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Vertical Movements in Proterozoic Structural Provinces [and Discussion]

Janet V. Watson and R. N. Crockett

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Vertical movements in Proterozoic structural provinces

By Janet V. Watson
Department of Geology, Imperial College, London, S.W.7

The extent, consistency and timing of vertical movements both in cratonic and in mobile segments of the continental crust are discussed with particular reference to movements taking place during Proterozoic times. The distribution of unconformities and erosion-surfaces, and the variations in cover-successions, in metamorphism, in style of igneous activity and in the closing of isotopic systems are considered in this context. Many of the most ancient cratonic masses appear to have undergone only very small vertical movements over periods up to 2000 Ma in length. Erosion of the basement of many cratonic regions seems to have been concentrated in periods of only a few hundred million years and was not renewed by persistent later uplift. The responses of these cratonic regions were influenced by the distribution of Archaean massifs in them. The history of uplift in certain Proterozoic mobile provinces is seen to have a bearing on the problem of the origin of these provinces.

1. Vertical movements in relation to tectonic regime

The large horizontal displacements which have characterized the continental crust under the present plate tectonic regime have been systematically associated with vertical displacements amounting at most to a few tens of kilometres. Under the Proterozoic regimes discussed in this volume large horizontal movements also appear to have been closely integrated with limited vertical movements. An understanding of the extent and timing of vertical displacements is of importance in the context of current discussions concerning the possibility that there have been long-term changes in the tectonic regimes governing the behaviour of the crust for at least two reasons. In the first place, the connection between uplift and erosion means that the depth of the crustal section exposed at the surface in any tectonic province depends on the history of vertical displacements. The great age of the structural patterns revealed in Archaean and early Proterozoic provinces has inclined some geologists to regard these patterns as representing deep crustal levels. The old-established idea that the Precambrian shields have been the sites of prolonged and deep erosion appears in the light of more extensive reconnaissance studies to be at variance with the evidence to an extent which has important implications for the comparison of Precambrian and Phanerozoic tectonic patterns. A second point of interest concerns the evidence that the scale and sense of vertical movements in cratonic regions have been influenced by the constitution and architecture of the continental crust itself – a control which must have altered with time. The inherent complexity of the crust limits the precision with which responses to changes originating at depth can be identified.

2. The oldest cratons

Archaean tectonic provinces in which tectonic patterns formed prior to about 2500 Ma have been preserved with little subsequent modification seldom attain a diameter of more than about 1000 km. These small massifs are bordered by provinces in which the dominant structural patterns are of Proterozoic or Phanerozoic age (figure 1) and it is suggested that many of them have remained roughly constant in size since they first attained a cratonic condition towards the end of the Archaean era.

The effects of uplift and erosion towards the end of the period of evolution of the Archaean structures are recorded in many massifs by the occurrence of late Archaean or earliest Proterozoic cratonic cover-formations resting unconformably on granites or on metamorphic basement rocks. Dating of these formations (at least 2700 Ma for the Dominion Reef on the Kapvaal craton, > 2200 Ma for the Huronian on the Superior province, etc.) shows that, in some instances at least, uplift had taken place within a few hundred million years of the termination of tectonic activity in the basement. The metamorphic rocks exposed range from low greenschist facies in parts of granite/greenstone-belt provinces such as the Kapvaal and Superior provinces to granulite facies, for example, at the Labrador border of the Superior province. The thickness of cover removed in some provinces appears to have been very modest (Gay has suggested a thickness of 1.5 km for the Kapvaal province) and as accounts of granulites directly overlain by early Proterozoic sediments do not, so far as I know, suggest that these rocks are of high pressure types even the high-grade metamorphic complexes in this situation may not reveal a very deep crustal level.

