Evolution of the Continental Crust [and Discussion]

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Evolution of the continental crust

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At a time when it has been suggested that a large part of the resources of uranium available in readily accessible areas near the surface of the Earth may already have been found, and faced as we are by a demand which is likely to increase several-fold by the end of the century, it seems sensible to place any discussion of the geology of uranium on a very broad basis.

No student of the Precambrian, and it is in this capacity that I speak, can fail to be fascinated by some of the remarkable discoveries made during the search for uranium deposits over the last four decades. The close connection, as Bowie has pointed out on more than one occasion (Bowie 1970, 1977), that exists between many deposits and the presence of Precambrian rocks in their vicinity, the general lack of deposits in the very oldest Precambrian and the irregular distribution both in space and in time of workable accumulations of uranium, are all findings which bear on the evolution of the crust. Almost certainly an understanding of such questions as these, thrown up by the work of the mining geologist and geochemist, will in turn make our comprehension of crustal evolution that much clearer. In the other direction, the very fact that uranium deposits are not distributed regularly through time and space suggests that there are some fundamental rules to be found, clues to which lie in our general knowledge of the geological history of the crust, particularly through the Precambrian.

One of the most fascinating developments in Precambrian geology over the last decade has been the success with which the isotope geochemist has taken on the unexpected rôle of structural geologist and by exploiting knowledge of the distribution of unstable isotopes has been able to put forward models of the structure and development of the crust and mantle during the early Archaean. The surviving relics of Archaean crust over 3500 Ma in age are so small that field investigations alone are unlikely to indicate the large-scale processes which brought these rocks into existence. Although local studies in the field have produced invaluable accounts of the handful of early Archaean terrains as yet identified, one has to turn to geochemical data which alone can link crust and mantle, to produce hypotheses about the behaviour of the Earth as a whole in early Archaean times. Without this aid, a visualization of processes operating in the early Precambrian would be impossible; as matters stand this is difficult enough.

The ways in which granitic rocks may be formed, modified and destroyed during the evolution of the continental crust are central to an understanding of many processes which bring uranium into the upper crust in concentrations of economic interest. I propose, therefore, to take the geology of the granitic rocks as the theme of my paper.

Let us start with one of the most intriguing problems in geology: the intermittent production of granite which appears to have been the rule throughout the 3700 Ma of geological history of which we have some record. It was in 1960 that Gastil recognized that the mineral dates then available indicated that crystalline rocks (he was considering both metamorphic and igneous rocks), within continents, had not formed at uniform or at steadily changing rates through geological time, but had come into existence during a succession of periods of unusual activity separated by periods when fewer plutonic rocks were crystallizing within the continents. Gastil (1960), in a consideration of the last 2800 Ma, identified seven such periods, each marked by a peak of activity lasting some 100 Ma. In his paper Gastil commented on a hypothesis previously put forward by Tuzo Wilson (1949) that North America and other continents had been constructed during a sequence of events which had built up successive structural provinces about a central early nucleus. Gastil, however, followed Holmes (1952) in suggesting that continental development took place not so much around early nuclei but through some process which involved the periodic addition of new material in regions where continental crust had already formed. Of particular importance was the demonstration both by Holmes and Gastil that many structural provinces contain relics of older rocks indicating that continental crust was already present before the event which gave rise to the new rocks and structures, which completed the development of the province in question. Furthermore, the presence of early Precambrian rocks close to the present margins of continents suggests that continental crust as extensive as that of the present day may have existed early in the Precambrian.

