PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY A MATHEMATICAL, PHYSICAL & ENGINEERING SCIENCES

The Grenville Province in Helikian Times: A Possible Model of Evolution

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The Grenville Province in Helikian times: a possible model of evolution

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It is suggested that the Helikian (1650–1000 million years (Ma) ago) evolution of the Grenville Province in the Canadian Shield was marked by three events: emplacement of anorthosites around 1450–1500 Ma ago, rifting associated with opening of a proto-Atlantic ocean between 1200 and 1300 Ma ago, and continental collision responsible for the Grenvillian 'orogeny' about 1100–1000 Ma ago.

Emplacement of rocks of the anorthosite suite (anorthosites and adamellites or mangerites) into continental crust was accompanied by formation of aureoles in the granulite facies.

The Grenville Group was deposited in the southern part of the Province between 1300 and 1200 Ma ago and comprises marbles, clastic metasedimentary rocks and volcanics. It occupies a roughly triangular area limited on the northwest by the Bancroft–Renfrew lineament and on the southeast by the Chibougamau–Gatineau lineament. It is thought to have been accumulated in an aulacogen that would have developed along a fracture zone separating two basement blocks.

The Grenvillian thermotectonic event may represent a Tibetan continental collision in the sense of Burke & Dewey. The suture zone would now be hidden under the Appalachians. Collision would cause reactivation of continental crust and renewed movement on pre-existing lineaments. The east–central part of the Grenville Province appears to have been more intensively reactivated than the western part.

Introduction

The various attempts made in recent years to incorporate our limited observations in the Grenville Province to concepts of mountain-building and crustal evolution (for instance Wynne-Edwards 1972; Baer 1971; Martignole & Schrijver 1970; Donaldson & Irving 1972) have received new impetus from applications of plate tectonics to the Precambrian (see Baer, Emslie, Irving & Tanner 1974).

Dewey & Burke (1973) have recently proposed that the Grenvillian orogeny was caused by reactivation of an old basement alongside a zone of continental collision. Their paper sketches the framework in which such an event could have occurred. The present paper attempts to show that major geological features of the Province can probably be better accounted for by a model of this type than by other models.

It has been assumed for some time that the greater part of the Grenville Province represents reactivated basement material (Walton & de Waard 1963; Stockwell 1964; Wynne-Edwards 1964). Basement reactivation is a well known phenomenon, that has been studied for at least fifty years in many parts of the world. By combining our knowledge in this field with data on structural levels and tectonic styles ('étages tectoniques' of Wegmann 1956) one can estimate depth and temperature of reactivation of a given volume of rocks.

The hypothesis developed here is that three major events mark the Helikian evolution of the Grenville Province. The first one is the emplacement of rocks of the anorthosite suite around 1450–1500 Ma ago (Elsonian event). The second is an early opening of a proto-Atlantic ocean, accompanied by formation of a rift graben in Labrador (Seal Lake) and formation of an aulacogen in southeastern Ontario. This aulacogen is considered to have been the main area of deposition of the Grenville Group, around 1200–1300 Ma ago. The third event is the Grenvillian orogeny, (about 1100 Ma ago) resulting from continental collision of North America with a paleo-Africa, along a belt that has now disappeared under or in the Appalachians. The Grenville Province is thus seen as a block of reactivated continental crust adjacent to a suture zone on its southeast side.