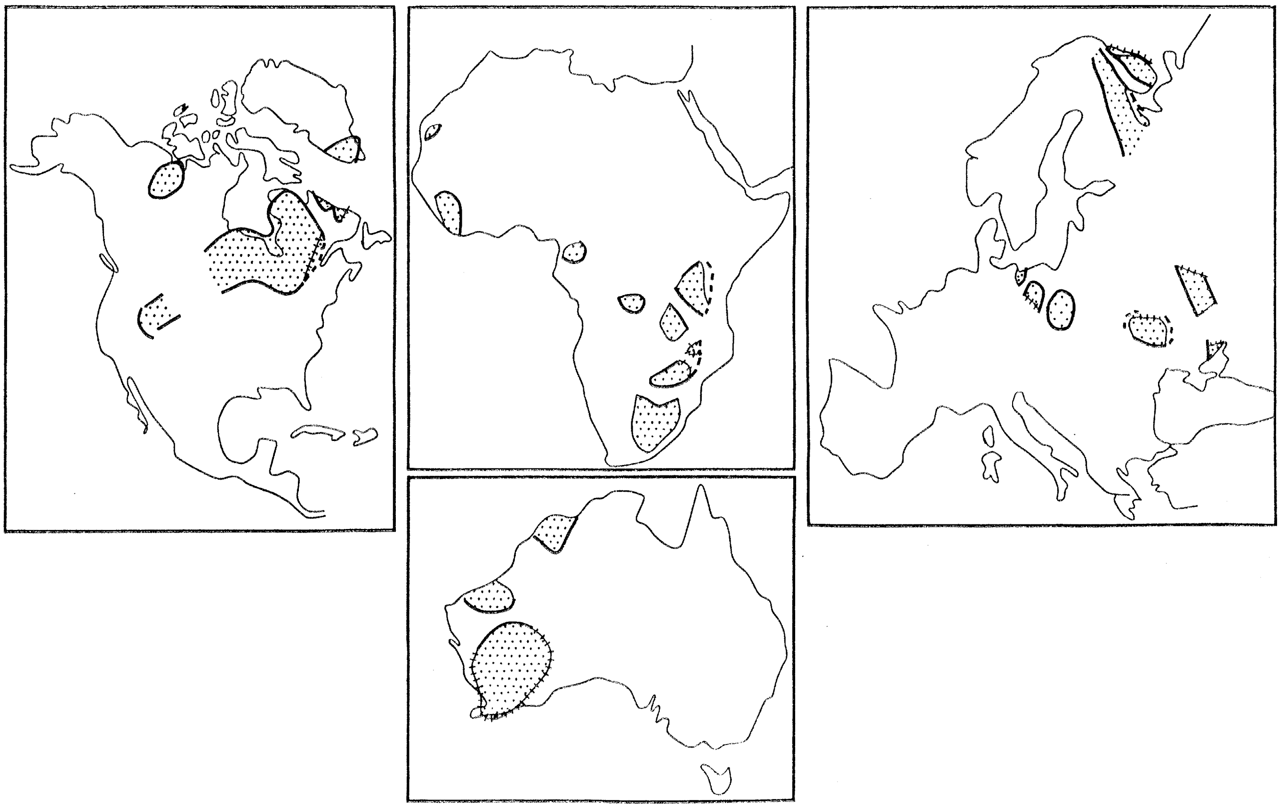

FIGURE 1. The principal Archaean tectonic provinces of four continents. Province boundaries established in early Proterozoic times are shown with heavy lines; hatched lines, no evidence.

Where the cratonic cover of late Archaean or earliest Proterozoic age is preserved it is selfevident that there has been no later erosion of the basement and that the sum of later vertical movements must be of the same order as the height of the basal unconformity above or below sea level. In most provinces for which data are available this distance is not more than a kilometre or so. Cratonic cover-successions resting on Archaean massifs seldom exceed 2 km in thickness although the equivalent successions may thicken greatly at the margins of these provinces (p. 632) and with the exception of the Wyoming massif entangled in the Front Range, Archaean massifs seldom form land more than a kilometre above sea level. The Kapvaal craton, unusual in many respects, carries a cover regarded as cratonic for which an aggregate thickness > 15 km is inferred.

Where no early Proterozoic cover is preserved, the possibility that elevation and erosion continued through later periods cannot be automatically excluded. Several lines of evidence suggest, however, that vertical movements after, say, 2000 Ma were of limited extent. Where variations of metamorphic grade in the basement are known, as in the Rhodesian and Superior massifs, there appears to be no consistent increase of grade away from outcrops of early cover-formations which might suggest the subsequent unroofing of deeper levels. There appear to be no consistent decreases in the outcrop proportions of structurally high units (intermediate-acid volcanics and sediments relative to basic volcanics in greenstone-belts: greenstone-belts relative to granites) in the same direction.