The 17 years since Gastil first published his conclusions have seen a great increase in radiometric dating. On the whole this has confirmed his central hypothesis and has shown that the major periods of plutonic activity were world wide events during which great volumes of igneous rock – largely, but not wholly, granitic – were added to the continental crust. In 1963 I suggested that such activities formed part of a succession of shield-forming events which I named *chelogenic* or shield-forming cycles. I wished to express the idea that periodically, particularly extensive plutonic activity affected the crust and that on each occasion after this activity had died down, parts of the crust remained relatively inert as cratons while other parts were reactivated in later periods of activity. This appears to be the process by which the shields have grown, for each peak was less extensive in its effects than its predecessors. As a metaphor one might take the successive high tide marks left on a beach in the days following a spring tide. A record of diminishing high tides survive in the marks on the beach, but at the same time we know very well that each high tide was separated by a low tide of which there is less direct evidence. The Earth's crust retains a record of this nature though we are dealing with periods of abnormally great transfer of material from mantle to crust rather than tides, and the time scale is not one of days but of hundreds of millions of years. After each peak of granitic formation, plutonic activity retreats to leave regions of stable crust, parts of which are reactivated at the peak of the succeeding cycle, while other portions remain permanently stabilized as lasting additions to the continental shields. Two aspects of the chelogenic cycle are particularly relevant to the search for uranium: first, the possibility of periodic rechargings of the crust with uranium whenever massive transfers of granitic material from mantle to crust take place; secondly, there is the redistribution of uranium following erosion of the newly developed granitic rocks which may be expected in the later waning stages of each cycle after the peak of igneous activity. At that stage uranium may be dissipated by erosion or concentrated within new cover rock sequences or near the unconformities between cover and underlying basement. The extent and distribution of the granites of each successive cycle, and the tectonic relief which controls subsequent erosion and deposition, are thus of critical importance. During the early history of the Earth both the distribution of granites and the manner in which they were eroded may have been very different from the way in which Phanerozoic granites are largely concentrated in mountain chains and subsequently eroded as the uplifted chains are worn down in post orogenic time.

As the Precambrian history of the crust has become clearer, three very different advances in knowledge have thrown light on this history of such periodic accretions within the crust. First, isotope studies, notably of Rb/Sr and U/Pb, have indicated that the new igneous rocks have entered the crust fresh from the mantle and that we are not dealing, as I and others had wrongly supposed, with the reworking of older continental crust so much as with the addition of new material to pre-existing crust. The related question as to how much old crustal material was returned to the mantle I leave on one side for the moment, though this is of fundamental importance in deciding whether the crust has been increasing in volume with each period of activity or has maintained a constant volume.

A second advance has been in improved knowledge of the extent and manner of distribution of the rocks formed in each cycle. This has resulted from geological mapping and from age determinations. It has confirmed the view that older periods of activity were more extensive than younger, and has thrown new light on changes in geological activity since early Precambrian times. A point relevant to the search for uranium deposits is that each successive cycle which has brought new uranium into the crust and rearranged existing concentrations has developed in a distinctive fashion. Each cycle was accompanied by events which dispersed or concentrated uranium under conditions which, while not unique, were nevertheless in many ways distinctive of the cycle.

The third advance arises from the palaeomagnetic research which has shown that large parts of the Precambrian continents periodically altered their direction of motion relative to the magnetic poles at intervals of several hundreds of millions of years. Irving has referred to these major changes in the apparent polar wander path as 'hairpins' (Irving & McGlynn 1976). There is some connection between the distribution of hairpins through time, and the periods of maximum plutonic activity in successive chelogenic cycles. This suggests that from time to time, convection within the upper mantle has altered in such a way as to redirect the movements of continents and cause unusually large transfers of molten rock from mantle to crust. The new intrusions are linked with a variety of large structures, possibly formed in the continents in response to the altered circulation of the underlying mantle. The periodic modification of the continental crust by intrusion and deformation is one of the most distinctive characters of the Earth. Although we do not understand the origin of these periodic changes except in general terms, they must provide a more effective way of losing heat through extensive transfer of igneous melts to the upper crust than convection alone can provide. The surface covered by new igneous rocks diminishes from cycle to cycle and at the same time less of the crust exhibits plastic deformation and more is affected by brittle fracture. With each successive chelogenic cycle the areas in which unmetamorphosed or slightly metamorphosed cover-rocks can survive become larger and the area occupied by medium to high grade metamorphic rocks smaller. These changes must affect the distribution of useful deposits.