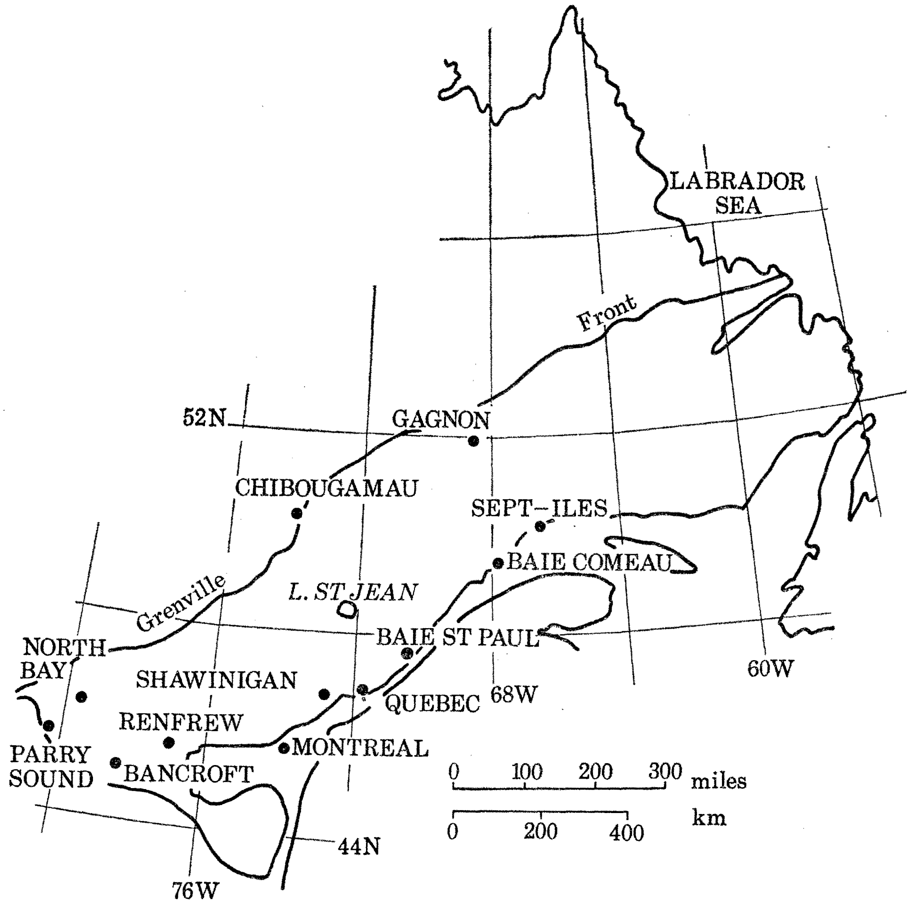

Figure 1. Principal topographic names referred to in this paper.

Early Helikian times

Little is known of the period that immediately followed the Hudsonian Orogeny. One can conjecture that folded Aphebian rocks now found in the Labrador Trough and in the Gagnon Group of the Normanville sub-province extended farther than at present. They must have been continuous with the present Mistassinni Basin and rocks of the Otish Mountains region, and they probably extended as far west as Lac St Jean.

Farther west, Aphebian gneisses of Huronian affinities extended presumably east of the Grenville Front in Ontario to the vicinity of the Gatineau valley in Québec. Plutonic and tectonic activity along the Grenville Front in Ontario (Bell Lake granite, 1550 Ma: Krogh, Davis & Frarey 1971; Wanless & Loveridge 1972); lineated muscovite 1600 Ma: Krogh & Davis 1969) may represent a late episode of Hudsonian activity.

Emplacement of the anorthositic suite

'Anorthositic suite' is used here to describe collectively rocks varying in composition from an anorthosite and gabbro to mangerite and adamellite and commonly associated in the field. The term does not necessarily imply that they all are co-magmatic. These rocks were emplaced in a broad belt running generally northeast from the Adirondacks to Labrador. Presently available

