

Geological problems in estimating mantle geothermal gradients

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Abstract

There are two major sets of problems in using mantle-derived ultramafic rocks as direct means of estimating mantle geothermal gradients. The first set includes the uncertainties in defining the appropriate reactions and determining their temperature and pressure dependence for a useful range of ultramafic compositions. Currently, no technique offers a fully determined or satisfactory answer, but preliminary estimates offer a useful base for geological interpretation. The second problem, involving the evaluation of the geological context of the sample, is illustrated by comparison of the estimated equilibration temperatures and pressures for the Mount Albert ultramafic intrusion and xenoliths from the San Quintin alkali olivine basalt volcanic field. The Mount Albert mass, which has been intruded as a solid diapir into crustal rocks, is composed of a core of undeformed rocks equilibrated at higher temperatures and pressures than a more intensely deformed suite of rocks adjacent to the margin. The distribution of temperature and pressure outlines a trajectory rather than the ambient geothermal gradient. Xenoliths from San Quintin show the same range of deformational types and a comparable distribution in temperature-pressure space to the Mount Albert rocks. In addition, the distribution of textural types with temperature is the same in both cases, suggesting a comparable mode of origin. The similarity of textures and mineral chemistry for all spinel peridotite xenoliths and massifs suggests caution in their use for estimating ambient geothermal gradients. Rather it appears that the temperatures and pressures record their mode of emplacement.

Introduction

One goal of geothermometry and geobarometry is the elucidation of the thermal structure of the upper mantle from samples derived from that region. Currently, there are two major classes of problems that confront an adequate solution to the problem. The first incorporates the calibration of temperature- and pressure-dependent reactions that are appropriate for the bulk compositions concerned. In this area there are a number of problems. Current research and theoretical analysis have shown that for mantle composition the reactions are dependent on both extensive and intensive variables, and the derived parameters are seldom fully determined. Thus experimental calibrations of important reactions which are most easily solved for simple systems seldom include the effect of other compositional variables. In contrast, theoretical analyses of chemical equilibria falter on the

inadequacy of the knowledge of the thermodynamic parameters. Coupled with the above are unresolved discrepancies between experimental results from different laboratories, and an over-dependence on unresolved assumptions in the theoretical analyses. The net result is an uncertain confidence in the absolute values of temperature and pressure now being determined, although it seems that the relative disposition of samples is more secure and forms a preliminary base for interpretive discussion.

The second class of problems includes a definitive knowledge of the geological history of the sample, which essentially requires a solution as to whether the sample records a static or dynamic environment. The former allows a simple statement of ambient parameters, while the latter points more to processes operative in the mantle. The abundant evidence from plate tectonics for a dynamic mantle makes it important to geologically resolve the two alternatives.

The paper examines the significance of two different suites of mantle rocks within the context of the

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above problems. The suites include samples from the Mount Albert ultramafic intrusion, an example of a high-temperature peridotite (MacGregor, 1962 and 1964; MacGregor and Basu, 1976), and ultramafic xenoliths enclosed in alkali olivine basalts from the San Quintin volcanic field, Baja California, Mexico (Basu, 1975). To what extent do either of the above samples inform us of the ambient conditions in the mantle?

General geology

Mount Albert ultramafic intrusion

The Mount Albert Intrusion (MacGregor and Basu, 1976) is composed of a mass of harzburgite intruded into the metavolcanic rocks of the Shick-shock Group. Gravity data (Tanner, 1958) indicate that it is part of a regional intrusion of ultramafic material along the spine of the Gaspé Peninsula, Quebec, and that locally it forms an essentially solid right circular cylinder with an approximately three-mile radius and extending for approximately 30,000 feet beneath the surface (Tanner, personal communication). Along the northern contact the intrusion is concordant with the structures in the country rocks and is bounded by a well-defined contact-metamorphic aureole, which increases in grade from the regional greenschist facies through epidote-amphibolite and almandine-amphibolite to pyroxene-granulite facies at the contact. The southern boundary is a fault which has probably controlled the initial intrusion and along which post-intrusion movement is evident. Within the intrusion the structure is marked by layers of dunite and harzburgite and occasionally pyroxenite, defined solely by the varying proportions of orthopyroxene from layer to layer. The rock textures may be described with increasing degree of deformation from coarse-granular through porphyroclastic to tabular and equigranular mosaic (Mercier and Nicolas, 1975; MacGregor and Basu, 1976). The geographic distribution of the textural types indicates that the rocks become progressively more deformed from the core to the margin of the intrusion (MacGregor and Basu, 1976). The deformation cross-cuts the layering and is interpreted as a secondary feature superimposed on the layering during intrusion. The layering is thought to be a primary feature inherited from a previous history in the mantle.

Chemical variations in both whole rocks and their constituent minerals are crudely concentric with the contacts, subparallel to the variation in degree of

deformation, and cross-cut the primary layering (MacGregor and Basu, 1976). The harzburgites are most highly serpentinized near the intrusion boundaries and become less serpentinized towards the core.