Many of the successive structural provinces preserved within large areas of Precambrian such as the Canadian or Baltic Shields were first identified early this century before radiometric measurements had revealed their ages. Once age determinations had shown that structural provinces formed in widely separated continents had developed at similar periods of time (Holmes 1952; Wilson 1960; Stockwell 1961), the possibility that worldwide change had taken place became apparent. I attempted (Sutton 1963) to summarize the position suggesting that the main structural units established by geologists working in widely separated areas began their development in one of the following three periods: 2900–2700 Ma; 1900–1700 Ma; 1200–1000 Ma.

These developments form the basis for the chelogenic cycles I proposed in 1963 and for the subdivisions recognized by Soviet workers such as Vinogradov, Tugarinov and Salop in their discussion of crustal development. Underlying the views of all these workers in the early 1960s is the view that the Earth has passed through a number of stages of development and that successive stages were accompanied by periodic bursts of igneous activity. This work, published in early 1960s or before, finds confirmation in more recent studies, notably in Moorbath's prolonged and detailed analyses of data provided by Rb/Sr and U/Pb determinations. This has led Moorbath (1976) to suggest that 'there seems to be a grouping of major terrestrial rock forming events at *approximately* 3800–3500; 2900–2600; 1900–1600; 1200–900 and 600 Ma ago'. Moorbath (1976) went on to suggest that global tectonics have differed in degree rather than in kind over the last 3700 Ma. This I feel may be underestimating the distinction between events in successive episodes, though I accept that velocities of crustal movement do not appear to have changed over the last 2300 Ma and that the length of time over which a peak of igneous activity has lasted appears to fall in the range of 50–150 Ma wherever it can be determined. Perhaps as a field geologist I am over-impressed by the distinction between say the greenstone–granite associations of Archaean times and the mobile belts of the Proterozoic, but my present inclination is to suggest that there were real differences both in extent and structural make-up between the successive complexes of new igneous rock added to the continental crust during the bursts of activity just mentioned.

At all events I wish to emphasize three points in this discussion of continental evolution: that growth was episodic, with peaks of activity during the Precambrian around 3600, 2700, 1800 and 1050 Ma ago; that the nature of geological activity was such that the tectonic setting of the newly formed igneous rocks and their extent changed with time, and thirdly that the modifications to the crust, and presumably also to the upper mantle developed in successive cycles, established long-lived heterogeneities which can play an important part in subsequent developments. One of the clearest examples of the latter is the relation recognized by Kennedy (1965) between the location of the margins of the continents established by the opening of the oceans initiated in Mesozoic and Tertiary times and the presence of late Precambrian or early Palaeozoic mobile belts such as the Pan-African and Gondwanaland or the Caledonides of northwest Europe and Greenland. Almost without exception the Atlantic and Indian oceans came into being along fractures in pre-existing continental crust which followed the lines of these much older mobile belts. The Archaean rocks of the Hebrides, southeast Greenland and the Ivory Coast underlie quite subordinate stretches of the Atlantic seaboards as compared with those underlain by late Precambrian or Palaeozoic rocks and structures. At that distant time some permanent change was produced in the lithosphere which determined where fractures were to develop several hundreds of millions of years later at the break-up of Laurasia and Gondwanaland.

With these three points in mind we can turn to the Precambrian record of continental evolution.

No more than 5% of the exposed continental crust is composed of rocks that were in existence 2700 Ma ago. These survive in isolated blocks usually no more than several hundred kilometres across. To find more or less continuous belts dating from the Precambrian, which may be followed for several thousand kilometres and which might be compared with

Phanerozoic mobile belts, we appear to be restricted to late Precambrian times, say from 1200 Ma onwards.

As is well known, the distribution of exposed Precambrian rocks is controlled by younger events. Africa and the once adjoining parts of Arabia, India, Australia and Antarctica and South America provide large exposures of Precambrian, which presumably formerly extended into the outer parts of Gondwanaland below what are now the younger circum-Pacific fold belts and nearby sedimentary basins. The uplift which exposed the Precambrian of central Gondwanaland preceded the opening of the Indian and Atlantic oceans and must date back to at least pre-Karoo time. A still earlier uplift contributed to the concentration of Precambrian outcrops found in the Canadian shield, Greenland and northwest Europe. Devonian deposits in this region are largely of continental Old Red Sandstone facies laid down on land or in shallow waters.

