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Regional metamorphic zones: tectonic controls

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Factors governing the development of well-characterized metamorphic zones in orogenic belts showing moderate to high-pressure regional metamorphism are considered. Features recorded in the rocks concerning: variations of temperature with pressure (both across metamorphic belts and in single rocks), ages of metamorphism and uplift history, are compared with those predicted by the elegant quantitative thermal models of Richardson, England and co-workers. Across metamorphic zones in the well-known Scottish Dalradian and New England Acadian terranes the rocks show much more complex histories and relationships than those expected from simple extrapolation of one-dimensional thermal models across the terranes, and it is clear that consideration must be given to the influence of tectonic movements and other controls in creating lateral variations in heat flux across sets of metamorphic zones. In the Lepontine region of the Alps, present-day differential uplift must be affecting the metamorphic mineral assemblages presently 'freezing in' at depth. Qualitative models of the effect of tectonic displacement show that the 'freezing in' of the thermal effects of such displacements must potentially always be occurring at some depth in a terrane undergoing metamorphism. Tectonic movements will pass from post-metamorphic in shallower levels to synmetamorphic in deeper levels, and repeated or continuous tectonic movement may be potentially frozen into a considerable thickness of rock. Contrasts in thermal controls (such as heat generation) of provinces on either side of a tectonic boundary of long standing, may augment the lateral heat flux caused by tectonic dislocation in creating well-developed metamorphic zones that are not purely depth related. Such an origin is suggested for prominent sets of metamorphic zones seen adjacent to major dislocations in both the Scottish Highlands and New England. Within the Scottish Dalradian, tectono-metamorphic domains may be recognized at whose margins there are often changes in the character and pattern of metamorphic zones. It is concluded that prominent metamorphic zones are often the product of tectonic boundary conditions, and that the thermal history of the major part of an extensive orogenic segment is best seen away from such zones and within the interior portions of tectono-metamorphic domains where metamorphic grade is often relatively uniform.

1. INTRODUCTION

(*a*) *Setting and objectives*

The changes in mineral facies across a set of metamorphic zones provide clear evidence of variation in the conditions of metamorphism. In most cases temperature and pressure are seen as the principal controls whose variation gives rise to the gradients responsible for the metamorphic zones. Barring situations of overpressure, which are probably of very short term duration, pressure gradients are always depth-controlled. Heat loss at the Earth's surface in conjunction with an expected gross depth control over heat production, also mean a long-term depth control of temperature variation within the Earth.

The variation of both pressure and temperature as a function of depth led to their coupling in a single depth parameter of classification for regionally metamorphosed rocks by Becke (1903) and Grubenmann (1904). However, in considering the overall variety of regional metamorphic zonal sequences or facies series (see, for example, Miyashiro 1961) it is evident that temperature and pressure must be considered as independent variables. Individual facies series show different pressure–temperature gradients, but temperature variation within a given metamorphic belt may remain a simple function of depth. However, temperature variation independent of depth is commonly observed in metamorphic zones around magmatic bodies (Miyashiro 1973; Turner 1981), or where metamorphism occurs adjacent to hot obducted slabs (Jamieson 1980).

But is temperature variation independent of depth only important where there is an obvious local heat source? Our concern is with the origin of temperature conditions of orogenic metamorphism in situations where metamorphic grade shows no obvious local connection with the movements of magma or other hot bodies. In such situations, as elsewhere, well-developed sequences of metamorphic zones have naturally been the focus of much attention, and this is partly because they are perceived as guides to the development of metamorphic conditions throughout an orogenic belt. We therefore principally wish to address two important and partly related questions.

1. Are the conditions of metamorphism in such metamorphic zonal sequences simply a function of temperature variation with depth, *without* lateral temperature variation?

2. To what extent are the temperature and pressure variations in such zonal sequences representative of extensive segments of crust in orogenic belts?

In seeking answers to these questions we will principally examine well-characterized and broadly Barrovian sequences of metamorphic zones in the Dalradian belt of Scotland, the Acadian region of New England and the Lepontine area of the Alps. We largely avoid considering andalusite–sillimanite facies series of metamorphism because both geological observations and thermal calculations (England & Thompson 1984) suggest an involvement of magmatic convection of heat.

(*b*) *Geotherms, time and thermal models of orogenic metamorphism*

For many years the distribution of temperature and pressure within orogenic belts was compared with that seen in geotherms calculated from data on conductivity and heat production (figure 1*a*). Seeking such a comparison not only implies metamorphic temperatures to be a function of depth, but also fails to allow for variation in the geotherms through time. The problems of this practice were particularly noted by Richardson (1970) who showed that while geotherms show $\mathrm{d}P/\mathrm{d}T$ increasing with depth (pressure), metamorphic zones commonly show $\mathrm{d}P/\mathrm{d}T$ decreasing with pressure. Richardson (1970), Oxburgh & Turcotte (1974) and England & Richardson (1977) demonstrated that, in an orogenic situation, crustal thickening and subsequent uplift and erosion must cause substantial variation of the geotherms with time. Richardson & Powell (1976) and England & Richardson (1977) constructed one-dimensional thermal models showing how rocks at each depth would follow a pressure–temperature–time (P–T–t) loop defined by the evolving (transient) geotherms (figure 1*b*). They demonstrated that, given simple models of tectonics and erosion, the maximum temperature conditions of metamorphism would be reached progressively later with depth in the metamorphic pile. They suggested that the *array of these maximum temperature conditions* for rocks through

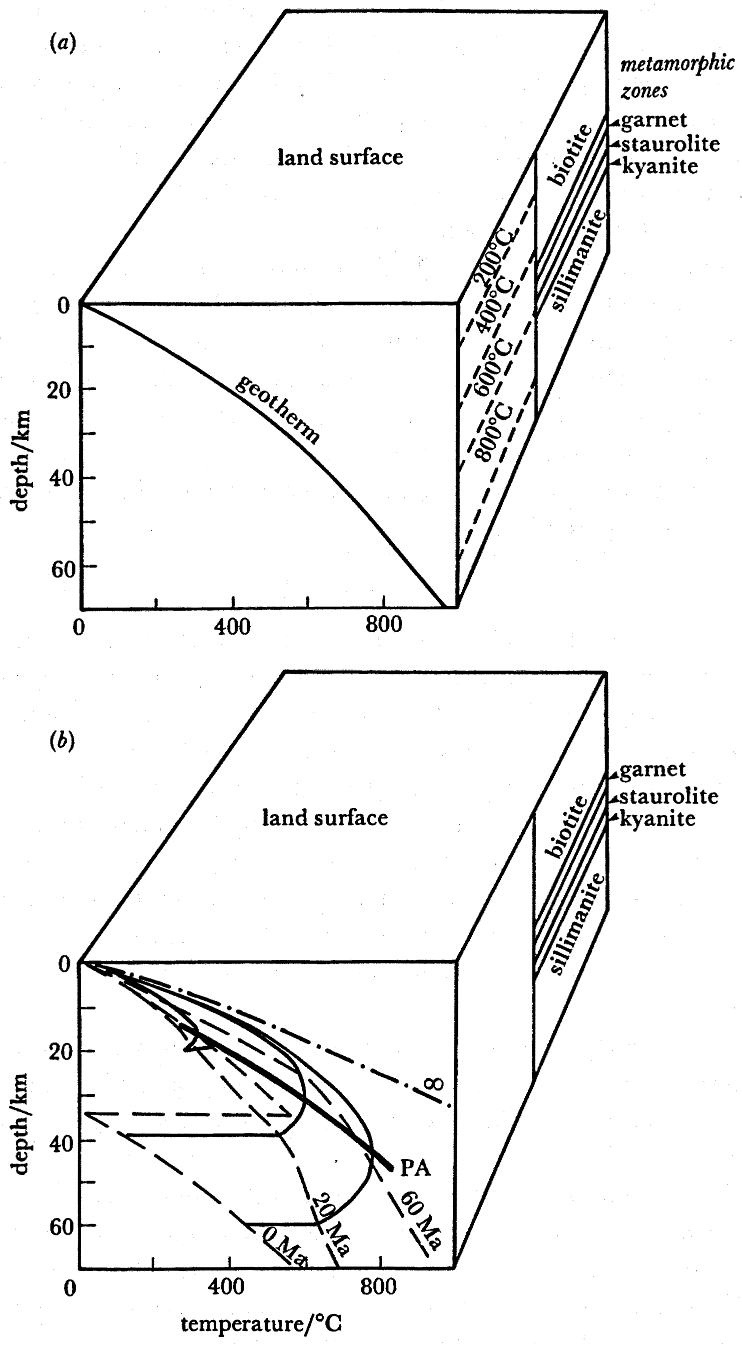

Figure 1. Diagrams of crustal blocks illustrating interpretations of metamorphic zones. (*a*) Zones interpreted in relation to a single geotherm (on front face) with isotherms and resultant zones shown on side face. (*b*) Zones interpreted as product of thermal evolution after crustal thickening by thrusting and subsequent erosion and uplift. Transient geotherms at various times (in millions of years, Ma) shown by broken lines, with illustrative P–T–t paths of rocks in solid light lines. The piezothermic array is shown as the heavy solid line (PA), and the metamorphic zones derived from this piezothermic array are shown on the side face. Transient geotherms and P–T–t paths after England & Thompson (1984, figure 1*a*).

a range of depths, *the piezothermic array*, should be compared with the temperature–pressure gradients of metamorphic zones. Piezothermic arrays generated by such models (England & Richardson 1977; England 1978; England & Thompson 1984) generally compare well with the P–T gradients shown by metamorphic zones and they provide an elegant solution to the problem of the form of these gradients. Since the P–T–t loop followed by rocks in the regional metamorphic pile is a function of depth, the thermal models call into doubt any concept of progressive metamorphism (Harker 1932) that deduces the P–T history of a rock by analogy with the nature of adjacent lower grade rocks.