San Quintin xenoliths

The San Quintin volcanic field, consisting of a dozen late Pleistocene to Recent volcanic cones and their associated alkali basaltic lava flows, is located approximately 260 km south of the United States-Mexico border on the west coast of Baja California. Mafic and ultramafic xenoliths occur abundantly, mostly in the northern part of the volcanic field, in both cones and flows. The xenoliths are predominantly lherzolites with some less abundant dunites, pyroxenites, gabbros, and green-spinel-bearing granulites.

Deformed textures comparable to those of Mercier and Nicolas (1975) and those found in the Mount Albert ultramafic intrusion occur (Basu, 1975). However, plastically-deformed diopside and aluminous spinel, in addition to the olivine and orthopyroxene porphyroclasts, are a conspicuous feature of the xenoliths.

Estimation of intensive parameters

Introduction

The chemistry of the coexisting phases for a suite of rocks from both localities has been analyzed with an ARL electron microprobe. For all elements, oxide standards have been used with the Bence and Albee (1968) correction procedure. Within the limits of X-ray statistics, the chemistry of the Mount Albert phases appears to be essentially homogeneous. The San Quintin xenoliths are comparably homogeneous except for a few samples where values for Al_2O_3 and Cr_2O_3 may vary by as much as 10 percent. The variations are generally related to exsolution phenomena rather than any systematics with reference to contamination by the host magma. Introduction of errors from analytical uncertainties are small by comparison with the ambiguities associated with other problems discussed in the text.

The following partial reactions have been used to obtain preliminary estimates of temperature and pressure.

Geothermometry

Partition of Ca and Mg between coexisting pyroxenes. The mutual solubility of diopside and enstatite has been determined by a number of experimen-

talists (Boyd and Schairer, 1964; Davis and Boyd, 1966; Warner and Luth, 1974; Nehru and Wyllie, 1974; Mori and Green, 1975). Each defines slightly different solvi, although the discrepancies are small for temperatures less than 1100°C. Similarly, below 1100°C the diopside solvus is essentially independent of pressure up to about 30 kilobars. Above 1200°C the diopside solvus widens with increasing pressure, although the pressure effect is relatively small. In contrast, the enstatite solvus is significantly dependent on pressure (Hensen, 1973), and its steep slope can cause serious error if pressure is ignored. A similar result is shown empirically by coexisting pyroxenes from xenoliths in kimberlite pipes (Boyd and Nixon, 1973). Although absolute estimates of temperature using the diopside solvus are uncertain for temperatures less than 1200°C, one may obtain a valid estimate of the relative temperatures within a suite of samples.

The pyroxene solvus is also dependent on composition. In particular for both the ortho- and clinopyroxene the mutual solubility is increased with increasing Fe^{2+} content, while increasing Al results in a widening of the diopside solvus, but the enstatite solvus is essentially unaffected (Boyd, 1970). Wood and Banno (1973) have proposed a theoretical correction for the effect of varying Fe^{2+} , while Boyd (1973) points out that use of $[Ca/Ca+Mg+Fe^{2+}]_{diopside}$ instead of $[Ca/Ca+Mg]_{diopside}$ is an effective method to account for variation in Fe^{2+} content for Fe^{2+} -poor compositions. The effect of varying Al content is not so easily accounted for, and although demonstrated, has been essentially ignored in all previous estimates of temperature.

The above discussion points to unresolved problems in the use of the pyroxene geothermometer, particularly with respect to the absolute values determined. However, for temperatures less than 1200°C where the pressure effect is slight, and by use of Wood and Banno's (1973) or Boyd's (1973) correction for Fe^{2+} content, one may obtain useful estimates of the relative temperatures within a suite of samples.

In the present exercise, temperatures have been estimated using the $[Ca/Ca+Mg+Fe]_{diopside}$ ratio (Davis and Boyd, 1966) (Fig. 1a), and using a linear assumption to Boyd's (1970) data for the effect of Al on the diopside solvus, a second value is estimated (Fig. 1b). The second estimate represents a first approximation to a solution of the problem in examining a suite of pyroxenes of variable Al_2O_3 content.

Partition of Mg and Fe^{2+} between coexisting

phases. A number of authors have examined the temperature dependence of Mg- Fe^{2+} exchange between coexisting phases. Two groups of reactions are important; firstly, reactions between silicates and oxides (Irvine, 1965; Jackson, 1969; Powell and Powell, 1974), and secondly between coexisting silicates (Ramberg and DeVore, 1951; Bartholomé, 1962; Kretz, 1963; Medaris, 1969). The above type of reactions are critically dependent on the ambient oxygen fugacity (Osborn, 1959; Speidel and Osborn, 1967). In the case of the Mount Albert intrusion, a parameter proportional to the oxygen fugacity (Irvine, 1965) illustrates that the rocks have equilibrated at lower oxygen fugacities in the core than the margins (MacGregor and Basu, 1976). Similarly, the Mg- Fe^{2+} partition between olivine and orthopyroxene, shown to be temperature independent (Medaris, 1969) but oxygen fugacity dependent (Speidel and Osborn, 1967), shows a pattern of variation comparable to Irvine's (1965) parameter (MacGregor and Basu, 1976). Further, the use of coexisting pyroxenes (Kretz, 1963) to estimate relative temperatures gives the anomalous result of a low-temperature core surrounded by a high-temperature margin showing a further effect of the variable oxygen fugacity.