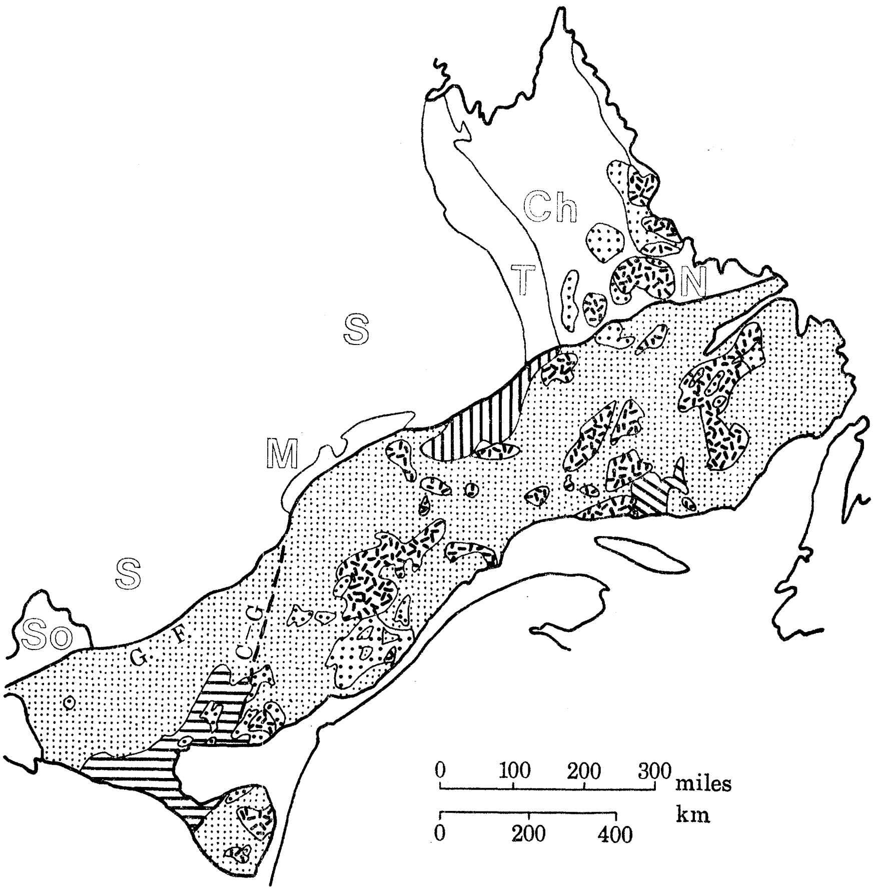

Figure 2. Sketch-map of the Grenville Province. Horizontal lines: Grenville Group; vertical lines: Gagnon Group; oblique lines: Wakeham Group; large dots: adamellites; short dashes: anorthosites. So, Southern Province; S, Superior Province; M, Mistassini and Otish basin; T, Labrador Trough; Ch, Churchill Province; N, Nain Province.

data suggest two different periods of emplacement. A number of plutons date from between 1450 and 1500 Ma ago (Krogh & Davis 1973; Baer *et al.* 1974) whereas others were emplaced between 1100 and 1200 Ma ago (Silver 1969; Wanless, Stevens, Lachance & Delabio 1973). One pluton at least has given an intermediate date of 1346 Ma (Marchand & Crocket 1974).

In the Grenville Province, rocks of this suite form large massifs and wedge-shape bodies. They are limited to the part of the Province that lies east of a major, north-trending structural zone following the Gatineau valley and extending as far as Chibougamau, where it joins with the eastern part of the Grenville Front. This zone is called here the Chibougamau–Gatineau lineament (figure 3). Its aeromagnetic expression is visible in figure 3. West of the lineament, anorthosites are commonly absent except for some small bodies in the North Bay area (Lumbers 1971) and a larger one on the Grenville Front. This difference may indicate that no anorthosites were intruded west of the lineament, but it may also reflect different levels of erosion. Probable Proterozoic rocks are abundant to the west of the lineament whereas Archean rocks appear to be abundant to the east of it. Anorthosites could therefore be present under thick Proterozoic successions, in the western Grenville Province.

FIGURE 3. Aeromagnetic expression of the Chibougamau–Gatineau lineament, contours in 10^{-9} T.

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Some anorthositic bodies are surrounded by irregular aureoles of gneisses in the granulite facies. These aureoles appear to have formed when the host-rock was invaded by the hot and dry anorthositic material (Wynne-Edwards 1972). The large area of granulitic terrain between Québec City and Gagnon (Douglas 1969) is not an aureole however but it may represent a section through the lower, granulitic, part of the crust.