Many granite/greenstone-belt provinces contributed detritus containing ore-minerals to the adjacent early Proterozoic cover-units (Witwatersrand, Blind River, Ontario, etc.). Although the presence of mineralized areas in the basement exposed today shows that such material was not entirely removed by early Proterozoic erosion, ore-minerals are scarcely represented in younger cover-units such as the Waterberg of South Africa or the Lower Palaeozoic at the margin of the Canadian shield, a contrast which suggests that the basement contributed little detritus during the accumulation of these units. Finally, Proterozoic or late Archaean intrusions in several Archaean massifs have geometrical forms which suggest emplacement under a rather thin cover. The Great Dyke of Rhodesia (2600 Ma), and Jimberlana 'dyke' of Western Australia (2400 Ma) both widen upward into boat-shaped layered complexes which could have been emplaced at an old basement-cover interface; and the Mashonaland dolerites of Rhodesia (1900 Ma) occupy flat fractures in the basement which seem unlikely to have been opened up at depth. Taken together, these lines of evidence suggest that the depth of section revealed today in some typical Archaean cratons differs little from that which had been exposed by erosion two thousand million years ago. Some variations in the apparent depth of section are clearly to be accounted for by irregular uplift before this date; for example, the granulites near the Labrador border of the Superior province appear to be covered unconformably by the Kaniapiskau Supergroup which is roughly coeval with the Huronian Supergroup resting on greenschist-facies rocks towards the south of the province; and the granulites of the Limpopo belt are considered by R. M. Shackleton (private communication) to have been juxtaposed with the much lower-grade rocks of the Rhodesian craton before emplacement of the Great Dyke at about 2600 Ma. It is plain that erosion over very extended time-periods had nothing to do with the production of these variations.

3. Early Proterozoic mobile belts

The phase of differentiation of a system of tectonically mobile crustal zones enclosing many cratonic masses of Archaean rocks which took place over the period 2700–2200 Ma provides an acknowledged landmark in the history of the continental crust. From this point onward, cratonic and mobile regions behaved in a radically different manner so far as vertical movements were concerned. For several hundred million years, the cratonic units of the system were represented simply by small granite/greenstone-belt or gneiss-granulite provinces of the type discussed above. From about 1800 Ma onward, however, more complex cratonic units in which such provinces were welded to stabilized provinces characterized by early Proterozoic tectonic patterns came into existence and complex cratonic units of this type have been features of the crust down to the present day. Many of the boundaries of Archaean cratonic massifs which were defined in early Proterozoic times coincide quite closely with the present boundaries of these massifs. Large portions of the adjacent early Proterozoic provinces bear the imprint of more than one cycle of Proterozoic or Phanerozoic mobility, whereas the Archaean massifs which remained tectonically unmodified in early Proterozoic times show evidence of later modifications only in rather few areas. This contrast, represented schematically in figure 1 and table 1, suggests that the responses of the oldest cratonic massifs have continued to differ from those of more recently-stabilized portions of the crust for at least two thousand million years.

Table 1. Border-relations of the earliest (> 2000 Ma) cratons

	percentage of total boundary defined before 2000 Ma, including sectors where adjacent provinces are polycyclic	percentage of total boundary defined after 2000 Ma
Australia	57	43
Africa	55	45
Europe	70	30
North America	90+	10−

Although the vertical motions of the basement recorded in many early Proterozoic mobile belts fit in the broadest sense into the pattern characteristic of Phanerozoic mobile belts there are distinctive anomalies, especially as regards the timing of the displacements. A phase of downwarping of the basement, associated with the accumulation of cover-successions much thicker than those on the adjacent cratons, has been recognized in many early Proterozoic provinces – for example at the northeastern and southern borders of the Superior craton where the Kaniapiskau and Huronian Supergroups thicken at the craton margin to at least 10 km. Thick prisms of supracrustal rocks may show relations similar to those which in Phanerozoic mobile belts are commonly taken to indicate deposition in graben or at continental margins above thin continental basement. Although the early Proterozoic fill of the Coronation geosyncline, at the western margin of Slave craton has been convincingly interpreted as a continental-margin succession (Hoffman 1972) other thick successions of equivalent age, and the tectonic provinces of which they form part, have been regarded for various reasons as ensialic units not related to the formation or elimination of major oceans (e.g. Dimroth 1970). It is these provinces about which controversy centres at the present time.

