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Deformation style way back when: thoughts on the contrasts between Archean/Paleoproterozoic and contemporary orogens

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Abstract

In many important ways, Archean and Paleoproterozoic ('older') orogens differ structurally from contemporary examples. This essay examines the premise that contrasts between older orogens and contemporary orogens reflect long-term changes in the temperature of the continental crust, in the density of supracrustal sections, and in exhumation rates. For example, if continental crust were warmer and exhumation rates faster, earlier in Earth history, then higher grade rocks would occur closer to the surface of older orogens, and the orogens would be lower and wider. This situation might contribute to the formation of wide belts of high-grade gneiss found in ancient crust. If the high-strength layer of the crust were thinner and supracrustal sequences denser, earlier in Earth history, then regional extensional tectonism might lead to crustal-scale boudinage and diapirism. This situation might explain formation of the extensive dome-and-keel provinces found in ancient crust. Testing such speculations, through the application of structural analysis coupled with petrologic studies, dating, and rheological modelling, will constrain models of Earth's long-term physical evolution.

1. Introduction

Geologists have long noted that tectonic features of 'older' (Archean and Paleoproterozoic) orogens contrast with those of 'younger' (Phanerozoic) ones (e.g. Kröner, 1981). For example, older provinces contain extensive high-grade gneiss terranes with shallow-dipping foliations while younger ones do not (e.g. Nisbet, 1987; Windley, 1995; Goodwin, 1996), and older provinces contain broad regions with dome-and-keel architecture while younger ones do not (e.g. Marshak et al., 1997). Further, regional trendlines in older provinces tend to be less linear than those of younger provinces, and older provinces do not contain obvious relicts of accretionary prisms or molasse basins while younger provinces do (Kröner, 1981). Are such contrasts merely a manifestation of differences in erosion level (e.g. we tend to see mid- to lower-crustal levels of older provinces while we tend to see upper crustal levels of younger provinces), or do they indicate that tectonic processes have evolved during geological time? Stated another way, should we be uniformitarians or non-uniformitarians when interpreting older orogens (see Burke et al., 1976; Hargraves, 1981; Kröner, 1981; Windley, 1981; Salop, 1983; Bickle, 1984; Davies, 1992; Passchier, 1995; Windley, 1995; Hamilton, 1998)?

The above debate recurs frequently in papers on Precambrian geology. Some geologists maintain a strict uniformitarian approach, but many researchers have come to accept the notion that, while plate tectonics did happen earlier in Earth history, there may have been notable differences in how it operated, because the younger Earth was hotter. Possible tectonic differences between the early Earth and today's Earth include: mantle convection was more vigorous; subduction did not completely consume oceanic lithosphere because oceanic crust was thicker (so oceanic crust became incorporated in continents, and depleted oceanic lithosphere accumulated under continents); hot spots were more abundant and larger; continental crust did not have a mafic lower crustal layer; the mantle lithosphere beneath continental crust was not

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fertile; and plate motions were faster (see Kröner, 1985; Sandiford, 1989a; Moores, 1993; Nelson, 1991; Durrheim and Mooney, 1991; Davies, 1992; Kusky, 1993; Hamilton, 1993, 1998; Kröner et al., 1994 for further discussion).

Most of the items noted above pertain to oceanic lithosphere, or to the deep crust and mantle. Were there also differences in the character of mid to upper continental crust and in its interaction with the atmosphere that could have influenced deformation style in older orogens? This brief essay explores the structural consequences of three possible differences, namely: (i) older orogens were hotter than contemporary ones; (ii) rheological and density stratification in the continental crust in Archean and Paleoproterozoic times were different from in today's crust; and (iii) weathering and erosion rates at the surface of the earlier Earth were faster than then they are today. Researchers do not agree about whether such differences exist, so this essay must take the 'what if?' approach. What if the thermal structure, compositional stratification, and erosion rate of continental crust back in Paleoproterozoic and Archean times were not the same as they are today—would old orogens contain deformational features that differ detectably from those found in contemporary orogens? If so, we could use studies of structure in ancient orogens to characterize physical conditions in the continental crust of the early Earth. I address these topics in keeping with the aims of this special issue of the *Journal of Structural Geology* to draw the attention of students to an issue, not to provide a comprehensive review.

