would further be expected that anatectic granitic melts could have been produced in this area. Evidence that this happened has been presented elsewhere (Chesworth 1969). It might also be suggested that some (at least) of the nepheline-syenites in the region could have arisen by anatexis. A detailed study of this possibility remains to be made. Certainly the assemblage nepheline-albite is, and should be, found in the nepheline syenites of Glamorgan township (Fig. 5).

Finally, and using the method of Turner (1967), a curve for the reaction Tremolite$+$3 Calcite$=$4 Diopside$+$Dolomite$+CO_2+H_2O$ was calculated, no doubt with a large uncertainty. However, it can be used to suggest the possible stability of the assemblage calcite-diopside-tremolite in marbles in the area. Again, this fact is confirmed by field observation.

The conditions deduced therefore appear to be consistent with the mineralogy of Glamorgan township as a whole. They appear also to be consistent with conditions deduced for the rather similar metamorphic assemblages found in parts of the Pyrenees. Hess, for example, estimates pressures between 4.0 to 4.5 kilobars for the central Pyrenees.

Conclusion

Metamorphic assemblages in rocks from Glamorgan township in the Haliburton Highlands show resemblances with those of amphibolite facies rocks in both the Scottish Highlands and the Abukuma Plateau. This would indicate that metamorphism in this part of the Grenville province is of Miyashiro's (1961) low pressure intermediate type.

A metamorphic grid, set up on the basis of three field observations, suggests that conditions of formation fell within the load pressure range 3.5 to 7 kilobars, and the temperature range 580 to 700 °C. This spread of conditions is consistent with other field data for which there is equivalent experimental evidence.

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