Uniformitarianism today: plate tectonics is the key to the past

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Abstract: James Hutton published the first two volumes of *The Theory of the Earth* in 1795 and the third volume was published posthumously by the Geological Society in 1899. Charles Lyell in his four addresses (1836, 1837, 1850, 1851) to the Society put the uniformitarian paradigm of Hutton (the present is the key to the past) into the perspective of his era. Uniformitarianism today can be expressed in the view that plate tectonics is the key to the past. This paper summarizes key data and ideas which confirm that the plate tectonic paradigm can be applied convincingly back to the beginning of the geological record. In spite of the fact that heat production was greater in the early Precambrian than now, tectonophysical and geochemical processes that produced oceanic and continental rocks since the early Archaean have not been fundamentally different from those that operate today.

‘The Present is the key to the Past’ was the uniformitarian paradigm of James Hutton (1788). He published the first two volumes of his book *Theory of the Earth* in 1795. In the conclusion of the second volume he said ‘In pursuing this object I am next to examine facts with regards to the mineralogical part of the theory etc’, but he never published his intended third volume before his death in 1797. The manuscript was passed via Playfair and Webb Seymour to Leonard Horner who gave it to the Geological Society in 1856, where it was re-discovered in 1895 by F.D. Adams (1938, p. 242). In 1899 the Geological Society published volume 3 of *Theory of the Earth* as a book edited and indexed by Archibald Geikie. The uniformitarian paradigm was promoted and developed by Charles Lyell in his *Principles of Geology* (1830 and in 10 subsequent editions). Lyell also presented to the Society two anniversary addresses (1836, 1837, 1850, 1851) to the Society put the uniformitarian paradigm of Hutton (the present is the key to the past) into the perspective of his era.

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The Phanerozoic

Accretionary and collisional orogens can be considered to be two ends of a spectrum of orogens (Murphy & Nance 1991). The former developed largely by the amalgamation of numerous island arcs, accretionary prisms and ophiolites, and they represent almost total crustal growth of juvenile material; Phanerozoic examples include the Kun Lun orogen in Central Asia (Şengör & Okurogullari 1991), and incomplete, ongoing, accretionary orogens include the Japanese islands and the Cordillera of western North America. Collisional orogens formed largely by the abutment of one continental block against another, and represent little or no crustal growth; modern examples include the Swiss Alps and the central-eastern Himalayas.

The important developments in Phanerozoic geology that are relevant to the uniformitarian argument will be considered in the Precambrian sections below where Phanerozoic analogues can be discussed in their appropriate context.

The Late Proterozoic (1.0–0.6 Ga)

Current evidence suggests that in the last 400 Ma of Proterozoic time, widespread terrane accretion and plate collision led to the formation of a supercontinent, which rifted and broke-up into separate continental blocks before the inception...
of the Phanerozoic. Most prominent are the many orogens grouped within the terms Pan-African, Cadomian and Avalonian. The Pan-African includes the Arabian–Nubian Shield, the Mozambique belt and the Damaran orogen.

Accretionary orogens

The Arabian–Nubian Shield. This is an assemblage of accreted island arcs, ophiolitic belts, and probable microcontinents and oceanic plateaus, and thus provides good evidence of processes of lateral crustal growth and modern-type obduction-accretion tectonics (Kröner 1985; Stoeser & Camp 1985; Windley in press a). Disrupted ophiolites occur in linear belts up to 900 km long defining sutures between island arcs and microplates (Kröner 1985; Pallister et al. 1988). Some ophiolites contain a complete (Penrose definition) succession (Shanti & Roobol 1979). In Arabia in addition to the island arcs there are remnants of pre-Pan African (i.e. > 1.0 Ga) microcontinents and possibly oceanic plateaus, whereas in Egypt and Sudan the deformed passive continental margin of the Mozambique belt was partly transformed into an active margin along which there are ophiolites and inter-thrust arc volcanic rocks (Kröner 1985).

In the Shield, there are three ages of island arcs that are very similar to modern arcs formed at sites of plate convergence (Stoeser & Camp 1985).

1. The earliest are chemically immature bimodal suites of low-K tholeiites and sodic dacites/rhyolites depleted in lithophile elements. After deformation, they were intruded by plutons of diorite and trondhjemite at 910 Ma. The lavas have chemical characteristics similar to immature island arcs such as the Tonga–Kermadec and Lesser Antilles arcs.

2. Younger lavas are predominantly calc-alkaline and low-K arc tholeiites, andesites, dacites and tuffs which were intruded by granitic batholiths dated at 816 Ma and 743 Ma. These are similar to more mature, partly emergent, intra-oceanic island arcs in the western Pacific.

3. The youngest voluminous lavas have calc-alkaline or high-K, calc-alkaline compositions with moderately high lithophile element abundances; they are comparable to volcanic arcs as in Central America and Indonesia which are transitional between island arcs and continental margin volcanic arcs.