For all the schemes involving Mg- Fe^{2+} partitioning, Irvine (1965) and Jackson's (1969) analyses are the only ones which attempt to incorporate the oxygen fugacity as a variable. Jackson's (1969) geothermometer has been evaluated for the Mount Albert rocks. Despite the fact that small errors in the thermodynamic parameters of Jackson's (1969) expression introduce large absolute errors (Loney *et al.*, 1971; Medaris, 1972), it appears that the relative values are still valid (Fig. 1c).

Partition of Cr-Al between coexisting pyroxenes. Mysen and Boettcher (1975) have derived an empirical, pressure-independent relationship between temperature and the distribution of Cr and Al for coexisting pyroxenes for a range of ultramafic compositions. Application to the present case indicates a range of temperatures from 873°C to 1245°C for the San Quintin rocks, and a temperature distribution shown in Figure 1d for the Mount Albert case.

Comparison of temperature estimates. Figures 1a, b, c, and d for the Mount Albert intrusion show the geographic distribution of temperatures determined from the diopside solvus (Davis and Boyd, 1966), Al_2O_3 -corrected value to the diopside solvus, Jackson's (1969) olivine-spinel geothermometer, and Mysen and Boettcher's (1975) technique, respectively. The geographic variation of temperature illustrates a

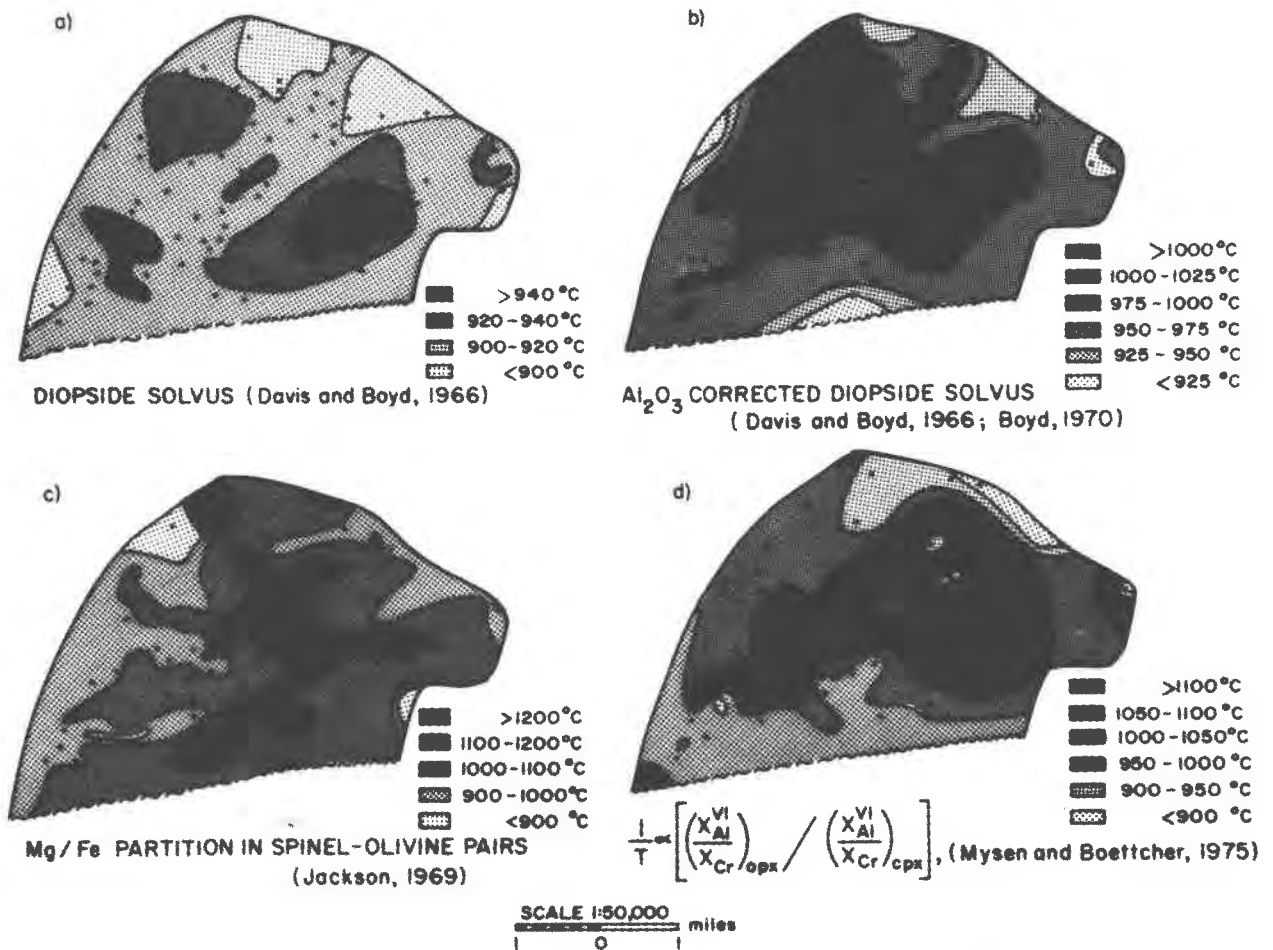


FIG. 1. Geographic variation of temperature in the Mount Albert intrusion using the following geothermometers: (a) diopside solvus (Davis and Boyd, 1966), (b) diopside solvus (Davis and Boyd, 1966) with correction for Al_2O_3 content of diopside (Boyd, 1970), (c) Mg/Fe partition in coexisting spinels and olivine (Jackson, 1969), and, (d) Cr/Al partition in coexisting pyroxenes (Mysen and Boettcher, 1975).

higher-temperature core surrounded by a lower-temperature margin. The range of temperature varies for each temperature estimate, and the location of the central region of higher temperatures is shifted to the north for the Al_2O_3 -corrected diopside solvus and Mysen and Boettcher's temperature estimates. The latter effect correlates with variations in the contact-metamorphic aureole, which shows that maximum temperatures were reached at the northern tip of the intrusion. The temperatures determined from the diopside solvus are too low to account for the observed contact aureole. Correction for the Al_2O_3 content of the diopsides gives more plausible results but is suspect because of the untested initial assumptions. Jackson's technique has documented problems. It is thus felt that Mysen and Boettcher's technique,

which gives geologically plausible data, yields the best temperature estimates, since this method empirically approximates natural ultramafic compositions for a pressure-independent partition.

