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Deep crustal metamorphism during continental extension: modern and ancient examples

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Granulite facies metamorphism in the lower levels of continental crust which is undergoing extension is indicated by unusually high heat flow in modern-day extensional regimes. For certain geometries of extension, particularly those involving crustal-penetrative detachment zones, this metamorphism may occur on a regional scale. The predicted pressure-temperature-time (P-T-t) paths for such metamorphism involve heating into the granulite facies at constant or decreasing pressure during extension, followed by cooling at constant or increasing pressure after extension stops, and thus they differ considerably from P-T-t paths of metamorphic terrains formed by continental convergence. Many granulite terrains from both the Precambrian and Phanerozoic record preserve P-T-t paths which involve substantial, essentially isobaric, cooling. In such terrains granulite facies metamorphism is typically associated with recumbent structures characterised by subhorizontal stretching lineations which are attributed to intense non-coaxial deformation. Such deformation may be expected for the deep crustal expression of detachment zones. These terrains may provide ancient examples of deep crustal metamorphism during extensional tectonics.

1. Introduction

Extensional tectonics is attracting widespread interest in the geological community, and geologists, in particular structural geologists, have begun to investigate the features which may be considered diagnostic of ancient extensional tectonic regimes [1]. Recently, extension associated with continental rifting has been proposed as a mechanism for the generation of high-T/low-P metamorphic terrains [2–4], and there is now a need to define the criteria by which metamorphism associated with extensional tectonics may be distinguished from the metamorphism of the more familiar terrains of continental convergence zones. In this contribution we discuss the evidence for deep crustal metamorphism during continental extension, the pressure-temperature-time (P-T-t) paths associated with such metamorphism, and, finally, a number of examples of deep crustal metamorphism which may have been associated with extensional tectonics.

The observation that heat flow through continental crust in modern extensional environments, such as the Basin and Range Province and the Aegean Sea, is much greater than the heat flow typical of stable continental crust [5,6] is most important because it suggests that the lowermost crust in these regions is experiencing granulite facies metamorphism. For example, the "reduced" heat flow [7] through the Basin and Range Province in Central-West U.S.A. is 50–100% greater than the "reduced" heat flow in stable regions of the North American craton, and, in areas such as the Battle Mountain high, the "reduced" heat flow is up to 300% greater [5]. These higher "reduced" heat flows correspond to an increase in temperature at 30 km depth from 450–500°C beneath stable cratons, to 700–900°C beneath most of the Basin and Range Province, to temperatures in excess of 1000°C beneath the Battle Mountain high [5]. At these depths, the amphibolite facies to granulite facies transition occurs at temperatures in the vicinity of 700°C, due to dehydration reactions involving the breakdown of biotite and hornblende, and, very probably, the production of granitic melts [8]. The calculated temperatures at the base of the crust in most of the Basin and Range Province are well in excess of those required for granulite facies metamorphism.

Dramatic increases in heat flow through extending continental crust are hardly surprising. As

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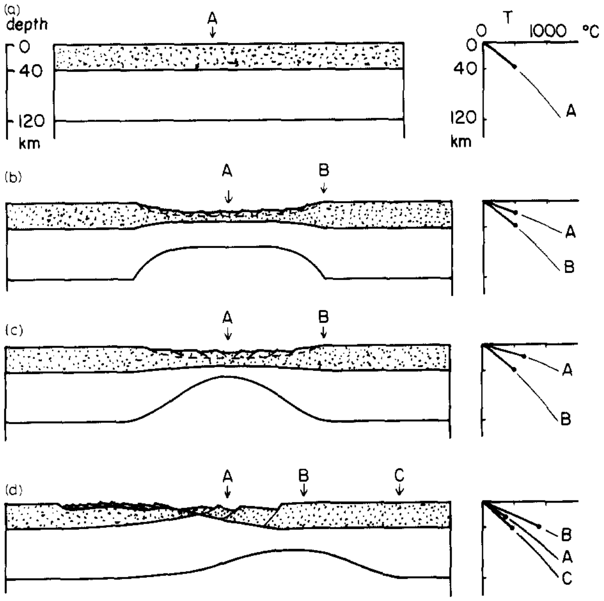