The buoyancy of central Gondwanaland and of the Northern Old Red Sandstone Continent raises the question of whether the underlying mantle has acquired some features differentiating it from that below other parts of the globe. It is of interest that certain much older anomalous features such as the unique Witwatersrand basin and the variety of Precambrian chromite deposits of Central and Southern Africa were located in what was to become the centre of Gondwanaland where the greatest Karoo vulcanicity occurred shortly before the break-up of Gondwanaland. There is thus a repeated suggestion that very long-lived heterogeneity may persist in certain parts of the upper mantle and crust.

Some Archaean developments

The existence of two types of Archaean terrain, regions composed of high grade crystalline rocks often reaching the granulitic facies, and those marked by associations of granites and low grade metamorphic, predominantly volcanic sequences usually known as greenstone belts, is well established. The well known tendency for volcanism within greenstone belts to proceed from ultrabasic or basic submarine lavas to acid pyroclastics often subaerial in nature, is well documented. Individual greenstone belts which may attain 15 km in thickness can contain more than one such volcanic cycle associated with a great variety of sedimentary rocks though these are usually subordinate in volume to the volcanics among which basic rocks predominate.

Two important new facts about greenstone belts to have emerged in recent years are first the evidence provided by isotopic measurements that the volcanics and the granites formed over the same period of time – a time span of some 50–100 Ma – and secondly that this process of greenstone and granite development was repeated on several occasions during the Archaean (see Moorbath (1976) for references).

The individual greenstone belts which may extend for several hundreds of kilometres appear to be relics isolated by erosion of much larger sheets. They are associated with a great variety of sediments including altered sandstones and comglomerates rich in igneous material derived from the granite and volcanic succession. In Rhodesia, two or possibly three sets of greenstones have been identified, of which the two best understood was formed about 3500 and 2700 Ma ago. The older sequence extends into the Transvaal and is approximately the same age as the oldest rocks located in the basement of the intervening Limpopo mobile belt, a structure separating the main greenstone–granite terrains of Rhodesia and South Africa. Each granite–greenstone outburst must have formed an upper layer many kilometres – possibly twenty or more – thick. This crust lay below water over much of the time when igneous rocks were forming, for pillow lavas are ubiquitous. Shallow water sediments, rare stromatolites and local evidence of subaerial vulcanicity suggest continental shelf rather than oceanic conditions. The great variety of sediments is consistent with local emergence of source rocks, and the evidence of erosion of parts of one greenstone sequence before the formation of a younger sequence all suggest a tectonically unstable and partly submerged continental crust as the environment in which the greenstone–granitic association formed. While it can be compared with parts of the present day circum-Pacific mobile belt system (Windley & Smith 1976), the Archaean examples extending as they do over much of the preserved continental crust of the time appear to have been much more extensive than any present day circum-Pacific volcanic province. Moreover, although the presence of metamorphosed limestone and quartzite successions in many high grade Archaean terrains, as for example in Greenland and Scotland, suggests a more stable régime with less vulcanicity (although no Archaean sequence of sediments is wholly free of volcanic rocks), there is nowhere in early Precambrian terrains evidence of extensive permanently stabilized areas. While temporarily stable areas may well have existed in the regions where marble and orthoquartzite survive, such successions were invariably folded and metamorphosed later in Archaean times, a relation which indicates that permanently stable regions such as present day Central Australia or the Great Plains of North America did not then exist. Indeed the submerged state of much continental crust suggests that the present day distinction between deep oceans and high standing continents may not yet have developed at the times when greenstone–granite associations were being formed.