The thermal models of Richardson, England and co-workers (*op. cit.*) have added huge insights in our approach to metamorphic evolution in orogenic belts. However, their generalized nature incorporates a relatively simple tectonic history. In addition, the extrapolation of these one-dimensional models to real situations implies a constancy of tectonic and thermal characteristics across the whole orogenic segment under consideration. Thus extrapolation to three dimensions implies constancy at any depth, and thus the metamorphic zones represented by a piezothermic array are simple functions of depth (figure 1 *b*). This bears directly on the questions posed in §1 *a*.

(*c*) *Approach*

Ideally, the answers to the questions posed in §1 *a* concerning the depth control of metamorphic zones and their applicability to extensive segments of orogenic crust, might be approached by delineating the three-dimensional characteristics of metamorphic terranes and interpreting pressure and temperature variation at specific points in time. Attempts to reconstruct the three-dimensional pattern of temperature and pressure variation (Chinner 1966; Harte & Hudson 1979) show that it is exceptionally difficult to do so without making structural assumptions about pressure–depth variations or assuming a similar pattern of isotherms and isobars during the course of metamorphic crystallization. Complete space–time reconstruction is, in fact, impossible until we are able to measure all three of temperature, pressure and age of formation of specific mineral assemblages across a wide section of a metamorphic terrane.

An alternative approach is to adopt relatively simple thermal models (see, for example, England & Richardson 1977; England & Thompson 1984) of metamorphism and see to what extent the actual mineral assemblages in metamorphic zones fit in with the characteristics predicted by the models.

The obvious features implied by the application of the one-dimensional thermal models to natural three-dimensional metamorphic zones, and which may be tested are as follows.

1. The temperatures (and times) of formation of metamorphic mineral assemblages should be a function of depth, i.e. isotherms (and isochrons) of mineral development should be parallel to and directly proportional to isobars of metamorphism.

2. The history of tectonic development (including uplift) and metamorphism should be regular and uniform across the orogenic segment considered. Thus the metamorphic histories shown by the P–T–t paths of individual rocks should vary regularly only as a function of depth, and the uplift history revealed by tectonics and radiometric dating should be uniform across the metamorphic belt.

In the following section we examine these features with respect to parts of the Scottish, New England and Alpine terranes.

2. Metamorphic development in specific terranes

(*a*) *The Scottish Dalradian*

Figure 2 shows the distribution of metamorphic zones in the Scottish Dalradian from the metamorphic facies subdivisions adopted by IGCP project 27 (Fettes *et al.* 1984). Leaving aside the Buchan area of lower pressure metamorphism in the north-east, the broadly Barrovian zonal assemblages show a generalized continuity, which led Kennedy (1948) to view the zones as part of a coherent depth-related thermal structure extending across the Scottish Caledonide orogen. Insofar as Kennedy's vision involved viewing the zones throughout the Scottish Highlands as being capable of representation by a single vertical rock column, it is analogous to interpreting the whole metamorphic zonal pattern as reflecting a single piezothermic array in a thermal model.

Kennedy's (1948) simple model of the Dalradian metamorphic pattern has not been sustained by subsequent detailed structural, petrological and radiometric investigations of the metamorphic zones (see Chinner 1966, 1978, 1980; Atherton 1977; Harte & Hudson 1979; Baker 1985; Dempster 1985; Watkins 1985). From the viewpoint of comparing metamorphic features in the Scottish Dalradian with those predicted by a simple thermal model (§1*c*) we may briefly note the following discrepancies.

1. The gross lack of correlation of temperature estimates with pressure estimates across the metamorphic belt. This is particularly manifest on comparing the original classic area of Barrow's zones (Barrow 1893, 1912) near the Highland boundary fault in the east with the southwestern area (figure 2). In the former area the whole spectrum of chlorite to sillimanite grades (?400–650 °C) occurs with pressure estimates mainly around 6 kbar† (Harte & Hudson 1979; Dempster 1983, 1985; Baker 1985). In the southwest, metamorphic grade is relatively low with the maximum temperature estimates around 500 °C (garnet zone), while pressure estimates are higher. By using the celadonite content geobarometer of Powell & Evans (1983), Graham *et al.* (1983) estimated pressures of *ca.* 10 kbar for the southwest Highlands, while estimates on the same basis for Barrow's area in the southeast Highlands are *ca.* 7 kbar.

2. In the southeastern area near the Highland boundary fault, the greatest pressure variation appears to have a NE–SW orientation while the temperature variation (clearly shown by the orientation of the zones) is NW–SE (figure 2), and thus the strong temperature gradient in Barrow's classic area appears to have formed at an oblique angle to vertical depth (Chinner 1966, 1980; Harte & Hudson 1979). (Note that the probable overturning of metamorphic isotherms and isobars immediately adjacent to the Highland boundary fault is most probably post-metamorphic (Harte & Hudson 1979) and therefore a separate phenomenon from the point addressed here.)

3. The uplift history documented by radiometric dating of minerals across Barrow's zones (Dempster 1984, 1985) shows that (i) Uplift did not occur uniformly through time, but with phases of little uplift alternating with relatively rapid uplift. Thus the *P–T–t* paths of the rocks show inflexions rather than smooth curves (figure 2). (ii) Uplift histories are not uniform across the zones, and furthermore in Barrow's type area it is the highest-grade zones that show the earliest pulse of uplift, so that the highest-grade assemblages are among the earliest to be frozen into the rocks.

4. In the Blair Atholl belt (immediately north of the Tummel steep belt, figure 2) the

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† 1 bar = 10^5 Pa.

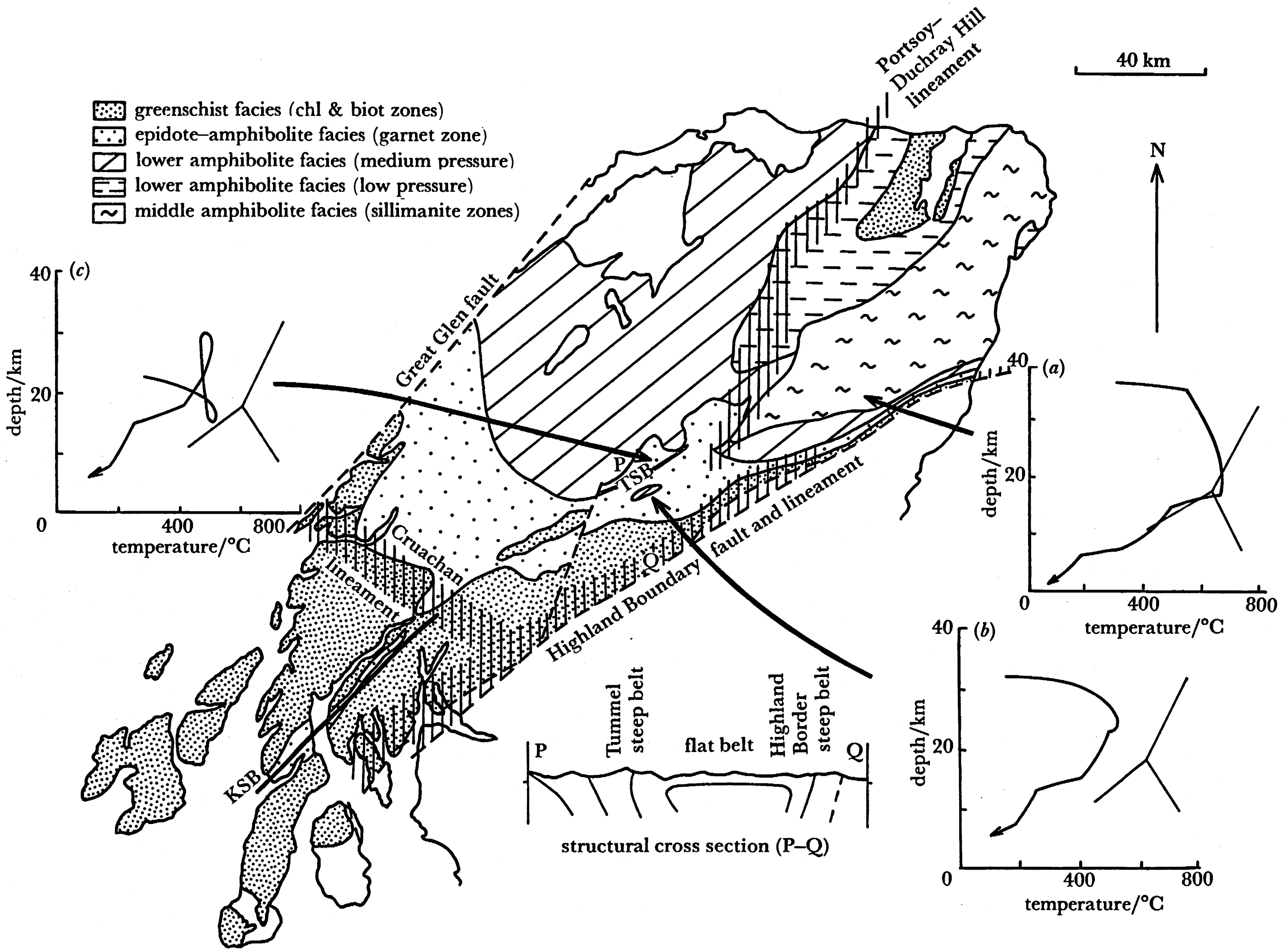

FIGURE 2. Map of metamorphic zones in the Scottish Dalradian and adjacent 'younger' Moine rocks (slightly modified after Fettes *et al.* (1984). The positions of Cruachan and Portsoy–Duchray Hill, lineaments or 'zones of discontinuity' are shown after Harte (1986) by vertical lining; the Highland Border steep belt is similarly picked out. The heavy lines labelled TSB and KSB refer respectively to the southern limits of the Tummel steep belt and Knapdale steep belt. The inset diagrams (*a*), (*b*) and (*c*) show *P–T–t* paths for rocks at the arrowed locations; (*a*) and (*b*) after Dempster (1985, figures 8 and 10), (*c*) after Dempster & Harte (1986, figure 3); the light lines show the stability fields of the Al_2SiO_5 polymorphs after Richardson *et al.* (1969).

metamorphic mineral assemblages for individual rocks document an increase in pressure during the time of their development (Dempster & Harte 1986) rather than the steadily falling pressures of the thermal model *P–T–t* paths (England & Richardson 1977; England & Thompson 1984). This increase in pressure appears to be related to the development of the Tummel steep belt. Increasing pressure during metamorphism is also shown in the replacement of andalusite by kyanite near Portsoy and Braemar along the Portsoy–Duchray Hill lineament (Harte & Hudson 1979; Harte 1986).