Collisional orogens

The Mozambique belt. This complicated high-grade and highly deformed orogen in East Africa is still understood only in reconnaissance outline. Shackleton (1986) suggested that widespread thrusts, nappes and high-grade metamorphism imply crustal thickening as a result of continent–continent collision tectonics, and Burke & Şengör (1986) proposed that the belt was the site of a Tibetan-style continental collision. Berhe (1990) described many ophiolitic remnants in deep crustal gneisses. The most detailed, recent work in the Mozambique belt was by Key et al. (1989) in Kenya who concluded from considerable field and geochronological results that the belt represents a deep crustal section through a Pan-African continent–continent collision zone.

Orogen surrounding the West African craton. This Precambrian craton is surrounded by Pan-African sutures, arcs and collisional orogens. In Morocco there is a complete ophiolite at Bou Azzer dated at 788 Ma that is overlain by an island arc
consisting of calc-alkaline lavas and dikes (Bodinier et al. 1984). Many ophiolites, accretionary mélanges and fore-arc occur as dismembered slivers on a suture between the craton and the island arc (Saquaque et al. 1989). In the Sahara on the east side of the craton in the central Hoggar, there is a collisional orogen that retains evidence of a complete Wilson Cycle spanning the period 900–550 Ma (Caby et al. 1981).

The Tertiary Alpine deformation in Europe. The northwest-terties with the Himalayas (Windley 1986). The northwest-teties with the Himalayas (Windley 1986). The northwest-

The result of these orogenies was the formation of the continent? but from 2.1 Ga to 1.6 Ga many orogens did form (Culotta et al. 1989), and which shares some fundamental similarities, have been widely regarded as metagreywackes and metapelites, which were most likely derived from accretionary prisms.

Thrusting and folding was associated with high amphibolite facies metamorphism that locally reached granulite grade. Crustal thickening led to the formation of three types of crustal melt granites, the last of which were 1.7–1.55 Ga rapakivi granites and coeval gabbros, anorthosites and basic dykes (Haapala & Rämö 1990). These formed as a result of the internal slow heating of the thickened crust, its final extension and collapse, and thus to decompression melting of the mantle and melting of depleted granulitic lower crust (Windley in press a).

The Ketilidian. This orogen in South Greenland (Allaart 1976) is an incomplete segment of an Early Proterozoic accretionary orogen which contains an Andean-type batholith (Fig. 2; Windley 1991 & references therein).

A northern foreland of Archaean gneisses is overlain unconformably by a shelf-foredeep succession deposited by turbidity currents into basins on the deepening shelf, a 30 m thick sulphide-facies iron formation (chert–pyrite–shale) similar to that which commonly occurs on the outer ramp of Early Proterozoic foredeeps, and tholeiitic pillow lavas and basic–felsic pyroclastics, like those in the axial zones of other Early Proterozoic foredeeps (Hoffman 1987). The above succession has been thrust northwards over the foreland and back-thrust near the suture, where it and the basement thrustted gneisses are intruded by several 1.775–1.675 Ga granites that contain appreciable crustal-melt components (Kalsbeek & Taylor 1985). These relations are comparable to those that occur in the deformed foreland of modern collisional orogens such as the Himalayas.

The Kobberminebugt suture is a 15 km wide vertical shear zone that contains relict gneisstock-grade pillow lavas and gabbros, copper and gold mineralization, and late 100 m thick mylonite zones. The Julianehaab batholith is a 80–100 km wide Andean-type tonalitic–granodioritic batholith that contains relics of pillow lavas, pyroclastic rocks and extensive noritic gabbros (Allaart 1976) that probably belong to an early island arc into which the major calc-alkaline batholith was intruded (Windley 1991). The arc rocks are similar to those in the Kohistan arc in the Himalayas of North Pakistan, the lower part (magma chamber) of which is occupied by the Chilas complex of noritic gabbros (Khan et al. 1989).

The southernmost part of the Ketilidian orogen consists largely of metamorphosed, accretionary prism-type, supra-crustal rocks that were deformed in three sub-horizontal thrust nappes and metamorphosed at 1.8 Ga. The thrust slab was
intruded by post-tectonic 1.755–1.74 Ga rapakivi granites. The emplacement of such granites within 60 Ma of the peak of regional metamorphism and associated thrusting is consistent with the time lag caused by slow thermal relaxation heating (Sonder et al. 1987; Dewey 1988), between the last thrusting during crustal thickening, and the intrusion of crust-mantle melts in extensional zones in a collapsing crust (Windley 1991).

The Birimian. The 2.1 Ga Birimian orogen in West Africa extends for about 1600 km across strike. It consists predominantly of greenish-grade mafic lavas and tuffs, volcanodetrital argilites and turbiditic wackes, and all were intruded by post-orogenic leucogranites. Sm-Nd isotopic data by Abouchami et al. (1990) indicate that the sediments are free of any Archaean or older recycled components, suggesting that they formed in ocean basins far from any continental influence, and they confirm contemporaneity of the Birimian sediments and volcanic rocks. Abouchami et al. (1990) found that the trace element signatures of the volcanic rocks are most comparable to those of basalts in modern oceanic plateaus and thus proposed that this is a very extensive accretionary orogen that formed in a short time around 2.1 Ga from juvenile, mantle-derived material.

