METAMORPHISM AND CRUSTAL DISPLACEMENTS: NEW INSIGHTS

by

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Focussing on research currently underway in metamorphic petrology, the author develops a dramatic picture of the path of metamorphism, uplift and erosion in the core of one of the world's younger orogens, and underlines the importance of this type of research to interpretation of the driving forces in core zones of other mountain belts.

Metamorphic Petrology: Past and Present

When Miyashiro (1961) pointed out the existence of paired metamorphic belts in orogenic regions, he presented perhaps the most important advance in metamorphic petrology in the last 20 years. Belts of rocks which were subjected to metamorphism under conditions of low geothermal gradient typically occur on the oceanic side of belts of rocks which were metamorphosed under conditions of high geothermal gradient.

The recognition of paired metamorphic belts was a natural result of the accumulation of descriptive data in several regions of the world, the recognition that the three polymorphs of Al_2SiO_5 could occur at a point in pressure (P) - temperature (T) space which was attainable within the earth's crust, and the deduction (based on the relatively high density of the phases involved) that glaucophane schists result from metamorphism at relatively high pressures. Paired metamorphic belts have since been interpreted in the context of the plate tectonic theory (Miyashiro, 1973, for example).

During the last decade or so, research in metamorphic petrology has generally emphasized the establishment of precise limits of P and T of metamorphism at particular localities. This has been made possible by a steady increase in the amount of published experimental data defining the P and T fields of stability of mineral associations (assemblages) similar in composition to those occurring naturally.

Because it is not practicable in most experiments to take into account the variations in composition of the naturally occurring minerals, thermodynamic models are used to correct the experimentally determined phase boundaries to positions appropriate to the compositions of the phases actually observed. The availability of the electron microprobe has made it possible for metamorphic petrologists to routinely, quickly and accurately determine the composition of any mineral, indeed, any portion of a mineral, in its natural textural setting as viewed in thinsection.

Nevertheless, in establishing accurate limits on P and T, difficult problems are encountered. Some minerals are particularly resistant to changing composition through self-diffusion, or to being consumed in a reaction when P-T conditions change: garnet is a notable example. Reaction curves for some important systems have been exceptionally difficult to reproduce in the laboratory because of sluggishness in reaction rates. For example, the locations of the phase boundaries between the phases kyanite, andalusite and sillimanite in the Al_2SiO_5 system are still debated.

Fluid inclusion studies have demonstrated the importance of salts in mixed $CO_2 + H_2O$ fluids, but experimentalists are still generally constrained to work with fluids consisting of only one or two components. The composition of fluid phases in nature, therefore, is not at all easily determined.

Each of these problems must be addressed to obtain reliable estimates of P and T from metamorphic assemblages. Understanding them can furthermore lead to other insights into geological processes. For example, pseudomorphs of one Al_2SiO_5 polymorph after another are commonly used to define the path of metamorphism in P-T space. In another example, the different temperatures at which minerals become closed systems with respect to retaining decay products or decay damage result in part from differing bulk physical properties of minerals. Consequently, measuring the different apparent ages in different minerals at single localities can lead to determining the rate of cooling of rocks. In regional metamorphic terranes, knowing the rate of cooling allows one to calculate uplift and denudation rates (Clark and Jagar, 1969). Another tool for estimating cooling rates will be available when diffusion rates of cations in minerals such as garnet are determined.

Current research in metamorphic petrology is turning increasingly towards using P and T information in broader geological contexts. Continuing efforts at establishing whether or not there have been changes through time of the average geothermal gradient in the continental crust (Saggerson, 1973, for example) serve to illustrate this. There is at least a qualitative trend from high to low apparent geothermal gradients: Archean metamorphic rocks typically contain mineral assemblages characteristic of low P at high T, whereas Phanerozoic metamorphic rocks generally contain mineral assemblages characteristic of higher pressures. Also, several authors have noted that glaucophane schists are virtually unknown in Precambrian terranes, suggesting that this may in part be due to a decrease of the average geothermal gradient with time.