5. The western margin of the classic area of Barrow's zones shows relatively rapid change in metamorphic grade (Baker & Droop 1983; Baker 1985; P. Upton, personal communication) at an oblique angle to the main trend of Barrow's zones, with possibly inverted metamorphic zonation near Duchray Hill in the south (Chinner 1980; McLellan 1985). This margin to the high grade region of Barrow's zones forms part of the Portsoy–Duchray Hill lineament in figure 2 (further discussed in §4*b*).

6. In the western part of the central area near Balquidder, Watkins (1985) has found support for Elles & Tilley's (1930) controversial recognition of inverted metamorphic zones, although the cause of their inversion is uncertain.

(*b*) *Acadian metamorphism in New England*

Regional metamorphic zones for the New England region of the Appalachian orogen(s) have been compiled by Thompson & Norton (1968), and more recently Robinson (1983) has separated zonal patterns of different ages, while Zen (1983) has suggested possible distinctions between terranes with quite different orogenic histories. In this paper we pay particular attention to the area dominated by Acadian metamorphism and most especially to recent work in western Massachusetts.

Figure 3 shows the Acadian metamorphic zones (Robinson 1983) in conjunction with a geological section across the centre of western Massachusetts (Robinson 1979) and *P–T–t* time paths of metamorphism (Tracy & Robinson 1980; Tracy *et al.* 1976) for different locations across this area. The structural and metamorphic history are complex. The broad structural evolution involves three principal stages: (*a*) early west-directed nappe formation; (*b*) backfolding on a major scale by east-directed folds; (*c*) formation of gneiss domes and tight isoclinal folds (see cross section in figure 3). The broad division of the region into the Bronson Hill anticlinorium and Merrimack synclinorium particularly reflects the concentration of gneiss dome formation within the Bronson Hill anticlinorium during stage (*c*) in the tectonic history. However, the approximate north–south trend of the boundary between these tectonic provinces is also seen in a progressive series of changes in the Siluro–Devonian stratigraphy (Robinson 1983), and Zen (1983) places the margin of the authochtonous Taconian basement along the eastern margin of the Bronson Hill anticlinorium.

The Acadian metamorphism in western Massachusetts appears to have reached its peak during the structural stage of major backfolding, and the temperature maxima on the *P–T–t* paths (figure 3) for the Bronson Hill anticlinorium and Merrimack synclinorium may be assumed to be roughly synchronous (Robinson 1979; Tracy & Robinson 1980). Metamorphic reaction and recrystallization did, however, continue through structural phase (*c*) especially in the Bronson Hill anticlinorium.

The differences, shown in figure 3, for *P–T–t* paths coming from within a coherent set of metamorphic zones, illustrate the inapplicability of extrapolating a one-dimensional thermal

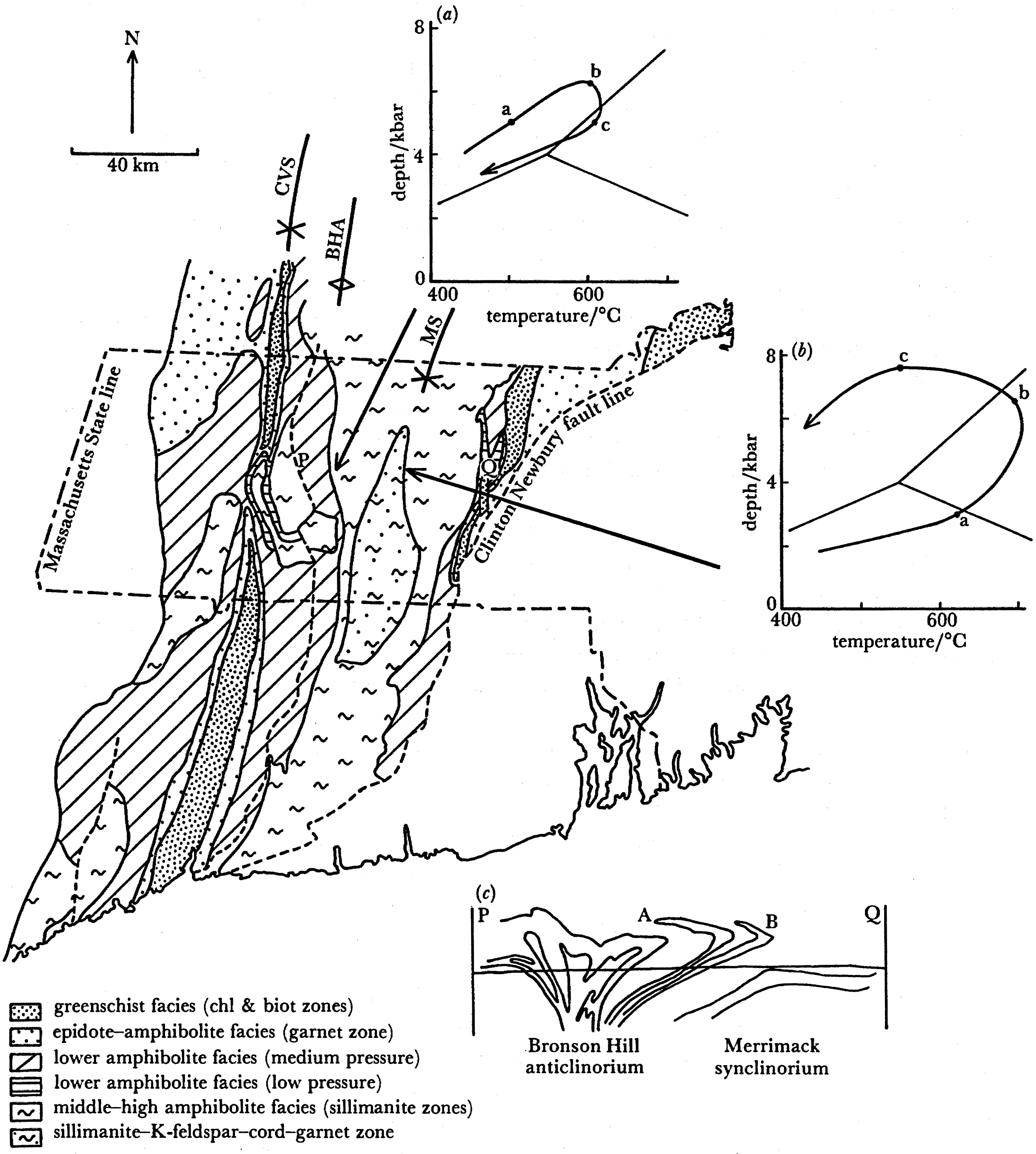

FIGURE 3. Map of distribution of Acadian metamorphic zones in Southern New England, U.S.A (after Robinson 1983). The heavy lines labelled CVS, BHA and MS indicate the trends of the Connecticut Valley Synclinorium, Bronson Hill anticlinorium and Merrimack synclinorium respectively. The inset diagrams (*a*) and (*b*) show *P–T–t* paths for rocks at the arrowed locations respectively in the Bronson Hill anticlinorium and Merrimack synclinorium, with the points a, b and c indicating pressure–temperature conditions at the times of: a, nappe formation; b, backfold formation; c, gneiss dome formation (after Tracy & Robinson 1980). The light lines in insets (*a*) and (*b*) show the stability fields of the Al_2SiO_5 polymorphs after Holdaway (1971). On the structural cross section, (*c*), a fold hinge associated with nappe formation is labelled A, and one associated with backfold formation is labelled B.

model across a structurally complex regional metamorphic terrane. The frozen mineral assemblages forming the metamorphic zones in western Massachusetts must represent a time-integrated response to a varying structural and metamorphic evolution across the whole terrane. The tectonic evolution and P–T–t paths make it clear that temperature distribution was not purely a function of depth during this evolution and that there must therefore have been lateral heat transport across the region during metamorphic crystallization.

To the north of Massachusetts, in southern New Hampshire, Chamberlain (1986) has recently documented evidence of how folding may affect the temperature–pressure characteristics of mineral assemblages frozen into metamorphic rocks. Chamberlain's study area is situated between the Bronson Hill anticlinorium to the west, and the Merrimack synclinorium, to the east. The pattern of metamorphic zones shows a clear relation to the disposition of antiforms and synforms in the two phases of upright folding that follow early nappe formation. The folding evidently occurred more rapidly than the time required for thermal relaxation to remove lateral temperature variations caused by the folding. Particularly important is Chamberlain's (1986) documentation of how the redistribution of heat caused by the folding of the isotherms is frozen into the mineral assemblages: rocks at antiformal fold intersections have P–T–t paths showing cooling, while synformal fold intersections have P–T–t paths showing heating, and where antiforms and synforms of the two fold phases intersect there are sharply hooked P–T–t paths. This work follows a previous study on Acadian metamorphism in Vermont by Fisher (1980), who noted prograde P–T–t paths in cores of synforms and retrograde P–T–t paths in cores of antiforms in a single phase of folding.

(*c*) *The Lepontine region, European Alps*

The metamorphism in the Alpine belt of Europe is characterized by a complex series of metamorphic events of variable timing and conditions (Niggli 1978). In this study we will consider the Oligocene Barrovian-type metamorphism of the Lepontine area in the central Swiss Alps (figure 4).