Collisional orogens

The Kola–Karelian. This orogen occupies the northern part of the Baltic Shield (Fig.1). It contains five Archaean terranes. The Murmansk and Inari terranes consist of high-grade gneisses, whereas the Sørvångar, Beloromian and Karelian terranes are composite, consisting of both low-grade greenstone belts and high-grade gneisses. In the period 2.0–1.9 Ga, these Archaean terranes collided and were amalgamated to form the Kola–Karelian orogen (Windley 1991, in press a, b). Early Proterozoic (2.4–1.9 Ga) rocks and structures added to these terranes include island arcs, Andean-type magmatic arcs, sutures and remnant shelf successions. The Early Proterozoic structure of this orogen is well constrained by geophysical data (Gaál et al. 1989; Marker 1989).

The Kola suture zone is a south-dipping thrust zone up to 40 km wide that has placed the Inari terrane against and over the Sørvångar terrane (Berthelsen & Marker 1986; Marker 1989). The borders of the suture zone are marked by mylonites and it contains at least two thrust-bound slices made up of the 2.4–2.0 Ga Pechenga Series that contains sediments from the rifted continental margin, shelf-rise transition, and trench and tholeiitic basalts with REE characteristics resembling those of MORB. On the south side of the suture zone there is a thrust-bound, greenish-grade Early Proterozoic island arc sequence that consists of weakly deformed abundant andesites, basaltic pillow lavas, minor komatiitic lavas, tuffs and sulphide-bearing carbonaceous pelites (Berthelsen & Marker 1986; Gaál et al. 1989). A further result of the southward subduction that gave rise to the island arc was emplacement of an Andean-type magmatic arc represented by 1.95–1.9 Ga calcalkaline plutons into the northern border of the Inari terrane (Barbey et al. 1984). The South Kola belt, containing Lapland granulites and gneisses, was metamorphosed at 1.9–2.0 Ga; its turbiditic precursors were possibly deposited in a back-arch basin (Berthelsen & Marker 1986).

The Wopmay. Wopmay is a 1.95–1.84 Ga orogen in NW Canada (Hoffman & Bowring 1984) that developed as a result of the collision between the Archaean Slave Province and an unknown Nahanni continental block to the west; a small island arc, the Hottah (that was built offshore on a 2.3–2.1 Ga crust) was trapped between the colliding blocks (Hoffman 1989). The western rifted margin of the Slave Province is overlain by shelf-rise sediments of the westward-facing Coronation Supergroup and succeeded by an eastward-migrating foredeep that formed in a late thin-skinned thrust-fold belt. The shelf began to collapse at 1.97 Ga, and collided at 1.91–1.90 Ga with the 1.95–1.91 Ga Hottah arc as a result of westward subduction below the arc. A new dextral-oblique, east-dipping subduction zone developed on the west side of the accreted arc and led to
formed shelf-rise. Terminal collision at about 1.8 Ga of the granites were generated from the metasediments of the deformed continental margin to the east. 1.86–1.84 Ga syenogranites in the west led to formation of the postulated generation of the 1.88–1.86 Ga Great Bear calc-alkaline batholith, partly on top of the Hottah arc and partly on the deformed shelf-rise. Terminal collision at about 1.8 Ga of the Nahanni terrane in the west led to formation of the postulated Johnny Hoe suture, indicated by gravity and magnetic highs.

Proterozoic plate tectonics

Current data suggest that the types of orogens that formed throughout the Proterozoic are fundamentally similar to those of the Phanerozoic. In particular, the two end-member types, accretionary and collisional, can be readily recognized back to the early Proterozoic.

There may have been a supercontinent in the mid-Proterozoic. The fact that platform carbonates and quartzites were common after, but not immediately before, 1.5 Ga suggests widespread transgressions such as would be expected at a time of continental break-up (Nance et al. 1986). Also Hoffman (1989) pointed out that most orogens in North America formed between 1.98 and 1.65 Ga and that they led to the formation of a supercontinent by 1.5 Ga.

The assembly and fragmentation of a mid-Proterozoic supercontinent would provide an ideal framework to explain the long-problematic mid-Proterozoic anorogenic magmatism. Windley (1993) proposed that there were two main periods of formation of such anorogenic rocks that were related to the formation of adjacent orogens. 1.76–1.55 Ga rapakivi granites and rhyolites formed about 60–200 Ma after the last deformation in the Svecofennian, Ketilidian and Penokean orogens, the time-lag being caused by the slow thermal relaxation of thickened lower crust that had been commonly depleted by the extraction of earlier granitic crustal melts. In contrast, 1.45–1.41 Ga anorthosites in eastern Canada and rhyolitic ash fall tuffs and peraluminous granites in central/southern USA formed in the continental margin of the Grenvillian ocean, modern analogues being found on the borders of the present-day Atlantic Ocean. Thus these anorogenic magmatic rocks formed in the extensional regimes during the formation and the break-up of the 1.5 Ga supercontinent.

Mafic dykes are typically intruded into a stable craton in the early stages of continental break-up associated with the formation of an ocean. After the closure of the ocean by plate subduction many of the dyke swarms may be preserved in the foreland of resultant orogens. Fahrig (1987) showed that in North America the 2.4–1.85 Ga Molson, Marathon and Mistassini swarms (Fig. 3) and the 1.2 Ga Mackenzie and Sudbury swarms are all orientated at high angles to, and commonly radiate from, their parent plate boundaries and are related to coeval volcanic belts along those boundaries. This suggests that these swarms occupy failed-arm environments and formed during early spreading. The Payne River dykes of Labrador are orientated parallel to their original passive margin (Fig. 3).

