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PROTEROZOIC ENSIALIC OROGENESIS:
THE MILLIPEDE MODEL OF
DUCTILE PLATE TECTONICS

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ABSTRACT. Proterozoic structural provinces are dominated by granitic gneiss complexes representing reworked sialic basement rocks covered by relatively thin metasedimentary sequences of platform-type. Metamorphism and deformation appear to have been predominantly ensialic, and this orogenesis cannot be easily reconciled with compressive plate margin-subduction tectonics. A ductile spreading model is proposed involving hot and ductile sialic crust that underwent extending and then compressing subhorizontal flow, as it moved unilaterally at a rate of the order of 10⁻¹ cm/yr over upwelling mantle. Basement and cover rocks were sequentially heated, metamorphosed, and deformed away from the cratonic front where spreading activity began. Aligned trains of plutonic complexes such as the anorthosites of the Grenville province provide relative movement vectors in the form of the tracks formed from igneous centers on the spreading system and are separated by major transform shear zones that are the expression in ductile crust of underlying transform movement between adjacent segments. This spreading model satisfactorily accounts for the evolution of the Grenville, Namaqualand, and Damara provinces and the Lake Superior Basin. The transformal shear zones are spatially related to major Proterozoic base-metal deposits and may have been conduits allowing metal-rich exhalative fluids from the underlying thermally upwelling mantle to reach the sediment deposited in epicontinental seas. These depositional basins were generated by ductile thinning of the crust during spreading.

INTRODUCTION

Sea-floor spreading and the interaction of rigid lithospheric plates account for the present distribution of seismicity, volcanism, and ocean basins so satisfactorily that they offer an irresistible model for the evolution of older orogenic belts. Subduction at plate margins is now widely accepted as the principal type of orogenesis with associated metamorphism, deformation, and plutonism and, together with continental collision, is thought to have resulted in the gradual evolution of continental crust throughout geological time. Spreading, being largely confined to ocean basins where the effects of metamorphism and deformation are relatively minor, has been largely ignored as an orogenic mechanism, tension not usually being considered orogenic. This paper proposes that ductile spreading followed by contraction of the crust, rather than subduction or continental collision, was in fact the dominant process for continental crustal reworking from about 2500 m.y. to perhaps 600 m.y. During that period ductile extension of hot sialic material rather than brittle rupture was the reason that large ocean basins characteristic of the Phanerozoic failed to develop.
The subduction model has been applied only locally, or only by invoking special arguments, to orogenic events during the roughly 2000 m.y. of the Proterozoic. Eugeosynclinal volcanic-clastic sequences are rarities, and recognizable island-arc sequences, blue-schist belts, and ophiolites are very scarce. The dominant part of the Proterozoic record in every continent is represented by vast tracts of gneissic metamorphic terrains which are the result of large-scale ensialic orogenesis. This orogenesis in general involves the reworking of granitic basement-gneiss complexes overlain by relatively thin miogeosynclinal or platform-type cover sequences. During this reworking temperatures were from about 550° to 800°C, and pressures about 5 to 8 kb, representing a superincumbent load of about 15 to 25 km. Typically the reworked and radiometrically updated basement is extensively exposed through complexly deformed cover.

There are Proterozoic structural provinces or sub-provinces with geosynclinal attributes to which a plate collision-subduction model has been applied well enough to suggest that some similar process was in operation, but they account for only a fraction of all Proterozoic mobile belts. In North America the geosynclinal examples are: (1) the Coronation geosyncline with the East Arm and Bathurst aulacogens (Hoffman, Fraser, and McGlynn, 1970; Fraser and others, 1972; Hoffman, 1973). (2) The Circum-Ungava geosyncline including the Labrador Trough (Dimroth, 1970; Dimroth and others, 1970; Davidson, 1972). Both these ortho-geosynclines contain Aphebian rocks with intense metamorphism, plutonism, and deformation at about 1750 m.y. (Hudsonian orogeny). They have miogeosynclinal and eugeosynclinal elements with counterparts in Phanerozoic continental margins and collision orogenic belts (Bird and Dewey, 1970). The Proterozoic orogens are different, however, in that they lie on sialic basement and have an extensive granitic and metamorphic hinterland, the Churchill province, that yields the same radiometric dates in large areas of reworked basement. The ortho-geosynclines thus account for only a small part of the 5 million sq km affected by the Hudsonian orogeny. (3) The Helikian Lake Superior Basin and mid-continent gravity high dated between 1150 and 1050 m.y. The structure is interpreted as an intracontinental rift zone (Smith, Steinhart, and Aldrich, 1966; Goldich and others, 1966; Muehlberger, Denison, and Likiak, 1967; King and Zeitz, 1971; Card and others, 1972). The basin is filled with Keweenawan basalts, continental clastics, and mafic and ultramafic plutons with an aggregate thickness of many thousand meters. The timing of this rifting overlaps with that of the plutonism, metamorphism, and deformation in the Grenville province. (4) The Grenville Province, a large area of high-grade metamorphism and deformation dated from 1200 to 900 m.y. The rocks exposed are extensive tracts of preexisting, reworked basement gneisses and miogeosynclinal metasedimentary rocks. There have been several attempts to fit the Grenville province into a plate-tectonic model. A preliminary version of the writer’s hypothesis elaborated here was presented at Ottawa in 1973 (Baer, 1974) accompanied by presentations by Burke
(Dewey and Burke, 1973) and Irving (Irving, Park, and Roy, 1972; Irving, Emslie, and Ueno, 1974; Irving and Lapointe, 1975). Dewey and Burke proposed a thickening of crust by continental collision along a subduction zone, likening the Grenville province to Tibet, in order to explain the reworking of basement. Irving and others have advocated a Grenvillia moving differentially toward Laurentia, citing as evidence the Grenvillian paleomagnetic loop. The interpretation is made difficult by the absence of undisturbed rocks of precisely known age in the 1000 m.y. range and by a considerable scatter in the data (Buchan and Dunlop, 1973). Unfortunately both these hypotheses require the presence of an as yet unrecognized suture. Because of structural and lithological correlations across the Grenville Front, this suture must be assumed to lie deep within the Grenville Province and, thus, in the heart of the 1000 m.y. metamorphic terrain. Recently Thomas and Tanner (1975) have postulated a “cryptic suture” related to a gravity anomaly south of the Grenville front.

