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Crustal Development in the Precambrian

B. F. Windley

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Crustal development in the Precambrian

By B. F. Windley
Department of Geology, University of Leicester

CONTENTS

The oldest Archaean rocks in most shield regions are largely granulites and gneisses, and in west Greenland there is evidence of 1000 Ma of crustal history before the final high-grade metamorphism. Archaean greenstone belts are mostly younger than the high-grade terrains although in some areas, such as southern Africa, this has not yet been proved reliably. The greenstone belts may have developed as oceanic crust in connexion with plate movements, the earlier continents being represented by the more deeply eroded high-grade regions.

Stabilization of the Archaean cratons is signalled by continental-scale intrusion of dolerite dyke swarms. Proterozoic mobile belts are exposed at two structural levels. Some early linear basins have mio- and eu-geosynclinal parts and may have been located along Proterozoic suture lines. More deeply eroded mobile belts are often floored by extensive, partly reworked, crystalline basement and probably developed along linear rifted zones which acted as loci for high heat flow and igneous activity; they lack ophiolites and are difficult to interpret as collision-type mountain belts. Most probably there were intra-continental plate movements in the Proterozoic.

Introduction

With the recent rapid advances in understanding of tectonic relationships, and in radiometric dating, it is appropriate at this time to take stock of what is known about Precambrian evolution. We are at the point when plate tectonic models are beginning to be applied to Precambran belts and it is now possible to follow the chronological evolution of the continents, albeit in a crude form, from about 3800 to 600 Ma ago – about seven-eighths of geological time. The aim of this paper is to provide an introduction or preview for this volume in the form of a framework for the Precambrian within which individual aspects may be seen in context.

The main time boundary used here between older Archaean and Proterozoic is 2500 to

2100 Ma. This was a period of stabilization in several continents, representing a fundamental break in Earth evolution, far more significant than that between the Precambrian and the Phanerozoic.

The earliest Precambrian crust

There are broadly two types of Archaean terrains exposed today (Windley & Bridgwater 1971): those dominated by high-grade gneisses and migmatites, and those by low-grade greenstone belts and granites.

Table 1. Selected age determinations from Archaean granulite–gneiss terrains

	country	rock unit	age (Ma)	method	reference
1	Swaziland	hornblende gneiss	3340	Rb/Sr	Allsopp *et al.* (1969)
		ancient gneiss complex			
	Swaziland	granodioritic gneiss	3440 ± 300	Rb/Sr	Allsopp *et al.* (1962)
2	Minnesota, U.S.A.	Montivideo gneiss	3550	Rb/Sr	Goldich *et al.* (1970)
3	W. Greenland	Amitsoq gneiss	3980 ± 170	Rb/Sr	O.I.G.L. & McGregor (1971)
		Godthaab	3620 ± 100	Pb/Pb	O.I.G.L. & McGregor (1971)
		tentative age of Fiskenaesset complex	3600	Rb/Sr	Evensen *et al.* (in prep.)
		granulite-grade metamorphism of Fiskenaesset complex	2900	Rb/Sr	Evensen *et al.* (in prep.)
		granulite facies metamorphism of Fiskenaesset complex and hypersthene gneisses	2850 ± 100	Pb/Pb	O.I.G.L. and Windley (in preparation)
4	Scotland	Scourian gneisses	2900 ± 100	Pb/Pb	Moorbath *et al.* (1969)
5	N. Norway, Lofoten islands	granulite facies gneisses	2800 ± 85	Rb/Sr	Heier & Compston (1969)
6	Aldan shield, U.S.S.R.	granulite facies gneisses	3300 ± 200	Pb/Pb	Rudnik *et al.* (1969)
7	Ukrainian shield	Yamburg migmatites	3500–3600		Semenenko (1967)
8	Guyana, S. America	Imataca complex gneisses and granulites	3000		Hurley *et al.* (1968*a*)
9	Sierra Leone	pyroxene granulites	3000		Hurley *et al.* (1968*b*)
10	S. India	oldest gneisses, granulite facies	3065 ± 75	Rb/Sr	Crawford (1969)
11	W. Australia	Yilgarn block gneisses	2800–3100	Rb/Sr	Arriens (1971)

For many years popular opinion has been that the oldest continental rocks are volcanics and sediments belonging to the greenstone belts (Goodwin 1968; Anderson 1969; Anhaeusser, Mason, Viljoen & Viljoen 1969; Glikson 1971; Green & Baadsgaard 1971; White, Jakes & Christie 1971; Cloud 1971). However, the time is ripe for a major reorientation in the assessment of early crustal material because recent reliable age determinations show that the oldest rocks in most continents are in a high-grade metamorphic state and that most greenstone belts are comparatively young.

Sutton (1967) pointed out that the oldest ages are found in migmatitic granitic gneisses, such as in the northern Eurasian shields, which have been through a long history of tectonic reworking; therefore they might contain even older material. Windley & Bridgwater (1971) proposed that more emphasis be placed on these high-grade terrains, which are often extensive and present on all continents, in order to redress the balance in appraising Archaean evolution. Over-emphasis in terms of volume of detailed studies has been placed on the greenstone belts.

The following points are relevant to this discussion:

(1) Shackleton (1970) concluded that greenstone belts in eastern Africa accumulated on older gneissic crust of continental type, while Bliss (1969) and Wilson (this volume, p. 389) suggested that relics of pre-Sebakwian gneissic basement occur in the Transvaal craton of Rhodesia, and Hunter (1970) suggested that the Swaziland gneisses pre-date the Barberton Mountain Land greenstone belt.

Table 2. Selected age determinations from Archaean greenstone belt–granite terrains

	country	rock unit	age/Ma	method	reference
1	Barberton Mountain Land, South Africa	Onverwacht group Swaziland system	3375 ± 20	Rb/Sr	Hurley *et al.* (1972)
		Hooggenoeg formation Swaziland system	3360 ± 100	U/Pb	Van Niekerk & Burger (1969)
		Fig Tree shales Swaziland system	2980 ± 20	Rb/Sr	Allsopp *et al.* (1968)
2	Rhodesia	pegmatite in Bulawayan granite	3370 ± 70	K/Ar	Vail & Dodson (1969)
3	Canada	Yellowknife group Great Slave Province	2650	U/Pb	Green & Baadsgaard (1971)
		Rainy Lake Superior Province	2750 ± 30	U/Pb	Hart & Davies (1969)
4	S. India	Dharwar lavas	2345 ± 60	Rb/Sr	Crawford (1969)
5	W. Australia	Kalgoorlie greenstone belt	2600–2700	Rb/Sr	Turek & Compston (1971)

(2) Catanzaro (1963) and Stern (1964) obtained zircon dates from the Morton gneiss in the Minnesota River Valley. When plotted on a concordia diagram their data define a straight line with an upper intercept at about 3600 Ma (Bickford & Wetherill 1965). More recently, Goldich, Hedge & Stern (1970) reported a 3500 Ma Rb/Sr isochron age for the Montivideo gneisses in the Minnesota Valley. The information from this area is particularly important as it shows that there was high-grade sialic crust in existence 1000 Ma before the nearby greenstone belts of the Superior Province were formed.