In the case of the San Quintin samples, there is little correspondence between the temperatures estimated by each technique. As with Mount Albert, the temperatures for the diopside solvus are much lower in absolute range and value. Unlike the Mount Albert example, the use of Jackson's (1969) geothermometer for the San Quintin rocks gives geologically impossible answers. The problem is particularly noticeable for the Al_2O_3 -rich compositions. The Al_2O_3 -corrected values to the diopside solvus give more plausible temperatures and show relative temperature distributions from sample to sample equivalent to

Mysen and Boettcher's technique. Following the example of the Mount Albert case, Mysen and Boettcher's temperature estimates are preferred.

Geobarometry

The only pressure-dependent reaction that is appropriate for ultramafic compositions and has been experimentally defined is the pressure-dependence of Al_2O_3 in pyroxenes associated with an aluminous phase (MacGregor, 1974). Current problems with the pyroxene geobarometer are as follows. There is contradictory experimental data on the slopes of the Al_2O_3 isopleths in the spinel stability field (MacGregor, 1974; Anastasiou and Seifert, 1972). Similarly, theoretical analysis (Wood, 1976) suggests that the Al_2O_3 isopleths are significantly less pressure-dependent than those shown by the experimental data (MacGregor, 1974). In the absence of a resolution to the above problems, both MacGregor's (1974) and Wood's (1975) data were used for our samples. Wood's (1976) method gave geologically unreasonable results or situations for which no solution could be found. Results using MacGregor's (1974) method are shown in Figure 2. Further problems in the use of MacGregor's (1974) data are the unknown data effect for other components. Wood and Banno (1973) have derived a successful correction for Fe and Ca in the garnet stability field, and using the same approach, Mercier and Carter (1975) suggest a correction for rocks in the spinel stability field. The neglect of the Cr content as an additional variable is also important and empirically demonstrated in Figure 2, where the $\text{Cr}/(\text{Cr}+\text{Al})$ ratio of the coexisting spinel may be contoured on a temperature-pressure plot derived from the three-component system (MacGregor, 1974). The estimated pressure is significantly more dependent on the $\text{Cr}/(\text{Cr}+\text{Al})$ ratio than variations in Ca or Fe. In order to mollify the effect of Cr, Figure 3 summarized the data for which the effective "Al" content has been summed as $(\text{Cr}+\text{Al}-\text{Na})/2$. A technique equivalent to that suggested by Mercier and Carter (1975) is used for calculation of the octahedral site occupancy of the trivalent ions. The estimates of pressure are also dependent on temperature estimates and thus include the ambiguities discussed in the calculation of that variable. In the present case, we have used Mysen and Boettcher's (1975) temperature values for calculating the pressures of equilibration in the Mount Albert and San Quintin rocks (Fig. 2 and 3).

The geographic variation of pressure using Mysen and Boettcher's (1975) technique and MacGregor's

(1974) data normalized to the 20 percent $[\text{Cr}/(\text{Cr}+\text{Al})]$ spinel isopleth (Fig. 2) shows a central core of higher pressures surrounded by a lower-pressure margin (Fig. 4).