Analogy with Phanerozoic terrains suggests that the downwarping necessary for the accumulation of such sequences as the Kaniapiskau of Labrador might be associated with extension and consequent thinning of the continental crust without the subsequent development of a new ocean. In Phanerozoic times, the processes of graben-formation and splitting of continents have not, so far as is known, been associated with regional metamorphism and ductile deformation or with the emplacement of granites. Shackleton (1969, 1973) and Hurley (1973) have envisaged such activities in the regions of rising mantle currents or crustal extension during the formation of certain Pan-African ($\geqslant$ 500 Ma) tectonic provinces and the possibility that important stages in the tectonic and thermal evolution of older ensialic provinces were related to extensional rather than compressional regimes seems worthy of consideration.

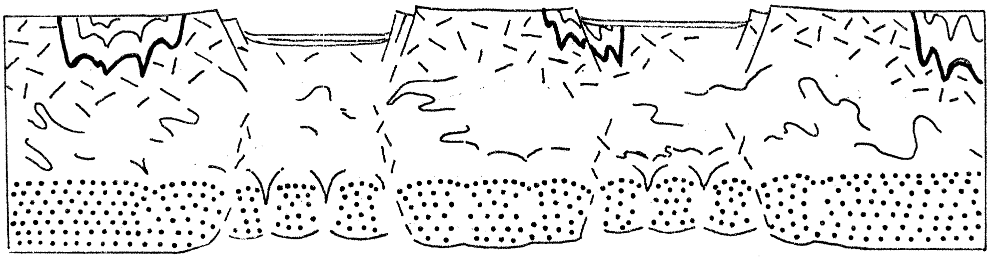

FIGURE 2. Schematic diagram suggesting a possible relation between crustal extension in an ensialic mobile belt of Proterozoic age and incipient break-up of a granulite layer near the base of the crust.

The rôle of extensional processes in the development of the Mount Isa complex of northern Australia is stressed by Dunnet (this volume). The emplacement of regional dyke-swarms of late Archaean and earliest Proterozoic age which involved some extension overlapped in time with phases of ductile deformation in tectonic provinces around the Pre-Ketilidian cratonic massif of Greenland and appears to have taken place under the same tectonic regime as that associated with the development of transcurrent lineaments or straight belts (Escher *et al.*, this volume). In the Lewisian complex of Scotland, originally situated near the eastern side of the Pre-Ketilidian massif, a distinctive feature of the tectonic evolution was the differentiation of crudely antiformal blocks composed largely of granulites and other dry rocks which suffered relatively little deformation over the period 2600–1700 Ma from intervening linear zones in which the effects of deformation and wet metamorphism were concentrated. In the Outer Hebrides, structures of early tectonic phases are developed with sub-horizontal XY planes arched over the relatively inert blocks (Coward, Francis, Graham & Watson 1970; Davies, Lisle & Watson 1975). The structural conditions needed to produce such an arrangement could have been achieved in the first place by tangential extension involving a form of boudinage of the dry and immobile granulites at depth and migration into the necks of the 'boudins' of more ductile (wetter?) gneisses (figure 2). Thickening of the crust would seem unlikely to have resulted from tectonic processes of this type and the massive slow uplift which appears to have taken place during subsequent stages of the evolution of the Lewisian complex suggests the operation of a different process.

Regional uplift and erosion during the closing stages of crustal mobility in early Proterozoic provinces is indicated both by the setting of K-Ar isotopic clocks and by the occurrence of mid-Proterozoic clastic formations resting directly on granites or on metamorphic complexes. Two lines of evidence suggest that the average rate of uplift could have differed by an order of magnitude from the post-orogenic elevation recorded in collision orogenic belts of Phanerozoic age. The early stages of elevation in the Lewisian complex took place slowly enough for partial metamorphic adjustment to take place (Dickinson & Watson 1975; Moorbath & Park 1972) while the stages which followed emplacement of late Laxfordian granites were slow enough to spread the values of K-Ar mineral dates over some 200 Ma. A similar broad band is occupied by K-Ar ages from the much larger Churchill province, the distribution in both contrasting sharply with that characteristic of the British Caledonides, where K-Ar mineral ages spread for little over 25 Ma after the emplacement of the late-orogenic granites (figure 3).