The succession of greenstone and granite complexes had already started by 3500 Ma ago and continued to form at intervals of a few hundred million years with little change until about 2700 Ma ago. From that time onwards this kind of intensive igneous activity retreated from parts of the crust and so allowed a region such as the Witwatersrand Basin to accumulate a predominantly sedimentary succession, which, though slightly metamorphosed, was never subjected to the intensive folding characteristic of greenstone belts. The basement below the Witwatersrand was mobile enough to develop a basin of several kilometres vertical relief, but was never as intensively deformed as the basement below greenstone belts which typically is so altered and injected by younger rocks as to be hard to distinguish from any cover rocks. The gold and uranium bearing sediments of the Witwatersrand appear to fall into place as having formed in a relatively stabilized area where the degree of metamorphism was slight, where volcanic rocks, though several kilometres thick as in the Ventersdorp group, were nevertheless restricted to parts of the succession. Reducing conditions developed in the basin at a time when contemporary igneous rocks in greenstone belts elsewhere were undergoing weathering in an oxygen rich atmosphere. The combination of local reducing environment and a thermal gradient low enough to produce little metamorphism in the cover and to leave the granitic basement far enough from the melting point to retain its strength so that it provided a strong substratum for the sedimentary fill, allowed the concentration for the first time of uranium in workable amounts. As far as I know neither the older quartzite successions which formed in temporarily stabilized areas nor the altered clastic deposits with early Archaean greenstone successions have proved to contain useful amounts of uranium.

The Witwatersrand basin on this view can be regarded as one of the earliest (the Pongola basin on the Swaziland–South African border is older) largely stabilized regions formed during a diachronous change which led to a reduction in the rate at which greenstone belts developed, and a corresponding increase in the proportion of crust stabilized as cratons which become larger and more numerous.

During this transitional period (2500–2000 Ma), the proportions of volcanic rocks within sedimentary successions decreased and individual basins became larger. Alongside this development there appeared linear belts of high strain; the so-called mobile belts. These came into existence both around cratons which were bounded by a network of mobile belts, and on a more restricted scale within the cratons themselves which were crossed by narrow lineaments which, though only a few kilometres wide, ran in some instances for many hundreds of kilometres reaching, no doubt, downwards into the underlying mantle.

Some Proterozoic developments

While some of the mobile belts were already in existence 2500 Ma ago they first became a dominant feature of continental tectonics during the Proterozoic when systems of stable cratons delimited by mobile belts characterized the continental crust. This arrangement provided a variety of new settings in which uranium might be concentrated. The mid-Proterozoic peak of igneous activity which occurred at about 1900–1700 Ma ago led to a network of mobile belts which isolated numerous small stabilized areas. The proportion of mobile to stabilized crust was the reverse of that found at the present day where large cratons are bordered by orogenic belts a few hundred kilometres across. Palaeomagnetic evidence suggests, but perhaps does not yet prove, that relative movement between neighbouring stabilized areas was small in comparison with the displacement of continental crust as a whole.

The hypothesis I would support is that the Proterozoic crust reacted to movement of the underlying mantle by horizontal displacements at rates of a few centimetres a year which affected the continental crust as a whole but which allowed differential movements to occur within the more mobile regions which made up perhaps three-quarters of the continental crust.

Deformation, on this view, was largely intracontinental and not as at the present day the result of intercontinental convergence and divergence of separately moving continental blocks. Even in early Proterozoic times subduction was going on at the outer margin of continents against the proto-Pacific, or whatever name is appropriate for the major ocean of those times. Hoffmann's analysis (1973) of the NW Canadian Shield where the Proterozoic cover on the Archaean Slave Province passes westward into a Proterozoic metamorphic belt gives strong support to his conclusion that a mobile belt developed in Proterozoic times in that region which was virtually identical both in scale and in time required for its development with those of, say, the Palaeozoic of eastern North America or western Europe.