2. What if the continental crust was a little hotter?

2.1. Could the crust have been hotter earlier in Earth history?

Most geoscientists accept the notion that earlier in Earth history the mantle was hotter overall than it is today (e.g. McKenzie and Weiss, 1975; Lambert, 1976; Thompson, 1984; Richter, 1985), because the young Earth held more of its primordial heat and held a greater concentration of radioactive elements than it does today. For example, decay of radioactive elements produced three times as much heat at the beginning of the Archean and about 1.8 times as much heat at the beginning of the Proterozoic than it does today (Richter, 1984). Thus, mantle convection in the younger Earth was probably more vigorous than it is today. But whether or not a hotter, more vigorously convecting mantle caused young continents to be warmer than those of today remains a point of contention (e.g. England, 1979; England and Bickle, 1984; Percival, 1994).

If excess heat of the Earth's interior was lost, in part, by conduction through the continents, then the continents must have been warmer. Higher temperatures could also reflect a greater amount of radioactivity in the crust, and perhaps even the occurrence of a warmer atmosphere whose presence would increase the temperature at the top surface of the crust. However, if the additional heat of the young Earth was lost only through convection involving the oceanic lithosphere (because spreading rates were faster, or spreading occurred at a greater number of ridges, or there were a greater number of hot spots), then the continental crust need not have been substantially hotter.

Researchers who argue in favor of the idea that the crust was not substantially hotter when it was younger, point out that young continents lay above a thick lithospheric root (e.g. Davies, 1979; Bickle, 1986; Sandiford, 1989a) and thus would have been insulated from the convecting asthenosphere. They note further that the lack of widespread minimum-melting granites in Archean shields implies that the temperature at the base of continental interior regions by Archean time was less than 700–800°C, the melting temperature of dry crustal rock (Burke and Kidd, 1978), and that the formation of diamonds in Archean subcontinental mantle requires that temperatures in the subcontinental mantle be similar to those today, by Archean time (Boyd et al., 1985; Richardson et al., 1985). Nevertheless, estimates based on studies of mineral assemblages in wide belts of high-grade Archean gneisses suggest that the crust reached 700–800°C at 10 kbar (35 km) when the gneisses formed (Tarney and Windley, 1977; Grambling, 1981). In fact, some geologists suggest that there has been a secular decrease in metamorphic temperatures since the Archean (e.g. Grambling, 1979, 1981; Sandiford, 1989a).

Uncertainty over the stability of the mantle beneath continents complicates interpretation of the thermal conditions in the continents. As Houseman et al. (1981) point out, the deep root of thickened, cooler mantle formed beneath collisional orogens may delaminate, at which time hot asthenosphere flows against the base of the continent, causing an increase in heat flow into the continent (e.g. Platt and England, 1993). Sandiford (1989a) notes that delamination would be more likely in the Archean because mantle convection was more vigorous, and attributes the prevalence of high-temperature metamorphism in Archean terranes to this process. He suggests that high-grade metamorphism occurred during extensional collapse when very hot asthenosphere replaced the delaminated root.

Certainly, the lack of abundant minimum-melting granites in older orogens implies that the continental geotherm could not have been radically steeper during

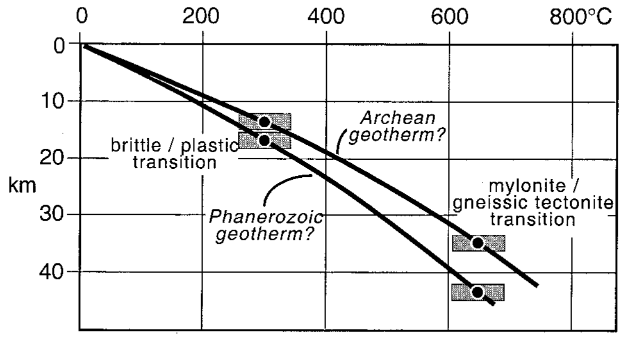

Fig. 1. A schematic diagram contrasting Archean and Phanerozoic geotherms in continental crust. If the average geothermal gradient were slightly greater in the Archean than it is today, the brittle–plastic transition and the mylonite–gneissic tectonite transition would occur at a shallower depth than it does today. Of course, geotherms in active orogens are different from those shown, because of heat advection by intrusions and because of shear heating on faults.

