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Article abstract

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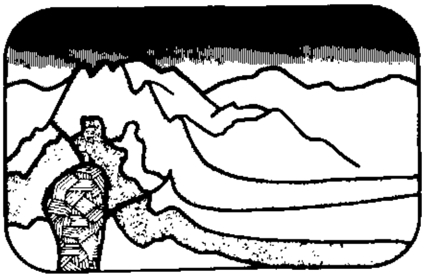

On Orogeny and Epeirogeny in the Study of Phanerozoic and Archean Rocks

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Abstract
The retention of the original, literal meanings of "orogeny" and "epeirogeny" is recommended. Orogeny is not a short-lived, chronostratigraphic feature nor is it a synonym for rock deformation or for widespread isotopic events. The term is applicable to tectonic deformation in belts, and which produced chains of mountains in Phanerozoic (and late Proterozoic) rocks. Therefore, it may be less appropriate in Archean rocks of the shield areas where broadly uniform isotopic events may be more appropriately considered as epeirogenetic phenomena.

Introduction
The paradigm of the synchroneity of orogenic phases is an old concept in geology (Stille, 1919, 1924, 1935). However, Gilluly (1949, 1950) is one of several scientists to have disputed this notion (replies by Stille, 1950a, 1950b). Nevertheless, many field geologists still tend to interpret the orogenic phase as a widespread, synchronous catastrophic event of short duration. This notion has been applied equally to orogenic phases signified by angular unconformities and to deformation events (e.g. designated D_1, D_2, etc.). It is quite possible that orogenic activity is gradually climactic and that the convenience of labelling deformation or orogenic episodes discretely at a given location presents an artificial impression of periodicity. Meanings of "orogenesis" and "epeirogenesis" have been extensively discussed (Stille, 1919, 1950a, b; Gilluly, 1949, 1950; Dennis, 1967; Gary *et al.*, 1972; Cebull, 1973; Wang, 1976). There are two main aspects to this discussion. Are orogenic phases episodic? and, what are "epeirogenesis" and "orogenesis"?

Episodicity
At the risk of oversimplification, the essence of the historical difference of opinion was that Stille held orogeny to be worldwide, synchronous and short-lived, while Gilluly considered it to be a more gradual process encompassing at least millions of years. Stille was unable to produce evidence of synchroneity and short duration, and left the burden of contrary proof with Gilluly. Similarly, Rutten (1949) rejected the episodic interpretation and, despite somewhat misleading criticism (Stille, 1950b, p. 110-111), Rutten's view that orogenic episodes were not short-lived chronostratigraphic markers held sway.

In practice many geologists continued to use the Stillean interpretation unconsciously. Many regional geological studies show this tendency. For example, Trümpy's classic Alpine synthesis (1973) stated that he began work as a "convinced Gillulian" and found that he became "moderately Stillean". In his table (1973, fig. 4) he draws all orogenic phases as lines perpendicular to the time axis for the alpine region.

Why do we continue to consider an orogenic event to be short-lived and synchronous over large areas? We are aware that the Gilluly-Stille debate revealed at least some serious flaws in this view. Perhaps we are reluctant to lose grip on a convenient notion which is almost invaluable for attempted correlation in the absence of biostratigraphy. To assess the seriousness of our expedient, but possibly flawed notion, we must consider the original meanings and some subsequent changes of meaning of orogeny and epeirogeny.

Orogeny and Epeirogeny
The first definitions are due to Gilbert (1890): "The displacements of the earth's crust which produce mountain ridges are called orogenic...Having occasion to contrast the phenomena of the narrow geographic waves with those of the broader swells, I shall take the liberty to apply to the broader movements the adjective epeirogenetic...The process of mountain formation is orogeny..."; and to Upham (1894) who defined orogeny similarly as:

"...processes of formation of mountain ranges by folds, faults, upthrusts and overthrusts affecting comparatively narrow belts and lifting them up in great ridges...".

More recently, definitions quite different from the original ones have been proposed in Glossaries by Dennis (1967) and Gary *et al.* (1972) and in papers by Brookfield (1971) and Cebull (1973). Orogeny has become to many workers a synonym for penetrative rock deformation; as examples of the many workers in shield regions who tend to favour this view we mention Gower and Clifford (1981) and in other terrains, Pannekoek (1960). Even Brookfield (1971) and Cebull (1973) state respectively that "...the term orogenesis means so many different things to different people..." and "... the concept of orogeny... has nearly ceased to be useful". Furthermore, Gilluly (1966) reminded us that orogeny meant mountain-building, but then in 1971, even he equated it with rock deformation. Platt (1966) has also raised objections similar to ours in the equation of plutonism with "orogeny" of some authors.