Petrogenesis

Intensive parameters

Estimates of the intensive parameters for the Mount Albert intrusion may be examined in two contexts. The first is their geographic variation. Figures 1d and 4 illustrate that the intrusion is composed of rocks that have equilibrated at higher temperatures and pressures in the core than in the margins. Secondly, on a temperature-pressure plot (Figs. 2 and 3), the distribution of samples shows an approximately linear trend. Since the wide range of temperatures and pressures is observed at a single stratigraphic level, it is apparent that the "trend" does not represent a geothermal gradient but rather a "trajectory" marking the path of the intrusion to the surface as an essentially solid rheid. Estimated maximum temperatures and pressures for the contact-metamorphic rocks (Fig. 3) plot on an extension of the "trajectory" and represent the final location of the intrusion.

The San Quintin rocks (Fig. 3) have a temperature-pressure distribution comparable to the Mount Albert intrusion, which raises the question as to their significance in defining ambient environmental conditions in a static mantle.

Textural relationships

The distribution of textures in the Mount Albert intrusion shows a close correlation with the estimated temperatures and pressures (Figs. 1d and 3). In general the higher temperature and pressure rocks of the core are the least deformed, with deformation increasing progressively to the marginal rocks equilibrated at lower temperature and pressure. The San Quintin rocks have the same variety of textures, but do not allow a geographic evaluation. However, the two suites may be compared on the basis of textural variation as a function of temperature (Fig. 5). For the Mount Albert intrusion (Fig. 5a), there is a systematic variation of the textural distribution such that the rocks are progressively more deformed with lower temperature. The San Quintin rocks (Fig. 5b) show a comparable but less well-defined variation, suggesting that with increasing temperature and depth, the distribution of textures becomes progressively less deformed. The more diffuse distribution of