Emplacement of the anorthosites must have been accompanied or followed by vertical displacement along the Chibougamau–Gatineau lineament, because 150 Ma later (see below), the Grenville Group was to be deposited on two distinct basement blocks on either side of this lineament. On the west side, the Group rests on leucocratic, quartz-rich gneisses of probable Proterozoic age, whereas on the east, judging from lithological similarities, it rests on rocks of Archean origin. Uplift of the eastern block could account for erosion from it of most Aphebian rocks prior to deposition of the Grenville Group and would also have brought large areas of lower-crust granulites to higher levels.

Anorthosites are commonly found nowadays along the interface between basement and supracrustal rocks and in particular along the probable base of the Grenville Group. As some anorthosites have been at least partly remobilized (Morin massif; Martignole & Schrijver 1970; Lac Rouvray massif: Kehlenbeck 1972; Borgia pluton: Baer 1976) those field relations need not reflect primary emplacement and do not necessarily imply by themselves that the Grenville Group is older than about 1450 Ma.

Deposition of the Grenville Group

The history of deposition of the Group is seen through a thick metamorphic and structural veil, so that only major aspects of this evolution can be reconstructed. Because of extensive field-work and abundant geochronological data southeastern Ontario and the Adirondacks are particularly favourable for such studies.

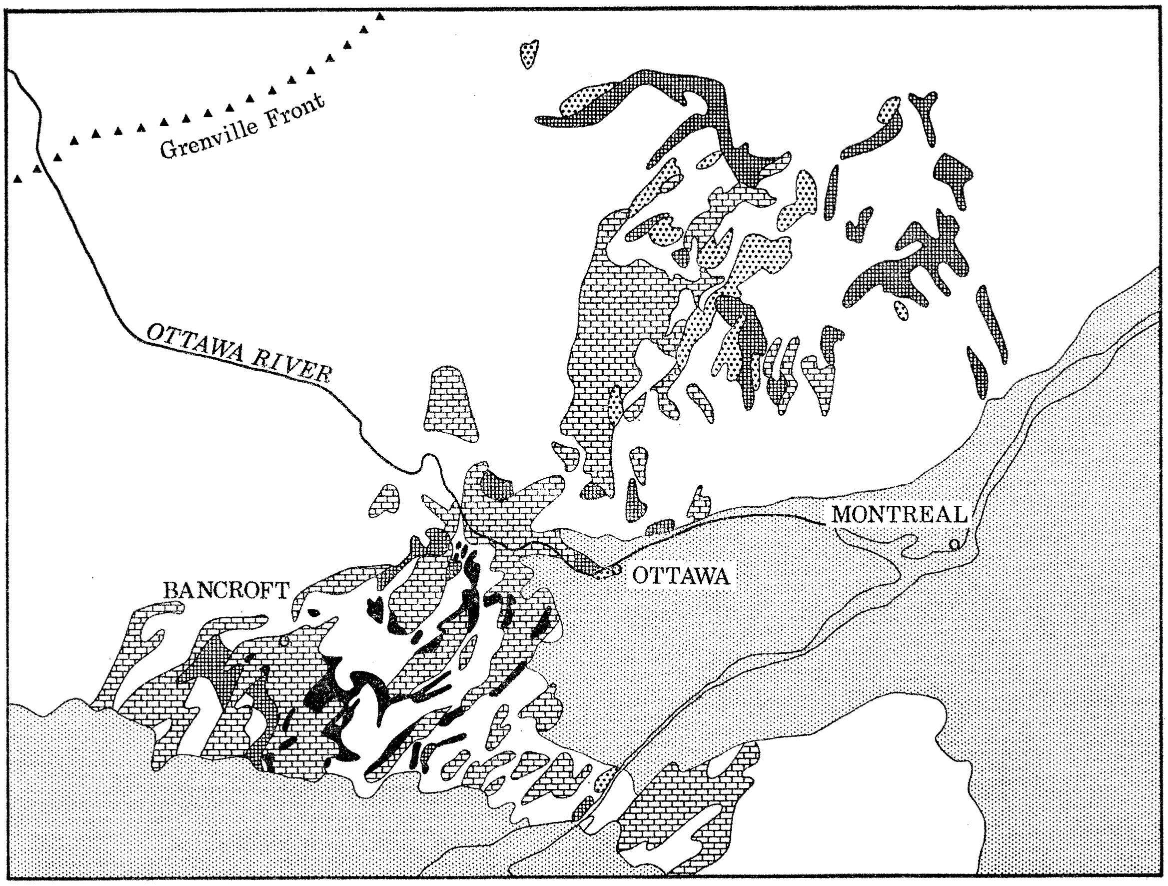
Lithology of supracrustal rocks

Members of the Group are dominantly marbles, metavolcanics and clastics ranging from conglomerates through quartzites to schists. Evaporites have been reported from the Adirondacks (gypsum casts, Engel & Engel 1953).

The group extends from the edge of the Shield almost to Gouin Reservoir, sixty miles south of the Grenville Front, in a roughly wedge-shaped zone limited on the east by the Chibougamau–Gatineau lineament and on the northwest by another lineament running through Bancroft, Renfrew and Lake Baskatong, and called here the Bancroft–Renfrew lineament (figure 4).

Slivers and infolds of similar lithologies have been found outside this zone, and extend to the east as far as the St Maurice River valley north of Shawinigan, and to the west as far as North Bay and Parry Sound. Since these occurrences are not in continuity with rocks of the type-area, their attribution is uncertain. It is highly probable however that marble and amphibolite of Parry Sound area are true equivalents of the Grenville Group. The same can be said of some supracrustals east of the Morin anorthosite. Uncertainty increases rapidly farther east, and 'Grenville-like' metasediments around Lac St Jean and east of it are not considered here to belong in the same Group. They may belong to the Aphebian Gagnon Group, or to some other group.