We believe that orogeny and epeirogeny are useful terms which should not be abandoned. We recommend the retention of the definitions of Gilbert (1890) and Upham (1894) as above.

Evidence from Phanerozoic Orogenic Sedimentary Rocks
One of Gilluly's arguments for the longevity of orogenesis was the volume of orogenic sedimentary rocks. Such sequences indicated that tectonic uplands were eroded over many millions of years. Modern results favour this view. Strain-rates estimated from micro-structures (White, 1975), from finite strains (Pfiffner and Ramsay, 1982), nappe thrust and fault motions (Price, 1975; Sibson, 1977; Scholz, 1977) and finally from ocean-basin closure-rates all indicate crustal shortening rates in centimetres per year. Correspondingly, uplift must be at least equally slow.

However, in the Phanerozoic record stratigraphy provides the bulk of the evidence for orogenic longevity. In the Alpine chains, such as the Western Alps (Trümpy, 1960), and in the Papuan orogen (Hermes, 1968) this process took tens of millions of years. The great thicknesses of flysch (alternating pelagites and turbidites) testify to the continuous presence of tectonic uplands. The immaturity of the detritus indicates that extensive shelves were absent. In the Alps the varying composition of the detritus indicates that the tectonic uplands were ephemeral and migratory (Trümpy, 1960, fig. 3). These data show that for 60 Ma there were always small tracts of land being eroded somewhere in the system. Individually, these lands were too small to have supplied all the detritus if they had been formed in a short Stillean event of 0.3 to 1 Ma duration. Nor is the continued isostatic uplift of the same small eroding landmasses a satisfactory solution, for the rates of uplift would be comparable to those in the present Alps (1 m per millenium, Clark and Jäger, 1969). Such rates could not be maintained unless there was unrelenting compression in the flysch basins to maintain the elevation of the uplands. Rather, we believe that as a result of the compression, different tectonic landmasses were repeatedly emergent at different locations. These transient landforms were short-lived as individuals and supplied flysch syn-orogenically. More uniform, regional uplift subsequently supplied the molasse.

It is the writers' opinion that the definitions of Gilbert and Upham, being no more than elaborations of literal meanings, still properly emphasize the essence of the process at an elementary and fundamental level. Accordingly we differ from Dennis (1967), Gary *et al.* (1972)(A.G.I. Glossary), Brookfield (1971), Gilluly (1973), and Cebull (1973) who equate orogeny with rock deformation. Although Cebull (1973) stated that the concept of orogeny is "... the subject of many interpretations...vague and varied in definition and implication..." this is no reason to reject or change the meaning of simple useful terms.

Apart from upsetting historical precedent this indicates a certain inertia to fully express new interpretations arising from more modern sophisticated research. New hypotheses should be expressed more fully if we wish to preserve communication for an international audience, rather than to redefine simple, useful terms.

Archean Terrains

Although the present Earth, and indeed Phanerozoic Earth, can be divided readily into more active portions that appear as long narrow belts in map view, and less active "cratonic" portions that are more equi-dimensional in map view, it is not clear that the same contrast existed in the Archean Eon. In the Archean, mobility or tectonic activity was distributed in a more mixed-up way with a less clear-cut bimodal distribution.

The terms orogeny and epeirogeny were coined to name the two modes of the more modern bimodal set-up and hence are not suitable terms for use in an eon when the situation was perhaps not bimodal.

We accept the immense practical value in using tectonic events on the *broadest* scale to sub-divide Precambrian time within specific regions (Stockwell, 1982; Douglas, 1980). However, when one freely equates the subdividing isotopic events with orogeny, as understood in the Phanerozoic column, we may blur some important distinctions between the two. A "Phanerozoic" approach to Archean geology is inherent in our everyday discussions leading, for example, to attempts to establish a type sequence of deformation events or type location for the Kenoran orogeny. While we are about to discuss a difference in approach to the concept of Archean "orogeny" we do not wish to engage in a futile discussion of whether or not the Uniformitarian principle applies to Archean geology. We feel that the original intention of Lyell and Hutton would have been to recognise the uniformity of physical laws (Glikson, 1981), at least over the time-span of the Earth's history (Nisbet, 1985). That is to say, the laws of gravitation, of motion, the theories of crystal defects may be applied in a uniformitarian manner on rocks of whatever era we choose to study. On the other hand, geosynclinal theory, continental drift and gravity tectonics are examples of ephemeral paradigms which merely labelled the way in which geologists united their working hypotheses at different times or in different schools of thought. Since these are not to be confused with physical laws it is pointless to muddle the two and suggest that we question the philosophical principle of unformitarianism in the case of Archean geology.