The existence of Proterozoic sutures between originally allochthonous continental blocks has long been suggested on the basis of geological and geophysical data (Burke et al. 1977; Fountain & Salisbury 1981). Several sutures in the Canadian Shield (Fig. 4a) show paired negative and positive gravity anomalies (Fig. 4b). Gibb et al. (1983) and Gibb & Thomas (1976) proposed that the positive anomaly is related to an increased density and thickness of the younger block, and that the negative anomaly is an expression of the increase in crustal thickness of the older block towards the suture. Re-evaluating these data in the light of the more recently established correlation between the age of continental lithosphere at the time of
the loading in mountain belts and its flexural rigidity (Karner & Watts 1983), Pilkington (1990) demonstrated that the negative anomaly may be the result of flexure of the older lithosphere as it is thrust under the younger, more buoyant block, and that the positive anomaly is related to the presence of a subsurface load, indicated by the absence of any visual correlation between topography and observed gravity. Figure 4c shows that the sutures of the Grenville Front (1.1 Ga), Labrador Trough (1.58 Ga), Cape Smith belt (c. 1.8 Ga) and Thelon Front (c. 2.0 Ga) demonstrate a systematic increase in lithospheric rigidity with age at the time of suturing and loading, and that these relations are in agreement with comparable data for the Alps, Himalayas and Appalachian and oceanic lithosphere.

Sutures contain two diagnostic rock groups: blueschists and ophiolites.

**Blueschists.** Late Proterozoic examples occur in the Mona Complex on Anglesey (560–550 Ma; Dallmeyer & Gibbons 1987), in the Akso Group of Xinjiang Province of W. China (698–718 Ma; Nakajima et al. 1990), the Hoggar–Iforas orogen in the central Sahara (undated; Caby et al. 1981), and the Delhi orogen in Rajasthan, NW India (undated; Sinha-Roy & Mohanty 1988).

**Ophiolites.** There are many ophiolites in the Pan-African of the Arabian–Nubian shield. Beyond Africa there are three important and well-dated early Proterozoic ophiolites, all of which have sheeted dykes: the 1.96 Ga Jormua ophiolite was thrust onto the shelf of the Svecofennian orogen (Kontinen 1987); the 1.9 Ga Purduul ophiolite in Canada obducted onto the foreland of the Cape Smith belt (St Onge et al. 1989); the 1.73 Ga Payson ophiolite in Arizona developed on a 1.76–1.75 Ga magmatic arc (Dann 1991).

There are innumerable other geological data and relations which support the idea that modern-style plate processes were in operation throughout the Proterozoic, but the above examples suffice to make the point.

**The Archaean (4.0–2.5 Ga)**

The Archaean regions of the world contain two types of terrane: low-grade, volcanic-dominated greenstone–granite terranes that formed in the Archaean upper crust, and terranes dominated by high-grade granulites and gneisses that represent the Archaean mid-lower crust. Some regions contain both types and their mutual relationships are particularly important.
Greenstone–granite terranes

Archaean greenstone–granite terranes contain the oldest major belts of well-preserved volcano-sedimentary rocks, and so they give us much direct evidence of early crustal conditions. They vary in age from c. 3.6 Ga to 2.5 Ga. The volcanic rocks typically consist of a calc-alkaline basalt–andesite–dacite–rhyolite association, with basaltic and ultramafic komatiitic lavas as a minor but important component. Andesites make up 30% of Canadian greenstone belts, but form a far smaller proportion of belts in southern Africa and Australia. Rare alkaline to shoshonitic volcanic rocks are like those in modern arcs. Most greenstone volcanic rocks show depletion in Nb, Ta and Ti relative to the rare earth and the large ion lithophile elements, this being a geochemical signature of subduction-derived igneous rocks. All the features described above are very similar to those in modern immature to mature island arcs (Condie 1989). Intrusive diorite–granodiorite–granite plutons are coeval with the volcanic rocks; they mostly have arc-type chemical characteristics.

There is now general agreement that most greenstone belts formed as a result of seafloor spreading followed by subduction or subduction–accretion processes associated with island arcs (de Wit et al. 1987; Hoffman 1990; Taira et al., in press). Possible modern analogues include obducted slabs of ocean floor (de Wit et al. 1987, 1992), island arcs built on oceanic crust (Sylvestre et al. 1987), segments of arcs ranging from forearcs to closed backarc basins (Ludden et al. 1986), intra-arc basins, collages of disparate arcs, arcs thrust onto continental crust (Spray 1985), volcanic arcs and pull-apart basins developed on an active continental margin (Thurston & Chivers 1990), and accretionary prisms that seal amalgamated arcs (Hoffman 1990; Percival & Williams 1989; Kusky 1990).