(3) Oxford Isotope Geology Laboratory and McGregor (1971) found that amphibolite facies gneisses in West Greenland had a Rb/Sr isochron age of 3980 Ma (a more accurate, revised date is 3787 ± 85 Ma, Moorbath, personal communication) demonstrating that 'windows' of extremely old crustal material may be found in Archaean high-grade terrains.

(4) Several unconformities are known between greenstone belts and older high-grade gneisses and granites: in the Superior province of Canada at Steeprock Lake (Jolliffe 1966) and at Cross Lake (Rousell 1965); in India where the Dharwar greenschists overlie a granulite-gneiss basement (Nautiyal 1965). At Que Que, in Rhodesia, the Bulawayan basal conglomerate lies against granitic gneisses; and at Point Lake in the Slave province of northern Canada a basal conglomerate of the Yellowknife Supergroup overlies granite bordering the greenstone belt (Stockwell 1933); McGlynn & Henderson (1970) review other data suggestive of a basement to the Yellowknife Supergroup.

Although K/Ar dates have been widely used in assessing the age of Precambrian rocks, their value has been questioned (Moorbath 1967) as they are considered to represent, not the peak of orogenic activity, but the termination of an ^{40}Ar diffusion event related to the uplift and stabilization of continental blocks (Green & Baadsgaard 1971). Continuous diffusion of radiogenic argon may take place at depths of as little as 3000 m in orogenic belts (Hurley, Hughes, Pinson & Fairbairn 1962). Therefore Windley & Bridgwater (1971) predicted that the oldest rocks would be found with more sophisticated dating techniques in the high-grade Archaean terrains, because they would not become closed systems to radiogenic ^{40}Ar diffusion until their uplift following that of the higher level greenstone belts. For these reasons it is important to rely on more accurate radiometric age determinations made by the mineral and total rock Rb/Sr, Pb/Pb and zircon U/Pb methods.

In tables 1 and 2 age determinations are listed from all continents demonstrating that the higher grade parts of most Archaean complexes tend to be older than the lower grade greenstone belts. Several points of interest emerge from these tables:

(1) Whereas the radiometric determinations on the greenstone belts give an approximate idea of the age of their formation, those on the gneissic terrains are mostly dating the age of the last high-grade period of metamorphism; the recent evidence from west Greenland shows that the 2850 to 2900 Ma granulite-grade metamorphism was the culminating high-grade event of 1000 Ma of earlier crustal history. Therefore, while the high-grade rocks in many shield regions have isotopic ages older than those of nearby greenstone belts, if their evolution has been in any way similar to that in West Greenland, they may be expected to contain evidence of very early crustal history.

(2) The isotopic data suggest that most continents experienced a period of high-grade metamorphism in the general period 2800 to 3200 Ma. Most probably there were local diachronous hot spots developed as a result of early thin crust, steep geothermal gradients and fundamental fracture zones.

(3) Greenstone belts in Canada, Australia and India formed in the period 2345 to 2750 Ma. These are the oldest dates on the earliest volcanics; associated granites have younger ages. Since the Precambrian is now known to extend back as far as about 3800 Ma, these greenstone belts must be seen as belonging to the latest Archaean, or even the early part of the mid-Precambrian.

(4) The ages of events in southern Africa are significantly older than those in other continents, but it is emphasized that the geological relationships (i.e. the types of rock belts) are not different. The greenstone belts apparently developed diachronously, those in southern Africa forming before those in other shield regions. Although it is considered by Anhaeusser *et al.* (1969) and Viljoen & Viljoen (1969) that the Swaziland System of the Barberton Mountain Land greenstone belt contains the oldest rocks in South Africa, there are three groups of nearby high-grade gneisses that may well be older: the Swaziland gneisses, as suggested by Hunter (1970): the Nelspruit gneisses of the Barberton Mountain Land; and the gneisses of the Limpopo mobile belt, which form the basement to the Messina Formation (Mason, this volume p. 463). Note from tables 1 and 2 that the Swaziland gneisses are as old as the Swaziland System.

The most reasonable conclusion to be drawn from the available evidence is that the continental crust as a whole evolved diachronously. The development in what is now southern Africa appears to have been consistently ahead of that in other continents: some of the earliest gneisses are to be found there (but they have so far received very little detailed attention); the earliest greenstone belts formed there; and the early stabilization of the Archaean craton, consisting of the greenstone belts/granites and the gneisses, allowed platform deposits such as the Dominion Reef System to be laid down by 2800 Ma (Van Niekerk & Burger 1969), i.e. at a time when greenstone belts were still forming on several other continents.

The high-grade gneissic terrains did not go through continuous mobility or plutonism as they contain relic layers of meta-supracrustal rocks, evidence of high-level crustal stability before the high-grade metamorphism and deformation. In West Greenland the Malene supracrustals in the Godthaab area probably formed not long after 3800 Ma, and in the Fiskenaesset area the preliminary age of the formation of the major anorthosite complex is 3600 Ma (Evenson, Rama Murthy & Windley, in prep.), in which case the supracrustal rocks in which it formed (now metavolcanic amphibolites with rare marbles and schists) are older. The Swaziland gneisses contain relic layers of supracrustal rocks which, according to Hunter (1970), pre-date the Swaziland System. The high-grade gneiss terrains also contain abundant agmatitic basic fragments, largely of amphibolitic composition; Windley & Bridgwater (1971) regard these as the broken-up remains of very early supracrustal rocks which, if they had been preserved in basin-shaped form, would be termed 'greenstone belts'. In other words, the earliest supracrustal basins or greenstone belts were fragmented as their underlying crystalline basements were still mobile at such early stages of Earth history. What we interpret as 'greenstone belts' today are merely those that have survived.

Archaean granulite/gneiss complexes

Although some regional granulite facies metamorphism occurred in the Proterozoic, most occurred in the early Archaean, in particular in the period 2800 to 3200 Ma. Some high-grade Archaean complexes are extensive and well preserved, others are small and relic. For many years Russian geologists (e.g. Salop & Scheinmann 1969) have emphasized that the northern Eurasian Archaean complexes are in a high-grade metamorphic state, as greenstone belts are rare or absent there. The North Atlantic craton (Bridgwater, Watson & Windley, this volume, p. 493), extending from Labrador through West and East Greenland to the Scourian of Scotland, is one of the more extensive and best exposed terrains of this type from which many of the following details are drawn. Four important features of these high-grade complexes are:

(a) *The reworking of earlier crystalline material*

It is commonly implied that regional granulites formed from the metamorphism of an already crystalline basement; Winkler (1967), for instance, suggested that the dry nature of the rocks may be due to their secondary origin by remetamorphism of a partially dried out suite of crystalline rocks. However, in West Greenland the results of O.I.G.L. & McGregor (1971) show that the granulite-grade metamorphism was late in a long sequence of events and thus it was superimposed on already gneissic/granitic rocks. Bridgwater, Watson & Windley (this volume, p. 493) emphasize that high-grade gneisses were derived more by the remetamorphism of older granites and gneisses than by isochemical recrystallization of supracrustal rocks.

