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SHORT NOTES

Criteria for identifying structures related to true crustal extension in orogens

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Abstract—Faults and shear zones in orogens may be related to crustal shortening or extension or both. True extensional structures should ultimately intersect the Earth's surface when traced out in a direction opposite to that of hangingwall transport; the present dip of a fault in an orogen, and its relation to local layering, are unreliable guides. The observation of low-pressure metamorphic rocks structurally above high-pressure metamorphic rocks is *not sufficient* to diagnose crustal extension. A valid metamorphic criterion is the difference in pressure–time *histories* between footwall and hangingwall: if the footwall was decompressing faster than the hangingwall during shear zone movement, then the shear zone was truly extending the crust. The pressure–time history can be constrained via the temperature–time and pressure–temperature histories. Ideally, crustal extension inferred from structural data should be confirmed using diagnostic *PTt* information.

INTRODUCTION

Crustal extensional structures have been documented within many orogens including the Western U.S.A. (Lister & Davis 1989), the Himalayas (Royden & Burchfiel 1987), the Betics (Platt 1986), the Alps (Selverstone 1985), Alpine Corsica (Fournier *et al.* 1991) and Scandinavia (Andersen *et al.* 1991). It is not trivial to infer whether structures have extended or shortened the crust from their geometry alone. There is a key distinction between the extension or shortening of previous *layering* (which is relatively straightforward to determine in the field) and the extension or shortening of the *crust* itself (Fig. 1). This is particularly relevant in the internal zones of orogens where intense deformation may have created non-horizontal layering prior to the formation of possible extensional structures. So, the documentation of such structures should be as rigorous and objective as possible. In this Short Note we outline the various arguments which, with care, can be used to distinguish extensional and shortening features in orogens.

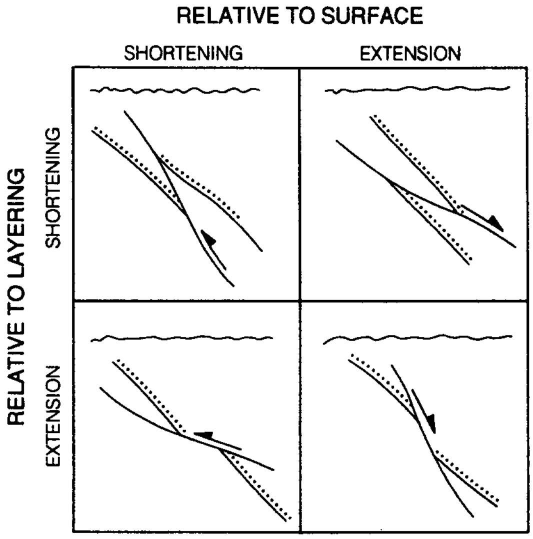

Fig. 1. Sketches to show that structures extending layering may not necessarily be extending the crust, and vice versa.

We restrict our discussion to faults or discrete, identifiable shear zones. Wider regions of complex deformation in orogens may also relate to extension but are more difficult to decipher, as are areas where extensional structures link to, and were synchronous with, shortening structures. Our arguments here provide a basic framework only. Key features of shear zones related to true crustal extension are that they cut down, away from the Earth's surface, in the direction of transport; and that they *sometimes* emplace relatively low-pressure metamorphic or unmetamorphosed rocks above high-