THE GRENVILLIAN OROGENIC BELT

In 1972 the writer reviewed the state of knowledge of the Grenville Province and attempted a tectonic synthesis (Wynne-Edwards, 1972). Figures 1 and 2 are modifications of figures in that paper and show general geology and representative cross sections. The essential features are summarized here, but a fuller description, discussion, and bibliography are to be found in that paper.

The Grenville province, being the exposed part of the Grenvillian orogenic belt and covering about 650,000 square km, is largely underlain by predominantly gray quartzo-feldspathic gneiss complexes thought to represent reworked preexisting sialic material. The reworking in some places involved a cycle of erosion and clastic redeposition prior to metamorphism to produce layered supracrustal paragneisses but in others was simply an episode of recrystallization, radiometric updating, metamorphism, and anatexis (Wynne-Edwards and Hasan, 1972). These quartzo-feldspathic gneisses represent the basement on which a relatively thin cover of platform type was deposited. The cover rocks probably range in depositional age from 1700 to 1200 m.y. and are predominantly Helikian and correlated with the Grenville Supergroup. The dominant lithologies are quartzite, marble, and garnetiferous and other aluminous paragneisses. The structure in both basement and cover is complex, but estimates of thickness for the Grenville Supergroup are of the order of 3000 to 9000 m.

Apart from the Grenvillian Foreland Zone north of the Grenville Front, where deformed cover rocks lie on unremobilized basement, the basement and cover sequences have been deformed and metamorphosed together and have reached equivalent ductility and metamorphic grade. The prevailing grade of metamorphism is upper amphibolite to granulite facies of intermediate-pressure type, typified by sillimanite, cordierite-garnet, and cordierite-garnet-hypersthene assemblages, with rare occurrences of either kyanite or andalusite. In the Hastings Basin of the Central Metasedimentary Belt and in the eastern Grenville province, the
Fig. 1. Tectonic subdivisions of the Grenville province after Wyne-Edwards (1972). The north-south boundaries previously drawn between the central metasedimentary, central granulite, Baie Comeau, and eastern Grenville segments have been overprinted by straight lines interpreted in this paper as transformal shear zones. A parallel north-south alignment of anorthosite massifs is emphasized by heavy lines. Known dates of primary crystallization of anorthosite-monzonite complexes are shown.
Fig. 2. Diagrammatic vertical cross sections through the Grenville orogenic belt.

Locations shown in figure 1 (after Wyman-Edwards, 1972).
grade of metamorphism locally declines to greenschist facies and in the Central Granulite Terrain reaches high granulite facies characterized by green-rock complexes of charnockitic character, but in general most of the Grenville province exhibits metamorphic recrystallization consistent with temperatures of about 700°C and a superincumbent cover of about 15 km.

Large anorthosite–monzonite–norite massifs occur in the broad north-east-trending belt from the Adirondacks to the Atlantic, where they lie north of the Grenville province in the Eastern Nain province of Labrador (Emslie, 1975). These are the dominant plutonic rocks of the Grenville province. North of the Grenville Front they are unmetamorphosed with primary igneous features well preserved, but within the Grenville province they are variously cataclastically deformed, recrystallized, and metamorphosed and have clearly participated in the Grenvillian orogeny from very early in its history (Wynne-Edwards and others, 1966; Wynne-Edwards, 1969; Martignole and Schrijver, 1970; Kehlenbeck, 1972). The relationship between their primary crystallization and metamorphism is still debated, and in some places they may have overlapped. Gravity anomalies suggest that some anorthosites in the eastern part of the Grenville province are still attached to a southerly displaced, more mafic root, but otherwise they occur as vast sheet-like intrusions which in many cases utilized the basement-cover unconformity.

The distribution of anorthosites in Eastern Canada is along several distinct north-south lines, making an en echelon pattern within the north-easterly trending anorthosite belt (fig. 1). Further, the available radiometric dates for emplacement and crystallization of these massifs (Rb/Sr or U-Pb zircon ages from monzonites or from contact hornfelses) become consistently younger southward along these north-south lines. The same pattern is evident in the metamorphic K/Ar thermochrons of Harper (1967; and fig. 3 of this paper). Each of these age vectors occupies a different segment of the Grenville province as subdivided in figure 1, these segments being bounded by major structural or metamorphic discontinuities.

In 1972 the writer divided the Grenville province south of the Grenville front tectonic zone into several segments along its length. The boundaries were major discontinuities of lithology, structure, or metamorphism as known from present mapping and are generally north-south trending. In figure 1 these boundaries have been updated and overprinted in straight north-south lines which fall within the zone of discontinuity and serve to emphasize the pattern. The boundary between the Central Metasedimentary belt and the Central granulite terrain is a prominent zone of cataclasis and mylonitization in Mont Laurier-Kempt Lake map-areas (Wynne-Edwards and others, 1966; Wynne-Edwards, 1969). There are broad north-trending belts of mylonite on both sides of the Morin anorthosite. The zone on the west is at least 10 km wide and is warped into a prominent concentric drag fold near St-Jovite that indicates sinis-
tral displacement (Wynne-Edwards, 1969, fig. 6). The eastern zone is broader and involves part of the anorthosite and the Lac-Quinn Formation, which also exhibits Z-shaped, sinistral drag folding (Martignole and Schrijver, 1972). The southward extension of the western dislocation separates the Adirondack Highlands from the Adirondack Lowlands, roughly along the garnet-clinopyroxene isograd of de Waard (1969).