There may be a common reason why much of the early Precambrian crust underwent granulite-grade metamorphism. As indicated by Ray (1970), geothermal gradients were no doubt steeper than at present (figure 1) – a response to a probable early thin crust and a high rate of radiogenic heat production, which Dickinson & Luth (1971) show was several times greater 3000 Ma ago than today (figure 2).

Archaean granulites have low contents of H_2O, K, U and Th compared with equivalent amphibolite facies rocks (Lambert & Heier 1967; Eade & Fahrig 1971: Heier, this volume, p. 429). The relative basification of the granulites may be due to at least two processes:

(i) Upward loss of the more volatile elements due to chemical fractionation of the crust during high-grade regional metamorphism: this is the more accepted view. A corollary of this mechanism is that granites would be produced in the catazone and would migrate to higher crustal levels. If the model of Fyfe (1970) were applied to the Archaean, the granulites would be regarded as a the low crustal residue from which granites were derived: these migrated upwards to invade the borders of the overlying greenstone belts.

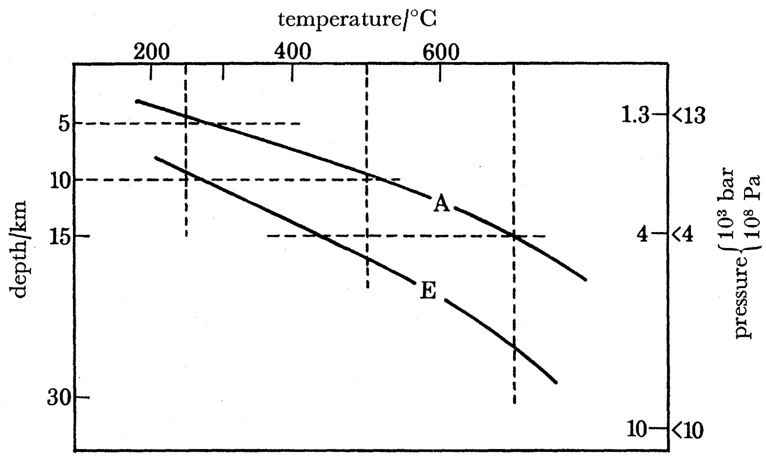

FIGURE 1. Geothermal gradients for (A) the Archaean and (E) the present (after Ray 1970).

(ii) O.I.G.L. & McGregor (1971) conclude that the greater part of the Godthaab area consists of tonalites which were emplaced as igneous complexes about 3100 Ma ago, before the granulite-grade metamorphism about 2850 to 2900 Ma ago. This means that the low potash content of many granulite facies gneisses may be due to isochemical metamorphism of pre-existing tonalites. Bridgwater, Watson & Windley (this volume) consider this to be a plausible mechanism for the derivation of many granulite facies gneisses, which lack potash feldspar and are poor in biotite, in the North Atlantic craton.

(b) *Layered igneous complexes with prominent anorthosites*

Calcic anorthosites (with bytownite to anorthite where best preserved) form a significant component of many high-grade Archaean terrains (Windley, in press). They are particularly common in west Greenland (at least 500 km strike length) and in the Limpopo mobile belt of southern Africa (at least 100 to 150 km strike length) and also occur in the Scourian of Scotland, India, Madagascar, West Africa and probably East Africa and Australia. The anorthosites occur with other rock types in conformable layers with a maximum thickness of 8 km in high-grade gneisses. The Sittampundi complex of southern India contains layers of chromite and was regarded by Subramaniam (1956) as a metamorphosed layered igneous body. In west Greenland the Fiskenaesset intrusion, which is at least 200 km long (strike length of the folded layers), is shown by Windley, Herd & Bowden (in press) to have an internal stratigraphy passing upwards from lower ultramafics (dunites, peridoties and pyroxenites) through mafic gabbros, cumulate gabbros, anorthosites, chromitites to garnet anorthosites, and a bulk igneous differentiation trend which is well preserved despite subsequent granulite and amphibolite facies metamorphism. Cryptic variation trends of individual minerals, such as plagioclase, olivine, orthopyroxene and hornblende, are also intact (Windley & Smith, in press). The complex formed from a magma with the composition of a hydrous high-alumina basalt and the tentative age of its formation is 3600 Ma (Evenson *et al.* in prep.). As these are the first major basic intrusions in West Greenland, it is tempting to think that the early mantle was degassing extensively at this time. Just as there is a marked uniformity in the character of Archaean greenstone belts in several continents (Anhaeusser 1971), so too is there a remarkable similarity in these anorthositic complexes – most likely there was a uniform, diachronous development of these rocks in different parts of the early continental crust.

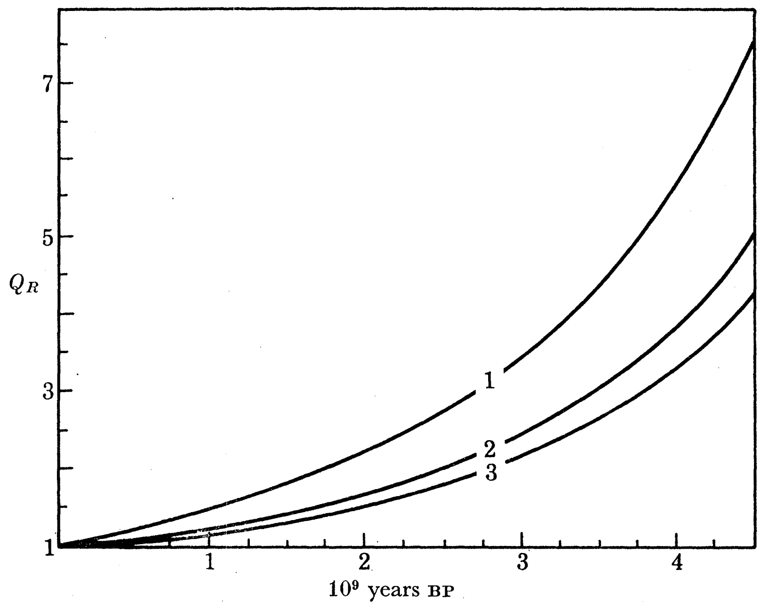

FIGURE 2. Relative radiogenic heat production in the past (after Dickinson & Luth 1971). Q_R is the ratio of heat production at any time in the past to that currently observed. BP is time before the present. Curves indicate values for Q_R calculated for following Earth models: (1) the chrondrite model, (2) the carbonaceous chrondrite or Orgueil model, and (3) the Wasserburg model.

(*c*) *Infolding of cover sequences into underlying basement gneisses*

Wilson (1958) suggested that infolded cover rocks would have the form of synclinal keels at the present levels of exposure. In high-grade gneisses these infolded rocks are most commonly represented by layers of amphibolite, mica schist and quartzite, but it is usually impossible to demonstrate that these sequences have a synclinal form, largely because lack of stratigraphy in the rocks prevents their structure being determined. However Windley *et al.* (in press) have demonstrated that parts of the Fiskenaesset intrusion, which is bordered by meta-supracrustal rocks, has a duplicated stratigraphy repeated in reverse order with internal synclinal closures and thus that the intrusion, and the cover rocks into which it had been emplaced, were infolded synclinally into a gneissic basement.