Fig. 1. Lithosphere cross-sections and geotherms. Crust is indicated by stippling in the cross-sections. The crustal geotherms are indicated by thick lines, whilst mantle lithosphere geotherms are indicated by thin lines. (a) "Normal" continental lithosphere structure, and the associated geotherm; note bottom crust temperature of about 500°C. (b) Axially symmetric extension with uniform pure shear of (a), with associated perturbed geotherm, *A*, in relation to unperturbed geotherm, *B*. The geotherm *A* is for no substantial convective heat transfer, so decompression, but no heating, is involved in the thinned lithosphere. (c) Axially symmetric extension with non-uniform shear of (a), with associated perturbed geotherm. Extensional strain is partitioned into the mantle lithosphere such that it thins more rapidly than the crust; consequently the geotherm involves both heating and decompression. (d) Asymmetric extension accommodated in the upper lithosphere by simple shear along a detachment zone, modified after [15]. Below the detachment zone, extensional strain is distributed in a ductile region of pure shear. Note that the most perturbed geotherm, *B*, occurs where the lithosphere is thinnest, and is therefore displaced from where the crust is thinnest, *A*.

illustrated by McKenzie [9], thinning of the continental lithosphere is a necessary corollary of crustal extension. Considering the lithosphere-asthenosphere boundary as the 1200°C isotherm, thinning of the lithosphere must necessarily result in a steepening of the lithosphere geotherm (Fig. 1). This steepening of the lithosphere geotherm consequent upon extension may be enhanced by two forms of convective heat transport. Firstly, the replacement of lithosphere by asthenosphere as the lithosphere thins may promote sufficient mantle melting, for example by adiabatic decompression, for melt segregation and loss upwards. This melt will be a most efficient transporter of heat into the lithosphere [10]. Secondly, if lower crustal temperatures are such that substantial melting of the lower crust takes place, then uprise will further steepen the crustal geotherm, promoting crustal metamorphism at higher levels in the crust. The controls on this process are the proportion of suitable lithologies for melting, and the slopes of the melting reactions. The pronounced positive dP/dT, as seems likely for the appropriate H_2O-absent reactions involved in granulite facies melting [8], will greatly enhance the ability of such melts to rise through the crust and hence contribute to further perturbation of the geotherm. The occurrence of both basaltic and silicic volcanic activity in modern extensional regimes, for example, the Basin and Range [11], confirms the existence of one or both of these processes, promoting convective heat transfer in extending lithosphere.

2. Hypothetical *P-T-t* paths for deep crustal metamorphism during continental extension

The tectonic interpretation of metamorphic rocks is greatly enhanced by a knowledge of the *P-T-t* paths which may be generated in different tectonic settings [12]. This is well illustrated by metamorphic rocks from Alpine and Caledonide terrains which exhibit clockwise *P-T-t* paths due to the interaction of, (1) a heat source involving a basal heat flux and a crustal radiogenic component, with (2), crustal thickening, induced by convergence, and (3) erosion, induced by the isostatic response of the over-thickened crust [12]. As briefly discussed by Thompson and England [13], *P-T-t* paths due to extension are likely to differ considerably from such convergence-related *P-T-t* paths. It is our aim in this paper to discuss in detail the nature of the paths expected during metamorphism of the deep crust in extensional regimes, and, in particular, to show how such paths may be expected to vary for different mechanical models of extension.

