The Pachmarhi Regional metamorphic zone: tectonic controls

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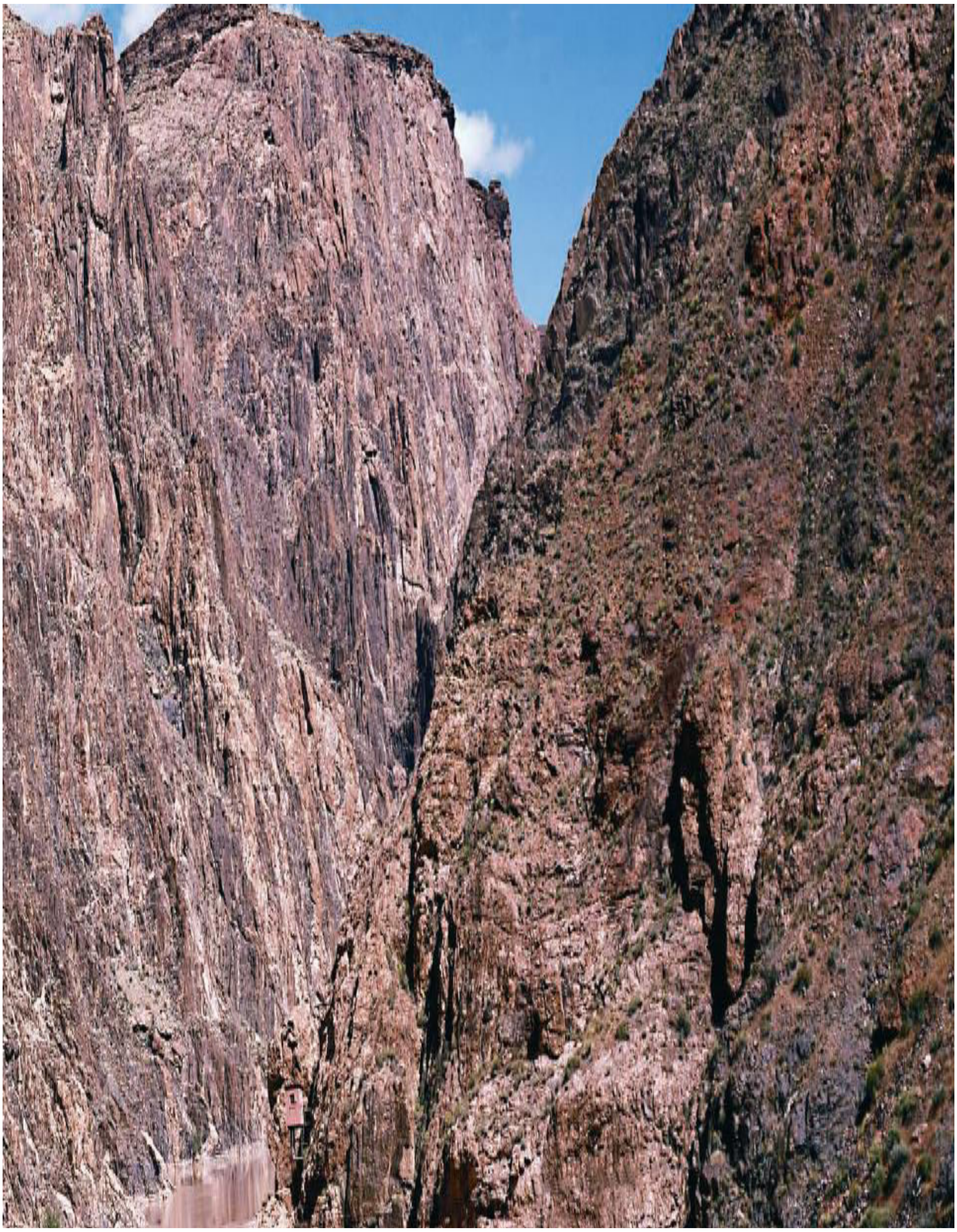

ABSTRACT - Factors governing the development of well-characterized metamorphic zones in orogenic belts, showing moderate to high-pressure regional metamorphism are considered. Features recorded in the rocks concerning: variations of temperature with pressure (both across

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 Mahadeva-Satpura 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 Mahadeva, 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, as 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 Mahadeva. Tectono-metamorphic domains may be recognized at those 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.