Another way of demonstrating this age relationship has been found by McGregor (this volume, p. 343) who, by observing that amphibolite dykes are absent in meta-volcanic amphibolite layers but are present in adjacent gneisses, concluded that the cover rocks must have been tectonically emplaced into their underlying gneissic basement.

(*d*) *Regional structural style*

The granulite/gneiss terrains are characterized by complex fold interference patterns that lack a linear regional trend. The constituent folds may be domes, basins, luniform-shaped or refolded isoclines, and they may be several kilometres across (Windley & Bridgwater 1971). This type of structural style occurs, for example, throughout the Archaean block of West Greenland, the Limpopo belt of southern Africa and the Aldan shield of Russia. Salop & Scheinmann (1969) point out that the folding process was closely associated with the formation of granitic masses by partial melting with consequent diapiric rise of granites in the cores of domal folds. Somewhat similar relationships exist in West Greenland where the cores of some domes consist of more homogeneous gneiss than is found in surrounding gneiss layers, demonstrating structural control of selective homogenization of the gneisses. This tectonic style and close association with partial melting of granitic gneisses is indicative of a high degree of plasticity during the regional deformation and metamorphism.

The formation of these non-linear structures over enormous areas is less likely to have been caused by lateral deformation associated with continental drift than by vertical movements caused by the role of gravity in a system with inverted density stratification as modelled by Ramberg (1967). It is particularly significant that the cover rocks are dominated by dense basic volcanics that were infolded into less dense granitic gneiss basement. The domes tend to reach a maximum size of about 15 km and, according to Ramberg's theory, the diameter of the domes and the spacing between them should be proportional to the thickness of the source layers. This might provide a means of assessing the thickness of the early Precambrian crustal layers.

Archaean greenstone belt/granite complexes

Much has been written on these low-grade belts and only brief mention will be made here of some main problems concerned with their relationship with the high-grade complexes just described and their mode of origin.

Where their original form is best preserved, as in western Australia, the greenstone belts form parallel linear belts and they ideally are basin-shaped. Anhaeusser *et al.* (1969) have demonstrated that their primary shape has often been modified by the emplacement of bordering late granitic plutons so that their boundaries are arcuate. An eventual stage may be reached where star-shaped basins are located between three granitic bodies.

The greenstone belts have an idealized stratigraphy ranging from lower ultramafics through largely basic volcanics to an upper, larger clastic, sedimentary group capped with chemically precipitated banded iron formations and cherts. Anhaeusser *et al.* (1969) and Anhaeusser (1971) have emphasized that the stratigraphy and the structures of the greenstone belts are sufficiently similar on many continents to indicate a uniform stage of development of the crust.

One of the major problems concerning the mode of occurrence and origin of the belts lies in the surrounding 'granitic' rocks which have received relatively little attention compared with the supracrustal sequences. Although they were earlier thought to be homogeneous granitic plutons, a major advance was made by the Geological Survey of Rhodesia in distinguishing different types of granitic/gneissic rocks with variable age relationships (Wilson, this volume, p. 389). Some granitic areas contain so much relic gneiss material that they are considered to be partially reactivated basement gneisses but other, more massive or homogeneous, granites have intrusive relationships. McGlynn & Henderson (1970) suggest that some of the granitic rocks bordering the Yellowknife greenstone belt of northern Canada represent a possible basement to the belt. They point out that a positive terrain of sialic composition must have existed nearby to provide by erosion the tremendous quantities of silicic sediments infilling the basins. They also suggest that diapiric granite bodies were intruded preferentially between the positive (basement) and negative (greenstone basins) regions of the crust – an idea very similar to that of Windley & Bridgwater (1971). The actual contacts of the greenstone belts with the high-grade gneiss complexes are thus obscured by a bordering screen of partly to completely mobilized granitic plutons. This relationship can be demonstrated in Sierra Leone, where Wood (1972) confirms Wilson's (1965) conclusion that the Mano Moa granulites constitute the basement to the Kambui Schist belts. The latter have the general form of an isoclinal syncline bordered conformably by reactivated basement. The actual boundary between the Schist belts and the basement is occupied by homogeneous granite in clear contrast to the more distant granulite-migmatite basement. Future ideas on the mode of formation of the greenstone belts are as likely to come from studies on the marginal 'granites' as they are from the supracrustals themselves.

Pettijohn (1970) makes the interesting observation that the late Palaeozoic or Mesozoic greenstones, volcaniclastic sediments and granitic plutons of the Sierras of California are reminiscent of those of the Archaean terrains. He suggests that this pattern of granite and volcano-sedimentary basins will develop anywhere and any time a thick sequence of denser lava rests on lighter sialic material. A kind of convective readjustment takes place with rising diapiric granitic stocks and downsagging of greenstone basins.

Windley & Bridgwater (1971) have interpreted the greenstone belt/granite terrains as having formed a high crustal level, whereas the granulite/gneiss terrains formed at relatively deep levels. Windley *et al.* (in press) estimate a pressure of at least 700 MPa (7 kbar) for the formation and metamorphism of the Fiskenaesset complex, West Greenland. It is important to distinguish between different erosional levels that are at the surface of the crust today and thus it is conceivable that some late Archaean belts of low-grade basic volcanic sequences in the high-grade terrains are the infolded root zones of greenstone belts. It is also conceivable that granulites occur under the high level greenstone belt/granite regions, such as the Superior Province of Canada, the Yilgarn and Pilbara blocks of Australia and the Transvaal and Kaapvaal cratons of southern Africa.

Models of greenstone belt evolution

So far two main models have been proposed to explain the mechanism of formation of Archaean greenstone belts.

(1) The greenstone belts are postulated by Anhaeusser *et al.* (1969), Martin (1969), and McGlynn & Henderson (1970) to have formed in downsagging basins on a thin crust. According to this model the greenstone belts are intra-continental mini-geosynclines (Clifford, in press), which are predecessors of early Proterozoic proto-oceans and the high-grade gneissic terrains occur below and/or between the greenstone belts.

(2) The greenstone belt sequences are considered by Glikson (1971), Anhaeusser (this volume, p. 359), and Talbot (this volume, p. 413) to have formed as oceanic crust between separating continental fragments. Although these authors only deal with the oceanic setting,

this plate tectonic model implies the prior existence of continents which accordingly would consist of the high-grade gneissic terrains described above. This model views the drifting sialic masses as mini-continents (Talbot, this volume).