The mechanism of extension, which dictates the extent and geometry of lithospheric thinning, is central to the discussion of the thermal evolution of extensional terrains. Many extensional terrains are localised linear features, for example, grabens. The high heat flow regions associated with these are also localised, and clearly cannot be responsible for regional scale metamorphism [14]. They may, however, be responsible for more limited metamorphisms, for example the granulite massifs in the Pyrenees [2–4]. In contrast, the sort of extensional regime which has given rise to the Basin and Range Province, which extends over 1.3×10^6 km^2, is sufficient to promote lower crustal metamorphism on a regional scale. The profound asymmetry of terrains such as the Basin and Range Province is attributed to the influence of shallow-dipping detachment zones which penetrate, in places, as far as the Moho [15]. An important feature of the detachment zones is that they cause a regional variation in the depth at which extensional strain is accommodated [15]. In particular, they result in the region of most pronounced crustal thinning being considerably displaced from the region of minimum lithosphere thickness, and hence from the region where the crustal geotherm is most perturbed (Fig. 2). Importantly crustal extension, and, consequently, thinning, in the vicinity of the steepest geotherm may be minimal. In a region where lithosphere thinning is pronounced but crustal thickness remains constant, *P-T-t* paths are essentially isobaric during heating (Fig. 2). Towards the area of maximum crustal extension, the geotherm is progressively less perturbed, but the heating path will involve progressively more decompression. Obviously the temperatures reached in the lower crust will depend not only on position in relation to the structures accommodating extension, but also on the amount of extension and the duration of extension.

For axially symmetric models of crustal extension (Fig. 1b and 1c), the steepest geotherms will occur where the mantle lithosphere is thinnest, corresponding to the position of maximum crustal extension. In order to consider the nature of *P-T-t* paths associated with this geometry of extension, it is necessary to consider the role of convective heat transfer, and the nature of strain partitioning between the crust and lithosphere [16,17]. In the case of uniform extension with little or no convective heat transfer, extension will not be accompanied by heating, and the *P-T-t* paths will involve only decompression. Maximum decompression will be associated with maximum extension. However, if uniform extension is accompanied by convective heat transfer induced by decompression, as seems likely for substantial extension, heating of the crust may be induced during decompression. Maximum heating by such heat transfer should be associated with maximum decompression (Fig. 2). Similar *P-T-t* paths will occur for non-uniform extension with or without convective heat transfer, if the mantle lithosphere thins more rapidly than the crust (Figs. 1 and 2) as has been suggested for the Labrador Sea margin [16]. In contrast to asymmetric models of extension, there is no displacement between areas of thinnest crust and areas with highest lower crustal temperatures during axially symmetric extension. The diagnostic feature of *P-T-t* paths during axially symmetric extension will be that maximum temperatures will be associated with paths showing the greatest decompression. In the models shown in Fig. 1 we have considered only the effects of conductive heat transfer on the geotherm. Obviously this represents a limiting case, and, in the presence of substantial convective heat transfer through the lithosphere via magmas, geotherms will be more perturbed than illustrated in Fig. 1. The magnitude of this additional perturbation will depend on the nature and amount of the resulting magmatic accretion to the crust.

While prograde metamorphic paths are obviously important in understanding metamorphism, they are very difficult to deduce from rocks, particularly high-temperature rocks, because assemblages tend to equilibrate readily and increase their grain size with increasing temperature, and hence preserve little mineralogical evidence of the prograde path. In contrast, high-temperature metamorphic rocks such as granulites commonly preserve evidence of the retrograde *P-T-t* path [18–21] because equilibration is greatly reduced during cooling. Before considering the origin of ancient granulite terrains, it is therefore useful to consider the hypothetical deep crustal cooling paths of extensional terrains such as the Basin and Range province. The cessation of extension and the removal of the thermal anomaly associated with extension will, of course, result in a large reduction in heat flow, with the geotherm returning to a stable one (Fig. 2). This geotherm may differ from the original pre-extension geotherm if