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, (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 developed Gondwana sequences of metamorphic zones in the Pachmarhi belt of Satpura. The metamorphic rocks may be divided into three main divisions: (1) A very ancient granitic-gneiss, (2) A calcareous group overlying this, and (3) A much more recent formation character is by the presence of banded quartz-hematite or quartz-jasper rocks. Groups (1) and (2) have been subjected to great pressure which has folded them into minute folds with an $E.N.E.$ strike. Group (3) occurs only in the gorges and is said to be less folded. Unfortunately, I have been unable to see it myself. In addition to the main groups there are epidiorite, and pegmatite intrusions, which have also been in most cases crushed, and rolled out.

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.

Geotherms, time and thermal models of acrogenic 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 dP/dT increasing with depth (pressure), metamorphic zones commonly show dP/dT 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 a range depth, the piezothermic array, should be compared with the temperature-pressure-time 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 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 organic 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.

Approach

Ideally, the answers to the questions posed in 1a 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 (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 the Pachmarhi a part of Satpura.

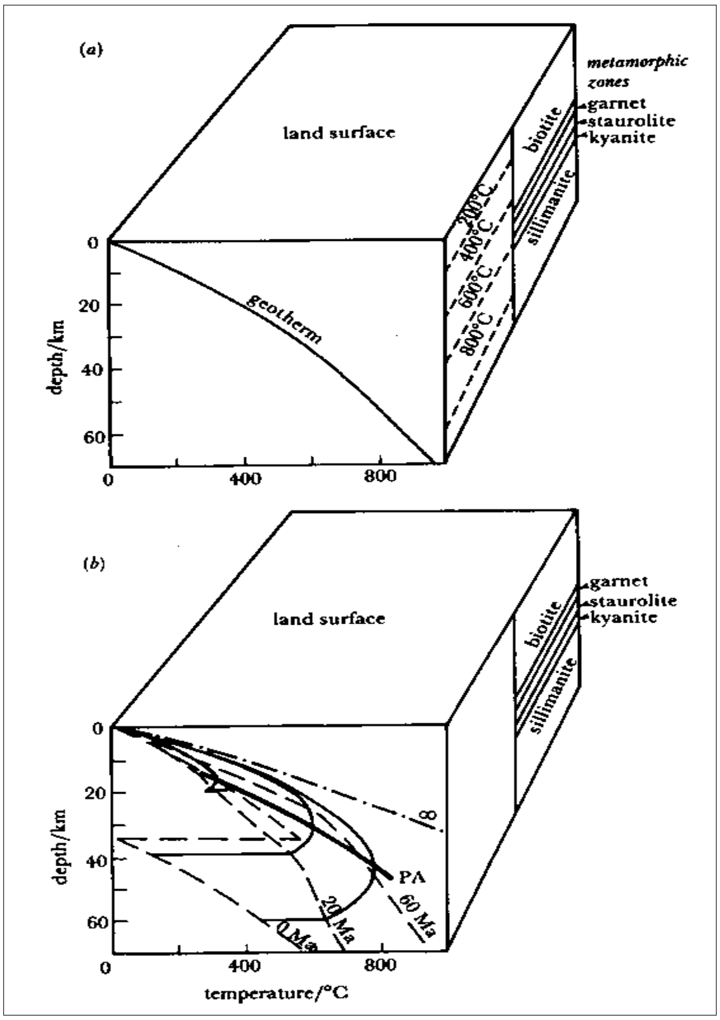

Figure 1 . Diagrams of crustal blocks illustrating interpretations of metamorphic zones, (a) Zones interpreted in relation to a single geotherm (on front face) with isotherms and resultant zones shown on side face, (b) Zones interpreted as product of thermal evolution after crustal thickening by thrusting 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 1a).

Metamorphic development

Leaving aside the Pachmarhi area of lower pressure metamorphism in the south and south -east, the broadly zonal assemblages show a generalized continuity, to view the zones as part of a coherent depth-related thermal structure extending across the Pachmarhi. In so far as my vision involved viewing the zones throughout the Pachmarhi Highlands as being capable of representation by a single vertical rock column(Fig;2,3 and 4), it is analogous to interpreting the whole metamorphic zonal pattern as reflecting a single piezothermic array in a thermal model.

Simple model of the Pachmarhi 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 Pachmarhi Mahadeva.

Figure 2 . The zones throughout the Pachmarhi 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.

Figure 3. The Pachmarhi 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.

Figure 4 . The zones throughout the Pachmarhi 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.

Figure 5 . 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 Pachmarhi Satpura zones, near the Highland boundary fault in the south with the south eastern area.

Figure 6 . Kala Pathar : The strong temperature gradient in Pachmarhi classic area appears to have formed at an oblique angle to vertical depth.