Mountains of granite gneiss and migmatite in Skeena River Valley, B.C., Canada

Tectonic interpretations have resulted from observations of metamorphic assemblages. Three examples are illustrated by P-T paths A, B, and C in Figure 1. Le Fort (1975) has correlated inverted metamorphic isograds with the Main Central Thrust (MCT) of the Himalayan mountain ranges and used this result in concluding that the MCT is a major zone of underthrusting which has juxtaposed relatively hot crust over cold crust. The thermal response to this event has apparently been recorded in the metamorphic assemblages.

Figure 1. Pressure - Temperature paths expected for rocks which have (A) increased in pressure through addition of load, (B) increased in pressure and temperature by subduction, and (C) been rapidly uplifted, with load having been removed by erosion. Path A is schematic but may be inferred from Le Fort (1975); path B is taken from Ernst (1977); path C is taken from Figure 4 of this paper.

A similar study has recently been made by Crawford (1978) on a portion of the Appalachian Piedmont in eastern Pennsylvania. Low P metamorphic assemblages there have been overprinted by higher P metamorphic assemblages without any recorded intervening temperature changes. She interprets this as resulting from an abrupt increase of load pressure by overthrusting - a reasonable hypothesis in the broader geological context of the area. A schematic P-T path similar to the ones deduced by Le Fort and Crawford is shown as Path A, Figure 1.

Assemblages recording increase of P at low T, followed by increase of T, have been described in several areas and interpreted as resulting from thermal equilibration of cold crustal rock subducted into lower crust or mantle. Such paths are similar to Path B, Figure 1. Examples from California, Japan, and Italy have been summarized by Ernst (1977).

An example of reduction of P initially without much cooling (Path C, Fig. 1) in the Massif Central (France) has been reviewed by Albarède (1976). Recently obtained data from the Coast Mountains of British Columbia (Canada) suggest a similar phenomenon. Reduction of first P and later T in the British Columbia example is recorded by combining observations on the metamorphic mineral assemblages with information on the physical properties and compositions of fluid inclusions and "ages" determined by whole rock and mineral dating. From these results one may deduce an episode of

relatively rapid uplift which brought hot metamorphic rock to within a few kilometers of the earth's surface before it had time to cool appreciably.

Documentation for deducing Path C (Fig. 1) in the example from the Coast Mountains of British Columbia (B.C.) follows. It should give the reader an understanding of how available petrologic data may be used in deducing P-T paths, and how these data can be combined with age determinations to add the third dimension of time.

Metamorphically Recorded Uplift: B.C., Canada

Path C on Figure 1 is based on occurrences from a locality geographically near the center (both longitudinally and transversely) of the B.C. Coast Mountains crystalline belt (Fig. 2). The general geology summarized in Figure 2 is modified slightly from reconnaissance geological reports by Hutchison (1967, 1970) and Roddick (1970). Much of the following data comes from unpublished theses presented at Princeton University, U.S.A. by Lappin, Kenah, Hampson and Selverstone. Other data are in papers by Crawford, et al. (1979), Hollister and Burruss (1976), Hollister (1975) and Hollister (1977).

Figure 3 shows the phase equilibria pertaining to mineral associations found in rocks of several compositions associated with migmatite within region A, Figure 2. The curves have been corrected from relevant experimental data to take account of the compositions of the phases, and the probable partial pressure of H_2O , in each of the associations. The shaded region (Fig. 3) encompasses the most probable limits of P and T, and is the final recorded P and T for mineral equilibration.

The most diagnostic assemblage is cordierite - garnet - biotite - quartz - plagioclase - orthoclase - ilmenite - graphite - sillimanite. Cordierite occurs as rims on garnet, separating the garnet from nearby sillimanite. Quartz, biotite, and sillimanite do not occur in mutual contact, and orthoclase is a trace interstitial component. The compositions of the coexisting garnet and cordierite at the estimated partial

Figure 2. Location of plutons and distribution of migmatite near Prince Rupert in the Coast Mountains of British Columbia, Canada (after Hutchison, 1967, 1970 and Roddick, 1970). Metamorphic conditions have been determined at A and B.