In the same area, the north-south distribution of the anorthosite-monzonite suite is also very clear on a larger scale (Wynne-Edwards, 1969, fig. 4). In addition, alkali syenite plutons with K/Ar dates of 967 m.y. or younger in the Lachute-Mont Laurier area of Quebec are again arranged in north-south trains (Wynne-Edwards and others, 1966; Wynne-Edwards, 1969, fig. 3). They could represent waning alkaline igneous activity related to the anorthosites as may the still younger carbonatite complexes.

Fig. 3. Thermochrons (contours of equivalent cooling age) based on K/Ar determinations of metamorphic biotite (Harper, 1967).
and veins prevalent north of the St. Laurence River east of Quebec (Laurin, 1970). The north-south pattern of plutons and sheared gneisses of the Mont Laurier area can be traced northward to the Grenville front tectonic zone south of Chibougamau in a series of major aeromagnetic anomalies.

Farther west the Canoe Lake-Rideau Lakes fault in the Frontenac Axis is a significant shear zone in the Central metasedimentary belt. It is a broad zone of refolded, faulted, and mylonitized gneisses with quartz monzonite plutons in dilatant zones dated at 1050 m.y. (Wynne-Edwards, 1957, 1967a; Brown, ms; Krogh and Hurley, 1965). The zone has sinistral displacement like the others in the western half of the Grenville province. The north-south train of gneissic granitic and syenitic plutons southwest of Bancroft in the Haliburton Highlands, bordered by a mylonite zone, may be a further well-documented example (Hewitt, 1957; Best, 1966). Both these zones are shown in figure 4.

The boundary between the Central granulite terrain and the Baie Comeau segment is similarly one of north-south cataclasis and is marked by a change from granulite to amphibolite facies east of Lac St-Jean. The eastern margin of the Baie Comeau segment is less well known but is drawn along a metamorphic boundary separating the Baie Comeau segment from lower grade metamorphic rocks in the Eastern Grenville province northward from Havre St-Pierre.

The K/Ar dates related to metamorphism and folding in the Grenville province due to the Grenvillian orogeny are 950 ± 150 m.y. (Stockwell, 1964). Harper (1967) showed that the K/Ar dates on metamorphic biotite become systematically younger southeastward away from the Grenville Front (fig. 5), a fact generally attributed to earlier cooling in more uplifted rocks near the front. The equivalent whole-rock Rb/Sr dates are about 1200 m.y., suggesting that cooling between the two blocking temperatures for the migration of strontium and argon, from about 650° to about 250°C, took about 250 m.y. Dated anorthosite-mangerite massifs range in age from 1480 to 1050 m.y. Many Archean ages, some older than 3000 m.y., have been found preserved within the basement complex (Krogh and others, 1970; Frith and Doig, 1971). In Ontario the Grenville Front has a history beginning about 1550 m.y. ago (Davis, Krogh, and Hart, 1970; Krogh, Davis, and Frary, 1971).

The tectonic style of the rocks of the Grenville province is one of complex flow folding and refolding, with northeast-trending Grenvillian structures overprinted on inferred Kenoran and Hudsonian structures in the basement and on Hudsonian structures in parts of the cover sequence (Wynne-Edwards, 1963, 1967a, 1969, 1972). The Grenvillian folds are generally gently northeast-plunging with southeast-dipping axial planes, so that they verge toward the Grenville Front. The cross sections of figure 2 illustrate this and also show the localization of anorthosite massifs along the deformed unconformity and the present close relationship of this unconformity to the present erosion surface at an elevation of about 400 m.
Fig. 4. Tectonic interpretation of the Grenville province using the millipede ductile spreading model. Relative movement vectors between continental lithospheric and oceanic spreading are shown by vectors derived from tracks of large-scale and highly deformed shear zones. These vectors deforming an overlying continental lithosphere may subsequently have moved this zone giving ambiguous displacement relationships similar to those of oceanic transform faults. The Appalachian orogen may initially have been patterned on the same spreading system.
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The latter suggests that the whole Grenvillian orogenic cycle of deposition, burial, metamorphism, and erosion ultimately restored the sialic crust roughly to its ancestral level and thickness of about 35 km. Apart from a small area in the Hastings Basin of Ontario (in the Central Metasedimentary Belt of fig. 1) where pillowed greenstones, carbonates, gabbros, and granodiorite plutons suggest that a local ensimatic ocean may have developed at about 1500 m.y. (Brown and others, 1975), the deformation was evidently entirely ensialic, involving preexisting continental crust and its platform cover sequence.

THE MILLIPEDE MODEL OF DUCTILE SPREADING

The sequence of events in the Grenvillian orogenic cycle briefly summarized above is relatively simple. Several thousand meters of platform-type sediments accumulated on sialic basement in relatively shallow water, perhaps beginning as early as 1700 m.y. ago. Later, starting at about 1500 m.y., basement and cover were intruded by anorthosites, gabbros, norites, and associated envelopes of monzonites and charnockitic granitic rocks. Within the Grenville province, all these rocks were then metamorphosed and deformed. In much of the province a depth of about 15 km and a temperature of about 700°C were reached at the deformed basement-cover unconformity, which is statistically close to the present level of erosion (fig. 2). A pattern of northwest-verging, northeast-trending folds was developed. Uplift and erosion followed producing Rb/Sr and K/Ar dates of about 1200 m.y. and 950 m.y. respectively. Any tectonic interpretation should account for these characteristics.