Although not yet widely recognized, there were probably many oceanic plateaus in the Archaean. Kusky & Kidd (1992) suggested that in the Bellingwe region of Zimbabwe there are major thrusts between the three groups of greenstone belts. In particular, a major detachment separates underlying gneisses from a 2.7 Ga allochthonous block (the Mberengwa allochthon) which contains 6.5 km of lavas including abundant basaltic and peridotitic komatiites, and which therefore they interpreted as a fragment of an accreted oceanic plateau. They went on to suggest that many of the other stratigraphically comparable greenstone belts in the Zimbabwean craton may be dismembered fragments of this large oceanic plateau.

The Superior Province of Canada is composed of several 2.7–2.75 Ga subparallel greenstone belts (Fig. 5) of contrasting lithology, age and metamorphic grade that are very similar to modern arc collision zones. There are two main types (Hoffman 1989; Card 1990): (1) volcanic–plutonic terranes, which appear to be composites of several island arcs; (2) metasedimentary belts which resemble accretionary prisms. Sub-volcanic complexes in the Abitibi Belt range from pyroxenite cumulates to gabbros (Raudsepp & Ayres 1982), and hornblende-bearing gabbros to anorthosites (Ashwal et al. 1983; Morrison et al. 1986). These appear to be intrusions derived from the magma chamber in deep parts of island arcs; they are comparable to the Jurassic Border Range complex in Alaska (Burns 1985), and the Chilas complex in the Cretaceous Kohistan Arc in the Himalayas of Pakistan (Khan et al. 1989). Considerable isotopic data indicate the major arc terranes get younger southwards; the main terminal orogeny occurred about 2.725 Ga in the Uchi–Sachigo terranes, about 2.705 Ga in the Wabigoon terrane, and about 2.695 Ga in the Wawa–

![Fig. 5. Map of the Archaean greenstone belts of the Superior Province of the Canadian shield in terms of island arcs and accretionary prisms, and an interpretive plate tectonic history.](http://mem.lyellcollection.org/)

Abitibi terrane (Card 1990). Thus the arc terranes were assembled progressively from north to south before finally colliding with the Minnesota foreland in the south, as illustrated in Fig. 5.

The Slave Province of Canada comprises two fundamentally different tectonostratigraphic terranes that collided at c. 2.6 Ga; an older gneissic microcontinent in the west and a composite greenstone-granite terrane containing a paired island arc and accretionary prism in the east (Kusky 1990). Most important is an ophiolitic complex (Helmstaedt et al. 1986). Although it is much thicker (11 km) than a typical equivalent section of Phanerozoic ophiolites, there is an obvious resemblance of the whole sequence, and in particular of the sheeted dyke complex, to a modern ophiolite. The implication is that mid-oceanic accretionary processes were active in the formation of the greenstone belts of the Slave Province, and this in turn implies that subduction and collision processes were also in operation in the Archaean. These greenstone belts are the remnants of a trench accretionary complex of juxtaposed island arcs and other crustal bathymetric highs such as fracture zones, seamount chains and oceanic plateaus, de laminated from subducting oceanic lithosphere and overlain by trench turbidites. Subsequently the foreshortened accretion-
ary complex was extensively intruded by crust- and mantle-derived plutons of the prograding magmatic arc (Hoffman 1990).

Storey et al. (1991) pointed out that Archaean komatiites are chemically comparable to the Tertiary komatiites of Gorgona Island off the coast of Columbia. Peridotitic komatiites (> 18% MgO), which have an eruption temperature greater than 1650 °C, require a very high degree of melting (50–80%) of the mantle. This fact may be explained by shallow depths of melting, which may be consistent with expected high rates of heat flow in the Archaean that were concentrated in mantle plumes that may have facilitated the formation of many oceanic plateaus, like the Kaapvaal craton.

Similarities between Archaean arc volcanoes in Canada and modern arc volcanoes include (Ayres & Thurston 1985): (a) an upward change from basaltic to calc-alkaline volcanism, and an accompanying increase in the proportion of tuffs and volcanioclastic rocks, reflecting a progressive upward chemical trend in the evolution of the volcanoes; (b) subduction signature of trace elements such as a negative Nb anomaly; (c) a gradual emergence of oceanic islands from submarine to subaerial, and the tectonic alignment of these islands. The differences include: (i) very magnesian peridotitic komatiites do not exist in modern arcs; (ii) there are less andesites, more rhyolites and more bimodal volcanic suites in Archaean volcanics; (iii) alkaline shoshonitic volcanics are uncommon in the Archaean; (iv) more rapid eruption rates of Archaean volcanoes during their subaquous, komatiitic and tholeiitic basaltic phase resulted in a higher incidence of non-pillowed sheet flows, thicker flows, and lava plains; (v) development of larger, longer-lived, zoned magma chambers during the later felsic stages of Archaean volcanism.