Marble has long been considered the most characteristic member of the Group. It is thickest and most abundant along the western margin of the major outcrop area and it thins out to the east and southeast. Estimated thicknesses decrease from a high of 15000 m near Bancroft to a few thousand feet east of the Morin massif. Although a basal unconformity has yet to be found, the original carbonates appear to have rested directly upon basement gneisses, along part of the Bancroft–Renfrew lineament.



marble | metasediments | Palaeozoic
volcanics | quartzite

FIGURE 4. Distribution of the major rock-types in the Grenville Group.

Metavolcanics are well known from southeastern Ontario (cf. Lumbers 1967) where primary textures and structures have been locally preserved in regions of low-grade metamorphism. They are dominantly basalts with alkalic affinities, but andesitic and rhyolitic material is also present (Lumbers 1967; Baragar 1972). Their total thickness surpasses 8000 m and their distribution appears limited to that part of the Grenville Group in Ontario which lies southeast of Bancroft and northwest of Perth. Metavolcanics are also known from the Adirondacks. None have been recognized in Québec, but the various amphibolites found in this region could be their metamorphic equivalents.

Radiometric dating (Silver & Lumbers 1965) gives an age of 1310 ± 15 Ma for volcanics in the lower part of the southeastern Ontario section and about 1250 ± 25 Ma for rhyolitic material of the Burnt Lake Formation (Lumbers 1967).

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Quartzite is limited to specific areas. It is abundant near the northern and eastern edges of the present distribution area of the Group, but relatively scarce elsewhere. Near Mont Laurier it is most common near the base of the section (Wynne-Edwards *et al.* 1966) whereas near Kingston it occupies more than one stratigraphic level (Wynne-Edwards 1967*b*). Conglomerates are most common in Ontario, where they form long and narrow strips parallel to the regional trend (Hewitt 1964). They appear limited to outcrop areas of volcanic rocks. They and other clastic sediments were derived, in part at least, from a crystalline basement that did outcrop inside the basin during sedimentation and volcanism. (Lumbers 1967). Where detailed mapping is available, it shows extremely complex interfingering of lithologies (see Lumbers 1967, fig. 4*b*). Lateral and vertical alternations of metavolcanics, marble and clastic metasediments are characteristic and they do not in any way correspond to a simple progression from a mio- to a eugeosynclinal assemblage.