The distribution of anorthosites shown in figure 1 suggests a plate creeping northward (like a millipede) over a relatively fixed series of igneous centers in the mantle that were initiated at about 1500 m.y. and terminated at about 1000 m.y. This produced southward younging anorthosites in tracks with an exposed length of 500 to 800 km and an implied rate of relative movement on the order of 1 to 3 km per m.y. or 0.1 to 0.3 cm/yr. The K/Ar dates on metamorphic biotite (fig. 3), although related to a much younger cooling of the orogenic belt, give a comparable southward rate of movement, showing that cooling followed heating after a regular interval.

The pattern is made clearer in figure 4, in which the southward-younging tracks of anorthosites (represented by arrows) are shown as relative movement vectors left by igneous centers related to a spreading system. The Grenville province can then be envisaged as having moved slowly over an en-echelon series of magma sources arranged along an east-west spreading center staggered by transformal movement due to differential spreading activity in adjacent segments. The underlying transformal motion separating each igneous center is expressed through ductile sialic crust by the previously recognized structural and metamorphic discontinuities that separate the various segments of the Grenville province.
(Wynne-Edwards, 1972). The term *transformal shear zones*\(^1\) is used for these faults. The pattern in the continental lithosphere of the Grenville province is thus very like the pattern formed by spreading in Phanerozoic ocean floor.

The relative direction and amount of displacement between segments bounded by transformal shear zones can be seen from the positions in each segment of the northern limit of each anorthosite train, whence the underlying igneous centers were initiated at about 1500 m.y. From there the sialic lithosphere migrated slowly northward (fig. 4). The sense of movement for each transformal shear zone shown in figures 4 and 7 is that for the extensional phase of spreading, which offsets the northern end of the plutonic tracks. Later compressional deformation, which is probably most intense in the segments with the shortest tracks, may reverse this sense of displacement toward the southern end of a shear zone.

The transformal shear zones involved sinistral movement along most of the length of the Grenville Province, each segment being advanced more than its western neighbor to provide the northeasterly trend of the Grenville province. By no means all the differential movement is confined to these shear zones, the effect being distributed throughout the ductile gneissic rocks to produce dominantly northeast-trending folds and foliations dragged northward or southward at transformal segment boundaries. In figure 4 this is also shown by the pattern of K/Ar thermochrons, which have been taken from figure 3 (after Harper, 1967) apart from local modification from more recent data and local reinterpretation. In the eastern Grenville province the sinistral pattern of transformal shear is reversed, and the shear is apparently dextral on at least one dominant transformal shear zone. The long track of anorthosite massifs extending into the Nain province thus occupies the segment that has migrated the most over the thermal system in the 500 m.y. period indicated by geochronometry. Relatively, therefore, it was the most rapidly moving segment.

If rapid movement over an active heat source on the spreading system is equated with relatively short-term heating and hence lower maximum temperature attained in the overlying crust, a number of otherwise anomalous features in that part of the eastern Grenville province can be satisfactorily accounted for. These are the large volume of anorthosite (implying an active igneous center), the northerly elongate shape of some of the massifs, the change from regular northeasterly thermochrons to southeasterly trending ones to embrace young K/ar metamorphic dates well north of St. Lawrence River (fig. 3), the unmetamorphosed state of the anorthosites in the Nain province, the scatter of ages in the Nain province (Stockwell, 1965; Taylor, 1971, 1972) representing only partially

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\(^1\) The term *transformal shear zone* is employed here for localized transcurent shear expressed by drag folds, mylonite zones, or cataclastic zones that are the result in ductile lithosphere of underlying transform movement at spreading centers. *Transform faults*, as defined, occur only in ocean floor so that the term must be avoided here (Wilson, 1965a, 1965b; Garfunkel, 1972).
reworked and updated Archean crust, the ill-defined and indistinct Grenville Front east of the Labrador Trough, and the low metamorphic grade of the Wakeham Bay Group and other supracrustal rocks in that part of the Grenville province. The eastern Nain province thus represents a weakly reworked extension of the Grenvillian orogenic belt.

The Grenvillian segment in Ontario also has similar features. Either this western part of the Grenville province moved more slowly relative to the underlying spreading system than adjacent segments, or there was more subsequent compressional deformation to telescope the plutonic tracks. The indications are that it moved less than average in that northwesterly structural trends and 1800 m.y. dates (Hudsonian ?) are preserved in the basement gneisses of the Ontario gneiss segment with only a relatively weak Grenvillian structural and thermal overprint (Krogh and Davis, 1971; Lumbers, 1971). Further evidence is the relative scarcity of anorthosites and monzonites in Ontario and the shorter anorthosite track formed by the Adirondack and Morin massifs. This is also the segment that contains the Hastings Basin, part of which has recently been interpreted as an ensimatic island arc and ocean basin system dated about 1300 m.y. (Brown and others, 1975). If so, the rifting and subsequent partial closure of this zone may have accounted for much of the total activity of this western part of the Grenville province that is due to the operation of the spreading system.