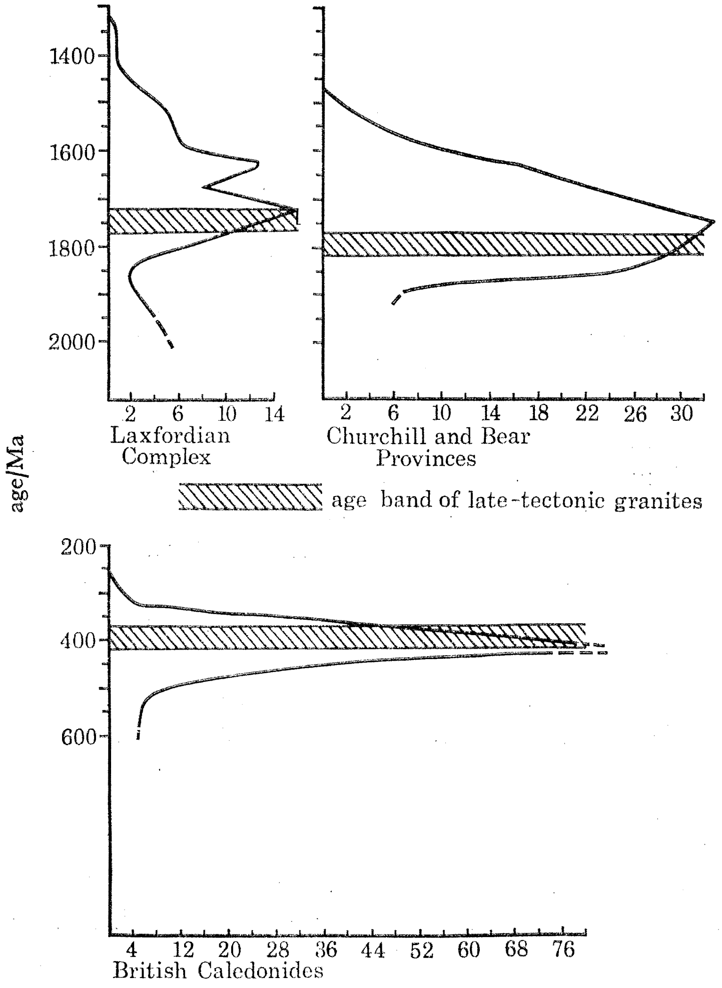

FIGURE 3. Histograms showing the scatter of K-Ar ages in relation to the time of emplacement of alte-tectonic granites in early Proterozoic mobile belts of Scotland and Canada. A similar histogram for the British Caledonides is shown for comparison below.

A second feature relevant to the history of uplift in early Proterozoic provinces is the rarity of thick marginal or intermontane formations with the time-relations of molasse. Such clastic formations as the Jotnian and Torridonian sandstones which lithologically resemble molasse-deposits have turned out to be several hundred million years younger than the terminal stage of mobility in the provinces on which they rest whereas the Molasse proper and the Old and New Red Sandstones were essentially coeval with the terminal stages of orogeny in the Alpine, Caledonian and Hercynian belts. An understanding of these relationships involves consideration of both the scale and the rate of uplift. It is clear, for example, that portions of the Svecofennide province had been eroded down to almost their present cross-section within a few tens of millions of years of the ending of mobility, since certain rapakivi granites dated at *ca.* 1700 Ma pass into sub-volcanic associates: but the low-pressure style of metamorphism and the preservation of low metamorphic grades suggest that less than 10 km of overburden may have been removed.

The timing and scale of uplift in the western Churchill province are of particular interest in the light of Burke & Dewey's (1973) inference that reactivated Hudsonian crystalline rocks in this province 'represent a Tibetan plateau environment' thickened by the underthrusting of a continental plate in continuity with the Archaean Superior province. Such an analogy, which implies massive uplift followed by erosion proceeding *pari passu* with isostatic adjustments, suggests that a deeper crustal section should be revealed in the province than that seen in the adjacent craton. The evidence reviewed by Davidson (1972) shows, however, that Archaean greenstone-belts preserved in the eastern portion of the Churchill province very closely resemble those of the southern Superior province in the features which are dependent on depth of section–breadth, proportion of acid volcanics and clastics to basic volcanics, extent of low-grade metamorphism, style of mineralization. This evidence, with that indicating a slow rate of uplift, seems difficult to reconcile with a hypothesis involving extensive crustal thickening in the Churchill province. The preservation over very large areas of the erosion-surface which underlies the Athabasca and Dubawnt groups suggests that there has been no further lowering of the general surface since the deposition of these groups the minimum age of which is 1200 Ma. Ambrose (1964) traces the erosion-surface, with a subdued topography and elevation of less than 1 km above sea level, for some 500 km to Great Slave Lake and further suggests that it may be nearly coincident with the yet more extensive sub-Palaeozoic unconformity. The fact that it is not deeply incised seems to rule out any major rejuvenation of the topography after cutting of the sub-Athabasca surface. The time-period available for the unroofing of large parts of the Churchill province was thus certainly less than 600 Ma.