the Archean or Paleoproterozoic than it is today. However, available constraints, notably metamorphic temperatures, do allow the geotherms to be slightly steeper in the past, perhaps especially during the extensional collapse phase of orogeny. For the sake of argument, let us compare the Archean geotherm with the present day geotherm. Say that rocks at a depth of 35 km in the Archean were 100°C hotter than they are today (Fig. 1; cf. Davies, 1979; Pinet et al., 1991). Would such a difference influence deformation style in

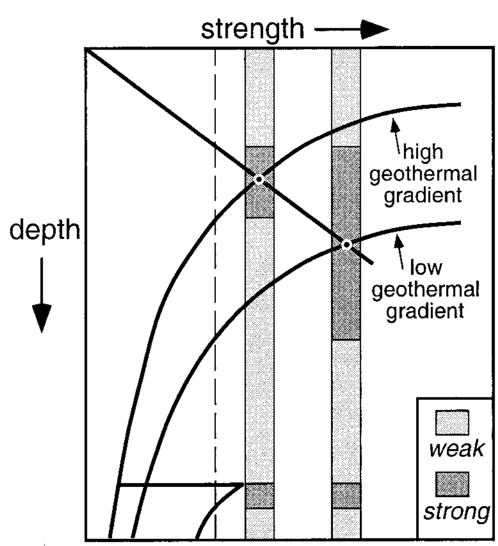

Fig. 2. A schematic diagram illustrating possible differences between the strength profile of continental crust during the Archean and that of today. Differences in geothermal gradient would cause differences in the thickness of the strong crustal layer (defined here as crust whose strength is greater than the value indicated by the dashed line) to be greater today than it would have been in the Archean. The abrupt increase in strength at depth represents the consequences of a change in crustal composition at depth. Modified from Dewey et al. (1986).

continents? Yes, because the depth dependence of rheology depends on the geotherm. For example, if the geotherm were steeper, the strength vs depth profile of the lithosphere would be different (e.g. Dewey et al., 1986), and the crustal brittle–plastic transition would occur at a shallower depth (Fig. 2). Below, I consider some implications of higher temperatures, as regards the deformation style in orogens, and the dimensions of orogens.

2.2. Implications for shear zone style

The style of a shear zone depends on temperature during its development because the activity of deformation mechanisms depends on temperature, as illustrated by representative deformation maps for minerals (e.g. Rutter, 1976). As a result, shear at shallow crustal levels yields brittle fault zones containing bands of breccia and gouge, grooved slickensides, fibrous veins, and solution cleavage. Closer to the brittle–plastic transition, shear creates zones of cataclasites. Below the brittle–plastic transition, where rock reaches greenschist through lower amphibolite metamorphic conditions, plastic deformation mechanisms generate shear zones of very fine-grained, strongly foliated and lineated mylonite (e.g. Sibson, 1977; van der Pluijm and Marshak, 1997). Still deeper in the crust, where rock reaches upper amphibolite and granulite metamorphic conditions, mylonite (*senso stricto*) does not form. Rather, shear yields 'gneissic tectonites' consisting of medium- to coarse-grained strongly foliated schist and gneiss (Davidson, 1984; Passchier and Trouw, 1996). These high-grade shear zones tend to be wider than low-grade ones (Ramsay, 1980), and may be hard to identify (e.g. Coward, 1984; Cunningham et al., 1996).

Because of the temperature dependence of shear-zone style, higher-grade shear zones would form at shallower crustal levels in warmer crust than they would in cooler crust. As an example, let us imagine that the brittle–plastic transition occurs at a temperature of about 300°C, and the mylonite–gneissic tectonite transition occurs at about 625°C (disregarding parameters such as strain rate or composition, which cause the transition to occur over a broader range of temperatures). According to the geotherms plotted in Fig. 1, the brittle–plastic transition would be 3 km shallower during the Archean than during the Phanerozoic, and the mylonite–gneissic tectonite transition would be 8 km shallower in the Archean than during the Phanerozoic. This rough estimate suggests that during the Archean, cataclasites (i.e. the seismogenic zone) and mylonites would be restricted to a thin interval of the upper crust that would rarely be preserved, while high-grade shear zones yielding gneissic tectonites might develop at depths where mylonites now form.