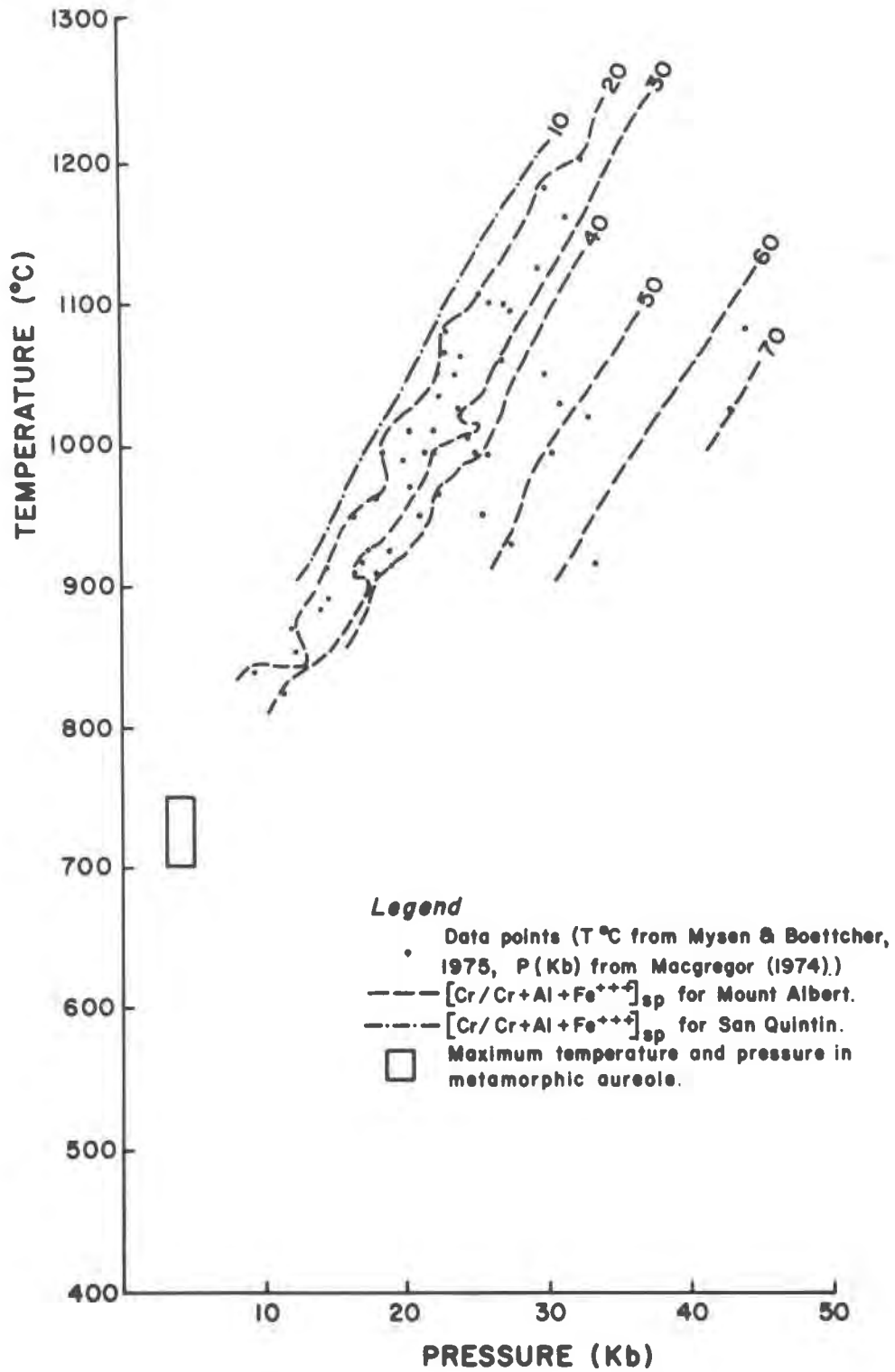


FIG. 2. Estimates of temperature and pressure for the Mount Albert and San Quintin rocks ($T^{\circ}\text{C}$ from Mysen and Boettcher, 1975; P (kbar) from MacGregor, 1974). Counters are isopleths of $[\text{Cr}/\text{Cr}+\text{Al}]_{\text{spinel}}$ coexisting with the orthopyroxene.

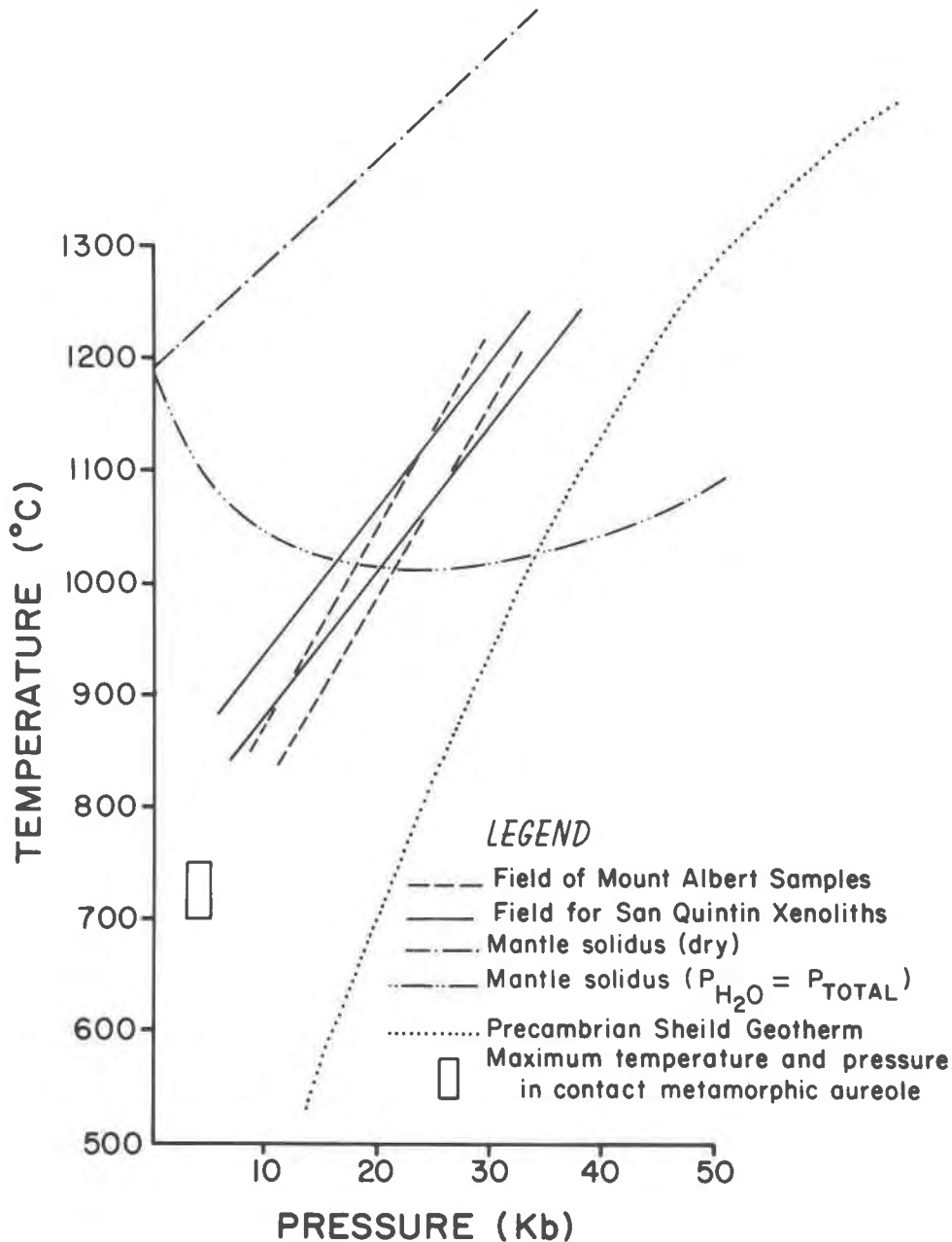


FIG. 3. Estimates of temperature and pressure for the Mount Albert and San Quintin rocks ($T^{\circ}\text{C}$ from Mysen and Boettcher, 1975; $P(\text{kbar})$ from MacGregor, 1974, with $\text{Cr} + \text{Al} - \text{Na}/2 = \text{octahedral Al}$).

the San Quintin samples may be understood if one considers that the Mount Albert samples come from a single stratigraphic level, while the San Quintin rocks sample a larger and more complex vertical section.