Intrusive rocks associated with sedimentation

It is evident from radiometric dating that various igneous rocks must have been emplaced in southeastern Ontario during deposition of the Grenville Group, or possibly during lulls in a major period of deposition (Silver & Lumbers 1965; Lumbers 1967).

The better known rocks of this type are certainly the nepheline syenites and associated nepheline gabbros, some of which give an age of 1280 Ma by Rb-Sr on whole rock (Krogh & Hurley 1968). Except for the Blue Mountain occurrence to the southeast, nepheline syenites line up through Bancroft and Renfrew along a northeasterly trending zone that marks the edge of the present extent of the Grenville Group (see Ontario Geol. map 2197, 1972). Northeast of Renfrew, isolated plugs of alkaline rocks are found along the projection of the same lineament into the Gatineau valley and beyond. The northernmost is in the Gouin Reservoir area, only 25 km from the Grenville Front (Laurin 1965). Some of those, at least, have been deformed and are thus pre- or syn-tectonic. They all line up along the Bancroft–Renfrew lineament and their distribution suggests that most belong in the same group (see also Baer *et al.* 1974, fig. 2). Other plutonic rocks varying in composition from gabbro to granite were emplaced in southeastern Ontario shortly after. Some appear to be epizonal intrusive equivalents of volcanic rocks (Albite granite and syenite group for instance, Lumbers 1967). The emplacement of others represents a major plutonic event, dated at about 1250 Ma. At that time, large trondhjemitic plutons (Weslemkoom, Elzevir) were emplaced selectively in areas of pre-existing volcanic rocks. As noted by Lumbers their distribution corresponds accurately to that of these volcanic rocks, by contrast with that of the younger (1150 Ma) more potassic plutons associated with the Grenvillian event. Sedimentation persisted after emplacement of trondhjemitic plutons, as shown by a conglomerate from Actinolite that contains pebbles lithologically similar to, and radiometrically coeval with these plutons (Boutcher *et al.* 1965).

The basement problem

Although original relations between rocks of the Grenville Group and their basement have not been preserved anywhere, most gneisses presently found in the vicinity of the Group certainly represent remobilized basement (Appleyard 1974; Francoeur 1975). These gneisses are quite different west and east of the present Grenville Group.

The western basement is formed principally of lithologically monotonous, banded, light-grey, northwest trending and gently dipping quartzo-feldspathic gneisses. The eastern basement is lithologically and structurally more complex, gneisses are richer in biotite, less well layered and not uncommonly garnet-bearing. The boundary between the two appears to run along the Chibougamau–Gatineau lineament, until it disappears to the south under rocks of the Grenville Group. Even allowing for uneven remobilization during the Grenvillian event, these two basements must have been lithologically different before deposition of the Group. The uneven distribution of abundant quartzites in the east and abundant marbles in the west further indicates a different environment of deposition along the eastern and western margins.

Although radiometric ages are scarce, a combination of all available data suggests that the western basement is essentially formed of (Lower?) Proterozoic rocks as opposed to a dominantly Archean eastern basement (Baer 1975). With the probable exception of the Burleigh and Anstruther domes southwest of Bancroft, no basement has been recognized inside the former basin, between the Bancroft–Renfrew and the Chibougamau–Gatineau lineaments. No evidence of oceanic crust has been found anywhere in the area either*, and detailed gravity profiles indicate that sialic material is continuous across it, from Bancroft to Madoc (W. Jacoby, private communication, January 1970).