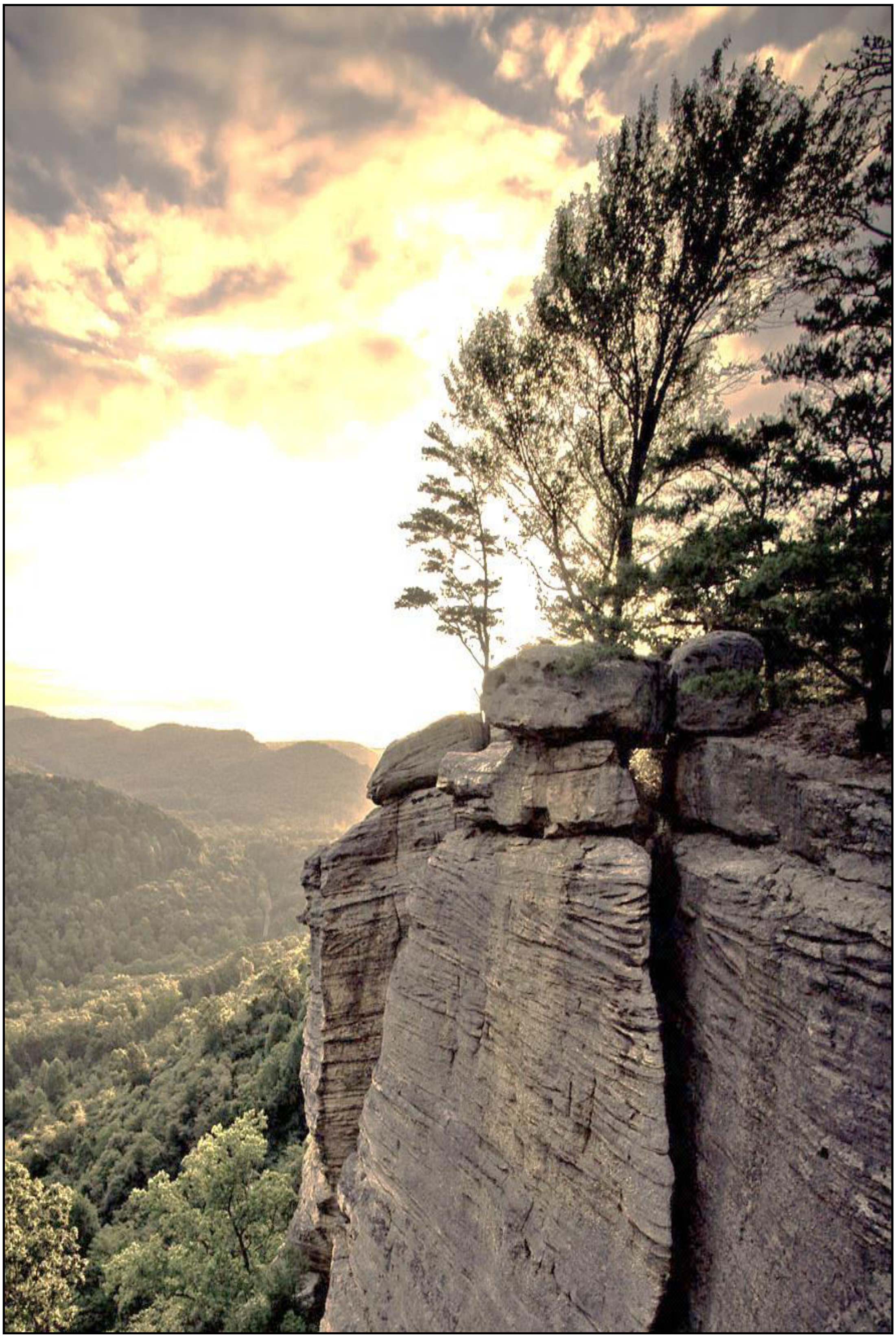

Figure 7. Mahadeva : Uplift did not occur uniformly through time, but with phases of little uplift, alternating with relatively rapid uplift. Thus the rocks show inflexions rather than smooth curves.

Figure 8 . The western margin of the classic area of the Pachmarhi grade at an oblique angle to the main trend of the zones.

Satpura 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 metamorphic belt. This is particularly manifest on comparing the original classic area of the Mahadeva and of Pachmarhi Satpura zones near the Highland boundary fault in the

south with the south western area (Figure 5). In the former area, the whole spectrum of chlorite to sillimanite grades ($400 - 650$°C) occurs with pressure estimates mainly around $6kbarf$. 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. $10kbar$ for the southwest Highlands, while estimates on the same basis for the area in the southeast Highlands are ca. $7kbar$.