Among the new settings that such a tectonic régime provided for the accumulation of uranium are those in which the well known conglomerates of Blind River and of the northwest U.S.S.R. formed around the margins of stable blocks early in the Proterozoic. The climax of the next chelogenic cycle with the massive input of mantle derived igneous rock emplaced in the crust between 1900 and 1700 Ma seems to have recharged the continents with uranium and to have led to a variety of deposits in the cooler parts of the structure. Notable are uranium deposits in folded and slightly metamorphosed Proterozoic cover over Archaean basement locally domed and intruded by a profusion of Proterozoic granites, as in Australia, SE Darwin. Stephansson & Johnson (1976) have suggested that separation of the numerous Proterozoic domes which in North Australia lie some 24 km apart could be explained by the strength of the underlying crust made up in part of Archaean crystallines and a Proterozoic cover. It has been suggested that the resulting deformation of the cover and the Proterozoic granites may contribute to the localization of Proterozoic uranium deposits such as those of Rum Jungle (Stephansson & Johnson 1976). Abnormal though not necessarily economic concentrations of uranium may be found along the narrow zones of high strain within major Precambrian blocks such as those formed within the Canadian Shield. Indeed, through North America from Colorado northwards a number of uranium occurrences are grouped along NE–SW lines which lie over long-lived shear belts active from early Precambrian times onwards (Watson 1976). These lineaments, as remarked earlier, are rather characteristic structural features of the Proterozoic when large continental blocks underwent limited internal deformation during extended horizontal displacements during the Precambrian (Briden 1976; Sutton & Watson 1974; Piper 1976). During the period separating the peaks of activity in the Middle Proterozoic (1900–1700 Ma) and the late Proterozoic (1100–900 Ma), an extensive stabilization of the crust occurred such as is characteristic of the late stages of a chelogenic cycle. In Greenland, for example, extensive Ketilidian migmatites led to large Rapakivi granites, many of which formed close to the surface in graben-like structures bounded by down folded rocks (Bridgwater, Sutton & Watterson 1974). Upwards the Rapakivi granites pass into roughly contemporary acid volcanics indicating that the granites had reached a very high level within the crust. In section these granites appear to form laccolithic masses spreading sideways from narrow feeding channels. The granites which were accompanied by thermal metamorphism which reached the granulite facies, were followed by true graben in which sandstones and volcanics accumulated in down-faulted blocks cut locally by the well known South Greenland alkaline massifs with uranium contents in the range of 100–800 parts/10^6. The Athabasca deposits of Canada and the Australian Carpentarian formations are examples of sediments laid down at the period of reduced igneous activity which separated the middle and late Proterozoic climaxes. Many uranium deposits were associated with such sediments which accumulated in the mid-term of the chelogenic cycle developed in the period 1800–1100 Ma, and with alkaline rocks found locally very late in that cycle. That period of time marked a distinctive stage in continental evolution when for the first time extensive stabilized areas marked by graben, incipient rifting, local alkaline intrusions and widespread flat-lying, sedimentary formations, came into existence.

As a result of the reduction in igneous activity at the peak of each successive chelogenic cycle as compared with its predecessors, there was both a larger area of relatively cool crust in which uranium might accumulate and also a greater span of time between one peak and the next. The Witwatersrand basin, which appears to have been virtually unique in late Archaean times, came into existence in a small area free from the igneous activity which characterized the almost ubiquitous greenstone belts and associated granites forming elsewhere at that time. In contrast, Proterozoic developments led to the appearance of more environments such as the unmetamorphosed sedimentary successions derived from Archaean volcanic and granitic terrains, the low grade metamorphic rocks, deformed and intruded by Proterozoic granites, and the major lineaments extending for many hundreds of kilometres resulting from intracontinental displacements, in all of which uranium might accumulate. Proterozoic deposits, as is well known, occur in the sedimentary successions, at the unconformable base, and apparently also in the older basement below. Last of all in the Proterozoic chelogenic cycles were the rare and unusual alkaline bodies such as those of South Greenland, with uranium contents as high as 800 parts/10^6 which are as yet unused because of the mineral dressing problems involved in extracting uranium from the rock forming silicates.