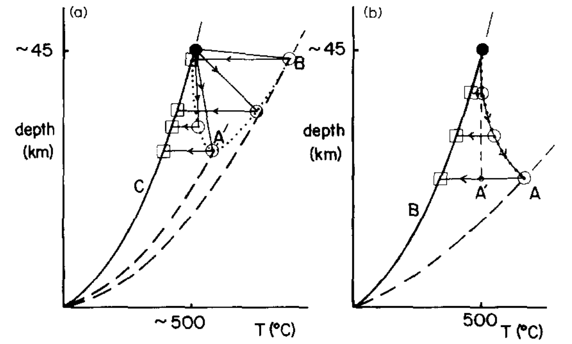

Fig. 2. Qualitative *P-T-t* paths for extensional terrains. (a) Asymmetric extension. The letters correspond to the labels in Fig. 1; *A* and *B* are the maximally perturbed geotherms for these positions with respect to the structure accommodating strain. The arrowed lines are *P-T-t* paths for rocks at the bottom of the crust. For simplicity, the *P-T-t* paths are drawn to return to the original stable geotherm. The dotted line is the locus of maximum temperatures reached at the bottom of the crust across the structure. For substantial convective heat transfer, the right limb of the dotted loop becomes shallower; for greater extension, the dotted loop becomes deeper and wider. (b) Axially symmetric extension. *A'* corresponds to the maximally perturbed geotherm for (b) in Fig. 1, for uniform pure shear. *A* corresponds to the maximally perturbed geotherm for (c) in Fig. 1, for non-uniform pure shear. It also corresponds to the case of substantial convective heat transfer with uniform pure shear. The arrowed lines are *P-T-t* paths for rocks at the bottom of the crust for the non-uniform case. The dotted line is the locus of maximum temperatures reached at the bottom of the crust across the structure; in this case *P-T-t* paths follow this locus. For stronger partitioning of strain into the mantle lithosphere and/or for greater convective heat transfer, the dotted curve becomes more strongly curved; for greater extension, the dotted line reaches to shallower depths.

the crust has been thinned or if metamorphism has caused a redistribution of the heat-producing elements in the crust. This may be the case, if, for example, extension was accompanied by the formation of granites and their emplacement higher in the crust. In this latter case, the final steady-state deep crustal geotherm may be expected to be cooler than the initial geotherm [7].

In the detachment zone model for continental extension, the consequence of cooling will depend on position with respect to the detachment zone accomodating extension. Where the geotherm was most perturbed, a small amount of thermal subsidence will occur, but the lower crustal rocks will cool essentially isobarically. Towards the area of maximum crustal extension, thermal subsidence will be enhanced due to the isostatic response of the thinned crust [16], and may allow for the generation of sedimentary basins. A similar effect will occur with cooling following axially symmetric extension. The formation of sedimentary basins will mean that lower crustal cooling paths will involve increasing pressure. For values of extension between 1 and 2, sedimentary successions in basins induced by thermal subsidence will be less than 5 km thick [9]. Thus deep crustal cooling paths may record increases in pressure of the order of 1 kbar (Fig. 2), a difference which is beyond the sensitivity of current geobarometric methods.

3. Ancient examples of extensional metamorphism

The extremely large temperature decrease predicted for deep crustal cooling in extensional terrains such as the Basin and Range Province (300–500°C, Fig. 2), allows for the possibility of substantial mineralogical changes during cooling. In metamorphic rocks with this history, we would expect evidence for such deep crustal cooling to be "frozen-in" in the form of mineral zoning profiles, coronas and symplectites, indicating the crossing of mineral reactions at high pressure during cooling. In the following discussion, we describe a number of regional scale metamorphic terrains which may provide analogues of Basin and Range style metamorphism.