How then should we go about applying our knowledge of physical and mechanical principles to Archean tectonism? It would seem worthwhile to separate the little we know about Archean geology from conjecture and particularly from inference from theoretical models. While theoretical models are normally proposed in science in order to focus attention on the premises they use, for Archean geology a proliferation of models appear to be offered directly as speculative solutions (e.g. see review by Condie, 1976, p. 249 and commentary by Nisbet, 1985). Let us consider a few known items, of which some are not normally emphasized as important features and others which may be regarded as conventional wisdom.

First, we know of no long ranges of mountains with linear tectonic patterns nor long belts of metamorphism which were produced in Archean times. Indeed it is even a matter of complex interpretation, ultimately a point-of-view, as to whether or not mountains existed on a scale comparable to those of today (England and Bickle, 1984). Even the belt structure of the Superior Province has a non-linear tectonic pattern when we examine the structure and distribution of metamorphism of the volcanic (greenstone) subprovinces (Thurston and Breaks, 1978; Blackburn, 1981).

Generally, the syn-tectonic uplift of greenstone belts was located about *centres*, which have usually been interpreted as diapiric in the broadest sense (Schwerdtner, 1984a, b; Salop, 1972). These resulted in non-linear patterns of downwarped stratified rocks between uplifted granitoid bodies affecting rocks which were usually already folded. From the outset it appears inappropriate to establish deformation sequences D_1, D_2...D_n for one area and to equate them with another non-adjacent area (Thomas and Tull, 1982). Indeed, diachronism makes this an unwise procedure even in younger linear mobile belts (Hobbs *et al.*, 1976, p. 351) and we favour Harland's (1969) recommendation that episodes be designated by location, e.g. D_{1A}, before they are actually traced from one area into another.

Thus in the absence of long mobile zones bounded by single blocks of more rigid terrain we rule out any general regional applicability of a local deformation sequence. Further in this regard, the obliquity of isograds to structural trends favours an irregular geographic pattern of heat sources, probably related to proto-diapirs, plumes or other equi-dimensional but deeper heat sources. At any rate, the heat sources were not constrained by the belt structure typical of subduction or collision zones in Phanerozoic time and we cannot expect broadly uniform ductility of tectonites in identifiable long zones. Rather, reaction-enhanced ductility would encourage higher strains or more episodes of deformation in certain localities which would possess an irregular areal pattern.

A second set of facts and observations compounds the evidence favouring a tectonic style with a poorly constrained geographical distribution. Extensive continental crust much older than 3500 Ma is unknown, when the earth's surface temperature was below the boiling point of the surface waters, yet the earth was much hotter (Windley, 1981). This favours at least locally steeper geothermal gradients, especially near the surface, which are perhaps witnessed by metamorphic gradients (Grambling, 1979, 1981). While it may be difficult to establish the actual values of geothermal gradients at the relatively shallow depths of greenstone terrains (Perkins and Robinson, 1985), it does seem that the gradients were high compared with most younger metamorphic areas (Watson, 1978; Pirie and Mackasey, 1978; Thurston and Breaks, 1978; Drury, 1977). The higher temperatures would ensure lower viscosities in the Upper Mantle and thus a thinner lithosphere. Also, since the differentiation of granitophile material was a progressive process, it is believed that initially there were few, small pieces of continental crust. Since the early units of continental crust must have been small, and just as equi-dimensional as today, their interactions would be necessarily along markedly non-linear and short boundaries. Later, in Archean time, as the size of the continental units became larger their boundaries might have become slightly "straighter". However the scale of the irregularities of the continental margins is not expected to change with time much more than the rate of increase of lithosphere thickness.

The consequence of this set of factors is that if any lateral interaction of continental crustal units did occur it would produce discontinuous short belts of deformation with marked diachroneity of deformation episodes due to the impingement of the irregular outlines of small crustal units upon one another. Furthermore, any relative vertical motions, for example diapirism, would be rapid, and substantial topographic elevation could not be maintained for long periods by a thinner lithosphere above an asthenosphere of lower flow strength (Tarling, 1980). Such minimal deductions may be supported by lithological evidence. For example, clastic high-energy environment deposits are localized in extent and there was denudation of the rising domes from which already-schistose granodiorite and tonalite pebbles were provided. This complex pattern of local uplifts and short-lived relief near overlapping centres of tectonic activity provides a further contrast with Phanerozoic tectonism. In the Phanerozoic, distinct facies, flysch and molasse, are associated with tectonism because deposition, syn-tectonic uplift and post-tectonic denudation form a cycle with respect to a given belt. In the Archean, multiple overlapping centres caused the cycles of adjacent centres to be interspersed so that the concepts of flysch and molasse facies are less useful in delimiting "orogeny" if deposits cannot be uniquely associated with a given tectonic centre.