**Granulite-gneiss terranes**

These terranes have undergone deep crustal metamorphism that ranged from amphibolite to granulite facies. Harley (1989) pointed out that Archaean granulites formed within a wide range of pressures (6–12 kbar) and temperatures (750–980 °C) and that some have near-isothermal decompression $P$–$T$ paths (S India; Aldan Shield, Scourian, NW Scotland; Limpopo belt), and others have near-isobaric cooling paths (W Greenland; Napier Complex, Antarctica; Pikwitonei, Canada). He suggested that the decompression granulites formed in crust thickened by collision, with magmatic additions that were commonly calc-alkaline tonalites, and that the isothermal paths were generated during rapid thinning (1–2 mm a$^{-1}$ exposure) related to tectonic exhumation during moderate or waning extension. In contrast, the deep-level isobaric cooling granulites formed in thickened crust which underwent very rapid (5 mm a$^{-1}$) extensional thinning subsequent to collision. These conclusions confirm structural relations that indicate substantial tectonic intercalation of rock units by thrusting and of massive injection of tonalities in many regions. For example in West Greenland the long history of thrusting since c. 3.8 Ga culminated in the juxtaposition of four distinctive thrust-slabs or gneissic terranes at 2.75–2.55 Ga (Friend et al. 1987; Nutman et al. 1989). Because the granulites today are still underlain by some 30–35 km of continental crust, it can be reasoned that the orogenic belts must have reached by the end of the Archaean a crustal thickness of some 60–75 km, comparable to that of the modern Himalayas and Tibet.

**Archaean plate tectonics**

The deep crustal levels of Archaean terranes are obviously more difficult to unravel in terms of modern tectonic environments, but Wedepohl et al. (1991) found no systematic changes in chemical composition with age of early to late Archaean granitoid rocks from West Greenland, and concluded that typical modern processes of crust formation started to work early in the Archaean.

In terranes of the Superior Province of North America, granulite metamorphism formed in three distinct tectonic environments (Percival 1989): (1) the Minnesota River Valley terrane was metamorphosed at modest pressure (4.5–6.5 kbar) in a continental collision zone—it was the continental foreland that collided with the collage of accreted arcs (greenstone belts) to the north; (2) the Kapuskasing and Pikwitonei terranes formed at 7.5–9 kbar in the roots of the island arcs of the greenstone belts; (3) metasedimentary belts between composite island arcs which represent accretionary prisms that were tectonically thickened and metamorphosed during uplift at 4.5–6.5 kbar.

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These terranes have undergone deep crustal metamorphism that ranged from amphibolite to granulite facies. Harley (1989) pointed out that Archaean granulites formed within a wide range of pressures (6–12 kbar) and temperatures (750–980 °C) and that some have near-isothermal decompression $P$–$T$ paths (S India; Aldan Shield, Scourian, NW Scotland; Limpopo belt), and others have near-isobaric cooling paths (W Greenland; Napier Complex, Antarctica; Pikwitonei, Canada). He suggested that the decompression granulites formed in crust thickened by collision, with magmatic additions that were commonly calc-alkaline tonalites, and that the isothermal paths were generated during rapid thinning (1–2 mm a$^{-1}$ exposure) related to tectonic exhumation during moderate or waning extension. In contrast, the deep-level isobaric cooling granulites formed in thickened crust which underwent very rapid (5 mm a$^{-1}$) extensional thinning subsequent to collision. These conclusions confirm structural relations that indicate substantial tectonic intercalation of rock units by thrusting and of massive injection of tonalities in many regions. For example in West Greenland the long history of thrusting since c. 3.8 Ga culminated in the juxtaposition of four distinctive thrust-slabs or gneissic terranes at 2.75–2.55 Ga (Friend et al. 1987; Nutman et al. 1989). Because the granulites today are still underlain by some 30–35 km of continental crust, it can be reasoned that the orogenic belts must have reached by the end of the Archaean a crustal thickness of some 60–75 km, comparable to that of the modern Himalayas and Tibet.

The deep crustal levels of Archaean terranes are obviously more difficult to unravel in terms of modern tectonic environments, but Wedepohl et al. (1991) found no systematic changes in chemical composition with age of early to late Archaean granitoid rocks from West Greenland, and concluded that typical modern processes of crust formation started to work early in the Archaean.

In terranes of the Superior Province of North America, granulite metamorphism formed in three distinct tectonic environments (Percival 1989): (1) the Minnesota River Valley terrane was metamorphosed at modest pressure (4.5–6.5 kbar) in a continental collision zone—it was the continental foreland that collided with the collage of accreted arcs (greenstone belts) to the north; (2) the Kapuskasing and Pikwitonei terranes formed at 7.5–9 kbar in the roots of the island arcs of the greenstone belts; (3) metasedimentary belts between composite island arcs which represent accretionary prisms that were tectonically thickened and metamorphosed during uplift at 4.5–6.5 kbar.

**Archaean plate tectonics**

The late Archaean (2.9–2.7 Ga) greenstone belts of the Superior and Slave Provinces of Canada that formed largely by the amalgamation of island arcs and accretionary prisms are comparable to Proterozoic arc-accretionary orogens like the Pan-African of the Arabian–Nubian Shield and the Japanese islands today (Taira et al. in press). The late Archaean (3.1–2.6 Ga) Kaapvaal craton evolved by formation of Pacific-type continental margin orogens and Himalayan-type collisional tectonics (Table 1; de Wit et al. 1992). If the late Archaean (3.1–2.55 Ga) craton of W Greenland is the exposed deep level of a Tibetan-type plateau, then there are few fundamental tectonic differences between these late Archaean arc-accretionary and collisional orogens and modern orogens.