The metamorphic zones of the Lepontine area roughly define a dome-shape, which is centred on the Pennine domain but transgresses the Helvetic domain to the north and is cut to the south by the large Insubric fault line. The dome-like distribution of mineral zones is generally thought to reflect either a 'tectonic doming' (Niggli 1970), by which a post-metamorphic tectonic effect is implied, or a 'thermal domig' (see, for example, Wenk 1970; Thompson 1976) implying a dome-shaped structure for the isotherms at the time of metamorphism. Since the thermal doming might result from differential uplift during metamorphism (§3) and therefore also have a tectonic origin, we shall principally refer to these two hypotheses as those of post-metamorphic and syn-metamorphic doming.

A compilation of estimates of peak metamorphic conditions by Frey *et al.* (1980) (see also Bucher-Nurminen *et al.* (1983)), suggests that differential erosion of the cover has occurred between the higher temperature and pressure area in the south of the dome and the lower temperature and pressure area to the north, assuming a roughly similar age of metamorphism. More early rapid unroofing of the higher grade areas to the south relative to areas in the north is also suggested by some aspects of the radiometric mica ages (Purdy & Jäger 1976; Wagner *et al.* 1977; Frey *et al.* 1980). These features largely support a post-metamorphic tectonic doming of the isograds. However, the age data are complex, and although the distribution of the high-grade rocks may be largely accounted for by their post-metamorphic differential

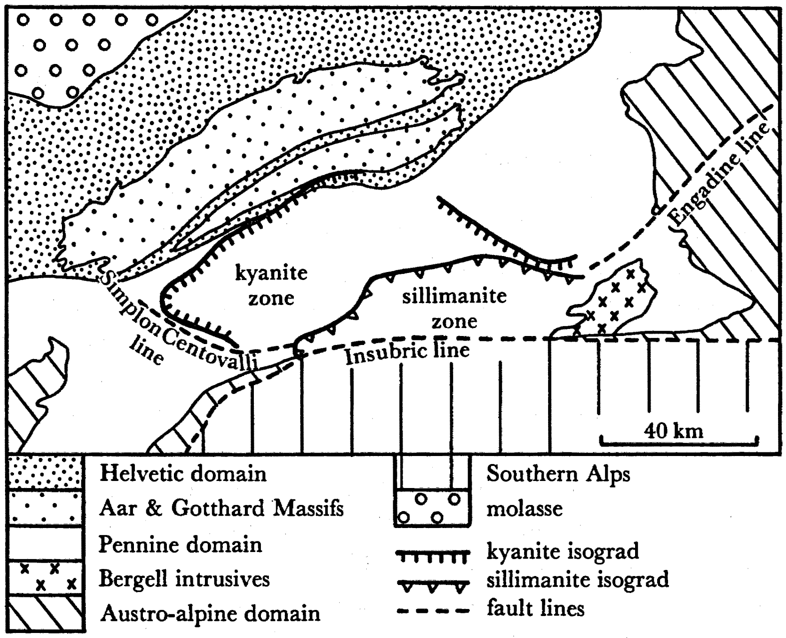

FIGURE 4. Map of the Lepontine region in the European Alps showing the area of high-grade rocks as defined by the kyanite and sillimanite isograds and bounded to the south by the Insubric line (after Bradbury & Nolen-Hoeksema 1981).

uplift, it still remains possible that a syn-metamorphic domed pattern of isotherms existed in the south during metamorphism (Thompson 1976).

Interpretation of Lepontine metamorphic history is also complicated by its spanning of the boundary between Pennine and Helvetic domains. Frey *et al.* (1980) note that higher $\mathrm{d}T/\mathrm{d}P$ gradients are given by the metamorphic rocks of the Helvetic domain than the Pennine domain, with gradients of 35–40 °C km^{-1} for the former and 20–30 °C km^{-1} for the latter. These features also cast doubt upon the above syn-metamorphic thermal dome model (Frey *et al.* 1980), but they also appear to be symptomatic of probably significant differences between the Helvetic and Pennine domains. The lower $\mathrm{d}P/\mathrm{d}T$ of the Helvetic domain may be caused by the exceptionally high heat production of the granitic rocks (Labhart & Rybach 1976) of the Helvetic domain. Recent studies (Dempster 1986) have suggested significant variations in the timing of peak metamorphic conditions of Meso-Alpine metamorphism, with a maximum 25 Ma age in the lower-grade areas of the Helvetic basement compared with a 38 Ma age in the lower- and intermediate-grade Pennine nappes. This may reflect differential movement between the Pennine and Helvetic domains that halted metamorphism in the upper thrust sheets to the south and delayed thickening, uplift and metamorphism in the Helvetic domain to the north. An additional feature pointing to prolonged tectonic division between Helvetic and Pennine domains is the absence of significant Eo-Alpine metamorphism in the former. This also suggests that the higher grade and earlier time of Meso-Alpine metamorphism in the Pennine domain might partly be a consequence of the preceding Eo-Alpine heating (J. C. Hunziker, personal communication).

The Central Alps or Lepontine region obviously provide a good example of how a relatively simple metamorphic pattern may be difficult to interpret, and of the complexities of deciphering the effects of syn-metamorphic from post-metamorphic movements. These are important points, but the features noted have even further significance when we remember that the Alps are still an active orogenic belt. A further 20 km thickness of rock must be removed from a large area of the Central Alps if it is to return to normal crustal thickness (Müller *et al.* 1980), and this will exhume a younger pattern of metamorphic zones, which will have been affected while undergoing metamorphism, by the more recent tectonic events. Major uplift in the high-grade Lepontine area at about 20 Ma linked to movement on the Insubric (Hurford 1986) and Simplon-Centovalli lines (Hunziker 1970), while being post-metamorphic at the level of present exposure, would have been syn-metamorphic at greater depth (England & Richardson 1977). The syn-metamorphic juxtaposition of hotter and colder rocks should exert a control on the pattern of the metamorphic zones eventually exposed, and will record the shift of centres of uplift with time (Purdy & Jäger 1976; Wagner *et al.* 1977) and its recent concentration in the Simplon area (Gubler 1976; Wagner *et al.* 1977).

3. MODELS OF METAMORPHIC ZONE DEVELOPMENT AT TECTONIC BOUNDARIES

In the preceding section we have presented evidence from metamorphic rocks forming part of metamorphic zonal sequences, of how tectonic displacement has resulted in differential movements across the zones during the formation of the mineral assemblages. Examples of isograd patterns, which are not purely depth controlled (isotherms parallel to isobars) have been seen, together with evidence of irregular burial and uplift histories. Often the relative tectonic displacements noted have a significant vertical component (uplift), and they must have caused displacement of depth-controlled isotherms and effected lateral heat transport in the rock pile. The preservation of the effects of relative tectonic displacements in the metamorphic mineral assemblages implies that the pattern of metamorphic zones must also bear an imprint of lateral heat flux.

However, if one approaches the question of the significance of lateral heat transport in terms of single tectonic displacements, the capturing of these events by metamorphic mineral assemblages seems somewhat unlikely. Thus an instantaneous vertical displacement of isotherms resulting in a horizontal (same depth) temperature difference of 200 K may be calculated (Carslaw & Jaeger 1967), with typical diffusivities seen in rocks, to be substantially dissipated by conduction over distances of a few kilometres in only 1 Ma. To counter this, we place emphasis below on three factors that considerably affect the chances of tectonic zones of movement influencing the mineral assemblages forming in metamorphic environments.

(*a*) Tectonic displacement may continue over a long time period or take place repetitively. This is likely to be the case at, or adjacent to, long-term tectonic zones separating crustal segments with differences in basement and/or cover successions.

(*b*) Long-term tectonic boundaries like those of (1), whose history may be traced back to differences in basement or basement lineaments, will often separate somewhat different geological provinces where differences in the total rock pile will result in different heat generation and other thermal properties. These in-built differences in thermal controls will operate continuously and be a constant cause of lateral variation across the tectonic boundary.

(*c*) During regional metamorphism a vertical rock pile may develop, along its length, mineral assemblages representing peak metamorphic conditions over a considerable time period. If we accept the basic tenet that the principal mineral assemblages eventually seen at

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the Earth's surface approximately represent the conditions of maximum temperature experienced at each depth within a thickened rock pile, then the formation or 'freezing in' of the mineral assemblages will usually occur progressively later with increasing depth (England & Richardson 1977; England & Thompson 1984). In such a model, at any instant of time during metamorphism, there will always be some depth where the mineral assemblages are 'freezing in' the *P–T* conditions that exist at that time. Thus, there will always be some depth, in an uplifting pile undergoing metamorphism, where even a short-lived lateral heat transport effect on *P–T* may be recorded.

In examining the effects of relative tectonic displacement and lateral heat transport within a crustal block undergoing metamorphism, one would ideally like to extend the one-dimensional thermal models of Richardson, England and co-workers into two and three dimensions. However, such modelling is beyond our means. In the following we use a very simple qualitative two-dimensional model, in which some elements may be constrained by one-dimensional modelling, to illustrate some of the controls and consequences of sub-vertical tectonic displacement on a crustal block undergoing metamorphism. The model is illustrated in figure 5*a*, with the zone of relative tectonic displacement simplistically depicted as a vertical fault surface separating two blocks with different uplift rates. Apart from this difference in uplift rate, the two blocks either side of the displacement zone have identical thermal controls (heat production, conductivity, heat flux at lower boundary). Heat generation along the displacement zone as a consequence of friction or strain is ignored.