I do not propose to discuss Phanerozoic events in any detail. The Proterozoic developments anticipate some of the situations which allowed economic deposits to accumulate in post-Precambrian times. One can see certain similarities with such Phanerozoic occurrences as the clastic deposits formed east of the tectonically active western United States, the small Devonian deposits locally present above the metamorphic rocks of the Appalachian, and with the uranium formed in the Karoo overlying the Pan-African and older crystallines of central Gondwanaland.

It is a commonplace in the occurrence of uranium, to find deposits of different ages in close proximity, and reasons for this have been frequently put forward. Without attempting to discuss the mechanisms by which uranium is taken into solution and precipitated, the very existence of such deposits, which in effect define uranium provinces, may throw light on some aspects of crustal development. If we consider for example the Precambrian crust in Canada, Greenland and the Baltic we find Proterozoic uranium identified in Sweden and the northwest of the U.S.S.R., in the centre and east of the Baltic Shield, and extensive occurrences around the Archaean Superior and Slave Provinces of Canada. In all of these regions the Archaean contains volcanic greenstone belts and associated granites. In Labrador, Greenland, Scotland and western Norway, Archaean rocks are widespread either as parts of the Precambrian Shield or as slivers of basement within the Caledonides. In these regions, greenstone belts are unusual and most of the Archaean consists of granulite and amphibolite facies gneisses containing metamorphic assemblages formed at depths of several tens of kilometres. Only in western Greenland are there volcanic sequences which might be compared with greenstone belts and these are small compared with those of, say, the Superior province of Canada.

It would appear that the Archaean from Labrador to western Scandinavia may have been eroded more deeply in Precambrian times than was the bulk of the Canadian shield to the west and the main mass of the Baltic Shield to the east.

In Scotland it has been possible to date the uplift which gave rise to this erosion which Dickinson & Watson (1976) found to have occurred largely in the Proterozoic before about 1900 Ma ago. Bearing in mind the known tendency of uranium to concentrate high in the crust, such an uplift and consequent erosion could bring about a loss of any uranium from the region in question, which before the opening of the Atlantic might have been some 1500 km across from east to west. It is probably premature at present to do more than look for possible links between the distribution of known uranium deposits and the nature of the nearby Archaean crust. There appears to be a positive link between the occurrence of some Proterozoic uranium deposits and the presence of Archaean greenstone–granite terrains in the general vicinity. What is not so clear is whether uranium deposits are lacking or scarce in regions where there is reason to suppose that erosion had removed the uppermost 20 km or so of Archaean crust later in the Precambrian to leave a high grade metamorphic terrain as the basement immediately below younger rocks.

Regional anomalies might be expected to form in quite a different setting, not as the result of erosion and removal of the upper crust but through the addition of new material from the mantle. I have been arguing that periodic transference of material from mantle to crust has occurred and that the amounts of such transfers have been reduced from cycle to cycle through geological time. If this hypothesis is correct the crust can be regarded as composed of blocks which have received varying numbers of these transfers from the mantle. The Superior province of Canada, or the Precambrian of Western Australia, has received no major transfer from the mantle over the last half of the Earth's history whereas central and southern Europe were injected by Hercynian granites which appear to have recharged that part of the crust with uranium less than 300 Ma ago. All of this is well known, but what is less clear is whether there are some underlying factors which controlled which parts of the crust were to become relatively inert shields 2500 Ma ago, and which were to be tectonically active in Proterozoic times and still later in the narrow belts affected by Phanerozoic orogenies. There are hints that this differentiation of the crust into regions which became relatively inert in mid-Precambrian times and into parts that continued to receive new draughts of matter from the mantle and that became involved in Proterozoic and younger plutonic events, may have its origins as far back as the Archaean.