De Wit et al. (1992) described the evolution of the Kaapvaal craton of South Africa in terms of a two-stage formation of an Archaean continent from 3.7 Ga to 2.6 Ga. During the first stage (3.7–3.1 Ga), dominant intra-oceanic processes similar to those operating along mid-oceanic ridges caused separation of continental lithosphere from the mantle and formation of an oceanic plateau comparable to the Ontong–Java plateau. During this stage the 3.5 Ga mafic–ultramafic Barberton greenstone belt was abducted onto volcanic arc-like rocks. Amalgamation of oceanic plateaus/terrains by subduction/accretion processes like those occurring today along oceanic convergent margins gave rise to the Kaapvaal shield by 3.1 Ga (Table 1). According to Matthews (1990) the 2.94 Ga Pongola Super-group was deposited partly on the passive continental margin of the newly created Kaapvaal shield and partly on an aulacogen extending into it. The second stage (3.1–2.6 Ga) of de Wit et al. (1992) records the accretion of crustal fragments by Cordilleran-type subduction/accretion processes, the formation of intermontane rifts and foreland basins, and finally Himalayan- and Tibetan-type continent–continent collision between the Kaapvaal and Zimbabwe cratons and consequent formation of the Limpopo orogen at 2.68 Ga (Treloar et al. 1992). Figure 6 shows that the Limpopo belt has a symmetrical thrust structure, which is similar to that of many Phanerozoic collisional orogens. Burke et al. (1985) postulated that the Limpopo collision was responsible for the deposition of the Witwatersrand Supergroup in
a foreland basin, and that the 2.64 Ga Ventersdorp rift system formed by post-collisional extension in the Kaapvaal craton.

Although de Wit et al. (1992) concluded that the Archaean thermal and tectonic processes resemble plate tectonic processes occurring today, they emphasize there were some differences. For example, during the first-stage the Kaapvaal oceanic-type plateau formed by intra-oceanic obduction-dominated tectonics that gave rise to stacking, tectonic loading and subsidence, and this resulted in melting of the lower parts of the thrust stack to yield extensive trondhjemite-tonalite melts.

MacGregor & Manton (1986) found that the variation of major elements with oxygen isotopes of Archaean eclogites from Cretaceous kimberlites in South Africa matches that calculated for modern oceanic volcanic rocks altered by circulating seawater in ridge crest hydrothermal systems, and thus they proposed that the eclogites were derived from subducted, buoyant Archaean oceanic lithosphere (Bickle 1986). Seismic shear velocities indicate that Precambrian shields are underlain by chemically depleted mantle roots of Archaean age (Jordan 1988), and Helmaatd & Schulze (1989) suggested that these roots were formed of imbricated slabs of partly subducted Archaean oceanic lithosphere.

**Discussion**

A review of current and recent data and ideas on crustal evolution indicates that Cenozoic-style plate tectonic processes have been in operation since the beginning of the geological record, but that there are some differences which we must consider.

According to Murphy & Nance (1991) the Pan-African and Cadomian– Avalonian belts developed by subduction and accretion on the outer margins of a late Proterozoic supercontinent (peripheral orogens), whereas the Mozambique belt formed by continent-continent collision and thus is situated within the supercontinent (internal orogen). Similar earlier Proterozoic accretionary and collisional orogens may have developed in relation to large continental blocks or supercontinents. However, in the early Archaean, when there was a more widespread primordial ocean, accretion was predictably the more important process in the generation of orogens (de Wit et al. 1992).

Secular thermal changes have important implications for plate tectonic processes. Total heat production in the Earth in the late Archaean was around three times that of the present and this would have given rise to a higher temperature Archaean mantle, which in turn would have led to increased depth and volume of melting, a thicker continental lithosphere (150–200 km), a thicker oceanic crust (20–50 km) and sea-floor spreading rates 2–3 times than at present (Sleep & Windley 1982; Bickle 1986). Archaean oceanic lithosphere was highly chemically depleted, and buoyant subduction was more common than today (Burke et al. 1976; Hoffman 1990). Plate tectonics could have operated very efficiently in early Earth history, the plates moving over an asthenosphere with a greater heat flux and lower viscosity than now (Nisbet & Fowler 1983). The relatively light, low-viscosity asthenosphere would have facilitated easy movement and rapid subduction of the oceanic plates. Simple models of thick relatively buoyant plates above a hot (c. 1700°C) upper asthenosphere suggest that the resistive forces to plate motion may have been considerably less in the Archean than today, and that the mean age of subducted oceanic crust would have been around 20 Ma compared with 60 Ma today (Bickle 1986; Nisbet & Fowler 1983). The younger net age of subducting slabs would favour widespread shallow-dipping subduction in the Archean (Abbott & Hoffman 1984) and the buoyancy problem during subduction could be overcome by delamination of upper oceanic crust (Hoffman & Ranalli 1988); these relations would be consistent with the widespread evidence of thin-skinned thrust tectonics (Taira et al. in press).

However the secular changes in heat production and loss were able to change the course of development of some igneous and metamorphic processes at subducting plate boundaries.