2.3. Implications for mountain-range elevation and crustal fabric

The maximum height of a mountain range on Earth depends, in part, on the strength of the crust, because crust collapses and spreads laterally under its own weight if the gravitational load of the elevated region exceeds the strength of weak rock at depth, and exceeds the magnitude of the horizontal tectonic forces that hold up the range (e.g. England and McKenzie, 1982). Intuitively, a decrease in crustal strength would mean that a mountain range could not grow as high during contractional orogeny, because a weak crust would allow the range to collapse and undergo lateral spreading before it built up as high as mountains do today.

Since the strength of the crust decreases as temperature increases, again because of the temperature dependence of deformation mechanisms, then crust with an Archean geotherm would be weaker than crust with a Phanerozoic geotherm (Fig. 1). This contrast would imply that the width and height of an Archean orogenic belt would be less than that of a Phanerozoic orogenic belt for a given amount of horizontal convergence. Thus, the cross-strike geometry of mountain ranges might have been different in the past—Archean orogens would contain wider belts of plastically deformed rock, much of which might contain shallowly dipping extensional fabrics formed during orogenic collapse (see Sandiford, 1989b and Windley, 1995, for discussion of shallowly dipping fabrics).

2.4. Implications for interpreting dome-and-keel architecture

Archean and Paleoproterozoic orogens include extensive dome-and-keel provinces, in which deep keels or troughs of supracrustal rocks (metasedimentary and/or metavolcanic rocks) surround domes of granitoid and/or basement gneiss and migmatite (see references in Marshak et al., 1997). In many Archean examples, keels typically include mafic/ultramafic volcanic and associated sedimentary rocks that are roughly the same age as the silicic/intermediate igneous rocks of the domes, suggesting that domes were emplaced magmatically. In Paleoproterozoic examples, by contrast, keels also contain platform strata (including thick intervals of banded iron formation) that are half-a-billion years younger than the gneisses of the domes, indicating that the domes were emplaced in the solid state by displacement on steep, supracrustal-side-down shear zones (Marshak et al., 1997). Marshak et al. (1997) refer to dome-and-keel provinces in which domes rose as magmas as Type-M provinces, and refer to dome-and-keel provinces in which domes were juxtaposed in the solid state against supracrustal keels as Type-B provinces.

Some authors suggest that structures very similar to early Precambrian dome-and-keel provinces developed in the Phanerozoic (e.g. Burke et al., 1976), and cite the balloon-like intrusions of the continental volcanic arc provinces and the mantled gneiss domes of the Appalachian/Caledonide system as examples. While there are certainly similarities, modern examples differ from early Precambrian examples in a number of ways. In the case of Type-M provinces, the keels tend to be deeper and to contain rocks that are more mafic than those found in Phanerozoic arcs. Further, Type-M provinces tend to be more equant in map view than Phanerozoic arcs. Type-B provinces contrast with Appalachian mantled-gneiss dome provinces in that the domes of Paleoproterozoic examples tend to be very steep-sided, they do not contain a granite core, they are bordered by supracrustal-side down shear zones on all sides, and they are bordered by pronounced metamorphic aureoles.

If early Precambrian dome-and-keel provinces really are structurally different from their Phanerozoic counterparts, does their existence tell us that deformational processes in early Precambrian orogens differ from those occurring in contemporary ones? Perhaps yes: In the case of Type-M provinces, the difference may have to do with the density contrast between supracrustal rocks and intrusions, as discussed in the next section; In the case of Type-B provinces, the difference may be due in part to density contrasts, but in addition the difference may reflect contrasts in the rheological stratification of the crust.