The greater uplift rate of the right-hand block in figure 5*a* causes thermal disequilibrium and therefore heat transfer across the displacement zone, with the result that the isograd surfaces separating the metamorphic zones are not horizontal (purely depth controlled) surfaces adjacent to the displacement zone. Away from the displacement zone on the sides of the two blocks, where lateral heat transfer has not had any effect, the metamorphic zones have developed in the normal way suggested in one-dimensional thermal models (figure 1*b*). Thus they represent piezothermic arrays controlled by the thermal parameters given in the caption to figure 5. During the course of development of the metamorphic zones the site of 'freezing in' of the mineral assemblages will have moved to progressively deeper levels, and once the mineral assemblages have frozen the differential movement across the displacement zone causes breaks in the continuity of metamorphic zones between the two blocks. The continuous surface (f–f) in the lower part of figure 5*a* represents the surface where mineral assemblages are on the point of becoming frozen at the moment of time depicted in the diagram, and this surface may be envisaged as an isograd surface not yet displaced by differential uplift subsequent to its formation. Above this surface a horizontal variation of grade across the displacement zone that was *syn*-metamorphic and caused by lateral heat transfer, has had *post*-metamorphic displacement superimposed on it.

During the course of development of the metamorphic zones in figure 5*a*, the continuous lateral heat flux across the displacement zone will have had progressively more effect with time in modifying temperatures across the displacement zone. Since the mineral assemblages become frozen progressively later in time with increasing depth, this means that the deeper, higher-grade mineral assemblages show more effect of the lateral heat transfer than the shallower ones. Thus in figure 5*a* the isograd surfaces show progressively more curvature away from the horizontal with increasing depth.

The magnitude of heat flux across the tectonic discontinuity at any time will vary in the

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simple model presented as a function of the thermal constants (heat generation, conductivity, heat flow into base) of the blocks and the uplift rates associated with the two blocks. In general, heat will be expected to flow from the more-uplifted to the less-uplifted block because of the upward translation of the isotherms with uplift. However, with time, a reversal of lateral heat flux might occur as erosion reduces the heat generating capacity of the more rapidly uplifted block.

A further consideration to note is that the tectonic zone of displacement might be inclined rather than the vertical 'fault' shown in figure 5. In this case the tectonic movement could cause loading and metamorphism under increasing pressure conditions in the footwall crustal block.

In the simple model of figure 5*a*, it is crucial to preservation of evidence of the lateral flux in a significant thickness of the pile (i.e. formation of metamorphic zones oblique to depth), that the tectonic movement continue over a long period of time. To enhance lateral heat flux and the chance of its preservation, the differences between the two blocks of figure 5*a* may be enhanced in several ways as already partly indicated.

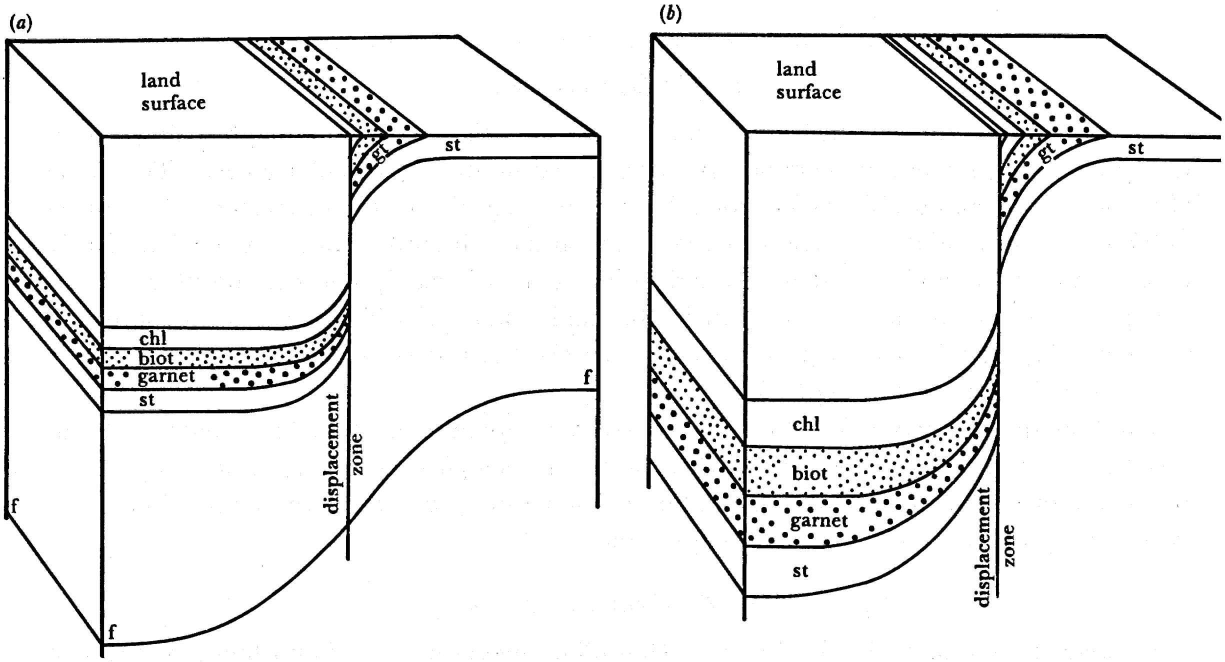

FIGURE 5. Schematic illustrations of metamorphic zones formed in adjacent crustal blocks having differing rates of continuous uplift. In each diagram the right-hand crustal block has the greater uplift rate and the zone of displacement between the two blocks is shown as a simple 'fault' surface; 'chl', 'biot', 'gt' and 'st' indicate chlorite, biotite, garnet and staurolite zones. At the left-hand and right-hand sides of both diagrams (*a*) and (*b*), the zones are based on piezothermic arrays (England & Thompson 1984) with the zones representing temperatures of crystallisation in the range 300–600 °C. In (*a*), the two crustal units either side of the 'fault' both have the same heat production, conductivity and lower boundary heat flux (appropriate parameters are: heat production 1.6 μW m^{-3}; conductivity 2 W m^{-1} K^{-1}; heat flux at lower boundary 32 mW m^{-2}). In (*b*), the crustal block to the right of the 'fault' has the same thermal parameters as in (*a*), but the left-hand block has: heat production of 0.8 μW m^{-3}, conductivity of 2.5 W m^{-1} K^{-1}, with a heat flux at the lower boundary of 24 mW m^{-2}. Note the resultant differing width of the metamorphic zones in (*b*) and the greater width of thermal exchange next to the displacement zone. The lowermost line (f) in model (*a*) represents the surface along which mineral assemblages are 'freezing in' at the time shown by the diagram. All mineral assemblages above this surface have become frozen and thus the metamorphic zones on either side of the displacement zone have been separated by post-metamorphic displacement (see text).

(*a*) The blocks have different heat generating capacities, as a consequence of either different thicknesses of material, or different composition of material, or both. This is shown in figure 5*b*, where the different thermal controls generate different widths of zones in the left-hand block. Lateral heat flux would occur here even without the tectonic displacement.

(*b*) The tectonic behaviour of the two blocks is more extreme; for example, one might be undergoing subsidence and rapid sedimentation with depressions of temperatures at a given depth, while the other was undergoing uplift.

(*c*) Other features might be associated with the metamorphic domain on one side of the tectonic discontinuity, but not the other. For example, there might be enhanced mantle heat flux, or rise of magmas in the lower crust, on one side of the tectonic discontinuity but not the other.

Perhaps such factors might even combine together, and the extent to which they occur will obviously relate to the magnitude of the tectonic boundary involved. To further examine and seek examples of these effects it is useful to return again to the metamorphic terranes previously described.

4. FURTHER OBSERVATIONS ON METAMORPHIC ZONES

(*a*) *The Lepontine region*

The relevance of some of the features of the simple models described in the preceding section to aspects of the Lepontine metamorphism described in §2*c* is particularly clear. The dome of high-grade metamorphic rocks probably owes its exposure to the occurrence of localized uplift and, in terms of the rocks now present at the surface, this uplift appears to be dominantly post-metamorphic, although there are indications that it is partly syn-metamorphic. This is strongly suggestive of the features seen in the model, and even if one was to discount any syn-metamorphic effects in the presently exposed rocks, the models show why syn-metamorphic effects must be expected at depth (§2*c*).

The boundary between the Pennine and Helvetic domains in the Alps is potentially an excellent example of the model type where a major geological boundary is not only one of syn-metamorphic tectonic displacement, but also separates provinces with marked differences in thermal properties, particularly heat production.

(*b*) *The Scottish Dalradian*

References to studies on the Scottish Dalradian suggesting the importance of tectonic displacement during metamorphism have already been made (§2*a*), and we wish to concentrate here on those situations where there is evidence of the influence of long term tectonic boundaries. Recently some attention has been focused on the existence of 'zones of discontinuity' across which the pattern of distribution of metamorphic zones changes, and thus there is evidence of change in the pattern of temperature–pressure variation during metamorphism (Baker & Droop 1983; Baker 1985; Graham 1986; Harte 1986). Furthermore, Graham (1986), Harte (1986) and Fettes *et al.* (1986) have noted that these zones of discontinuity are often marked not only by metamorphic but also by structural, stratigraphic and igneous features and they suggest that the discontinuities are probably related to basement structures or lineaments. It is suggested that a series of tectono-metamorphic domains or provinces are bounded by these lineaments (where a lineament may refer to a zone up to 20 km wide that contains a series of subparallel geological discontinuities). Particularly pertinent to the present discussion are the lineaments bounding three of these tectono-metamorphic domains and corresponding to the Cruachan and Portsoy–Duchray Hill lineaments and the Highland Boundary fault in figure 2.