Although these two models satisfy many requirements when tested against the data shown by the rocks, neither is totally satisfactory. The first takes no regard of current plate tectonic models (there were probably at least proto-plates in the Archaean), whilst the second requires

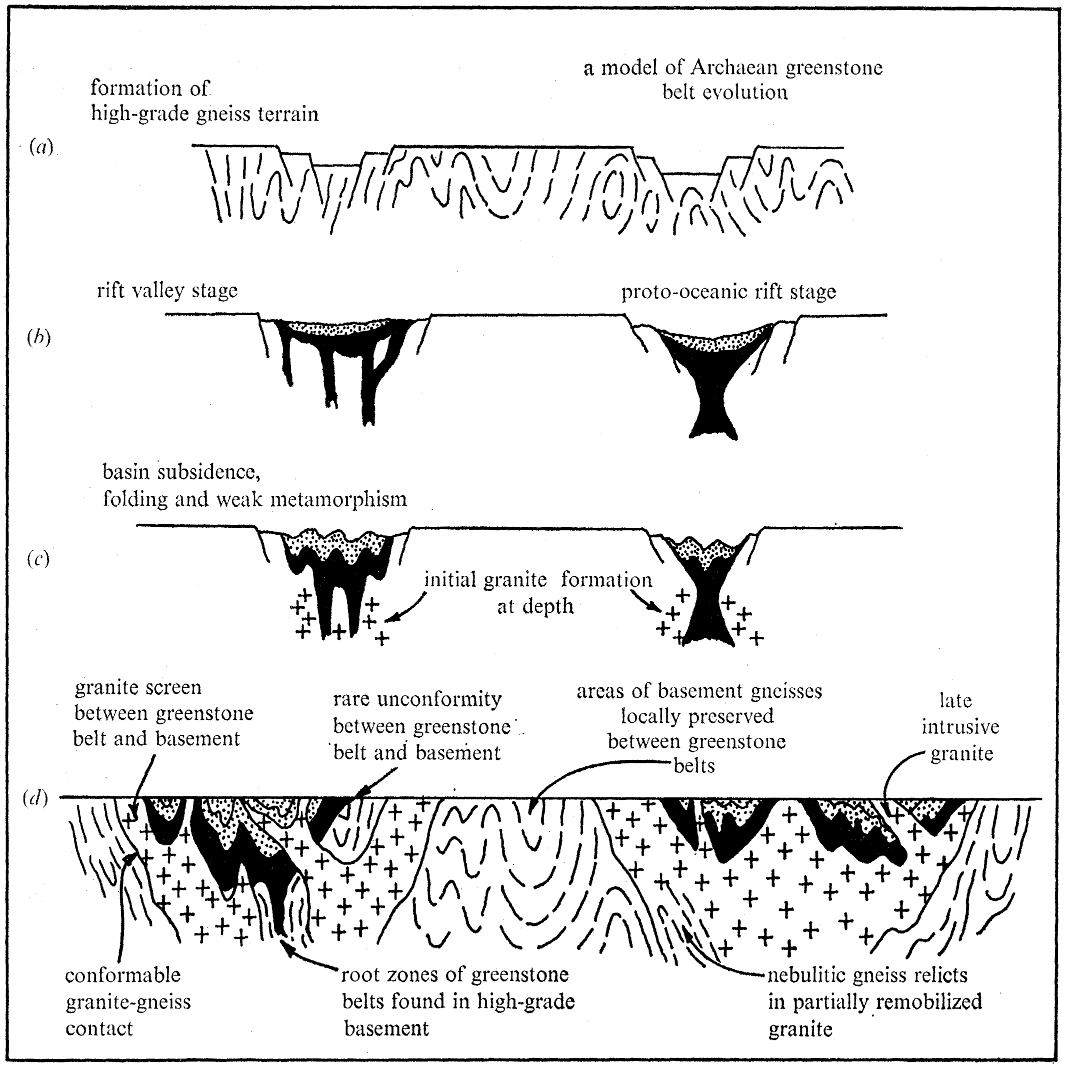

FIGURE 3. Proposed stages in evolution of Archaean greenstone belts.

extensive continental drift and ocean floor spreading, for which in fact there is no evidence (a serious drawback of Talbot's model is that the basins are symmetrical and are infilled with coarse, clastic sediments which implies the existence of nearby eroding source areas on both sides and deposition in subsiding basins rather than over widespread oceans). Neither takes into account the earlier high-grade gneissic terrains nor uses the types of ore deposits in the belts as petrogenetic indicators. The two models approach extremes of interpretation, the one implying no, and the other extensive, continental drift. Most probably the answer lies somewhere between these extremes and thus a model is proposed here which satisfies the essentials of both (figure 3).

There has been much discussion as to whether the greenstone belts are analogous to recent island arc or oceanic environments. A major advance was made by Glikson (1970, 1971) who, by detailed geochemical comparisons, was able to show that the basaltic assemblages conform to recent oceanic tholeiites with respect to K, Na/K, Sr, Zr and Fe^{3+}/Fe^{2+}. A geochemical aspect bearing on this problem that has been largely neglected concerns the well-known ore deposits in the greenstone belts – in particular Au–Ag, the tellurides and Cu–Zn. These are accumulations of elements which have just as an important bearing on the mode of origin of the associated volcanic rocks as the potassium and sodium, etc. Where comparisons are made with Recent environments similar deposits occur, for example, in the Basin and Range province, a high heat flow rift zone which is the northward continental extension of the East Pacific Ridge, and in the Red Sea, a proto-oceanic basin. In other words they are characteristic of early extensional plate boundaries.

A further important tectonic feature to consider is that the volcanic complexes in the greenstone belts have a linear distribution and probably formed as fissure eruptions parallel to the margins of the belts (Goodwin & Shklanka 1967; Goodwin & Ridler 1970).

If an attempt is now made to relate the greenstone belts to the modern plate tectonic model, when all the above points are taken into consideration they best fit one type of tectonic environment – a proto-oceanic ridge zone (figure 3), the nearest present-day equivalent of which is probably the Red Sea basin. The fact that the basalts have chemical affinities with recent oceanic tholeiites need not mean there was extensive continental drift and ocean floor spreading, but merely the formation of a proto-oceanic rift system involving only small amounts of crustal separation. In terms of the general concept of orogenesis according to lithospheric plate tectonics (Bird 1970) the incipient stage in the separation of crustal plates is represented by linear graben-like rifted zones which are the site of intense volcanic activity and which are later infilled with rapidly deposited molasse or turbidity sequences from the nearby continental areas – the ideal environment for greenstone belts. Subsidence of these high density accumulations would give rise to downsagging basins with vertical stretching and upright folds, typical features of the belts, while the contact zones between the negative basins and the positive areas would be the site of remobilization of the adjacent gneissic crust to form granitic plutons.

It is suggested that this model of a proto-oceanic ridge system best explains the featues of the greenstone belts. Although one type of mechanism is envisaged, there was probably more crustal separation and more oceanic crust generated in some belts than in others. There may in fact have been all gradations from ensialic graben-like rift zones to narrow, linear oceanic basis caused by relatively small amounts of 'drift'. Broad belts such as the Abitibi in southern Canada probably involved separation of crustal segments of a few hundred kilometres.

Proterozoic mobile belts

During the Proterozoic, taken here to extend from about 2500 to 600 Ma, there were many complex events too numerous to document in detail here. Particular rock groups or types of mobile belt are often broadly similar on several continents and formed at definite stages in the development of the crust (Salop & Scheinmann 1969).