Interpretation

It is apparent that the temperature-pressure plot of the Mount Albert samples does not represent a geo-

thermal gradient, but rather the path of the Mount Albert diapir to the surface. In a comparable way, the significance of the San Quintin data (Fig. 3) may be questioned as to whether the pressure-temperature trends represent static or dynamic mantle environments. The equivalence of the textural varieties, and similar distribution in both cases would favor a dynamic interpretation, suggesting that the San Quintin rocks are samples of a mantle diapir, comparable to

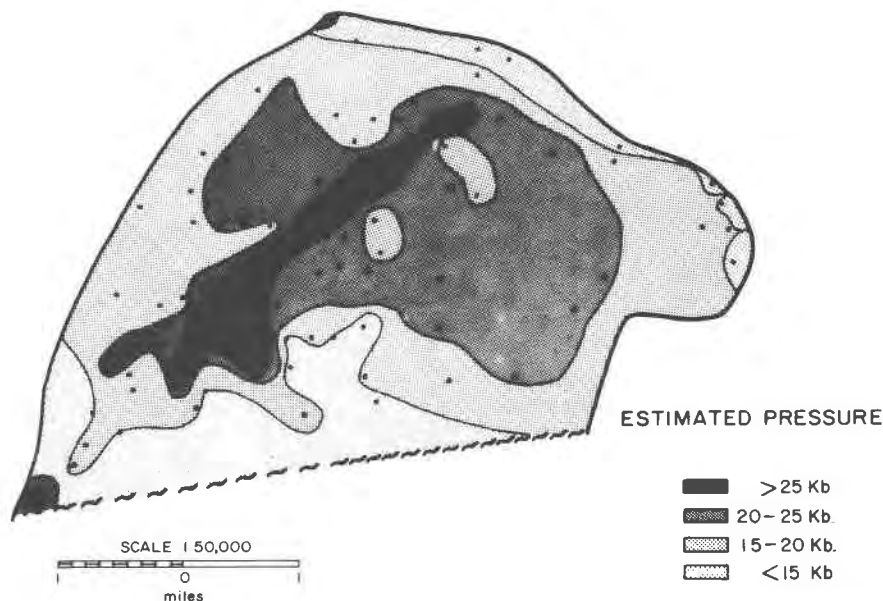


FIG. 4. Geographic variation of pressure in the Mount Albert intrusion ($T^{\circ}\text{C}$ from Mysen and Boettcher, 1975; $P(\text{kbar})$ from MacGregor, 1974, normalized to 20 percent $[\text{Cr}/\text{Cr}+\text{Al}]_{\text{spinel}}$ isopleth of Fig. 7).

the Mount Albert intrusion, but sampled at greater depths and over a larger vertical range. Thus in both cases the rocks represent samples of mantle material diapirically rising to the surface as an essentially solid rheid. It is interpreted that the environmental conditions record the active process of diapiric intrusion rather than a reequilibration to the ambient conditions of the environment into which they have been thrust. The trends in the temperature-pressure plots should therefore be interpreted as paths or trajectories rather than geothermal gradients.

Discussion

The introduction focussed on two major problems in estimating ambient mantle geothermal gradients. The first involves the estimation of the intensive parameters and the second an evaluation of the geological context. It is apparent that the techniques for estimating temperatures and pressures in spinel peridotites are still primitive. Essentially there are more variables than defined equations, and at present unsatisfactory assumptions lead to temporary but limited answers. However, despite the problems, there is still a framework of useful relative information that allows the use of the intensive parameters to evaluate the geological context of the samples.

The geological samples chosen, one from an ultramafic massif and the second a suite of xenoliths from alkali olivine basalts, cover the two major occur-

rences of ultramafic rocks which appear to be the best samples of mantle material. The correlation of the textures and textural distribution with respect to temperature and pressure suggests that the samples record dynamic events in the mantle. It appears that the textural varieties noted in our study are a general feature of peridotite massifs (Avé Lallemant, 1967; Darot, 1973; Nicolas *et al.*, 1971 and 1972) and xenolith suites from alkali olivine basalt magmas (Mercier and Nicolas, 1975), leading to the more general interpretation that all mantle samples from the above two environments record dynamic phenomena and should not be used as an expression of the ambient geothermal gradient. The ambient geothermal gradient should always be less steep than that shown by the "trajectories." The geologic association of spinel peridotite xenoliths with alkali olivine basalts is almost identical (Forbes and Kuno, 1964), leading to a further suggestion that the generation of the basalts may also be tied to the diapiric process.