As previously noted, the southwest Scottish Highlands are marked by a generally low grade of metamorphism despite evidence of substantial depths of burial. In the metamorphic zonal pattern, the extensiveness of the low-grade area is seen to be related to the local deflection to a NW–SE trend of the garnet isograd along the line of the Cruachan lineament. This particular lineament was initially defined by a strong gradient in gravity measurements (Hall 1985), and it appears to correspond with changes in basement constitution, Dalradian depositional history and the limit of extensive development of basic igneous rocks within the Dalradian pile of the southwest Highlands (Graham 1986). The lineament thus appears to be a long-standing feature of the regional geology, which exerted a major tectonic control during the development and filling of the Dalradian basin in the southwest Highlands and thus extended its influence upwards through the thickness of Dalradian deposits before metamorphism. The contrasting heat generation characteristics of the basement and Dalradian pile in the southwest Highlands by comparison with the central Highlands may then have led to differences in overall metamorphic grade and influenced the metamorphic zonal pattern (Dempster 1983; Graham 1986; Fettes *et al.* 1986; Harte 1986). Thus the Cruachan lineament provides an example of a situation where a long-term tectonic boundary influences the metamorphic zonal pattern not so much through syn-metamorphic displacement but as a consequence of causing differences in heat generation.

Moving to the eastern Scottish Dalradian, the pattern of zones in Barrow's type area is interrupted to the west by the relative rapid termination of the sillimanite, kyanite and staurolite zones (figure 2). Geothermometric estimates (Baker 1985; McLellan 1985) further document the fall in temperatures and Chinner (1980) has suggested the existence of a metamorphic inversion. These changes occur across the southern end of the Portsoy–Duchray Hill lineament marked in figure 2. As pointed out by Harte (1986) and Fettes *et al.* (1986), the southern part of this lineament is also marked by a series of pre-metamorphic serpentine bodies and changes in detailed stratigraphy, while it is also the locus of post-metamorphic fault displacement. Clearly there is evidence here of a long-term tectonic boundary influencing the mapped distribution of metamorphic zones by a combination of pre-, syn- and post-metamorphic displacements.

Harte (1986) and Fettes *et al.* (1986) suggest the continuation of a zone of discontinuities, or series of adjacent lineaments, northward along a system of shear zones defining the western margin of a distinct Buchan crustal block (Ashcroft *et al.* 1984), that are also partly coincident with the boundary of the Buchan (andalusite-bearing) metamorphic terrane. Baker & Droop (1983) and Baker (1985) have advocated syn-metamorphic tectonic displacement across the western margin of the area of Buchan metamorphic zones and the Portsoy–Duchray Hill zone of discontinuities.

Before leaving the Dalradian it is appropriate to turn our attention to Barrow's (1893, 1912) type area and its exceptionally narrowly spaced metamorphic zones with very strong temperature gradients away from the Highland Boundary fault. Harte & Hudson (1979) argue that these gradients are syn-metamorphic and show little relation to depth. More recent pressure estimates (Dempster 1983, 1985; Baker 1985) also show little variation across the narrowly spaced zones. Dempster (1985) finds evidence of early syn-metamorphic uplift of the high-grade zones relative to the lower-grade zones. Harte & Hudson (1979) suggested the major importance of a tectonic boundary close to the present Highland Boundary fault, which not only caused tectonic displacement during metamorphism but separated regions of exceptionally profound differences in geology with uplift and igneous activity at depth to the north of the tectonic discontinuity and subsidence and cold sediment accumulation to the south. Bluck (1984) and Harte *et al.* (1984) provide evidence of a major and long-lived tectonic boundary with both horizontal and vertical movements sub-parallel to the present Highland Boundary fault during the Lower Palaeozoic development of Scotland, and Harte *et al.* (1984) note that evidence for this tectonic boundary is seen in the distribution of pre-metamorphic structural features. The high thermal gradients preserved in Barrow's zones are therefore viewed as a consequence of the lateral chilling effect of this tectonic boundary, coupled of course with the existence in the eastern Scottish Dalradian (both Barrovian and Buchan) of the high heat flux associated with the high-grade assemblages.

(*c*) *New England Appalachians*

Examining the gross pattern of the metamorphic zones in the New England Acadian terrane, a noticeable feature is the way the major high-grade area passing through central Massachusetts (figure 3) is bounded to east and west by narrowly spaced chlorite, biotite, garnet and sometimes staurolite zones. On the east these narrow zones are partly aligned along the major Clinton–Newbury fault system of middle to late Palaeozoic age, which has the characteristics of a major plate boundary (Zen 1983, p. 70). The terrane to the southeast of this fault zone also shows a narrowly spaced set of metamorphic zones against the fault zone, although these are probably not of Acadian age (Robinson 1983; Zen 1983). Although the present disposition of features about this fault system is doubtless affected by post-metamorphic movement, we think it most likely that the disposition of the metamorphic zones at the time of crystallization owes much to the presence of a major tectonic boundary.

On the western side of the extensive high-grade region crossing central Massachusetts occur a narrowly spaced set of metamorphic zones (figure 3) following the Connecticut Valley synclinorium (Osberg 1978; Zen 1983), which has in fact roughly symmetrical sets of narrowly spaced, relatively low-grade zones on both its sides and separates a western Acadian realm of metamorphism from an eastern Acadian realm of metamorphism (Robinson 1983). The regularity of the Connecticut Valley synclinorium with its paired sets of narrow metamorphic zones flanked by chains of gneiss domes is striking. It is particularly well seen in the southern Vermont and New Hampshire and western Massachusetts, where it separates the Bronson Hill anticlinorium to the east from the Berkshire and Green Mountain massifs together with the Rayponda and Chester domes to the west. That it represents a geologic boundary of long term significance is strongly supported by its apparent separation of Grenvillian gneisses to the west from younger gneisses to the east (Osberg 1978; Zen 1983). Osberg (1978) and Robinson & Hall (1980) have suggested that the Bronson Hill anticlinorium may represent an island arc from across the Iapetus Ocean which became accreted to North America. The general trend of the Connecticut Valley synclinorium was also roughly followed in the south during the formation of the Triassic basin. The line of the Connecticut Valley synclinorium may thus represent the junction of quite different crustal domains and we speculate that the distinctive alignment of metamorphic zones along it is not just a result of post-metamorphic movement but also reflects the influence of this boundary at the time of metamorphism.

(*d*) *Other areas*

We have concentrated above on three metamorphic regions, but it is interesting to note that other areas show a correlation of metamorphic zonal development with tectonic boundaries, even though it is often difficult to unravel evidence of syn-metamorphic tectonic effects from post-metamorphic tectonic displacement.

In the Sanbagawa belt, Nakajima (1982) depicts metamorphic zones showing a closer spacing adjacent to the Medium Tectonic Line. In New Caledonia (Bell & Brothers 1985), the high thermal gradients shown in the higher-grade zones suggest the possibility of lateral heat transport given the overall high pressure (blueschist–eclogite) nature of the metamorphism.

Superficially, the high-grade part of the Haast schists, occurring along the margin of the New Zealand Alpine fault, appears to support our arguments. This 25 km zone of Alpine schists has been substantially affected by uplift adjacent to the Alpine fault (Wellman 1979; Adams & Gabites 1985) in the Kaikoura (Miocene–Recent) Orgeny. However, this uplift phase is far removed from the probable time of formation of the metamorphic mineral assemblages that is believed to have been in the Rangitata (Jurassic to Cretaceous) Orogeny (Adams & Gabites 1985). Thus, we cannot simply annex the New Zealand Alpine schists as an example of tectonic control on the *formation* of metamorphic zones.

5. Discussion

(*a*) *Tectono-metamorphic domains and boundaries*

We believe that not only the disposition but also the development of conspicuous sets of metamorphic zones is often strongly influenced by tectonic boundaries. The pattern of distribution of metamorphic zones as mapped on the ground frequently shows alignments with geological boundaries or zones of discontinuity whose nature suggests significant and/or repetitive tectonic displacement. These relations are not just the result of post-metamorphic displacements, although such late-stage displacements must be expected since earlier tectonic discontinuities must often be exploited by later events.

In terms of the two specific questions posed in the introduction (§1*a*) to this paper, we particularly suggest that closely spaced sets of metamorphic zones of medium- to high-pressure facies series are often partly a tectonic boundary phenomenon, reflecting significant lateral heat flow at the margins of relatively discrete crustal blocks. Such zones neither reflect temperature distributions, which are purely depth controlled, nor do they typify the metamorphic evolution of the interiors of crustal blocks away from the tectonic boundaries. The dimensions of well-developed sets of metamorphic zones is commonly far from comparable, in either width or depth, with that of orogenic belts as a whole, and such zones are not appropriate models of metamorphism on the large scales considered by England (this symposium).

Following from the recognition of the importance of tectonic boundaries and associated discontinuities, it is suggested that orogenic belts may often be subdivided by such boundaries into a series of tectono-metamorphic domains or provinces. Such domains have been suggested for the Scottish Dalradian terrane (figure 2) by Harte (1986), and the fact that these may sometimes be detected in a wide variety of data (stratigraphic, structural, geophysical, magmatic, metamorphic) has been emphasized by Fettes *et al.* (1986). The boundaries of the domains commonly appear to be steeply orientated zones of discontinuities, which have propagated upwards through the crustal pile, probably as a result of initial basement (*sensu lato*) control of major tectonic lineaments; they may retain considerable influence even though they may have been overridden during nappe development.

The metamorphic facies developed within a domain are a function of the nature (e.g. heat-generating capacity, conductivity) of its crustal rock pile, together with heat introduction from beneath, and tectonic history. This means that the metamorphic facies of a domain may form an integrated expression of both basement characteristics and long-term aspects of the sedimentological, igneous and structural history of the domain.

In the Scottish Dalradian the larger well-defined domains, such as the southwest Highlands, appear to be about 100 km across. Some small (less than 20 km across) domains, such as the type area of Barrow's zones (southeast Highlands) are probably really broad tectonic boundary zones. In the Acadian of New England (figure 3) the Merrimack synclinorium, varying from about 50–150 km across, appears to be a good example of a tectono-metamorphic domain. It is within the centres of such domains, where metamorphic grade often shows relatively little lateral variation, that we should seek to determine the metamorphic history of major crustal segments, not within the conspicuous metamorphic zones at their margins.