In effect such a hypothesis would maintain that certain provinces of the crust (and underlying mantle) possessed a property built in during the Archaean which predisposed them to a relatively inert, or on the other hand to a relatively active, Proterozoic and Phanerozoic history. This may seem an absurd proposition but it appears to be supported by a number of small clues. A most interesting discovery was made a few years ago in Greenland near the boundary between the pre-Ketilidian, an Archaean block containing incidentally some of the oldest crust yet identified, which was in existence over 3700 Ma ago, and the Ketilidian province to the south which was affected by prolonged Proterozoic igneous activity, deformation and metamorphism. Workers in east and west Greenland (Bridgwater, Escher & Watterson 1973), investigating structures in country close to the boundary between the Proterozoic Ketilidian province established *ca.* 1800 Ma ago and the older Archaean rocks to the north, found features which distinguished the crust to the north and south of the boundary but which had formed before the boundary developed 1800 Ma ago. It was discovered that a dyke swarm about 2000 Ma old, which extended into both provinces, had taken on an unusual form near the line of which was later to become the margin of the Proterozoic metamorphic province. The dykes in this abnormal zone were intruded as isolated masses and in networks of intersecting intrusions which often offset one another in contrast to more regular, larger and more widely spaced dykes which developed both to the north and south of the abnormal region. In other words the crust at the time of the dyke intrusions 2000 Ma ago was already in an unusual tectonic state within the belt which several hundred million years later was to define the boundary between a block which retained its Archaean character and one to the south which was to receive a major addition of granitic rock from the mantle. Bridgwater and his colleagues were able to carry this story still further back for they found that the dyke swarm cut steeply dipping belts of highly strained rocks which had formed as the result of still earlier deformation and which are probably Archaean in age (Bridgwater, Escher & Watterson 1973).

In the Canadian shield the aeromagnetic and geological mapping of the Geological Survey of Canada has identified a number of such steeply inclined belts of strong deformation which define sets of lineaments crossing the shield. Some, but not all, of these lineaments have become well known for the mineral occurrences which include uranium deposits developed along their length. In certain instances these lineaments can be shown to have originated in Archaean times, though it was in the Proterozoic that they played a major part in the intracontinental deformation that led to the definition of the Hudsonian metamorphic provinces with their accessions of Proterozoic granites, as distinct from the parts of the Shield such as the Slave and Superior provinces which have retained their Archaean character. In turn, much later in the

Earth's history one finds that the much younger Phanerozoic igneous activity tends to be concentrated in regions that had been active in Proterozoic times but on the other hand much more rarely affected regions which had been relatively inert since the Archaean. Gass (1970) has pointed out that much Mesozoic and Tertiary igneous activity in Africa is concentrated in regions affected by the late Precambrian and early Palaeozoic Pan African movements. The point has already been made that as Kennedy appreciated in 1965, the late Mesozoic and Tertiary igneous activity that produced the ocean floors of the Indian and South Atlantic Oceans was initially concentrated largely along the sites of Pan African belts and only very locally developed in Archaean crust.

Bearing in mind the connections between economically useful occurrence of uranium and Archaean and Proterozoic developments of the crust that have already become apparent, it might well be useful in the future to attempt to catalogue the geological histories of uranium-rich and uranium-poor provinces. Such an enterprise might aim to understand the factors that determine that while certain parts of the crust received a succession of draughts of new material from the mantle throughout the early Precambrian until the end of the Archaean but subsequently no more, other regions received further accessions in the Proterozoic, while still smaller regions remained active and received still further mantle material at times during the Phanerozoic. It is this succession of events, whose effects are variously distributed across the continents coupled with the progressively lessening intensity of the transfer of igneous rock from mantle to crust in each successive cycle, that appear to offer in ways which we still only dimly understand, a basis for comprehending the evolution of the continental crust.

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Discussion

M. DAVIS (*Nuclear Energy and Electricity European Communities*, 200 *rue de la Loi*, 1040 *Brussels, Belgium*). Can Professor Sutton say whether South America exhibits any analogies to the Precambrian that he has described in southern Africa?

J. Sutton. There are very many similarities between the Precambrian of South America and that of central and southern Africa, so there can be little doubt that as the geological exploration of the less well known parts of South America proceeds, a range of Precambrian rocks similar to those in Africa will be revealed. Everything that is known about South America at present points in this direction, although one does not know whether individual mineral deposits can be matched.