4. LATER PROTEROZOIC MOBILE BELTS

The crustal belts subjected to tectonothermal activity after the stabilization of early Proterozoic provinces at about 1800 Ma fall into two time-groups – those whose evolution terminated at about 1000 Ma (Grenville belt, Karagwe-Ankole belt, etc.) and those whose period of activity spanned the Proterozoic–Palaeozoic boundary. Many of the first and some of the second group – the Pan-African and related belts of Gondwanaland – present problems similar to those of early Proterozoic provinces for which ensialic origins have been proposed. They contrast with the remaining members of the second group such as the Caledonides, Appalachians and Uralides which are generally considered to have evolved at continental margins during cycles terminated by collision of continental plates.

Interpretations in terms of collision of continents and the elimination of oceanic basins which have been proposed for such belts as the Grenville and the Nigerian sector of the Pan-African system (Burke & Dewey 1973) involve the inference that reactivation of older continental material was the result of underthrusting by an advancing continental plate and consequent thickening of the crust. The suggested analogy with the Tibetan plateau again implies a terminal orogenic stage of massive uplift associated with deep erosion.

In this context, several aspects of the regional geology are of interest. The first is the scarcity of marginal or intermontane deposits with the time-relations of molasse. Such deposits are represented in the Tibetan–Himalayan system both by the huge alluvial and deltaic deposits that fringe the Indian craton and in the fault-bounded basins within the Tibetan area. If the entire Himalayan range were planed off level with the top of the Indian craton the basin and delta deposits at its southern border would still have thicknesses of $>$ 10 km. In portions of the Pan-African belts (for example, the Mozambique belt of Tanzania) the oldest post-orogenic sediments are Karroo deposits dating from about 200 million years after the ending of tectonic mobility. Where older deposits rest unconformably on an eroded surface of Pan-African metamorphic rocks these are usually of very modest thickness. At the northern side of the Hoggar where Ordovician overlies Suggarian and Pharusian (e.g. Legrand 1975) and in South Africa where the Lower Palaeozoic Cape system overlies granites and low-grade metamorphic rocks, the basal unconformity passes without major change of level onto older basement rocks in the adjacent craton. This arrangement indicates that there has not been strong differential uplift of the Pan-African provinces mentioned since very early Palaeozoic times. More generally, the distribution of successions of Karroo facies and of their marine equivalents does not suggest that the Pan-African belts formed mountain tracts in late Palaeozoic times and these belts do not form high ground relative to the adjacent cratons today.

These relations offer little support for the proposition that mobility in the Pan-African belts was terminated by rapid uplift similar in rate and scale to that suffered by the Himalayan region and Tibetan plateau. Evidence that considerable uplift did take place is provided by the occurrence in certain areas, such as the Mozambique belt of Rhodesia, of deep crustal granulites at the same level as the greenschist-facies greenstones of the adjacent Archaean craton. Most of these granulites, however, are considered to have originated long before the elevation of the belt (Clifford 1973; Shackleton 1973) and there seems nothing to exclude the possibility that their uplift was spread over a period measurable in hundreds rather than tens of millions of years.