The history of the Grenville province implies that the key to Proterozoic ensialic orogenesis is that it results from a process involving ductile crust rather than rigid plate motion and spreading rather than subduction (fig. 5). The tectonic pattern therefore more closely resembles that of present-day ocean floor than that of present-day continental margins. Ductile crust would extend and thin above upwelling mantle material and then, retaining cohesiveness, would move unilaterally off the spreading system in one direction or the other and enter a compressional tectonic regime. Large volumes of crust might thus pass over a long-lasting spreading system, sequentially reworking large tracts of continental crust. The initial thinning of the crust, presumably expressed by normal faulting and shallow rifting in the upper part of the crust and by subhorizontal extending flow in the lower, would produce a shallow epicontinental sea above the thermal rise which would migrate slowly across the continental mass as the latter moved. Typical platformal sediment would accumulate in the depression in the process. The igneous expression of spreading is plutonic rather than volcanic, being recorded by mafic and anorthositic massifs and by their related monzonite-charnockitic plutons, the latter possibly resulting from crustal anatexis around and above the high level heat-sources represented by the mafic rocks. These would lie along the tracks of relative motion of crust and spreading system, like fossil plutonic footprints of the millipede, as the lithosphere moved slowly and unilaterally over the underlying spreading system, undergoing heating, recrystallization, and radiometric updating in the process. Locally, where fractures
Fig. 5. Sections illustrating the development of Proterozoic orogenic belts by the sequential deformation of ductile, unruptured continental crust over a spreading center, using the millipede model. The crust initially thins in extending flow over a zone of thermal upwelling to form an epicontinental sea and then moves unilaterally over a spreading system. The zone of extending flow and sedimentation migrates to remain over the spreading system and the passing lithosphere and cover experiences compressing flow and deformation against the unaffected craton.

Propagated to the base of the crust, extensive volcanic and volcanioclastic rocks developed instead, as in the Lake Superior Basin and the Hastings Basin.

As the crust migrated laterally at rates of the order of $10^{-1}$ cm/yr, it became recrystallized and metamorphosed as heat rose within it, and local migmatization and granitic anatexis followed. The catazonal deformation changed from extending to compressing flow away from the spreading center, the crust thickening against the cratonic foreland that lay beyond the line of initiation of mantle upwelling. The supracrystal cover rocks, product of deposition in the epicontinental sea, likewise became heated, mobilized, and tectonically thickened and uplifted by flow folding at depth and by recumbent folding and thrusting near the surface, generat-
ing structures verging toward the craton. The continental crust moved sequentially over the thermal rise system, so that plutons, sedimentary cover rocks, folds, and both metamorphic and cooling dates should all become progressively younger in the same direction (southward in the Grenville province). Dates available for the Grenville province show that the plutonic ages and K/Ar cooling dates do show this trend, but stratigraphic and structural analyses are not yet adequate to prove that sedimentary rocks and deformation exhibit the same progression. The width of the orogenic belt is presumably controlled by the duration of the underlying spreading system.

The direction of spreading and transformal movement illustrated by the anorthosite tracks and segment boundaries is initially one of extensive flow and latterly one of compressive flow. The effect of the differential spreading movement due to the differing amounts of thermal upwelling and igneous activity is expressed by the relative volumes of plutonic rocks, by the width and intensity of the transformal shear zones, and by a rotation of the direction of maximum compression toward the direction of motion in each ductile segment. This rotation causes extension parallel to fold axes and may account for the prominent mullion structures and boudinage parallel to fold axes common in such metamorphic terrain. Without transformal shear motion the folds and foliation produced dur-
The millipede model of ductile plate tectonics

ing the period of compressive crustal shortening presumably would be oriented normal to the plutonic tracks. Alternatively, with extreme differential transformal movement, the folds and dominant foliation would be transposed more nearly into the direction of motion and of transformal shear, so that orogenic belts with folds parallel to the direction of tectonic transport are conceivable. Later the Damara belt of Africa will be proposed as an example of this.

The coexistence of cataclasis, mylonitization, and flow by recrystallization in this terrain reflects only the interaction of the rate or recrystallization (dependent on $X$, $P_{\text{tot}}$, $P_{\text{vol}}$, and $T$) and the rate of strain. If all strain is accommodated by recrystallization, true flowage results, and the product is an equant metamorphic fabric. If the strain rate exceeds the rate of recrystallization, textures from flaser to mylonitic result instead. Thus a mylonitic transformal shear zone may develop in an area of rapid strain adjacent to an area of simultaneous and ongoing pure flow folding (Wynne-Edwards, 1967b).

The total amount of relative motion of the ductile crust over the spreading center is at least the length of the plutonic tracks. The differential movement of the orogenic belt relative to its unworked cratonic foreland is expressed by compression contained in flow folding and other deformation within the belt. Because of this, the transformal shear zones die out at the cratonic edge of the mobile belt, where movement across them decreases to zero, and the amount of differential displacement represented by the shear zone increases progressively away from the orogenic front. The interface between the unworked, less ductile craton and the reworked orogenic belt is the "front," the Grenville Front being a typical example. Thrusting, faulting, folding, mylonitization, and metamorphic and radiometric age transition all mark this boundary at different places depending upon the degree of heating that occurred there (Wynne-Edwards, 1964, 1972).

The equivalent structure behind the orogenic belt, marking the line along which active spreading ceased, is not known for the Grenville province but should consist of rift faulting features and relatively younger and weakly metamorphosed rocks. It is possible that the Appalachian-Caledonian orogen initially developed in this manner, following the Grenvillian orogeny. The inferred spreading pattern at 1000 m.y. shown in figure 7 mimics the shape of the Appalachian fold belt (as the latter mimics the still younger present day continental margin), suggesting that the Appalachian-Caledonian orogen initially developed in a rift or subsidence dependent on late-stage Grenvillian events. Similarly the Damara belt of southwest Africa appears to have been patterned on the earlier evolution of the Namaqualand-Bushmanland (Sanama) province, and the present western continental margin of Africa may have been predetermined by the evolution of the Damara belt (figs. 8 and 9).