Figure 3. Phase equilibria pertaining to locality A, Figure 2. Abbreviations are: andalusite (And), kyanite (Ky), sillimanite (Sill), quartz (Q), almandine garnet (Gar), staurolite (Staur), annite (Fe-Bio), ferroan cordierite (Fe-Cord), cordierite with $\text{Fe} = 0.41$ (Cord (Fe₄₁)), anthophyllite (Anth), and enstatite (En). Shaded area encloses limits of last recorded metamorphic pressures and temperatures at locality A. Curves (1) and (3) adopted from Holdaway and Lee (1977); (2) from Ghent, et al. (1979); (4) from Ganguly (1972); (5) from Richardson (1968); (6) from Greenwood (1963); (7) from Egger (1972); (8) from Holdaway (1971).

pressure of H_2O ($P_{\text{H}_2\text{O}} = 0.5 P_{\text{total}}$) were used to locate curve 1 on Figure 3, based on the studies of Holdaway and Lee (1977). Curve 2 uses the compositions of plagioclase and garnet in this assemblage and is based on the work of Ghent, et al. (1979).

The absence of mutual contacts between quartz, biotite, and sillimanite imply that final equilibration of the rocks occurred on the high T side of reaction 3; the cordierite rims on garnet imply crossing reaction 1 from high P to lower P (Hollister, 1977). The pressure error from all sources determined at any T on any of the reaction lines is about ± 1 kb. Thus, the pressures along the segments of the garnet-plagioclase and the garnet-cordierite curves, within the shaded P-T region on Figure 3, are within the outer limits of this error range.

Temperature is constrained by curves 4, 5 and 6. Quartz-free assemblages containing staurolite and/or the reaction products hercynite plus sillimanite (and garnet) imply temperatures approached 775°C (on curve 4 at 4 kb), but persistence of the staurolite relics in quartz-free assemblages suggests the temperatures exceeded those on reaction 5. Widespread occurrence of hypersthene + quartz implies temperatures exceeded those of reaction 6. The absence of the high P assemblage garnet + clinopyroxene + hypersthene places P-T conditions within the low-pressure granulite facies, consistent with the P and T estimate of the shaded area on Figure 3.

The widespread occurrence of migmatite, with a leucosome predominantly of quartz + plagioclase + minor amounts of biotite, suggests partial melting. An appropriate partial melting curve (curve 7), which is consistent with the metamorphic assemblage data, is drawn for reference; it is the solidus for andesite at $P_{\text{H}_2\text{O}} = 0.5 P_{\text{total}}$ as determined by Egger (1972).

Kyanite occurs as inclusions in garnet in some sillimanite-bearing rocks collected from locality A, implying that these rocks were once in the kyanite stability field. Because the textures of the cordierite-bearing rocks at locality A suggest they were experiencing a release of P at high T when final P-T conditions were recorded, it is reasonable to suggest that this decompression had begun from a P within the kyanite field some 4-5 kb higher, as illustrated in Figure 4. Support for such a trajectory comes from the fact that at a lower grade near Prince Rupert (B, Figure 2) metamorphic conditions have been deduced by Crawford, et al. (1979) to be in region B on Figure 4. The suggestion implied by the information plotted on Figure 4 is that the migmatitic rocks in locality A were at metamorphic conditions reflected at B prior to subsequent heating, which resulted in partial melting followed by decompression.

A whole-rock Rb/Sr isochron on migmatite fractions near region A gives an age of 51.5 ± 2 Ma (Armstrong and Runkle,

Flow-like folds in migmatite approximately 50 km E of Prince Rupert, B.C., Canada.

1979). This is presumed to be the time when the melt solidified which, from Figure 3, would be when the rocks were at 4 kb and 775°C.

The subsequent P-T path is constrained by the occurrence of small fluid inclusions containing immiscible mixtures of CO₂ and H₂O. It has shown that these inclusions have been trapped in the rocks at temperatures above 380°C (Hollister, et al., 1979). The rocks of region A must have crossed the isochore (Figure 4) for the lowest density CO₂ + H₂O inclusions at a temperature above 380°C. The fact that most of the inclusions which contain mixed component fluids have characteristic shapes indicative of autodecrepitation (Lemlein and Kliya, 1954) suggests that the rocks containing these inclusions probably crossed the isochores from pressures at least 850 bars above the P at decrepitation (Hollister, et al., 1979; Burruss and Hollister, 1979; Leroy, 1979).