The occurrence of Palaeozoic and Mesozoic formations lying above the eroded Pan-African complexes in a manner which indicates that there has been no strong differential uplift of these complexes since the initial period during which they were unroofed recalls the relations of the Dubawnt and Athabasca successions with the western Churchill province (p. 635). In all these provinces, the initial period of uplift and erosion, perhaps lasting for a hundred million years or more, was not followed by further uplift of the belt as a whole relative to the adjacent cratons. The erosion surface formed after the initial phase either remained near base-level, as in the western Churchill province, or was displaced by vertical movements affecting mobile belt and adjacent craton together as in the Pan-African belts. The timing of vertical movements provides a strong contrast to that recorded in collision orogenic belts such as the Caledonides, Urals or Appalachians where initial rapid uplift and erosion has been followed over periods of at least 400 Ma by one or more phase of renewed differential uplift and rejuvenation of the topography continuing, for example in Britain, into Tertiary times. The behaviour of these belts is consistent with a history of isostatic adjustment to unroofing in a crustal structure possessing considerable residual buoyancy. In some portions of the belts – for example the northern part of the Appalachians – the fact that the crust is still thicker than that of the adjacent craton suggests that such adjustments are likely to continue for some time to come. The lack of a history of repeated adjustment suggests that the Pan-African belts, in which activity ceased no more than a hundred million years before the close of the Caledonian cycle, suggests that they had no residual buoyancy and could be an indication that they do not represent thickened crustal welts.

5. Later Proterozoic cratons

The cratonic crustal units which flanked the mobile belts of middle and late Proterozoic age incorporated both Archaean complexes which had been stable for many hundreds of millions of years and early Proterozoic provinces stabilized at or after 1800 Ma. The presence of Archaean massifs appears to have exerted an influence on the subsequent evolution of the cratons in at least two ways which are relevant to the subject of this paper.

Systems of graben-structures were developed in several large cratons during the period between 1500 and 1100 Ma, the best-known examples being those in the terrains around the North Atlantic. Some at least of these graben were developed, like the majority of Phanerozoic rift valleys, at the crests of broad crustal upwarps. The Ryazan-Saratov downwarp for example, which extends southeastward for 800 km from the vicinity of Moscow and contains at least 1 km of Proterozoic sediment, traverses a region of crystalline rocks the surface of which appears to have been subject to erosion on the shoulders of the rift but descends outward beneath a cratonic cover (Keller & Predtechensky 1968). These structures – the broad upwarps and graben – are commonly located in early Proterozoic provinces or near the junctions of such provinces with Archaean massifs. They consistently avoid the interior parts of the oldest cratons; the mid-continent gravity high of North America, for example, approaches but does not enter the Superior province (the Kapiskasing belt, sometimes regarded as an early rift, appears to me to have closer affinities with the northeasterly transcurrent lineaments which cross the Canadian shield); the Gardar rift lies within the Ketilidian province close to the southern border of the Pre-Ketilidian massif in southern Greenland; and the Jotnian graben of the Baltic shield and Ryazan-Saratov downwarp of the Russian platform are both situated in Proterozoic provinces. These relations suggest that Proterozoic rift-systems tended to skirt Archaean massifs in the same manner as does the much younger African rift-valley system.

On a broader scale, the location of Archaean massifs appears to bear some relation to the distinction between shield and platform areas. This distinction – between cratonic regions which did not, on balance, accumulate cover-formations and those which did – was established early and maintained over very long periods in some cratons. In the European craton, for example, Sinian (latest Precambrian) and in some places late Proterozoic cratonic formations underlie much of the Russian platform, including almost all the regions in which the platform-cover has a total thickness in excess of 1500 m, but are very restricted on the Baltic and Ukrainian shields (cf. Nalivkin 1973, figs. 11 and 12). In North America, the platform deposits of the United States rest in many places on later Proterozoic quartzites or volcanics which are of restricted importance on the Canadian shield. Broadly speaking, the shield areas in both cratons have therefore differed from the platform areas for something like a thousand million years. The contrasts have, furthermore persisted through periods of radical change in the size, shape and relations of the two cratons. Through earliest Palaeozoic times, the European and North American cratons most probably formed separate plates divided by a proto-Atlantic ocean. In mid-Palaeozoic times they were welded together to form the Laurasian supercontinent only to be separated once more in Mesozoic times by the opening of the North Atlantic.

When the crystalline basements of the Baltic and Canadian shields are compared with those of the Russian and North American platforms, as they are known from Precambrian inliers and from the rather abundant borehole data, a possible difference in architecture becomes apparent. Both shields incorporate Archaean massifs which occupy a substantial proportion of their total area; both platforms are underlain by Proterozoic crystalline complexes with which only small Archaean terrains are associated (table 2).