A third peculiar feature of Archean stratified sequences is the nature of some of the major folds. Primary folds which are recumbent are rare and they are not always accompanied by their own penetrative-fabric forming event (Hudleston, 1976; Poulsen *et al.*, 1980; Coward *et al.*, 1976; Key *et al.*, 1976). Such folds might be related to some gravitational mega-slumping in response to doming. Such recumbency is rarely preserved because the prominent major folds of Archean terrains have steep axial surfaces of variable strike and are sideways or variable in their structural facing (Borradaile, 1976, 1982; Poulsen *et al.*, 1980). However, the steep axial surfaces and sideways-closing folds are normally adjacent to granitoid domes and we may attribute their orientation to the tilting of earlier recumbent folds in some cases (Borradaile, 1982). The steep orientations of these primary fold hinges, and particularly the absence of coeval tectonic fabrics with some recumbent folds, is not normal in linear, post-Archean "orogenic" belts.

A fourth group of observations emphasized by Goodwin (1981) as one of the most striking features of Archean geology, is the unique lithological constitution of the Archean crust. Broadly, 40% of the now visible Archean crust is comprised of volcanic rocks with tholeiitic and calc-alkalic rocks in a 3:2 ratio. Unequivocal basement is not recognized but neither do exotic ophiolites form contacts with the volcanic crust. Instead, the volcanic rocks are invaded by granitoid bodies of which some may be paragneisses of remobilized basement origin. While the presence of paragneiss would lend support to the notion that a basement existed in some areas, an ubiquitous, rigid, marginal floor to the deforming rocks has not been proved. Such a rigid marginal floor is a minimum requirement of Phanerozoic orogenic belts interpretable in terms of plate tectonics. The volcanic crustal materials may have been accreted in an environment comparable to a back-arc region (Windley, 1981) but the tectonic style was not belt-defined at the right scale; it was located about and between geographically-overlapping and probably chronologically-overlapping doming centres. The deformational style is quite unlike anything produced by the closure of a marginal basin or an ocean basin and in general is not reproduced closely enough or often enough by younger examples to warrant analogies to be accepted universally. In the absence of any substantial continental basement relicts it is similarly unwise to devise unique tectonic solutions such as ensialic orogeny or cyclical rifting and compression. These solutions also require rigid boundary conditions which would have imposed instead a consistent tectonic grain on greenstone belts, whatever their movement history.

Fifth, and finally, we draw attention to a well-known feature of Archean terrains: the nearly uniform ages for large equi-dimensional areas of crust. These earliest proto-continents have not only remained thermally inactive since the Archean, but acquired their isotopic ages rather synchronously over immense areas, notwithstanding the generosity of a 200 Ma range (Nisbet, 1985). In contrast, the admittedly more refined geochronological patterns recognized from Phanerozoic mobile belts are much more structured. Typically elongate-domal or belt-like contours of Phanerozoic isotopic ages may be identified (Dewey and Pankhurst, 1970; Borradaile and Hermes, 1980).

In the Phanerozoic cases, there exists some clearer isostatic relationship between tectonic deformation and the subsequent uplift and cooling. Neither the spatial nor the temporal pattern is usually apparent in terrains of Archean tectonism. Archean tectonism occurred around or between multiple (diapiric?) centres which clearly behave independently (Salop, 1972). Metamorphic patterns (Poulsen *et al.*, 1980; Fraser and Heywood, 1978) were offset from, though not necessarily unrelated to, the centres of tectonism, which may have migrated relative to underlying heat sources. Nevertheless, the subsequent cooling of Archean greenstone terrains was not influenced strongly by the local tectonic pattern. Cooling evidenced by isotopic data is intimately related to uplift and denudation (Nisbet and Fowler, 1982) and it affected broad regions. The ingenious suggestion that the deep subcontinental geotherm may have been closely parallel to a phase boundary over a great vertical distance provides one explanation for such widespread epeirogeny (Tarling, 1980; Ringwood, 1975).

The typical Archean tectonic event affected broad equi-dimensional areas without consistent tectonic grain and with post-tectonic metamorphism of low baric type associated with steep geothermal gradients in the upper crust. The accretion of crustal material to a thin lithosphere may have occurred in an environment perhaps somewhat similar to a back-arc region. However, the accretion process was essentially independent of the dominantly diapiric tectonic style which generated steep and often sideways-closing major folds, sometimes on recumbently-folded, but otherwise not penetratively deformed, volcanic and sedimentary rocks. The first penetrative deformations were associated with centralized tectonics and not directly with the process of accretion. Remarkably widespread epeirogeny, for example at about 2700 Ma in many regions, isolated Archean crustal material above the resetting isotherm for remaining geological time.

Conclusion

In conclusion we hope that this reinforces our notions of the use of the terms orogeny and epirogeny, the former in its classical sense being inapplicable to Archean terrains.

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