The Archaean shield areas underwent considerable erosion and uplift in the initial stages of stabilization, which generally took place in the period 2500 to 2000 Ma. However, because the southern African cratons themselves stabilized slightly earlier than those in other continents, they were subjected to intrusion and sedimentation at an earlier time: the Dominion Reef System was deposited 2800 Ma ago (Van Niekerk & Burger 1969) and the Great Dyke of Rhodesia was intruded about 2550 Ma ago (Allsopp 1965). These were followed by the deposition of the Witwatersrand, Ventersdorp (2300 Ma, Van Niekerk & Burger 1964) and Transvaal Systems, the emplacement of the Bushveld Igneous Complex 1950 Ma ago (Nicolaysen, de Villiers, Burger & Strelow 1958), and the intrusion of the Umkondo and Mashonaland dolerites in the period 1600 to 1850 Ma (Vail & Dodson 1969; Wilson, this volume, p. 389).

In other continents there was intrusion of extensive dyke swarms, most with tholeiitic but some with ultrabasic compositions: in western Australia there is the Widgiemooltha Dyke Suite including the Jimberlana Dyke (2420 Ma, McCall 1971), and the Binneringie Dyke, at least 320 km long (McCall & Peers 1971); there is a prominent northwest trending dyke swarm extending across the Canadian Shield from Ungava to the Slave Province (2000 Ma, Clifford 1968). In the North Atlantic craton there is the Scourie Dyke swarm of the Lewisian of Scotland, more than 250 km wide (2400 to 2200 Ma, Bridgwater, Watson & Windley, this volume, p. 493), the Kangamuit Dyke Swarm of West Greenland, and the dyke swarm in East Greenland (Bridgwater & Gormsen 1969); these dykes were intruded in fracture zones that later became the site of the Archaean–Proterozoic tectonic boundaries and thus were subjected to varying degrees of amphibolitization and deformation (Bridgwater, Escher & Watterson, this volume, p. 513).

The overall change in the character of the crust from Archaean to Proterozoic time was progressive stabilization or cratonization, well documented in Africa by Clifford (1970). Stable areas became larger enabling extensive platform deposits to form and mobile zones became more confined and linear.

There are broadly two types of Proterozoic mobile belts: linear belts, consisting largely of low-grade deformed geosynclincal sediments and volanics (e.g. the Labrador trough and the Coronation geosyncline); and mobile zones, consisting mostly of medium- to high-grade reactivated basement, maybe with some infolded supracrustal rocks (e.g. the Grenville of Canada and the Nagssuqtoqidian of Greenland). With respect to the orogenic belts in Africa – the Eburnian and Huabian (1850 + 250 Ma), the Kibaran (1100 + 200 Ma) and the Damaran-Katangan or Pan-African (550 + 100 Ma) – Clifford (in press) has concluded that the mobile zones are floored by older crystalline basement and that no geosynclinal sequences were deposited on extensive areas of oceanic crust: he suggested that these two types represent different structural levels through an idealized mobile belt. Shackleton (this volume, p. 317) makes the important point that there are no offsets of earlier structures across these belts.

For the first time in the history of the crust miogeosynclinal and eugeosynclinal sequences can be distinguished (Salop & Scheinmann 1969). Hoffman (this volume, p. 547) has suggested that the stratigraphic and structural evolution of the Coronation geosyncline (2000 Ma) in northern Canada are sufficiently similar to those of late Phanerozoic geosynclines to warrant the conclusion that it is located along a Proterozoic plate boundary. Likewise the Labrador Trough (2000 Ma) has recognizable mio- and eu-geosynclinal facets (Dimroth 1970) thought to be located on a Precambrian suture line by Gibb & Walcott (1971).

There were appreciable changes in the kind of sediments and volcanics deposited in Proterozoic compared with Archaean basins. Chemically precipitated banded iron formations and cherts form minor components of greenstone belts but they reach a peak of development in the 2000 Ma old basins (e.g. Hamersley, western Australia, Mauritania, and the Labrador trough).

With progressive photosynthesis and increased oxidizing conditions the former gave way to red beds in mid- to late-Proterozoic shallow basins (Cloud 1968). Stromatolites, rare in greenstone belts, become abundant in early Proterozoic basins (Hoffman, this volume, p. 547), and in Russia are even used as a mid-Proterozoic zone fossil. Due to the high carbon dioxide content of the Proterozoic atmosphere and hydrosphere limestones and in particular dolomites were formed in abundance.

Archaean volcanism was characterized by low-potash basalts chemically comparable with present-day abyssal tholeiites (Glikson 1971), more primitive ultramafic types, and repeated cyclicity with late pyroclastic phases. In contrast, Proterozoic volcanics consisted typically of potash-enriched, continental type tholeiitic basalts, trachytes and rhyolites (Anhaeusser, this volume, p. 359). There was a comparable increase with time in the potash (and TiO_2 and Na_2O) contents of Canadian dolerite dykes (Eade & Fahrig 1971).

Gibb (1971) has suggested that the Slave Province of Canada drifted northwards from the Superior Province, that early Proterozoic oceanic crust was generated near the axis of rotation and that the Churchill Province formed by accretion of new material. This concept is difficult to reconcile with the fact that the axis area in northwest Greenland consists entirely of early Proterozoic high-grade gneisses and granites (see Tectonic/Geological Map of Greenland by the Geological Survey of Greenland, 1970), while the Churchill Province apparently consists of reworked Archaean greenstone belts and granites.

Following the early Proterozoic geosynclinal, tectonic and metamorphic activity in the northern hemisphere in the period 2000 to 1800 Ma, there was a major period of post-orogenic magmatic activity between 1700 and 1000 Ma in a belt extending from the Ukraine to the western United States characterized by massive labradorite to andesine anorthosites, rapakivi granites and related intermediate to acid plutons, acid volcanics, tholeiitic basalts and dykes, and finally alkaline complexes (Bridgwater & Windley, in press). A similar anorthosite belt in the southern hemisphere (Herz 1969) is confined to the Proterozoic mobile belts extending from South America, through Africa, Madagascar, India to Australia. The emplacement of the early intrusions and extrusions (1700 to 1400 Ma) in the 'North Atlantic' belt was controlled by east–west trending major tectonic lineaments which acted as guidelines for the formation of late graben structures which, in turn, controlled the deposition of continental sandstones and basic to trachytic lavas (*ca.* 1300 Ma) and the intrusion of late alkaline complexes (1300 to 1000 Ma, Allaart, Bridgwater & Henriksen 1969). Bridgwater, Escher & Watterson (this volume, p. 513) show how these rocks in south Greenland are arranged in east–west zones which are parallel to and just north of the Grenville Front on a pre-continental map. In fact they lie in the marginal foreland of the Grenville mobile belt, which was clearly sited on a crystalline sialic basement as it contains abundant remains of partly reworked Archaean and early Proterozoic rocks (Wynne Edwards 1969). For example, the banded iron formations of the Labrador trough (2000 Ma) can be traced as distinctive markers well into the Grenville belt and the massive anorthosite bodies (1400 Ma) are well preserved within it.