Table 2. Percentages of shield and platform regions underlain by Archaean rocks stabilized before 2500 Ma

	Europe	North America
shield areas + regions with cratonic cover < 1 km	13	30
platform areas with total cratonic cover > 1 km	6	15

These figures, though obviously only very approximate, suggest the possibility that those portions of the cratons in which Archaean massifs were most closely clustered were less readily depressed when loaded by sediment than were the portions underlain by Proterozoic provinces. I have already mentioned evidence suggesting that many Archaean massifs have remained in roughly the same position relative to base level since early Proterozoic times. Their distribution within the Baltic and Canadian shields is in harmony with this suggestion. The African craton presents a rather different picture in that the numerous Archaean massifs are widely scattered instead of being clustered together; perhaps it is more than a coincidence that the cratonic cover also has a patchy distribution and that it includes a high proportion of non-marine sediments.

6. Conclusions

The lines of evidence explored in this paper lend little support to the view that Archaean and early Proterozoic provinces exposed in Precambrian shield areas have as a rule undergone repeated elevation and erosion since the time of their formation. In a number of regions which have the structural and metamorphic features familiar in such terrains there seems to be convincing evidence that erosion down to the present level of exposure had been completed in periods of no more than three or four hundred million years soon after stabilization. Assuming that average rates of uplift were no faster than those recorded in more recent times – I have already suggested that they were in fact less rapid in some instances – the crustal levels revealed need therefore be no different from those which might be revealed in an eroded Caledonian orogenic belt.

This inference does not, of course, necessarily conflict with suggestions that some ancient provinces, those in which metamorphic or other indices suggest that deep crustal levels are exposed, have undergone upward movements of the order of 20–25 km and have been very deeply eroded. Portions of the Limpopo, Ubendian, Nagssugtoqidian, Lewisian and Mozambique belts may turn out to have had such a history; but the geobarometers used now are neither precise nor unambiguous and data for the scale and rate of uplift are seldom complete. Geological problems of many kinds arise in connection with the interpretation of the evidence. The relatively trivial volumes of erosional detritus preserved in the vicinity of provinces thought to have undergone deep erosion may perhaps be explicable in terms of slow uplift and consequent wide dispersal of the erosion-products. The indications that topographical rejuvenation did not follow the initial unroofing of such terrains as the western Churchill province and parts of the Pan-African system have a bearing on the mechanism of uplift, since isostatic adjustments to erosion would be expected in regions where uplift was associated with marked crustal thickening, as in many Phanerozoic orogenic belts. Uplift initiated by thermally-controlled changes in the mantle, on the other hand, might terminate without leaving a residual buoyancy effect.

The patterns of behaviour of cratonic regions have been conditioned to some extent by the nature of the basement. The oldest cratonic units have been relatively inert. Tectonic activities of kinds associated with the development both of later mobile belts and of graben systems have been preferentially concentrated at their borders or in adjacent parts of the cratons. Vertical movements have been very limited in many of these Archaean cratonic units through later Proterozoic and Phanerozoic times – they have been subject neither to persistent uplift nor to continued downwarping beneath a cratonic cover. The unsinkable character of these massifs (cf. Armstrong 1968) suggests that their crustal thickness has remained roughly constant while their general inertia may correlate with the characteristic low heat-production of the surface rocks (cf. Darnley 1972) and the low mantle contribution to heat-flow beneath them. The geological processes which differentiated them from adjacent Proterozoic mobile provinces, many of which incorporate apparently similar Archaean material, were responsible for permanent and important changes in the properties of the continental crust.

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Discussion

Dr R. N. Crockett (*Institute of Geological Sciences, Exhibition Road, London S.W.7*). Professor Watson's point concerning the lack of widespread deposits of molasse type associated with the Mozambique belt is worthy of further emphasis as is also the converse situation noticeable in southern Africa where certain important sedimentary formations were difficult to fit into a geotectonic context. In this respect I disagree somewhat with earlier views expressed by Dr A. Kröner that the Waterberg sequence of continental sediments, superficially of molasse type, could be wholly related to mobile belt developments in Namaqualand and the Orange River region. Such a correlation is extremely doubtful in the case of the extensive Waterberg sedimentation in eastern Botswana and in the western Transvaal. The Waterberg of this region appears to have been deposited as a vertical tectonic environment characterized by the formation and development of enormous horst and graben structures.

I wonder whether the principle of vertical tectonics of ensialic type does not have some relevance in considering the subsequent Phanerozoic history of the African craton. For example, the sedimentary pile of the Karroo System could more easily be related to the internal vertical tectonic history of the African craton rather than the plate tectonic context of the African plate itself.