(*b*) *Inverted metamorphic zones*

Metamorphic zones showing grade increasing upwards may sometimes be readily explained by special local heat sources: e.g. overthrusts of unusually hot material as in the case of some ophiolite bodies (Jamieson 1980; Spray & Williams 1980) or shear heating (Graham & England 1976). Where there is no special local heat source, explanation of the zones in terms of upside-down thermal gradients in rocks is difficult, because the inverted gradients generated by overthrusting or recumbent folding of normal crust are not expected to be preserved (Oxburgh & Turcotte 1974; England & Richardson 1977). In the situations where a sufficient local heat source is not apparent, then attention turns to the question of whether syn- or post-metamorphic folding is responsible and it is upon this aspect that we wish to comment.

In some cases, syn- and post-metamorphic folding has been strongly advocated as causing, or at least playing a part in, rotation of the metamorphic zones (Harte & Hudson 1979; Mason 1984; St-Onge & King, this symposium). In other cases, such upside-down rotation of metamorphic zones, which are freezing into or have already frozen into the rocks, has been denied. Certainly in specific instances, such as the Balquhidder inversion in the central Scottish Highlands (Chinner 1978; Watkins 1985), there is no apparent evidence for a post-metamorphic structural rotation. However, in more general terms, Watkins (1985) has noted that regional metamorphism is often subsequent to nappe and thrust formation in orogenic belts, and has used this relation to argue that where inverted metamorphic zones are present in such belts then they must reflect the existence of upside-down thermal gradients. This argument implies that only recumbent folds or nappes can cause sufficient rotation to invert the metamorphic zones. We believe that this is not necessarily the case. If metamorphic zones may initially form as we have suggested with moderate normal dips, then the rotation needed to invert them at moderate angles is far less, and might be accomplished by the more-open folds and dome-uplift structures that appear common in the later phases of evolution of orogenic belts (Robinson 1979; Bradbury 1985). Where differential uplift follows the trend of a tectonic boundary that was active during metamorphism and affected the formation of metamorphic zones, then the vertical displacement subsequent to crystallization of those zones might readily cause their inversion. This seems to be the case next to the Highland Boundary fault in Barrow's type area (Harte & Hudson 1979). It is suggested that vertical movement associated with the formation of the Bronson Hill anticlinorium may have contributed to overturning of the metamorphic zones adjacent to that structure (Thompson *et al.* 1968; Robinson 1983).

(*c*) *Lateral heat transfer and P–T arrays of paired metamorphic belts*

In the consideration (§3) of simple models of heat transfer across tectonic boundaries, we noted that effects of such continuous transfer will become greater as one goes to greater depths in the original crustal piles. Thus the influence of lateral heat transfer on the temperatures and pressures of metamorphism recorded by a crustal pile should be more apparent in the higher-grade than lower-grade rocks. As previously noted, such lateral heat flux would generally be expected to cause relative cooling in the more-rapidly uplifting block. Clearly the extent of this heat transfer in both time and space will depend greatly on the thermal properties of the crustal blocks on either side of the tectonic discontinuity as well as the magnitude of their differential uplift. However, in the simple one-dimensional thermal models this history of relative heating and cooling would be recorded as subtle and complimentary curvature of piezothermic arrays formed on either side of the discontinuity. An infinite variety of relative heating–cooling histories between adjacent terranes may be envisaged, but we will just consider the likely effects of heat transfer on *P*–*T* arrays in one general case: that of paired metamorphic belts (Miyashiro 1961).

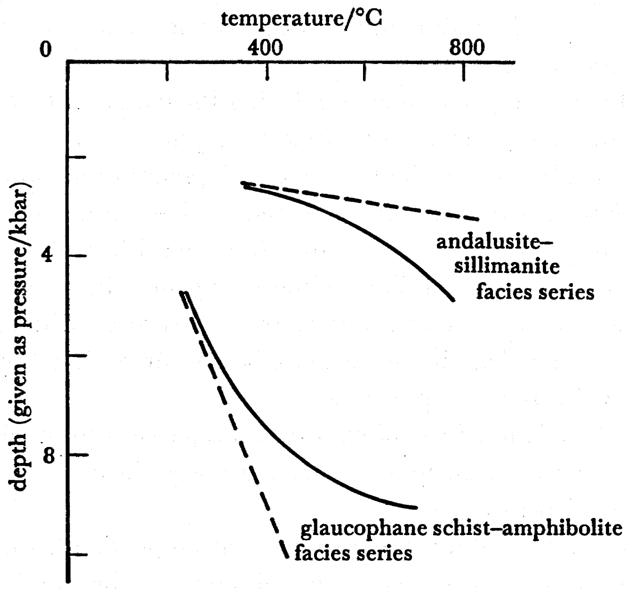

FIGURE 6. Schematic illustration of the possible effect of lateral heat flux on *P*–*T* arrays for adjacent andalusite–sillimanite and glaucophane schist–amphibolite metamorphic belts. The broken lines show the *P*–*T* arrays without lateral heat flux, the solid lines show the *P*–*T* arrays with lateral heat flux.

In paired metamorphic belts, lateral heat transfer across the major tectonic boundary will be from the high-temperature and low-pressure (often andalusite–sillimanite facies series) terrane, to the low-temperature and high-pressure (glaucophane schist–amphibolite facies series) terrane. With the effect of this heat transfer becoming greater with time and therefore having most effect on the higher grade parts of both terranes, it may cause curvature of the $P-T$ arrays of the facies series (or piezothermic arrays if related to one-dimensional thermal models). The expected results of the lateral heat transfer would therefore be to particularly increase temperatures at high grades in the glaucophane schist–amphibolite terrane, and decrease them at high grades in the andalusite–sillimanite terrane. Thus the curved $P-T$ arrays would be respectively markedly concave and convex to the temperature axis (figure 6). Such marked curvature is certainly indicated for some glaucophane schist–amphibolite terranes (Turner 1981, figure 11-6; Bell & Brothers 1985). However, where subsequent tectonic movement (often major strike-slip) has modified the disposition of crustal units since metamorphism, it becomes difficult to decide whether the lateral heat flux generating the curvature is of a regional origin, as here proposed, or of more local (hot body) origin. In either case, however, lateral heat flux provides a necessary explanation of the curvature, because marked concave to temperature axis curvature is not typical of piezothermic arrays (England & Thompson 1984). In andalusite–sillimanite terranes the possible curvature of the temperature–pressure path is not so clear because of the common influence of magmatic bodies at high grade.

6. CONCLUSIONS

Examination of the conditions of formation of metamorphic rocks and their cooling histories in parts of orogenic belts showing well-developed regional metamorphic zones shows the following.

1. Temperature may vary laterally as well as being a function of depth.
2. Tectonic displacement, including uplift, may vary across a set of metamorphic zones and be recorded in the mineral assemblages.
3. Depth of burial (pressure) may increase during the course of formation of metamorphic mineral assemblages in some parts of a set of metamorphic zones.
4. Uplift may be episodic during the time of development of metamorphic zones.

Taken together these features imply that the $P-T-t$ paths of rocks within a set of metamorphic zones may be quite variable, and that lateral heat flux must occur during the formation of the metamorphic mineral assemblages and may be caused by tectonic displacement. Thus comparison of the set of pressure–temperature conditions seen within a set of metamorphic zones with the piezothermic array of a one-dimensional thermal model based on uniform block uplift will rarely be appropriate.

Using a simple model of the effects of continuous relative tectonic displacement (differing magnitudes of uplift) across a steep tectonic boundary during metamorphism (figure 5) illustrates the following features.

(i) The disturbance of the metamorphic zones from simple depth control, as a consequence of lateral heat flux across a tectonic boundary, will normally become greater as one descends to deeper levels of the initial crustal pile (i.e. it will become greater with increasing grade of metamorphism because the later-formed higher-grade assemblages will have experienced lateral transfer of heat over a longer time period).

(ii) At any one time, the principal metamorphic mineral assemblages will be freezing into the rocks at a particular depth (assuming that these assemblages reflect the maximum temperature conditions experienced by each rock). Above this depth, the metamorphic mineral assemblages will already have frozen into the rocks and all subsequent tectonic displacement will be post-metamorphic for these shallower levels.

(iii) All metamorphic rocks must pass through the shallower levels of post-metamorphic displacement in reaching the Earth's surface, and thus post-metamorphic discontinuities along the tectonic boundary are always likely. There will be a problem in disentangling the changes in metamorphic grade across a tectonic discontinuity that are syn-metamorphic from those that are post-metamorphic.

(iv) Where lateral heat flux affects a rock column within which metamorphic mineral assemblages are forming, the effects of that lateral heat flux will be recorded at the particular depth where 'freezing-in' of the mineral assemblages is occurring. Since metamorphic zones are defined by sets of frozen mineral assemblages they must record the lateral heat flux if it occurs.

(v) For lateral heat flux across a tectonic boundary to have a conspicuous effect on the pattern of metamorphic zones, some combination of the following will be necessary: (1) continuous or repetitive tectonic displacement; (2) differences in the basic thermal properties of the crustal blocks on either side of the boundary.

Consideration of the distribution of medium- and high-pressure metamorphic zones and facies series suggests the following.

(*a*) The pattern of distribution of metamorphic zones often reflects that of major tectonic and geological boundaries.

(*b*) Narrowly spaced sets of well-developed metamorphic zones may be boundary phenomena at major tectonic discontinuities. Smaller, but still significant, tectonic boundaries may show as changes of orientation of metamorphic zone distributions.

(*c*) Tectonic boundaries separate a series of tectono-metamorphic domains, each of which is a product of its own distinctive crustal rock pile and tectonic evolution. The general wide-ranging metamorphic histories of these tectono-metamorphic domains should be sought in their interiors not in the narrow metamorphic zones at their boundaries.

(*d*) Inverted metamorphic zones may be formed by post-metamorphic tectonic angular rotations of less than 90° if the zones dipped at inception due to crystallization under conditions of lateral heat flux.