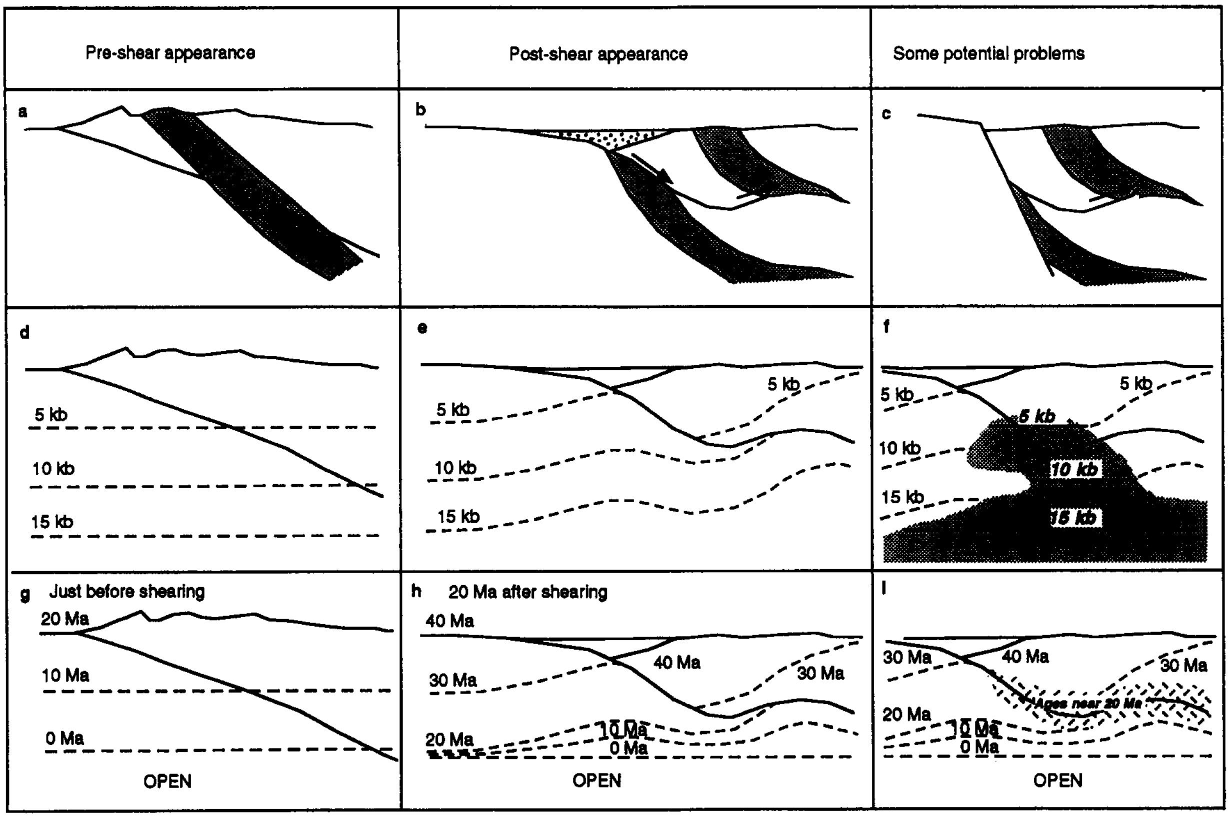

Fig. 2. Summary of structural (a–c), metamorphic (d–f) and geochronological (g–i) patterns associated with crustal extension. The first column shows the pre-shear-zone appearance, the second the post-shear-zone appearance. The third column shows some, but not all, of the phenomena which can complicate the basic picture. In (c), the shear has been cut by later structures so cannot be traced back to intersect the surface. In (f), the pre-shear-zone metamorphic pressure pattern has been overprinted by post-shear-zone re-equilibration, so that the metamorphic pressure break is, in places, obscured. In (g) an original age structure is assumed in which the oldest rocks are those nearest the surface: such a pattern would result from cooling by uniform erosional unroofing of a metamorphic pile. In (h), the footwall unroofed by shearing has cooled by conduction over the subsequent 20 Ma period. In (i) it is emphasized that ages may be reset near the shear zone to values near the age of shearing, both by conduction of heat from footwall to hangingwall and by recrystallization during deformation. See text for further discussion.

pressure metamorphic rocks. These statements encompass both structural and metamorphic aspects of extensional structures, but need to be more precise before these criteria can be applied with rigour. We will build on these basic concepts below, and show how geochronological arguments may also help to identify extensional structures. Each argument is listed under a separate heading for clarity, though in reality they are all linked: we also emphasize the limitations of each approach when used on its own.

STRUCTURAL CRITERIA

Principle

We assume that the relative movement of hangingwall and footwall can be determined, from offset of markers or from other kinematic indicators on the shear zone (e.g. Hanmer & Passchier 1991); if movement sense cannot be resolved, then it becomes more difficult to diagnose its tectonic significance. *If the shear zone was related to crustal extension then, as it is followed in a direction opposite to that of hangingwall transport, it should ultimately intersect the Earth's surface as it was at the time of movement, even if the shear zone was later folded* (Fig. 2b). If there has been net erosion since shear zone movement then it should intersect the present surface; if there has been deposition then the old surface trace of the shear zone will be buried. Use of this criterion is more rigorous than referring to the orientation of a shear zone relative to layering, as this is not a faithful guide as to its true significance, unless that layering is *known* to have been parallel to the Earth's surface at the time of the shear zone activity. Nor is the local orientation relative to the present surface of particular significance. Application of this idea relies on the ability to trace out the shear zone, and this may not be easy for several reasons. The orogen may be partly obscured by sediments, or partly submerged—such as the highly extended orogens of the Spanish Betics or the Aegean. The shear zone may die out in a zone of more distributed strain, or it may be cut by later structures, thus removing key parts of it (Fig. 2c).