Traditionally, Type-B dome-and-keel provinces were vaguely attributed to 'vertical tectonics,' a concept that did not sit well in the context of plate tectonic models. Subsequently, the provinces were attributed to thrusting and folding, but such interpretations cannot explain the kinematics and geometry of dome-border shear zones. More recently, they have been attributed to crustal extension (Marshak et al., 1992; Holm and Lux, 1996). The younger-on-older relationships found in these provinces, as well as radiometric dating which suggests that dome juxtaposition occurred after the contractional phase of a collisional orogen, have led authors to draw analogies between the provinces and Cenozoic Cordilleran metamorphic core complexes of the Basin-and-Range Province (USA). However, while field and geochronological evidence (e.g. in the Quadrilátero Ferrífero of Brazil, and the Penokean orogen of Michigan and Wisconsin) supports the contention that these provinces formed during syn- to post-orogenic extensional collapse, the geometry of these provinces does not resemble that of Cordilleran

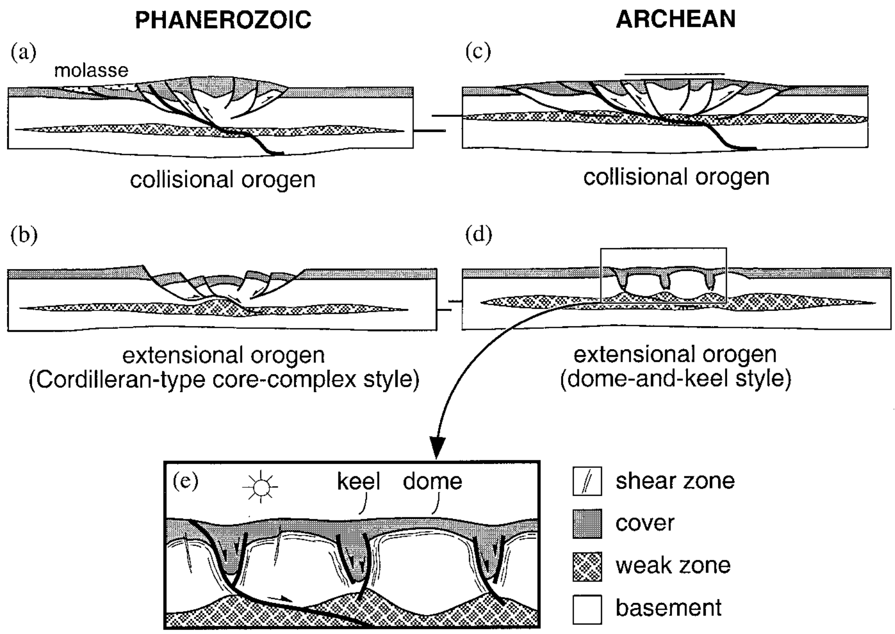

Fig. 3. Cross-sectional sketches contrasting collisional orogens of Archean/Paleoproterozoic time with those of Phanerozoic time. The shaded layer represents supracrustal rocks, the white layer represents basement, and the patterned lens represents a mid-crustal weak zone. (a) Phanerozoic collisional orogen with adjacent foreland (molasse) basin. (b) Phanerozoic Cordilleran core-complex-type extensional province. (c) Archean/Paleoproterozoic collisional orogen. The thin horizontal line above the orogen defines the height of the Phanerozoic orogen, for reference. (d) Archean/Paleoproterozoic extensional province with dome-and-keel formation. Note that the depth of the mid-crustal weak zone is shallower in the older crust than in the younger crust. (e) An enlargement of the proposed crustal boudin province, showing the relative positions of the domes and keels.

core complexes at all. Marshak et al. (1997) concluded that the field relations are compatible with an emplacement process during which dome rocks and keel rocks are juxtaposed by displacement on steep dip-slip normal-sense shear zones. In effect, the keels are steep-sided grabens. Considering that keels typically define an almost orthogonal pattern in map view, and considering that domes are on the order of 10–40 km across, the pattern of dome-and-keel provinces resembles chocolate-tablet boudinage on a crustal scale.