(*e*) Significant long-term lateral heat flux across a major tectonic boundary may cause marked curvature in pressure–temperature space of the set of conditions of metamorphism recorded by the rocks. In the case of paired metamorphic belts, the facies series of the glaucophane schist–amphibolite belt may be markedly concave to the temperature axis, while the facies series of the andalusite–sillimanite belt may be markedly convex to the temperature axis.

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REFERENCES

Adams, C. J. & Gabites, J. E. 1985 *N.Z. Jl Geol. Geophys.* **28**, 85–96.

Ashcroft, W. A., Kneller, B. C., Leslie, A. G. & Munro, M. 1984 *Nature, Lond.* **310**, 760–762.

Atherton, M. P. 1977 *Scott J. Geol.* **13**, 331–370.

Baker, A. J. 1985 *J. geol. Soc. Lond.* **142**, 137–148.

Baker, A. J. & Droop, G. T. R. 1983 *J. geol. Soc. Lond.* **140**, 489–498.

Barrow, G. 1893 *Q. Jl geol. Soc. Lond.* **49**, 303–358.

Barrow, G. 1912 *Proc. Geol. Ass.* **23**, 268–273.

Becke, F. 1903 *Compte rendu, IX: Session du congrès géologique internationale (Vienne)*, part 2, pp. 553–570.

Bell, T. H. & Brothers, R. N. 1985 *J. metamorph. Geol.* **3**, 59–78.

Bluck, B. J. 1984 *Trans. R. Soc. Edinb.* **75**, 275–295.

Bradbury, H. J. 1985 *J. geol. Soc. Lond.* **142**, 129–136.

Bradbury, H. J. & Nolen-Hoeksema, R. C. 1985 *Tectonics* **4**, 187–211.

Bucher-Nurminen, K., Frank, E. & Frey, M. 1983 *Am. J. Sci.* A **283**, 370–395.

Carslaw, H. S. & Jaeger, J. C. 1967 *Conduction of heat in solids*. Oxford: Clarendon Press.

Chamberlain, C. P. 1986 *J. Petr.* **27**, 63–89.

Chinner, G. A. 1966 *Q. Jl geol. Soc. Lond.* **122**, 159–186.

Chinner, G. A. 1978 *Geol. Mag.* **115**, 37–45.

Chinner, G. A. 1980 *J. geol. Soc. Lond.* **137**, 35–39.

Dempster, T. J. 1983 Studies of orogenic evolution in the Scottish Dalradian. Ph.D. thesis, University of Edinburgh.

Dempster, T. J. 1984 *Nature, Lond.* **307**, 156–159.

Dempster, T. J. 1985 *J. geol. Soc. Lond.* **142**, 111–128.

Dempster, T. J. 1986 *Earth planet. Sci. Lett.* (In the press.)

Dempster, T. J. & Harte, B. 1986 *Geol. Mag.* **123**, 95–104.

Elles, G. L. & Tilley, C. E. 1930 *Trans. R. Soc. Edinb.* **61**, 621–646.

England, P. C. 1978 *Tectonophysics* **46**, 21–40.

England, P. C. & Richardson, S. W. 1977 *J. geol. Soc. Lond.* **134**, 201–213.

England, P. C. & Thompson, A. B. 1984 *J. Petr.* **25**, 894–928.

Fettes, D. J., Long, C. B., Max, M. D. & Yardley, B. W. D. 1984 *Grade and time of metamorphism in the Caledonide Orogen of Britain and Ireland. Mem. geol. Soc. Lond.* no. 9.

Fettes, D. J., Graham, C. M., Harte, B. & Plant, J. A. 1986 *J. geol. Soc. Lond.* **143**. (In the press.)

Fisher, G. W. 1980 *Abstr. Progm. Am. geol. Soc.* **12**, 426.

Frey, M., Bucher, K., Frank, E. & Mullis, J. 1980 *Eclog. geol. Helv.* **73**, 527–546.

Graham, C. M. 1986 *Scott. J. geol.* (In the press.)

Graham, C. M. & England, P. C. 1976 *Earth planet. Sci. Lett.* **31**, 142–152.

Graham, C. M., Greig, K. M., Sheppard, S. M. F. & Turi, B. 1983 *J. geol. Soc. Lond.* **140**, 577–579.

Grubenmann, V. 1904 *Die Kristallinen Schiefer.* (105 pages.) Berlin: Gedrüder Bornträgger.

Gubler, E. 1976 *Schweiz. miner. petrogr. Mitt.* **56**, 675–678.

Hall, J. 1985 *J. geol. Soc. Lond.* **142**, 149–155.

Harker, A. 1932 *Metamorphism. A study of the transformation of rock masses.* (360 pages.) London: Methuen.

Harte, B. 1986 In *The Caledonian–Appalachian Orogen* (ed. A. L. Harris & D. J. Fettes). *Geol. Soc. Lond., spec. Publ.* (In the press.)

Harte, B. & Hudson, N. F. C. 1979 In *The Caledonides of the British Isles – reviewed* (ed. A. L. Harris, C. H. Holland & B. E. Leake), pp. 323–334. Geological Society of London.

Harte, B., Booth, J. E., Dempster, T. J., Fettes, D. J., Mendum, J. R. & Watts, D. 1984 *Trans. R. Soc. Edinb.* **75**, 151–163.

Holdaway, M. J. 1971 *Am. J. Sci.* **271**, 97–132.

Hunziker, J. C. 1970 *Eclog. geol. Helv.* **63**, 151–161.

Hurford, A. J. 1986 *Contr. Miner. Petr.* **92**, 413–427.

Jamieson, R. A. 1980 *Geology* **8**, 150–154.

Kennedy, W. Q. 1948 *Geol. Mag.* **85**, 229–234.

Labhart, T. P. & Rybach, L. 1976 *Schweiz. miner. petrogr. Mitt.* **56**, 669–673.

McLellan, E. 1985 *J. Petr.* **26**, 789–818.

Mason, R. 1984 *J. metamorph. geol.* **2**, 77–82.

Miyashiro, A. 1961 *J. Petr.* **2**, 277–311.

Miyashiro, A. 1973 *Metamorphism and metamorphic belts.* (492 pages.) London: Allen & Unwin.

Nakajima, T. 1982 *Lithos* **15**, 267–280.

Müller, S., Ansorge, J., Egloff, R. & Kissling, E. 1980 *Eclog. geol. Helv.* **73**, 463–483.

Niggli, E. 1970 *Fortschr. Miner.* **47**, 16–26.

Niggli, E. 1978 *Metamorphic map of the Alps.* (62 pages.) Leiden: Unesco.

Osberg, P. H. 1978 *Geol. Surv. Pap. Canada*, **78–13**, 137–147.

Oxburgh, E. R. & Turcotte, D. L. 1974 *Schweiz, Miner. Petrogr. Mitt.* **54**, 641–662.

Powell, R. & Evans, J. 1983 *J. metamorph. Geol.* **1**, 331–336.

Purdy, J. W. & Jäger, E. 1976 *Memorie Inst. geol. miner. Univ. Padova*, **30**, 1–31.

Richardson, S. W. 1970 *Fortschr. Miner.* **47**, 65–76.

Richardson, S. W. & Powell, R. 1976 *Scott. J. Geol.* **12**, 237–268.

Richardson, S. W., Gilbert, M. C. & Bell, P. M. 1969 *Am. J. Sci.* **267**, 259–272.

Robinson, P. 1979 In *Guidebook, Caledonides in the U.S.A., excursions in the northeast Appalachians* (ed. J. H. Skehan & P. M. Osberg), pp. 126–174. Boston College.

Robinson, P. 1983 In *Regional trends in the geology of the Appalachian–Caledonian–Hercynian–Mauritanide Orogen* (ed. P. E. Schenk), pp. 249–258. Dordrecht: D. Reidel.

Robinson, P. & Hall, L. M. 1980 In *The Caledonides in the U.S.A.* (ed. D. R. Wones), pp. 73–82. Virginia Polytechnic Institute, Memoir 2.

Spray, J. G. & Williams, G. D. 1980 *J. geol. Soc. Lond.* **137**, 359–368.

Thompson, J. B. Jr & Norton, S. A. 1968 In *Studies of Appalachian geology; northern and maritime* (ed. E-an Zen, W. S. White, B. J. Hadley & J. B. Thompson, Jr), pp. 319–327. New York: John Wiley & Sons.

Thompson, J. B. Jr, Robinson, P., Clifford, T. N. & Trask, N. J. Jr 1968 In *Studies of Appalachian geology; northern and maritime* (ed. E-an Zen, W. W. White, B. J. Hadley & J. B. Thompson, Jr), pp. 203–218. New York: John Wiley.

Thompson, P. H. 1976 *Contr. Miner. Petr.* **57**, 277–295.

Tracy, R. J. & Robinson, P. 1980 In *The Caledonides in the U.S.A.* (ed. D. R. Wones), pp. 189–195. Virginia Polytechnic Institute, Memoir 2.

Tracy, R. J., Robinson, P. & Thompson, A. B. 1976 *Am. Miner.* **61**, 762–775.

Turner, F. J. 1981 *Metamorphic petrology*. (5243 pages.) New York: McGraw-Hill Book Company.

Wagner, G. A., Reimer, G. J. & Jäger, E. 1977 *Memorie Inst. geol. miner. Univ. Padova*, **30**, 1–27.

Watkins, K. P. 1985 *J. geol. Soc. Lond.* **142**, 157–165.

Wellman, H. W. 1979 In *The origin of the Southern Alps* (ed. R. I. Walcott & M. M. Cresswell), *Bull. R. Soc. N.Z.* **18**, 55–66.

Wenk, E. 1970 *Fortschr. Miner.* **47**, 34–51.

Zen, E-an 1983 In *Contributions to the tectonics and geophysics of mountain chains* (ed. R. D. Hatcher, Jr, J. Williams & I. Zietz), pp. 55–81. *Geol. Soc. Am.*, Memoir 158.