The presence of relatively low density ($\rho = 0.75\text{g/cc}$), pure CO₂ inclusions in region A constrains the rocks containing these inclusions to having crossed an isochore nearly coincident with the 66°C/km line (Fig. 4), probably at a temperature below 380°C.

A continuous path of uplift combining the petrologic information with that from the fluid inclusions is illustrated in Figure 4 for region A. There are two time constraints along this curve: the first when melt presumably crystallized at $51.5 \pm 2\text{ Ma}$ (Runkle and Armstrong, 1979), and the second, based on the Rb-Sr and K-Ar "ages" of biotite and the fission track "age" of sphene, indicating that the rocks had cooled to 300°C by 47 Ma (Harrison, et al., 1979). According to the isochore for low density, pure CO₂ shown in Figure 4, the rocks would have been at about 1 kb when they had cooled to 300°C.

Figure 4. Inferred uplift path of locality A, and metamorphic conditions recorded at A and B, Figure 2. Isochores are for densities of fluid inclusions with $X_{\text{CO}_2} = 0.6$ and $X_{\text{CO}_2} = 1.0$; the rocks from area A, which contain secondary fluid inclusions whose isochores are plotted, must have crossed these isochores at some stage in the uplift history of area A; the broken arrows illustrate the interpreted total uplift path. The dates when these rocks were at 775°C and 300°C are from Armstrong and Runkle (1979) and Harrison, et al. (1979).

The rate of uplift implied by these data during the last stages of uplift is 2-3 mm/yr, which is within reason according to the models developed by Albarède (1976) to interpret uplift recorded by the metamorphic assemblages in the Massif Central. The average rate of uplift prior to 52 Ma must have been more rapid, perhaps as high as 8 mm/yr, to achieve such a high geothermal gradient at 52 Ma (Albarède, 1976).

Geological Interpretation of Results

One possible interpretation for the information plotted in Figure 5 is that locality A was stripped of 10-20 km of overburden during the early Tertiary. Assuming an average thickness of 10 km was eroded from the region shown in

Figure 5, about $3 \times 10^5 \text{ km}^3$ of clastic sediment should have been deposited during this time offshore from the central Coast Mountains of B.C. (Fig. 5). This region covers the approximate area over which high grade metamorphic and migmatitic rocks are widespread and which yield K-Ar ages in the Eocene.

East of the Coast Mountains only about $5 \times 10^3 \text{ km}^3$ of sediments of early Tertiary age occur in B.C. (Fig. 5), and most of these were probably derived from the mountains to their east. West of the Coast Mountains, on Queen Charlotte

Island and in Queen Charlotte Sound, about $5 \times 10^4 \text{ km}^3$ of sediment may be estimated based on seismic and drill surveys; another $5 \times 10^4 \text{ km}^3$ are in Tofino Basin. Most of these sediments, however, are known to be post-Miocene in age (Drummond, 1978). The ocean floor west of Queen Charlotte Islands is younger than Eocene; indeed, only post-Miocene sediments have been reported in drilling on the northeastern Pacific Ocean floor (Musich and Wesler, 1973).

Stacey (1975) infers from a gravity study that $2-6 \times 10^4 \text{ km}^3$ of sediment of early Tertiary age may be under a widespread Eocene rhyolite in Queen Charlotte Sound. Tiffin, et al. (1972) suggest some early Tertiary sediment in Tofino Basin.

Thus, perhaps $1 \times 10^5 \text{ km}^3$ at most of early Tertiary sediment can be accounted for in the vicinity of the uplift area of the Coast Mountains, although half that much would be a more realistic estimate.