Plate tectonics in the Proterozoic

The recent plate tectonic concept provides a wonderful opportunity to understand the mode of formation of some Precambrian mobile belts. That is, if their character can be found to be sufficiently similar to warrant application of the model. However, before embarking on the exercise it is worth noting that, since many types of Precambrian sediments, igneous intrusions, metamorphism, structures and mobile belts were significantly different from their late Phanerozoic counterparts, it might be expected that the types of plates and plate movements were different in the past. In other words, the recent sea floor spreading models may have to be flexibly modified to take account of the special conditions operating earlier in crustal evolution. There were most probably plates of some kind or another; the problem is to establish their character and assess their application.

The simplest type of Precambrian stable 'plate boundary' is represented by the Great Dyke of Rhodesia, which Bichan (1970) proposes developed during the stabilization stage of the Rhodesian craton in a major rift zone sited above a convective mantle updraft. Major basic dyke swarms are common in most shields, and Clifford (1968) suggests that they indicate tensional zones of continental proportions and that they are best explained by subcrustal flow in the form of mantle cell movements with the tensional axis of the dyke swarms (and associated plateau basalt provinces) localized over the position of the convective upwell. This is the most reasonable interpretation of the Karroo dykes and basalts emplaced in Trias times when early rifting was taking place along the axis of the convective updraft in East Africa. But most of the Precambrian dyke zones did not develop into a rift valley stage.

McConnell (1969, 1970) has emphasized that recent rift valley fault zones have been controlled by earlier Precambrian fracture systems and thus that the rift valleys overlie fundamental mantle lineaments. In a similar way some basic dyke swarms were localized along fundamental zones of weakness in the crust. For example, the Kangamiut swarm in West Greenland was intruded into a zone which later became the site of the Archaean-Proterozoic tectonic front (Bridgwater, Escher & Watterson, this volume, p. 513).

Late Phanerozoic plate movements have passed through two basic stages of development. First, basic dyke intrusion, formation of rift systems with a high heat flow, and finally (in the case of the East Africa rift valley) alkaline complexes and carbonatites; and secondly, lateral migration of continental crust, formation of new oceanic crust, drift of the continental plates and formation of mobile belts along continental margins. Rift valleys are sited over arrested convective upwellings and thus have undergone very little tensional separation (Harris 1970). The Rhine graben, for example, has opened only 4.8 km since middle Eocene time (Illies 1967).

The Keweenawan trough of central North America is a late Precambrian rift valley (Pettijohn 1970). It is almost 160 km wide and 1600 km long, is filled with continental red clastics and 15000 m of basic amygdaloidal lavas, and is expressed by the prominent mid-continental gravity anomaly. As suggested by Sumner (1969) it has the appearance of a late Proterozoic oceanic ridge crest, a rift zone, filled with high density lava flows, which has subsided. The offsets in the anomaly pattern might even be transform faults.

There is marked similarity in the evolutionary pattern of some Proterozoic high-grade mobile belts, such as the Grenville, and recent rift systems. The Grenville belt went through stages of rifting, basic dyking, formation of steep geothermal gradients giving rise to granulite-grade metamorphism in a narrow linear zone, and formation of late alkaline complexes and carbonatites (Doig 1970), distributed within, or near, the central high heat flow zone (figure 4). Shackleton (1969) concluded that heat has migrated upwards along this type of mobile belt as it should overlie rising and divergent convection currents. The Grenville belt does not resemble any of the present-day continental margin mountain belts and the Grenville front has no large linear belts of basic rocks such as characterize divergent or convergent junctures

(Irving, Park & Roy 1972). In fact the mobile belt has all the major ingredients of an arrested rift system and it clearly did not reach the continental drift-ocean floor spreading stage, as it is floored by reactivated sialic basement.

Ringwood (1970) pointed out that generation of new crust from the mantle has proceeded via two distinct types of differentiation processes: first, vertical mass transport involving fractional melting of the mantle and rise of magmas into the crust giving rise to high heat flow and intrusions and extrusions; and secondly, lateral mass transport associated with recent sea floor spreading, oceanic basalts being transported down subduction zones where they are fractionally

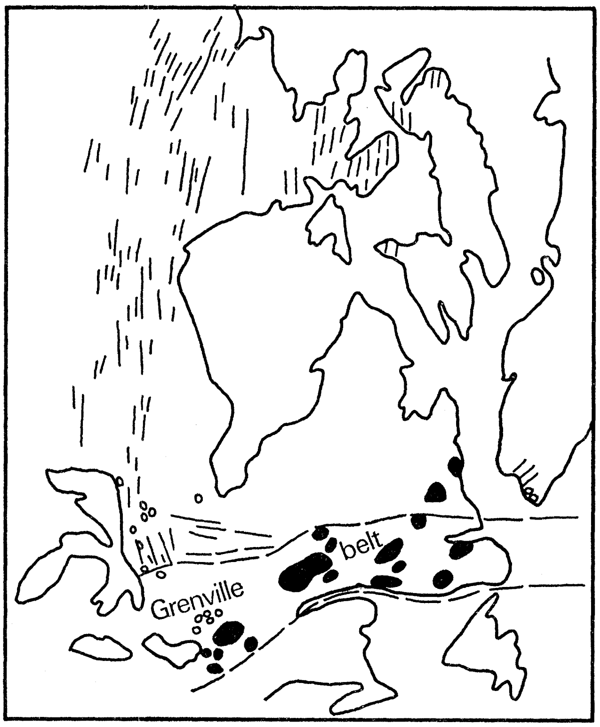

Figure 4. Northeast Canada and south Greenland on a pre-continental drift map showing the major 1300 to 1100 Ma old dolerite dyke swarms and the Grenville mobile belt formed 1000 Ma ago. Anorthosites in black. Circles, alkaline complexes 1100 to 850 Ma old (after Doig 1970). There are many more alkaline complexes 450 to 600 Ma old along the border of and within the Grenville belt (see Doig 1970).

melted to give rise to the calc-alkaline igneous suite that was intruded into the crust. Ringwood suggested that it is probable that the relative importance of these processes has varied throughout geological time and that the first type was more common in the Precambrian.

Many Proterozoic mobile belts have been uplifted and so deeply eroded that essentially their root zones are exposed. At the present deep structural levels it can be seen that they clearly contain abundant relic masses of earlier, partly reactivated, crystalline basement, e.g. the Eburnian and Huabian of Africa, the Nagssuqtoqidian and Ketilidian of Greenland, the Grenville of Canada. It might be suggested that these are collision-type mountain belts which should have sialic roots as a result of underthrusting of continental crust upon closing of the ocean (Bird 1970). This type of belt should contain ophiolites, remnants of the oceanic crust, in flysch-mélange suture zones. However, these Proterozoic belts lack ophiolites and in several it can be shown that there was no period of volcanicity or sedimentation before the 'orogenesis'; no oceanic crust preceded the plutonism. The most reasonable interpretation of these belts is that they are narrow, linear, rifted zones which acted as loci for the rise of geothermal gradients with consequent high heat flow and 'regional' metamorphism and abundant igneous activity. The zones are often associated with early fracture systems and underwent sufficient, although limited, intra-continental block (plate) movements to cause the deformation of basic dyke swarms and infolded sediments. Ringwood's first type of differentiation process – vertical mass transport along intra-continental linear rifted zones – with or without basin deposits best satisfies the formation of this type of mobile belt.