The difference between the millipede spreading model proposed here for Proterozoic orogenesis and Phanerozoic ocean-floor spreading may be
Fig. 7. The Grenvillian orogenic belt of North America interpreted using the millipede spreading model. Northward relative motion of continental lithosphere over a spreading system gave rise to north-south tracks of plutonism separated by transformal shear zones. The Lake Superior Basin represents local failure of the continental crust by rift faulting at about 1200 m.y.; elsewhere the deformation was ductile and ensialic.
due only to the differing responses of ductile and brittle continental crust to the same forces. Figure 6 traces the proposed thermal evolution of sialic crust and its consequent behavior through geologic time. The Archean sialic basement in Greenland, Africa, Canada, India, and Australia has radiometric ages from 3800 to 2500 m.y. in terrain characterized by granodioritic and tonalitic gneisses and plutons that have deformed and intruded greenstone belts. The continental crust may then have been relatively thin, discontinuous, and hot. Archean greenstone-graywacke belts have been compared with oceanic island-arc complexes by a number of authors and may be interpreted as being at least in part ensimatic. The associated continental quartzofeldspathic terrain is locally interpreted as older basement with respect to greenstone belts but most commonly shows intrusive relationships at greenstone boundaries. This suggests that greenstone belts were roughly coeval with rising granitic diapirs that were elevated and preserved by bottom underplating of continental crust as the sial thickened to its present average of about 35 km (Engel, 1968). In figure 6 the tectonic regime of this period is inferred to be one of hyper-
solidus diapirism in quartzofeldspathic rocks, enough liquid being present in the granitic rocks to cause intrusion in response to thermal upwelling from the mantle. At about 2500 m.y. the temperature at median depth in the continental crust is inferred to have fallen below about 700°C so that the dominant condition of the sial in the Proterozoic was subsolidus except around high-level heat sources or in the presence of excess water, as during the metamorphism of sedimentary cover rocks.

During the 2000 m.y. of the Proterozoic the pattern is very different. Vast tracts of quartzofeldspathic terrain were reworked and radiometrically updated without significant expression of vulcanism or ocean-floor tectonics, so that ophiolites, pillowed greenstone belts, and blueschists are not common. Yet there is the evidence cited earlier that conventional geosynclines of modern aspect and, hence, it may be inferred, continental margin tectonics did exist locally in that period, implying that some form of plate tectonics was an operative process. If we assume that in the Proterozoic there was a fully developed sialic crust that was hotter than today and cooling gradually, its response to thermal upwelling and an underlying spreading system would have been extension by ductile, subsolidus flow rather than brittle failure (fig. 6). There was then only local fracturing to the base of the continental crust, accounting for the few developed orthogeosynclines and rifts. The width of a Proterozoic belt is limited only by the persistence of the spreading center generating it, so that the
very extensive provinces of this age are readily accounted for. At about
600 to 800 m.y. cooling apparently allowed fractures in the sialic crust
under extension to propagate routinely to its base, so that in the Phaner-
ozoic, the generation of basaltic ocean floor became the dominant expres-
sion of spreading. If spreading in the Proterozoic did not in general
generate simatic ocean basins, the subduction or thermal descent (which
must have been equal to the amount of spreading around any great circle
in a constant-volume Earth) must have also taken place in general be-
neath sialic crust. The absence of abundant unequivocal evidence for sub-
duction in the Proterozoic suggests that the down-going motion may have
had little effect on the lithosphere above until cooling had progressed
sufficiently to produce a relatively rigid subducting slab, a phenomenon
that again did not appear commonly until brittle fracture and rigid plates
in the Phanerozoic permitted the deformation to be concentrated at plate
boundaries. The depositional history in both the Cordillera and the
Appalachians of North America begins with clastic rocks that are time-
equivalent (Neoheilikian) to the Grenvillian orogeny and may in part
represent detritus shed from the eroding Grenvillian orogenic belt (an
estimated 8 million cubic km from the Grenville province alone) (Wynne-
Edwards, 1972) and deposited at continental margins. This does not sug-
gest that substantial simatic ocean basins were in existence by this time.

THE LAKE SUPERIOR BASIN AND MID-CONTINENT GRAVITY HIGH

The Grenville province is only part of the Grenvillian orogenic belt
known to extend as a geochronological province in the subsurface base-
ment through the United States into Mexico (Muehlberger, Denison, and
Likiak, 1967). As already noted, the Keweenawan volcanics, the Duluth
gabbro, and the associated clastic rocks of the Lake Superior Basin also
have the age of the Grenvillian orogeny.

The pattern of north-south tracks of plutonism and parallel trans-
formal shear zones in the Grenville province is extended to the mid-
continent in figure 7 on the basis of the limited geophysical, geological,
and geochronological data available. The hypothesis is that the Gren-
villian episode of spreading, expressed by ductile extension in the Gren-
ville province, resulted in rifting and local rupture of the continental
crust farther west at the site of an active igneous center at about 1200 to
1100 m.y. This rift became the Lake Superior Basin, and the mafic vol-
canic and plutonic rocks of the mid-continent gravity high represent a
micro-ensimatic ocean within the Grenvillian orogenic belt. Further
spreading activity and heating caused ductile behavior as the lithosphere
moved northward, the orogenetic pattern being dominated by large oppos-
ing sinistral and dextral transformal shear zones framing the Lake
Superior salient, the dextral one along the Michigan gravity high, and
the more westerly sinistral one at the west end of Lake Superior through
Minnesota and Iowa, marked by a south-trending flexure in the gravity
and magnetic pattern and in the subsurface distribution of Keweenawan
volcanic rocks. A further more westerly sinistral transformal shear zone
may be marked by another discontinuity in Nebraska and Kansas close to the Nemaha Uplift. Muehberger, Denison, and Likiak (1967) report cataclastic rocks dated at 1160 m.y. from the zone of left-lateral offset between Nebraska and Kansas segments of the gravity high but tentatively correlate this with an east-west fracture zone rather than the north-south one proposed here.