An ancient extensional terrain, possibly analogous to the Basin and Range Province, is present in southeastern Australia where up to 25% of the surface expression of the early Palaeozoic Lachlan foldbelt comprises middle Palaeozoic shallow-level post-tectonic granites and silicic volcanics [22]. Much of this silicic magmatism, particularly strongly peraluminous suites (S-type), such as the Violet Town Volcanics [21], was pene-contemporaneous with mafic dyke swarms (e.g. the Woods Point dyke swarm) [22] and with narrow rift systems (e.g. the Eden rift) [23]. The formation and emplacement of the peraluminous silicic melts is therefore interpreted as having formed by melting of a crustal metasedimentary source in a regime of crustal extension. The silicic melts frequently contain assemblages involving hypersthene, garnet, cordierite, and biotite, with sillimanite and hercynite as less common accessories [24,25]. This association has been interpreted as indicating source temperatures of at least 800–850°C at 5–7 kbar [24,25]. The implied low $a(H_2O)$ of such assemblages indicate that melting was a product of granulite facies metamorphism. The widespread distribution of these granites suggests that much of the lower crust in this region underwent granulite facies metamorphism at this time. The subsequent cooling of the southeastern Australian deep crust, presumably following the cessation of extension, must have been isobaric because these unmetamorphosed silicic volcanics are still preserved at the Earth's surface, an observation which implies that there has been no substantial erosion since the emplacement of these rocks in the middle Palaeozoic. Therefore, the synmetamorphic crustal thickness in this region can have been no greater than the present day crustal thickness, which is typically between 30 and 40 km [26,27], and is consequently similar to the present-day crustal thickness in most of the Basin and Range Province [28]. The retrograde *P-T-t* path for the southeastern Australian deep crust granulites is therefore identical to that predicted for the cooling of the Basin and Range Province, once extension ceases there (Fig. 3).

Isobarically cooled *P-T-t* paths have been documented from a number of ancient granulite terrains varying in age from Phanerozoic to late Archaean (Fig. 3). The very high temperature late Archaean sapphirine + quartz granulites from Enderby Land, Antarctica, and Labwor Hills, Uganda, exhibit abundant reaction textures indicative of substantial cooling at deep crustal levels, at 20–30 km [17,20,29]. In the Fyfe Hills region of the Napier Complex, cooling took place from temperatures in the vicinity of 1000°C and pressures of about 9 kbar, to temperatures of about 600°C and pressures of about 7 kbar; in other words, substantial cooling with some decompression occurred [17,29,30]. This type of cooling is found throughout the Napier Complex, which outcrops over some 50,000 km [31]. The Napier Complex thus records the effects of an extremely perturbed transient geothermal regime, developed on a regional scale in a crust of only moderate thickness [29]. For the Labwor Hills granulites, cooling was isobaric, or may have involved a slight pressure increase, during cooling from temperatures in the vicinity of 900°C [21]. Unfortunately there is no

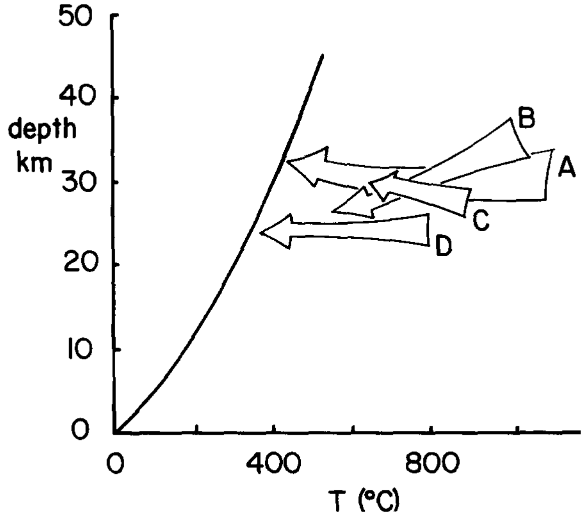

Fig. 3. Cooling paths for (*A*) Basin and Range (hypothetical); (*B*) Enderby Land (Fyfe Hills) [29]; (*C*) Labwor Hills [21]; (*D*) Victorian lower crust (this paper)

evidence for the prograde metamorphic history in either of these terrains. Similar retrograde *P-T-t* paths have been documented from early Proterozoic granulites in the Arunta Complex, Central Australia, [19], the Namaqualand metamorphic complex, South Africa [32], and the Hercynian granulites in Calabria, southern Italy, [20]. In the Calabrian granulites isobaric cooling is preceded by a period of decompression [20], while the Namaqualand granulites preserve evidence of near isobaric heating prior to isobaric cooling [32]. The Namaqualand *P-T-t* path is particularly interesting because it suggests that there was little change in crustal thickness during the high-temperature metamorphism. This type of path may be diagnostic of deep crustal metamorphism in the vicinity of *B* in the detachment zone model in Figs. 1d and 2b.