1. There has been a long-term change in the composition of granitic rocks over Earth history from more sodic to more potassic (Dewey & Windley 1981), the main cause of which may have been a change in subduction zone geometry. In Phanerozoic and Proterozoic magmatic arcs high-K magmatism was derived from dehydration-driven melting of the volatile-fluxed mantle prism, whereas in the Archaean when subduction zones were predictably shallower, dehydration melting took place of the hydrated amphibolites of the downgoing slabs, leading to more sodic magmas (Arculus & Ruff 1990).

2. There has probably been a long-term decrease in subduction geotherms (Ellis 1992, and references therein). Newton (1986) suggested that most Precambrian eclogites equilibrated at higher temperatures than younger eclogites (Fig. 7). Also the fact that they equilibrated beyond the stability of glaucophane may explain the absence of early Precambrian glaucophane schists.

Potassic granites of crustal melt origin are rare in the Archaean, but common in later orogens. This may be related to the paucity of Archaean clastic sediments as a result of a
predominant intra-oceanic stage of crustal development (de Wit et al. 1992), compared with later times when more cannibalistic recycling of both crust and sediments took place (Veizer & Jansen 1979). Experimental data show that a high proportion (up to 40%) of S-type granitic liquid can be produced by melting at about 850 °C of pelites (Vielzeuf & Holloway 1988) and greywackes (Patifio Douce & Johnstone 1991). From the late Archaean/early Proterozoic an increasing number of continental blocks were available for erosion, and thus more pelites and greywackes were deposited in accretionary prisms in trenches. It is speculated here that most crustal melt granites in Earth history formed in accretionary prisms, many of which were transported from subduction zones into the deep continental crust (Klemperer 1989) where they underwent adiabatic decompression melting during uplift in extensional collapse orogens.

Kröner (1984) considered that the formation of most Proterozoic orogens did not involve significant oceanic opening or oceanic subduction tectonics, and instead invoked a model of orogenesis based on intracontinental A-type continental subduction driven entirely by gravitational instability of lower crust and upper mantle. This model was adopted by Etheridge et al. (1987) to account for all the Proterozoic orogens in Australia. However, Ellis (1992) cogently demonstrated that such a speculative type of orogenesis does not happen. Indeed Myers (1990) showed that four Proterozoic orogens in Australia do have the characteristic signatures of modern collisional orogens. So, as Ellis (1992) pointed out, the explanation for Australian or other Proterozoic intracontinental orogens that have no sutures or magmatic arcs is not A-type subduction but rather the late Cenozoic, post-collisional Tien Shan orogen in central Asia, which has no suture or arc, and which is 2000 km from its deformation front, the India/Asia suture zone (Windley et al. 1990).

Uniformitarianism today means that plate tectonics provides a paradigm for understanding the past, but that does not mean that the present and the past are identical. Many features of the earliest Precambrian are predictably the result of the greater heat production at that time. With this thermal caveat it is possible to say 'It is unlikely that any of the continental material preserved on Earth today was produced by processes significantly different from those that operate now' (Burke & Şengör 1986). With this Hutton and Lyell would have agreed.

I wish to thank the Geological Society for the invitation to present a conceptual synthesis of what uniformitarianism means today for the Earth Sciences. M. Allen made valuable comments on the manuscript.
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Precambrian in North America?
Gentlemen,—It is now my duty, in accordance with the usual custom of my predecessors in office, to say something of the scientific labours of geologists during the past session. It is nearly twenty years since I announced, in the first edition of my 'Principles of Geology,' the conviction at which I had then arrived, after devoting some time to observation in the field, and to the study of the works of earlier writers, that the existing causes of change in the animate and inanimate world might be similar, not only in kind, but in degree, to those which have prevailed during many successive modifications of the earth's crust. I attempted to adapt the views which Hutton and Playfair had first promulgated, to a more advanced state of our science, and to extend their application, by showing, that should the same causes continue to act with unabated energy, for indefinite periods of the future, they must bring about revolutions not inferior in magnitude to those recorded in the monuments of past ages. After an interval of twenty years, during which Geology has been enriched by a vast accession of new facts, and when so many powerful minds, in every civilized country, have brought their intellectual energies to bear on the philosophy of our science, I may I think affirm that the idea of comparing the modern agents of change with those of remote epochs, as not inferior in power and intensity, appears even to the most sceptical a far less visionary and extravagant hypothesis than when I first declared my belief in its truth. As, however, there are not a few original observers, whose opinion I respect, who are still opposed to this doctrine, I cannot I believe do better on the present occasion than take a brief view of the bearing of some leading discoveries of modern date on this much-controverted question. I adopt this course the more

Gentlemen,—In my Anniversary Address of last year, I entered into an examination of the question, how far the leading discoveries of modern date tend to confirm or invalidate a doctrine which I had advocated twenty years before, in the first edition of my 'Principles of Geology,'—that the ancient changes of the animate and inanimate world, of which we find memorials in the earth's crust, may be similar both in kind and degree to those which are now in progress. But in order to keep myself within due bounds, I confined my remarks on that occasion to the revolutions of the inorganic world, reserving for the present opportunity a comparison of the organic creation in ancient and modern times, and a consideration of the light thrown by Palaeontology on the laws which govern the fluctuations of the living inhabitants of the globe.