The northward moving lithospheric plate model is further supported by the distribution of rhyolite and epizonal granite complexes with ages in the range 1200 to 1000 m.y. in the south-central United States (Muehberger, Denison, and Likiak, 1967). Like the anorthosite tracks of the Grenville province, these complexes are aligned in three subparallel north-south zones (fig. 7). These are taken to be near-surface expressions of motion relative to underlying igneous centers expressed through anatectic melting, high-level intrusion, and volcanism in and on the passing continental crust. The distribution of dates between 1350 and 1000 m.y. in central United States is generally consistent with this northward relative movement.

The phase of compressive lithospheric flow that follows initial extending flow in the millipede orogenic model is logically responsible for the southward-dipping faults and folds in the Lake Superior Basin (Card and others, 1972).

THE NAMAQUALAND AND DAMARA BELTS OF AFRICA

One satisfactory test of inferred relationships is in finding additional examples. The Namaqualand-Bushmanland mobile belt of South Africa provides an excellent illustration. This mobile belt, recently renamed the Sanama province by Pretorius (1975), extends southward from Orange River until covered by Karroo sedimentary rocks but has been inferred to extend into Natal. Like the North American Grenville province the radiometric ages are in the range of 1300 to 950 m.y.

The Springbok region in northwestern Cape Province has been extensively studied and mapped by geologists of O'okiep Copper Company Limited (Benedict, Wiid, and Cornelissen, 1964; Marais, Packham, and Schreuder, 1975) and adjacent areas by Joubert (1971, 1974a). Farther east there are areas mapped by Von Backström (1964) and Vajner (1975). The geology has recently been reviewed in a series of papers from the Precambrian Research Unit, Capetown (Kroner, 1974).

The geology of the Namaqualand mobile belt is similar to that of the Grenville province. Extensive tracts of gray and pink gneiss form a basement complex for thin metasedimentary sequences of quartzite, pelite, and calc-silicates, preserved as refolded synforms. The regional foliation is variable in trend but is dominantly east-west in the central region and gently dipping. Minor folds consistently verge southward. The grade of metamorphism is rather lower, muscovite being common, and true granulite facies is attained only locally, and mainly in the O'okiep Copper District.
The O'okiep Copper District is the largest area of plutonic intrusive rocks in extensive sheets of monzonite and charnockitic rocks with local cross-cutting steep structures carrying mineralized norite, diorite, and minor anorthosite. Separate stratiform units of monzonite and charnockitic rocks are identified by their degree of deformation and metamorphism, and reveal a long history of syntectonic igneous activity at about 1200 m.y. (Rb/Sr, Clifford and others, 1975), with the cross-cutting noritoid rocks following at about 1100 m.y. The monzonites are comparable in geochemistry and texture to the monzonites enveloping the anorthosite massifs of the Grenville province, leading the writer to postulate a subjacent anorthosite mass under the 1200 sq km of the Copper District with the monzonites representing its anatectic carapace and the mineralized noritoids a late-stage mafic differentiate. An extensive negative gravity anomaly centered on O'okiep supports this interpretation, as do the small masses of coarse-grained anorthosite that occur within the diorite and norite of the steep structures.

Masses of similar coarse-grained charnockite-adamellite and gabbro occur in several zones in the Namaqualand belt east of the O'okiep Copper District and are aligned in southeasterly arrays. Parallel, large linear belts of highly foliated or mylonite gneisses form several prominent southeasterly lineaments in the Sanama province (Blignault and others, 1974). They are clearly visible on E.R.T.S. imagery (Viljoen, 1975a). The longest is traceable for 270 km and passes near Pofadder. Recent studies by Too-good (1975) show it to have minimum dextral transcurrent displacement of 85 km. It is marked by a central core of mylonites and cataclasites between 2 and 7 km wide and a surrounding zone of reoriented earlier structures about 20 km across.

An interpretive tectonic sketch of the Sanama province is given in figure 8. The prominent lineaments are inferred transformal shear zones, and parallel lines of adamellite-monzonite-gabbro are taken to be crustal movement vectors relative to underlying igneous activity on a spreading system. The Namaqua front is generally assumed to lie north of the Orange River, but in the writer's view the south-verging folds rather imply a cratonic foreland to the south or southeast, so that the northern boundary is a possible Namaqualand behind. The area is one of andesitic volcanic rocks, rift faulting, and a significant gravity high (Pretorius, 1975).

If this is in fact the site where spreading activity ceased so that it represents the trailing rather than the leading edge of the Namaqualand mobile belt, the Damara belt to the north is in the same relative posterior position as the Appalachian belt is to the Grenville province. The Damara mobile belt has a metamorphic-tectonic age of 800 to 600 m.y., and metasedimentary rocks are dominantly exposed at the present level of erosion. Yet there is strong evidence that the Damara belt is also wholly ensialic in character, with exposed zones of reworked granitic basement (Martin, 1975). Like the Grenville and Namaqualand provinces, the Damara belt
has shelf-type sedimentary rocks, including extensive carbonates, and only minor volcanic rocks.