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 $NW - SE$, and thus the strong temperature gradient in Pachmarhi classic area appears to have formed at an oblique angle to vertical depth (Figure 6). The probable overturning of metamorphic isotherms and isobars immediately adjacent to the Highland boundary fault is metamorphic isotherms and isobars immediately adjacent to the Highland boundary fault is most probably post-metamorphic.

3. The uplift history documented by radiometric dating of minerals across Pachmarhi zones shows that(i) Uplift did not occur uniformly through time, but with phases of little uplift alternating with relatively rapid uplift. Thus the $\mathrm{P - T — t}$ paths of the rocks show inflexions rather than smooth curves (Figure 7). (ii) Uplift histories are not uniform across the zones and furthermore in the Pachmarhis 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 Pachmarhi–Satpura metamorphic mineral assemblages for individual rocks document an increase in pressure during the time of their development rather than the steadily falling pressures of the thermal model $\mathrm{P - T — t}$ paths. This increase in pressure appears to be related to the development of the steep belt. Increasing pressure during metamorphism is also shown in the replacement of andalusite by kyanite near Dhupgarh–Mahadeva–Chauragarh–Tamia Patalkot lineament.

5. The western margin of the classic area of the Pachmarhi zones shows relatively rapid change in metamorphic grade at an oblique angle to the main trend of the zones, with possibly inverted metamorphic zonation near Golandoh. This margin to the high grade region of the zones (Figure 8).

In the western part of the central area near Somgarh, Crookshank has found support from Fox for this controversial recognition of inverted metamorphic zones, although the cause of their inversion is uncertain.

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 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 modeling 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 modeling, 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 9), 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 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 1b). Thus they represent piezothermic arrays controlled by the thermal parameters. 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 9) represent 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 (Figure 9), 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 9) 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 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 9). 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 9), 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 9 a may be enhanced in several ways as already partly indicated.

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 9 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 behavior 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.

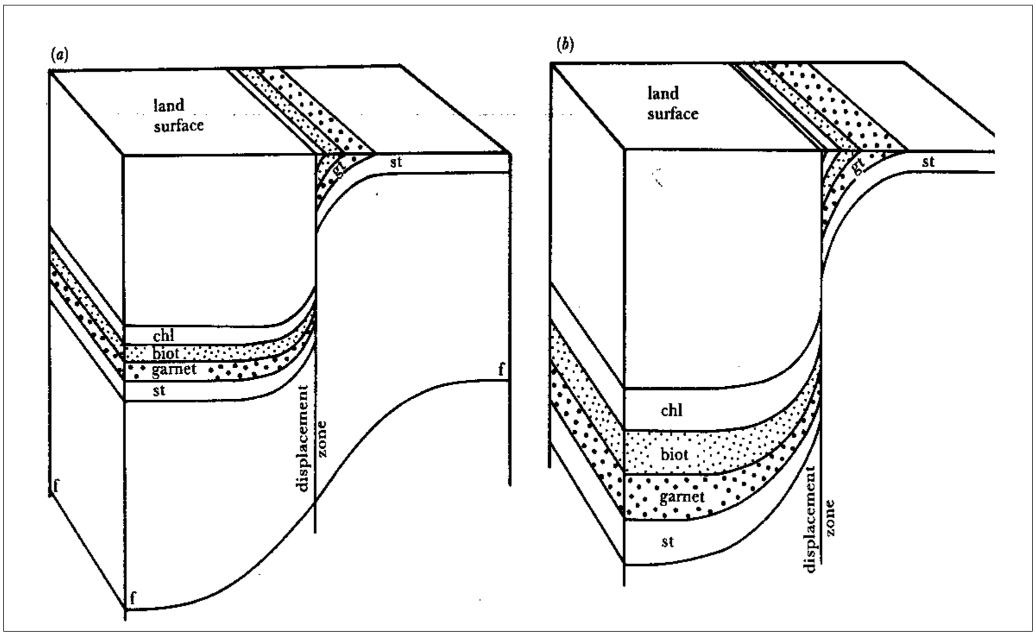

Figure 9. Schematic illustrations of metamorphic zones formed in adjacent crustal blocks having differing rates of continuous uplift. In each diagram the right-hand crustal block has the greater uplift rate and the zone of displacement between the two blocks is shown as a simple 'fault' surface; 'chl', '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 crystallization 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 $1.6\mu W\ m^{-3}$; conductivity $2\ Wm^{-1}K^{-1}$; 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 (0), but the left-hand block has: heat production of $.8\ Wm^{-3}$, conductivity of $2.5\ Wm^{-1}K^{-1}$, with a heat flux at the lower boundary of $24\ mWm^{-2}$. 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).