Figure 5 shows movement directions of three ensialic blocks (plates) in the North Atlantic region during the Proterozoic. The Nagssugtoqidian belt moved southwards overriding the Achaean North Atlantic craton (Bridgwater, Escher & Watterson, this volume), the Labrador Trough was thrust westwards (Dimroth 1970), and the Grenville belt underwent a northerly movement (Stockwell *et al.* 1970).

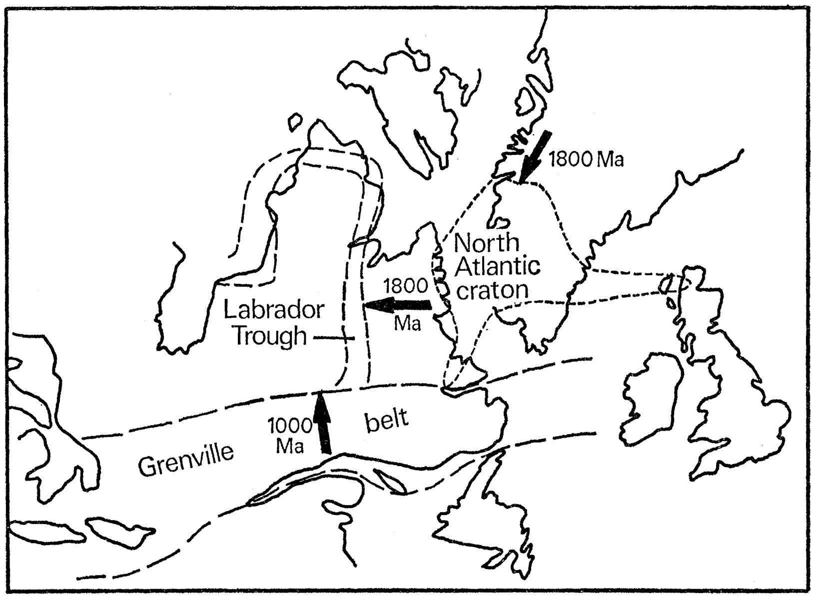

FIGURE 5. The North Atlantic region on a pre-continental drift map, showing the movement directions of three intra-continental blocks in the Proterozoic.

Discussion and conclusions

The evolution of the Archaean has to be seen in two parts, belonging to a single type of crustal development which was not repeated in the same way either in the Proterozoic or Phanerozoic. Many Archaean rock groups and structures (e.g. calcic anorthosites, widespread granulites, nonlinear structures on an 'orogenic' scale, greenstone belts) were seldom, if ever, developed in the Proterozoic while many Proterozoic rock groups, such as banded iron formations, massive Adirondac-type anorthosites and rapakivi granites, were seldom, if ever, developed in the Phanerozoic. Major alkaline complexes and carbonatites are most common in Sutton's latest chelogenic cycle. Much evidence suggests that several distinctive rock groups and structures developed at particular periods in the history of the continents; that is, the crust has evolved with time going through definite stages when certain rock associations formed in response to particular environments.

Many writers have demonstrated that the continents have been through progressive stabilization, the cratonic areas becoming larger with time. In particular, platform deposits became more extensive in the Proterozoic while mobile belts became correspondingly more confined and linear. Conversely, the early crust appears to have undergone a high degree of mobility, although the earliest Precambrian areas, characterized by granulites and gneisses, contain evidence of very old sediments and volcanics that represent a period of stability before the high-grade metamorphism. A major point of controversy at present is 'Where were the old granulite-gneiss complexes when the greenstone belts were formed?' Were they underneath and between them, or were they in the drifting continents at the time of formation of the greenstone belt oceanic crust? Remarkably little detail is known of the actual contact relations between these two types of terrains.

The oldest rocks known at present are 'granites' in West Greenland, found by McGregor in a low deformation and metamorphic area within the high-grade North Atlantic craton. One of the most interesting points to emerge from this work is that this high-grade terrain had been through 1000 Ma of crustal history before the granulite/high amphibolite facies metamorphism. It can be predicted that other high-grade terrains in the world will in future be found to contain very old material – much older than the greenstone belts. Ideas on the mode of formation of the high-grade terrains have been slow to evolve in comparison with those stemming from studies on greenstone belts because of the great difficulty in breaking through the 'conformability barrier' in these areas. Ramberg (1952) realized that one of the major problems of the catazonal regions is that all main rock types are mutually conformable. It is now known that this is a result of deformation, that all stratigraphy is tectonic, and that the conformable layers of meta-supracrustal rocks, i.e. amphibolites and schists, in gneisses commonly hide obliterated unconformities. Thus, as McGregor has done, it is possible to break through the late high-grade metamorphism and deformation to older stable environments.

Sutton (1963) proposed a concept of chelogenic cycles which are long-term shield-forming periods. With modifications due to recent advances the boundaries of the cycles are:

Archaean	*ca.* 3800 to 2500/2000 Ma with a diachronous end.
Proterozoic	*ca.* 2500/2000 to 1000 Ma.
Eocambrian–Phanerozoic	*ca.* 1000 Ma to present day.

In essence the latest cycle involved the establishment of a mobile belt system and as it decayed a rift system developed and continental drift began (Sutton 1971). The question arises 'Did the earlier cycles go through this complete sequence?'

The Archaean is now seen to have been through an early mobile phase, giving rise to high-grade terrains, followed by formation of greenstone belts, and finally basic dyking. The model proposed here is that the greenstone belts represent a stage of continental scale mega-fracturing with formation of rift zones, incipient oceanic ridges and a relatively small amount of oceanic crust. Tensional basic dyke swarms finalized this first shield-forming cycle.

The Proterozoic started with the formation of more linear mobile belts, some low-, some high-grade, it went through a major period of post-orogenic calc-alkaline igneous activity and culminated in a series of arrested rift systems with little evidence of extensive ocean floor spreading. The Keweenawan trough, for example, is very reminiscent of the Archaean greenstone belts and likewise may well have been a proto-oceanic ridge crest: it developed in the final stages of the second shield-forming cycle which was terminated by trans-continental basic dyke swarms.

Finally, a word for the Precambrian. Since so may features of Precambrian rocks are different from their late Phanerozoic counterparts, plate tectonic models should be applied with caution. In recent mobile belts the types of sedimentary, igneous, metamorphic and structural régimes are related to the associated plate boundaries and their movements. In the Precambrian geothermal gradients, shapes of mobile belts and their internal structures, sedimentary, igneous and metamorphic activity resulted from distinctive conditions at particular times in earth history which were often different from those operating in post-Mesozoic times. Therefore the types of plate tectonics should also have been different

In this preview paper it has been necessary to quote many publications, and if I have made any serious omissions, it has been entirely unintentional. I am grateful for many stimulating discussions over several years with my colleagues from the Geological Survey of Greenland, and in particular with D. Bridgwater. R. K. Herd kindly suggested improvements to the manuscript.

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