Figure 9 is a tentative interpretation of the Damara belt using the millipede model. It is of interest because it illustrates how major transformal shear zones can cause bends in orogenic belts in response to a constant direction of relative motion of crust and thermal spreading system. The inference of this interpretation is that there was a very large and active igneous center on the spreading system underlying the central part of the belt (and subsequently offshore or in South America) which generated a central line of northeasterly trending plutonic complexes and relatively rapid motion of the mobile crustal rocks. Deformation and translation of the adjacent segments were much less. The effect was to transpose most of the folds in the central segment into the direction of tectonic transport subparallel to the transformal shear zones, but to generate folds subperpendicular to this in the segments on either side. The position of the southern transformal shear zone follows the Matchless amphibolite belt, a remarkably thin and continuous sheet of amphibolite traceable for several hundred kilometers. The sense of motion along this zone can be seen to be dextral from minor reverse shearing reported by Viljoen (1975b) around the Otjihase deposit at the northern end of the Matchless amphibolite belt. The position of the northern transformal shear zone is inferred. The effect of the pronounced salient produced by a dominant segment of the spreading system, as already mentioned, is to transpose the dominant direction of folding and foliation into parallelism with these transformal zones with folds verging toward the adjacent craton.

The presence of one dominant igneous center may initially have generated a triple junction of three aulacogens which rifted to form the distinctive shape of the Damara belt. The ensuing deformation however is best accounted for by the millipede model of ductile spreading, and there is no evidence that the initial rifting, if any, caused actual rupture of the sialic crust to its base.

The foregoing examples serve to illustrate the proposed mechanism of plate tectonics inferred to be dominant in the Proterozoic and caused by the mechanical response of hot and ductile sialic crust to spreading in the asthenosphere. At about the end of the Precambrian the point was reached in the cooling history of the crust at which failure to its base by brittle fracture became the dominant response, leading to the plate tectonics of the Phanerozoic. If crustal ductility was the dominant feature of the Proterozoic, the millipede model should apply equally to such areas as Fennoscandia and the Churchill province of Canada. This test remains.

**METALLOGENIC IMPLICATIONS**

The granitic gneiss terrains of the Proterozoic structural provinces are not noted for their economic productivity in terms of metal deposits. In the Grenville province some economic deposits occur in remetamorphosed rocks of the basement complexes, such as a few massive sulphide bodies associated with basic volcanic rocks and the iron forma-
tions of the Wabush-Mount Wright area of Quebec-Labrador. Others are associated with anorthositic, gabbroic, and granitic plutonism, and uranium pegmatites and a variety of industrial minerals are also important. Volcanic sequences with associated base metals are sadly lacking as exploration targets in the Proterozoic ensialic mobile belts.

Recent discoveries of base metals in the Namaqualand and Damara belts, however, offer intriguing possibilities in the light of the spreading hypothesis advanced here (Wynne-Edwards, 1975). The investigation of exhalative deposits of iron, manganese, copper, lead, and zinc related to present-day transforms and ocean ridges has received much attention (for example, Degens and Ross, 1969). The circulation of water through cooling oceanic volcanic rocks may be the most important initial source of these metals in economic concentrations. In the Proterozoic ensialic belts similar exhalative processes may have been in operation during ductile spreading. Direct evidence of this is scanty but tantalizing. Joubert (1974b, 1975) reports the extensive development of piedmontite (Mn-epidote) in the Pofadder and Kakamas transformal shear zones of the Namaqualand belt, possibly the result of manganiferous exhalations along these zones. The Aggeneyes and Gamsberg deposits presently under development by Phelps Dodge of Africa Limited and O'okiep Copper Company Limited-Newmont Mining Corporation respectively lie on either side of a northwesterly linear zone visible on E.R.T.S. imagery and assumed to be a transformal shear. The Aggeneyes (Broken Hill) deposit is a metamorphosed magnetite-pyrite-galena-chalcopyrite-sphalerite stratabound massive sulphide lying stratigraphically a short distance above basement gneisses in a sequence that includes barite and spessartite and magnetite-quartzite (chert?) iron formations. The Gamsberg deposit, 20 km to the east is a metamorphosed pyrite-pyrrhotite-sphalerite-galena stratabound massive sulphide similarly situated in the cover sequence, again associated with manganiferous magnetite iron formation and also with extensive barite. The inference is that chemogenic deposits of the type presently associated with the deep ocean floor were formed in the Proterozoic in relatively shallow epicontinental seas in response to exhalative fluids rising through the crust from underlying active spreading systems, principally along transformal shear zones. The copper deposits along the Matchless amphibolite belt in the Damara province offer additional possible results of the same process, and the metallogenic pattern of lead and copper occurrences in the Damara belt suggests that two northeast-trending zones of mineralization, one through Tsumeb and the other lying to the south through Windhoek, developed in the general region of the transformal shear zones proposed in figure 9 (Martin, 1975). The only large and operating lead-zinc deposit in the Grenville province at Balmat, N.Y., occurs in a metamorphosed magnesian carbonate sequence in association with anhydrite and gypsum (Brown and Engel, 1956). It lies close to the major cataclastic boundary between the Adirondack plutonic highlands complex and the dominantly metasedimentary lowlands already inferred to be a transformal shear zone (fig. 4).


——— 1965, Tectonic map of the Canadian Shield: Canada Geol. Survey Map 4-1965.


Wilson, J. T., 1965a, Transform faults, oceanic ridges, and magnetic anomalies southwest of Vancouver Island: Science, v. 150, p. 482-485.
The millipede model of ductile plate tectonics