The discussion of granulite facies metamorphism has been in terms of thermal perturbations caused by conduction through a thinned lithosphere. We have shown that high temperature metamorphism is feasible even in this limiting case. Heat transfer is much more efficient if convection is involved, so it is even easier to cause high-temperature metamorphism if magma movement occurs. Models involving magmatic accretion beneath the usually exposed levels of granulite terrains will resemble the purely conductive models described above, with the proviso that magmatic accretion did not result in a substantially over-thickened crust. However, to produce even amphibolite facies metamorphism by addition of basaltic magma requires a large addition, up to 30%, depending on the original temperature profile [33,34]. To generate temperatures of 900–1000°C on a regional scale would seem to be impossible by accretion alone without significantly over-thickening the crust. Of course if accretion is balanced by thinning of the crust, extremely perturbed geotherms may be developed within extending lithosphere.

Granulite facies metamorphism is typically associated with recumbent structural regimes characterised by regionally consistent sub-horizontal stretching lineations which parallel axes of isoclinal folds [35]. While diagnostic non-coaxial deformation criteria are generally absent, such recumbent deformation has usually been attributed to a sub-horizontal shear couple applied to the lower crust, due to the space problems with other interpretations [36,37]. Traditionally such structures have been attributed to thrusting in an environment of continental convergence [37]. However, this interpretation is inconsistent with the prolonged deep crustal residence following metamorphism as implied by the isobarically cooled *P-T-t* paths [29,35]. These paths imply that tectonism occurred in a crust of only moderate thickness. In the case of the Napier complex, the synmetamorphic crustal thickness is estimated to be 35–55 km [29]. We conclude that the structural evolution of such terrains is unlikely to have involved convergence immediately prior to, or at the time of peak metamorphism. Strongly non-coaxial deformation at the lower levels of crust of moderate thickness at high temperature may therefore be better explained by mechanisms involving extension, in which extensional strain is strongly partitioned into zones of high resolved shear strain, such as might be expected for the deep-level expression of detachment zones [38].

The prolonged isobaric cooling of these granulite terrains implies that they must have been metamorphosed in the lower part of continental crust of normal thickness [29]. The subsequent emplacement of these terrains to shallow crustal levels in all cases occurred during much later, and causally unrelated, tectonic activity. In Enderby Land, late Proterozoic excavation, occurring some 1.5–2.0 Ga after granulite metamorphism, resulted in the development of assemblages in retrograde shear zones indicating rapid uplift, presumably associated with massive crustal thickening [39]. The assemblages in these shear zones preserve a record of isothermal decompression from about 20 km to about 10 km depth [39,40]. In Calabria, obduction of Hercynian granulites is attributed to Alpine collision [20]. In Central Australia, granulite obduction is attributed to Carboniferous tectonism associated with the development of a large-scale intracratonic thrust belt [19]. These observations are important in considering the fate of the deep crustal granulites inferred to be present beneath southeastern Australia and the Basin and Range province. Exposure of these isobarically-cooled granulite terrains awaits tectonism involving crustal scale thrusting. It is interesting to speculate that this thrusting may eventually be accommodated on the normal faults which have allowed extension. It is important to emphasise that the burial of metasediments to lower crustal depths, the metamorphism, and the resulting emplacement of the granulite facies terrain in the upper crust, are due to three separate, causally unrelated events.

In summary, deep crustal metamorphism associated with significant crustal extension is expected to involve regional granulite facies metamorphism for certain geometries of extension. The diagnostic feature of such metamorphism is expected to be mineralogical evidence for isobaric cooling at deep crustal levels. Such evidence implies that metamorphism occurred in response to a strongly perturbed geotherm in a thin to moderately thick crust. Evidence for isobaric cooling occurs in a number of granulite terrains which also have in common their inferred subsequent emplacement in the upper crust during a much later and unrelated tectonic event. These terrains may therefore represent ancient analogues of the crustal extensional environments such as those existing in the Basin and Range province today.

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