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 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 (1a) 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

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 Satpura terrane (figure 2, 3, 4 and 5), and the fact that these may sometimes be detected in a wide variety of data (stratigraphic, structural, geophysical, magmatic, metamorphic). 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 Pachmarhi larger well–defined domains, such as the southwest Highlands, appear to be about 100 kilimeter across. Some small (less than $20km$ across) domains, such as the type area of the zones (southeast Highlands) are probably really broad tectonic boundary zones. In the Satpura synclinorium, varying from about $50 - 100\ km$ across appears to be good example of a tectono–metamorphic domain, 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.

Inverted metamorphic zone

Metamorphic zones showing grade, increasing upwards may sometimes be readily explained by special local heat sources: e.g.over thrusts 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 over thrusting 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); 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 Pachmarhi inversion in the central Pachmarhi Highlands (Figure 10 and 11), 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 oderate 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).

Figure 10 . Jatashankar : Lateral heat transfer across the major tectonic boundary will be from the high–temperature and low–pressure terrane, to the low–temperature and high–pressure 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 inverted fault.

Figure 11. Handikhoh: Lateral heat transfer across the major tectonic boundary will be from the high-temperature and low-pressure terrane, to the low-temperature and high-pressure 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 inverted fault.

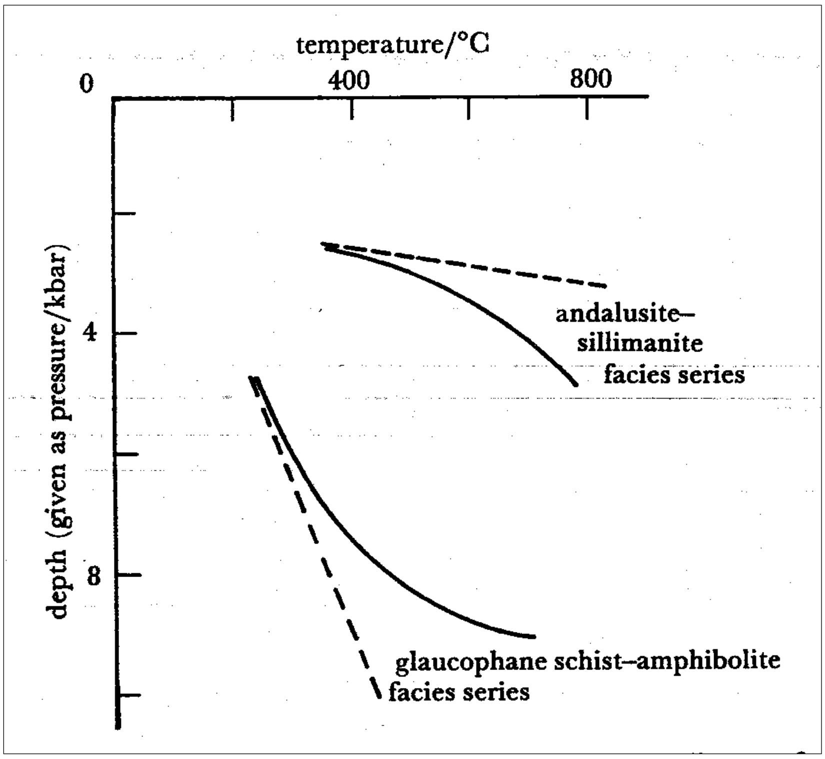

Figure 12 . Schematic illustration of the possible effect of lateral heat flux on *P* - *T* arrays for adjacent and alusite-sillimanite and glaucophane schist-amphibolite metamorphic belts. The broken lines show the *P* - *T* arrays without lateral heat flux, the solid lines show the *P* - *T* arrays with lateral heat flux.

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 Pachmarhi type area (Harte and Hudson 1979). It is observed that vertical movement associated with the formation of the Pachmarhi Hill anticlinorium may have contributed to overturning of the metamorphic zones adjacent to that structure.

Lateral heat transfer and P - T arrays of paired metamorphic belts

The 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). 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 $\mathrm{P-T}$ arrays of the facies series (or piezothermic arrays 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

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.

5. 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 figures illustrates the following features.

a. 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).

b. 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.

c. 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.

d. 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.

e. 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 high-pressure metamorphic zones and facies series suggests the following:-

1. The pattern of distribution of metamorphic zones often reflects that of major tectonic and geological boundaries.

2. 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.

3. 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.

4. 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.

5. 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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