An important observation is that the paths are distinctly nonadiabatic and contrast with other diapiric models (Oxburgh and Turcotte, 1968; Turcotte and Oxburgh, 1972). The observation seems adequate for small localized diapirs like Mount Albert and San Quintin where the heat losses may be large (Green and Guegen, 1974), but, in areas of extensive mantle upwelling such as those hypothesized for oceanic ridges, one may expect the paths to more closely

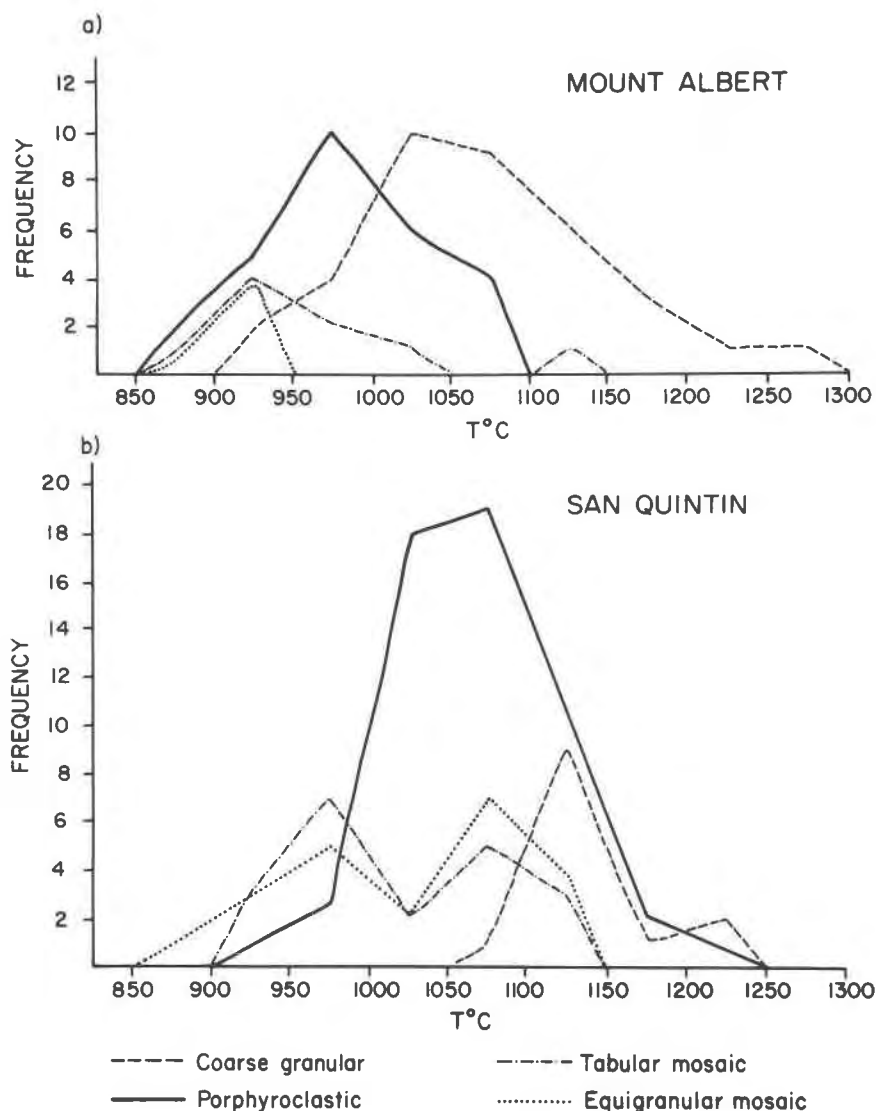


FIG. 5. Distribution of textural types as function of temperature: (a) Mount Albert intrusion, (b) San Quintin xenoliths.

approximate the mantle adiabat. However, the range of mineral chemistry in sections of the oceanic crust, as represented by the ultramafic portions of ophiolite complexes, are comparable to the above two examples, suggesting comparable trajectories, *i.e.* non-adiabatic. Thus analytical models of oceanic ridges (Slater and Francheteau, 1970; Forsyth and Press, 1971) may be using anomalously high temperatures following from an incorrect assumption of an adiabatic path. Perhaps a preferred model should incorporate a succession of smaller nonadiabatic diapiric-like intrusions into the axial regions of mid-oceanic ridges.

The advent of plate tectonics has emphasized the

dynamic nature of the upper mantle. New data from mantle samples show evidence of the dynamic processes involved, and confirm the hypotheses supporting large-scale diapiric uprise of mantle material as a major driving mechanism. The data also urge caution in the estimating of geothermal gradients. There must be a careful distinction between samples recording a dynamic process, such as diapirism, from those representing a static or passive mantle.

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