According to Cooper, et al. (1976), a spreading ridge (Fig. 5) migrated to its present position off northern Vancouver Island from the coast of southern Alaska between 70 Ma and the present. Therefore, any sediment deposited on the Pacific floor during this interval would have been transported either to the south or north, depending on which side of the ridge it was deposited. Some may have been subducted under the westward moving American plate. At an approximate average spreading rate of 5 cm/yr, sediment deposited 47 Ma ago to the west of the Queen Charlotte Islands would have moved an unobstructed minimum distance of 2300 km.

There are at least $9 \times 10^4 \text{ km}^3$ of early Tertiary sedimentary and volcanic rocks (surface area times assumed 1 km thickness) along the Pacific margin of Washington and Oregon (U.S.A.), 1800 km to the south, and $3 \times 10^4 \text{ km}^3$ or more along the Pacific margin of Alaska, 1200 km to the north (Fig. 5). Both localities lie in a direction nearly perpendicular to the presumed orientation of the spreading ridge during the Eocene (50 Ma, Fig. 5). The total estimated volume of sediment of early Tertiary age in the Pacific Northwest, therefore, approaches that which was eroded during the same time interval from the uplift area of the Coast Mountains of B.C.

In summary, the petrologic and radiometric studies of the Central Gneiss complex of B.C. have provided the volume, time interval and location of a major source of clastic sediment. Only a fraction of this volume now occurs in nearby basins. However, a spreading ridge located offshore from the source area may have provided a transportation mechanism to move much of the sediment away from its site of deposition to southern Alaska and to western Washington and Oregon, where clastic sediment of appropriate age occurs

in about the volume of that which was removed from the source area.

Significance and the Future for Tectonic Studies

There is a clear trend at present for metamorphic petrologists to apply their skills toward solving large scale tectonic problems such as: (1) determining the thickness of,

and geothermal gradients in, continental crust as a function of time; (2) calculating rates of uplift and denudation; (3) identifying suture zones between convergent plate boundaries; (4) locating regions of overthrusting where direct evidence has been lost by erosion; and (5) dating of deformational events from the ages of minerals whose relation to

Figure 5. Location of greatest early Tertiary uplift area in the Coast Mountains of British Columbia, and approximate present-day locations of early Tertiary clastic sediment. For southern Alaska, the stippled area includes Upper Tertiary as well as Lower Tertiary exposures; the estimated volume is probably a maximum for exposed Lower Tertiary sediment but includes Lower Tertiary sediment presumed to underlie the exposed Upper Tertiary sediment. The volumes for central British Columbia and for western U.S.A. are for Lower Tertiary sediment only and assume 1 km average thickness. The volumes for Queen Charlotte Island and Sound and for Tofino Basin are for known Upper Tertiary sediment. The amount of Lower Tertiary sediment in Queen Charlotte Sound has been estimated to be in about the same order of magnitude (Stacey, 1975). Very little Lower Tertiary sediment occurs in Tofino Basin (Tiffin, et al., 1972). Other sediment on the Pacific Plate is Miocene in age or younger. The position of the spreading ridge in the northeast Pacific at 70 and 50 Ma is taken from Cooper, et al., 1976.

a given deformational event is known. This paper summarizes an example of (2). Each of these problems has a dimension of time in the solution. We can therefore anticipate increased collaboration between petrologists and geologists who have instruments available for age dating.

Promising developments in the direct determination of the compositions of the fluid phase through study of fluid inclusions may lead to new insights. Stable isotopic studies have greatly expanded our understanding of the movement of fluid through rocks during metamorphism. In the future, we can expect to improve our understanding of the role of the fluid phase associated with metamorphism in heat and mass transfer.

Application of these new techniques and the emerging

results, together with the increasing cooperative team work between metamorphic geologists, stratigraphers and geochronologists, point to the exciting possibility of deciphering the motions and changes which must have taken place in the complex deep-seated core zones, and of interpreting deformations of higher level strata so dramatically exposed in the supracrustal rocks of younger mountain belts.

In short, metamorphic petrology is currently evolving from a field of specialists establishing methodology for determining P and T to a field of geologists applying the methodology of the specialists toward the solution of broad geological problems. This also adds an interesting new direction for research effort now being formulated by IUGS and IUGG under a proposed new international program in geodynamics.

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