The concept that crustal-scale boudinage occurred in the Paleoproterozoic in tectonic settings where Cordilleran-type core-complexes form today, could be an indication that rheological stratification of the crust was different in the Paleoproterozoic from what it is today. If the crust were warmer, the 'mid-crustal weak zone' apparent beneath some orogens today (Dewey et al., 1986) would have occurred at a shallower depth (Fig. 2). Thus, the rigid layer of basement above would be relatively thin. This layer, effectively, was sandwiched between weak supracrustal rocks above and weak basement rocks below, creating the precondition for boudinage. In summary, if the continental crust were warmer, the structural style of extensional collapse might have been different from today—extension could yield Type-B dome-and-keel provinces instead of Cordilleran-type core complexes.

3. What if supracrustal rocks were denser?

It is now well established that volcanic sequences in the Archean tended to be denser than those of today, for many contain komatiite flows. In the Paleoproterozoic, sedimentary successions commonly include thick sequences of dense Lake Superior-type banded iron formation, formed when oxygen-producing organisms changed the chemistry of the atmosphere and oceans (Windley, 1995). Thus, supracrustal cover in early Precambrian orogens may have been denser than the cover in modern orogens, and locally could have been denser than underlying basement rocks. If such density inversions did form, conceivably they may have affected basin formation (Cisne, 1984) and may have affected the style of deformation in orogens. For example, density inversions could have caused diapiric movements of magma or hot crystalline rock to be more pronounced than they are in contemporary orogens. Steep-sided keels in Archean and Paleoproterozoic dome-and-keel provinces may, in part, reflect this process. The greater density of supracrustal sequences may also have affected the geometry of thrust wedges in Paleoproterozoic fold-thrust belts, because the magnitude of the gravitational load at a given depth in a thrust wedge would be greater than it is today, so the critical taper angle might be less (Fig. 3).

4. What if erosion were faster?

Increasingly, geologists have come to recognize interconnections among the atmosphere, climate, erosion, and tectonics in the Earth system (Pinter and Brandon, 1997). If the atmosphere and climate were different during the Archean and Paleoproterozoic, then orogenic belts formed during that interval of Earth history may have been different, both morphologically and structurally, from modern orogens.

According to some models, the Earth's early atmosphere would have been more corrosive than the modern atmosphere, because of the greater concentration of volcanic gases (Cloud, 1988). If this were so, rainfall might have caused chemical weathering to occur at faster rates. Further, most authors agree that the Archean and Paleoproterozoic atmosphere was richer in CO_2 than the Phanerozoic atmosphere, and thus that even though insolation was less, the Earth was probably warmer most of the time (Cloud, 1988; Mackenzie, 1995; Windley, 1995). If temperatures were warmer, atmospheric circulation and oceanic evaporation might have been faster, leading to greater rainfall. Further, because continents were smaller during the Archean and Paleoproterozoic than they are today, storms would not be calmed by movement over broad areas of land. Thus, though far from proven, weathering and erosion rates may have been faster during the earlier history of the Earth than they are today.

If weathering and erosion rates were faster, then exhumation rates would be faster and isotherms in the crust would rise significantly (e.g. Koons, 1987; Winslow et al., 1995). To replace the mass deficit resulting from rapid erosion, rocks metamorphosed at great depth would be rapidly brought to the surface. This phenomenon would mean that the relicts of orogens would be wide metamorphic belts. When tectonism eventually ceased, the next succession of supracrustal rocks could be deposited directly on high-grade gneiss. Further, as pointed out by Koons (1987), Beaumont et al. (1992), Hoffman and Grotzinger (1993), and Willett et al. (1993), foreland fold-thrust belts would be smaller, basement structures would be reactivated in the foreland (because uplift of isotherms would bring hot rocks to the surface in the foreland), and deep foreland molasse basins would not develop.

5. Conclusion

This essay has presented a selection of issues concerning contrasts between contemporary orogens and orogens formed early in Earth history (Archean and Paleoproterozoic time). It makes the assumption that plate tectonics did occur in the early Precambrian, but that physical characteristics of the Earth, such as continental temperature, atmospheric composition, and sediment density were different. Reasonable changes in these parameters can change deformation style and dimensions of orogens. Turning this argument around, the explanation for contrasts between structural styles way back when and those developing today may provide insight into how physical conditions in the continental crust and at the surface of the Earth have changed through time. As is evident from the number of qualifiers used in this paper, these issues remain open and should challenge structural geologists for years to come.

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