Examples

In the Hornelen basin of western Norway, a shear zone carries Devonian sediments above metamorphic basement (Séranne & Séguret 1987). In this instance it can be inferred that the shear zone cut down relative to the palaeosurface since the sediments are broadly syntectonic and thus can be assumed to have been roughly horizontal. In the central Himalayas, a N-dipping shear zone with N-directed transport carries Ordovician sediments above Tertiary metamorphic rocks (Burg *et al.* 1984). Followed south, the shear zone intersects the present surface, but this is not sufficient in itself to demonstrate its extensional nature: it could be a folded and partly eroded backthrust. A complete cross-section through this part of the Himalayas (Royden & Burchfiel 1987) shows that there are no N-directed structures exposed in the chain to the south of this shear. The structure could not therefore have 'rooted' further south as a backthrust (unless it had subsequently been cut and buried by a forethrust; there is no evidence for this along strike), so is indicated to be extensional. It is important to note that, were the complete cross-section not available, the nature of this structure would be less easy to diagnose. A final example is from the western Alps where a SE-dipping shear zone with SE-directed movement separates the Sesia zone from the underlying Piemonte zone (Wheeler & Butler 1993). This could be a tilted backthrust: yet, when traced southeast this shear zone is not seen to re-emerge through the Sesia or other units, so it is likely to be extensional.

METAMORPHIC CRITERIA

Principle

If the shear zone was related to crustal extension then the pressure recorded by rocks in the footwall should, during shear zone movement, decrease faster than that recorded in the hangingwall (Fig. 2e).

This principle is carefully phrased for several reasons.

(1) It is not enough to find 'low-pressure' rocks above 'high-pressure' (a 'normal-sense' metamorphic break) to deduce the extensional nature of a tectonic contact. Reimbrication (breaching, Butler 1987) affecting a nappe pile in which high-pressure rocks were already thrust over low-pressure ones can easily reverse the stacking order, emplacing low-pressure rocks back above high-pressure units (e.g. Michard *et al.* 1993).

(2) Even without such restacking, it is dangerous to infer crustal extension from 'normal-sense' pressure breaks across a contact unless the timing of metamorphism is known. For example, 'high pressure' is often used to mean high recorded *peak* pressure. If the metamorphic peaks in rocks above and below the shear zone occurred at different times, or earlier than shear zone movement, then such a juxtaposition could be coincidental. When high-pressure rocks in the footwall are much older than the shear zone, they could have been exhumed prior to that movement. Conversely, a pressure break could be overprinted by later re-equilibration, thus obscuring it (Fig. 2f).

(3) It is conceivable that both footwall and hangingwall are being exhumed by erosion, or even movement on a structurally higher extensional structure, so it is the *relative* change of pressures in footwall and hangingwall which is significant.

(4) The principle argument makes no explicit reference to the temperatures recorded by rocks in footwall and hangingwall. In simple situations, where the temperature field is in equilibrium prior to extension, surfaces of constant temperature will parallel the surface. Therefore, the offset of such surfaces so as to juxtapose cool rocks in the hangingwall above hotter rocks in the footwall could indicate the extensional nature of the shear zone. However the main distinction from pressure data is the very dynamic nature of the temperature field. This evolves with time in response to movement of rock masses, and does not re-equilibrate for long times after such movements cease (England & Thompson 1984). Thus there is no guarantee that surfaces of constant temperature will be parallel to the surface at any particular stage of orogenic evolution. Apparent thermal offsets may thus be misleading. Thrusts transecting thermal domes could, for example, emplace cold rocks over lower pressure but higher temperature material. Moreover, as the shear zone itself moves, heat will be transferred from one side to the other and modify the temperature histories of footwall and hangingwall. Depending on how fast the shear zone moves, the hangingwall may experience significant heating and the footwall significant cooling. These signals will cause an otherwise sharp metamorphic temperature break to become diffuse.

So, in attempting to use metamorphic data to constrain whether a structure relates to crustal extension, the prime need is to constrain and compare the pressure–time *histories* of footwall and hangingwall. The link between pressure and time may actually be made via the temperature history which is more directly accessed by geochronological techniques (e.g. Selverstone 1988). The recorded temperatures themselves are of less diagnostic value.

Examples

In the internal western Alps of Italy, greenschist facies rocks (The Combin unit) are found above eclogite facies rocks (the Zermatt-Saas unit). It has been suggested on these grounds (e.g. Platt 1986) that the contact is extensional. Most age data from the area are cooling ages, not those of peak metamorphism of the units. The pressures at the time of juxtaposition are therefore not constrained: this is typical of the ambiguity involved in metamorphic arguments. Nevertheless, Ernst & Dal Piaz (1978) and others argue that the Combin unit has never experienced pressure above those of greenschist facies (10 kbar maximum), whilst the Zermatt-Saas has been buried, in part at least, to 30 kbar (Reinecke 1991). Therefore, at the time of the eclogite facies peak, the Combin unit must have been at least 60 km (20 kbar equivalent) closer to the Earth's surface than the Zermatt-Saas unit. Since this peak, 60 km of relative vertical displacement between the two units has occurred. This still does not *prove* that the contact was extensional. The Zermatt-Saas eclogites could have been unroofed by other extensional features, or arguably by erosion alone, prior to the tectonic emplacement of the Combin unit along either a thrust or extensional feature.

In the southern Pakistan Himalayas greenschist facies rocks of the Banna nappe rest upon a variety of higher-grade rocks including sillimanite schists (Treloar *et al.* 1989), exhibiting a 'normal-sense' metamorphic break. The shear zone separating the Banna nappe from the lower units is N-directed, in contrast to the dominant thrusting direction. It dips south and so has the appearance of a backthrust though, as argued above, the present dip is not a reliable guide to its original nature. More importantly, it does not re-emerge to the south: this structural criterion suggests it is backthrust, branching off one of the forethrusts. Low-grade rocks had been overthrust by high-grade units prior to this, and so the backthrust restacked the nappe pile. In this example, then, the metamorphic 'offset' along the contact is probably not a guide to its true nature.

GEOCHRONOLOGICAL FEATURES

Principle

Use of particular isotopic systems may, in favourable circumstances, indicate when a particular 'blocking temperature' (Dodson 1973) was passed through by rocks from different positions relative to a shear zone. Suppose that isothermal surfaces were parallel to the Earth's surface. Then, for a given isotopic system, rocks above a certain depth would already be below their closure temperature and would register pre-shear zone ages. *If the shear zone was related to crustal extension, and isothermal surfaces paralleled the Earth's surface then, along part of its length, the shear zone would juxtapose rocks with old cooling ages in its hangingwall against rocks with young ages in its footwall* (Fig. 2h). A thrust, by contrast, would carry younger rocks in its hangingwall.

This argument is dependent on assumptions regarding the behaviour of the temperature field, which should be assessed carefully. In particular, heat transfer from footwall to hangingwall could obscure the break in age patterns by partly resetting ages in the hangingwall (Fig. 2i); recrystallization during deformation in the shear zone itself may also modify apparent ages. In addition, interpretation of isotopic data from metamorphic terrains is not straightforward (Cliff 1985): the concept of closure temperature is not always sufficient to explain isotopic patterns. The increasing sophistication of geochronological techniques which help to distinguish isotopic patterns related to mineral growth, cooling and resetting (e.g. Vance & O'Nions 1992) means that such data will become yet more helpful in the future.

Examples

Selverstone (1988) discussed a W-dipping shear zone in the Eastern Alps, the Brenner Line, which relates to crustal extension according to metamorphic and structural criteria. Biotite K/Ar and Rb/Sr cooling ages from rocks in the hangingwall are typically 75–87 Ma whilst those in the footwall are 12–19 Ma, in agreement with the cooling age model for a shear zone related to crustal extension.

A second example concerns contrasting views of the Willimantic dome in the Appalachians. Rocks in the core of this dome include metagranites, with metapelites above a high-strain contact zone. Wintsch & Sutter (1986) interpret the contact as a thrust, partly because the metapelites are higher grade than the rocks below the contact. Getty & Gromet (1992a,b) show that the high-grade metamorphism in the hangingwall occurred at 400 Ma while the shearing at the contact was much later, at 275 Ma (direct dating of high closure temperature systems such as U/Pb in phases recrystallized during shearing). Metamorphism in the footwall gneisses was at *ca* 300 Ma. They argue that the hangingwall rocks were cool by 300 Ma, so that the present contact puts cool rocks above rocks that were metamorphosed only 25 Ma before shearing. This and other criteria are used to diagnose the shearing as relating to crustal extension, albeit superimposed on a thrust belt. As in the example of the basal shear zone of the Banna nappe, the metamorphic break across the contact does not relate simply to the tectonic significance of that contact.

CONCLUSIONS

We have shown how arguments regarding the crustal extensional nature of structures in orogens are based on certain assumptions which should be clearly stated. In particular, structural arguments based solely on the present orientation, or the orientation relative to layering, of shear zones are not reliable. Metamorphic arguments based on relative peak pressures of rocks on either side of tectonic contacts are also of limited value unless detailed timing data are available. Similar arguments based on relative temperature are still less reliable because of the many possible influences on the evolving temperature field during crustal deformation. These problems which we highlight are not intended to imply that recognition of extensional structures is impossible: rather, we hope that they will prompt much clearer statements of the assumptions made in work on extension in the diverse mountain belts in which it has been hypothesized. Finally, much depends on more refined geochronological data relating to deformation and metamorphism becoming available: the many new techniques developed in recent years will help this process.

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