Interpretation

Deposition of the Grenville Group began around 1310 Ma ago in an opening aulacogen limited on the west side by the Bancroft–Renfrew lineament and on the east side by the Chibougamau–Gatineau lineament. The timing would correspond to major rifting and opening of an early proto-Atlantic ocean. Opening of the Seal Lake graben would have occurred at this time (see Baragar in Baer *et al.* 1974). The main area of deposition of the Grenville Group is seen as a failed arm off a triple point located somewhere south of Lake Ontario. It is important to note in this regard that this failed arm follows an older boundary between two distinct cratonic blocks. This may well be the rule rather than the exception in the formation of such aulacogens (East Arm and Bathurst aulacogens of Fraser, Hoffmann & Irvine 1972 for instance).

Opening of the aulacogen coincided with volcanic activity along northeasterly trending dikes, that sliced the basement into fault-blocks. The environment of deposition was presumably quite similar to that of the present Danakil depression in the southern Red Sea (Hutchinson & Engels 1972). The upper surface of the fault-blocks would represent areas of relatively quiet carbonate sedimentation whereas faulted zones would allow for intrusion of volcanics, rapid erosion of basement material and deposition of coarse clastics. The greater thickness of marble in the western part of the basin indicates greater subsidence in this region, and the aulacogen probably looked somewhat like a complex half-graben. The chain of alkalic intrusions along the Bancroft–Renfrew lineament underlines a major rift-zone in the craton, that corresponded to greater subsidence during sedimentation. Trondhjemitic plutons in areas of volcanics possibly represent sialic basement that was remobilized and even molten where magmatic activity was most intense. Alternatively they could be thought to belong in an island arc structure, but other data, such as the nature of volcanic rocks do not support this model.

To the north, the aulacogen loses its characteristics. Volcanics are rare or absent, indicating that faulting was less intense and did not tap the upper mantle; nepheline-bearing plutons are scarcer than farther south and marble is thinner.

Outside the aulacogen, a thin veneer of limestone and minor clastics was deposited over

* This has recently been disputed by Brown *et al.*, in *Geosci. Can.* **2**(3) 141–144 (1975).

large expanses of older gneisses. Amphibolites of Parry Sound area probably represent a minor northeast trending fault-zone parallel to those of the aulacogen farther southeast.

Formation of the aulacogen with its northeast-trending faulting and rifting is most important because it will control the style and direction of structures during the later Grenvillian orogeny. This means that the deformation pattern will actually be guided by structures dating back to sedimentation time. Similar evolution is well known from younger orogens, such as the alpine belt for instance (Trümpy 1960; Baer 1959; Schindler 1959).

The Grenvillian event

As is the case in other polymetamorphic complexes, effects of the Grenvillian event are difficult to distinguish from those of earlier events. The topographic surface only gives us an essentially two dimensional view of the Province, and uneven distribution of metamorphic grade or of radiometric sub-provinces may reflect irregularities in the depth of erosion as well as variations of 'orogenic' activity or, more probably, a combination of both.

Structural trends

It is impossible in many cases to know what structural trend is or is not 'Grenvillian' in age. Pre-Grenvillian trends have been preserved in various areas (Wynne-Edwards 1972) but some are better documented than others.

True Grenvillian trends must include those formed by folding of rocks of the Grenville Group. They run northeast in the Adirondacks and in Ontario, but turn north along the Gatineau valley and can be followed along a narrow zone that extends farther north and reaches the Grenville Front near Chibougamau. Last movement along this north-trending zone is clearly late in the deformation of the region (Dimroth 1966).

Most deformation along the Grenville Front Tectonic Zone, from Chibougamau to the northeast, is also of Grenvillian age. It is important to note however that such deformation is absent from Lac Surprise area, southwest of Chibougamau (Déland & Grenier 1959) and from long segments of the Front Zone, southwest of there, to the Ottawa River. Another zone of probable Grenvillian deformation is a narrow southwesterly trending structural belt parallel to the St Lawrence River from Montreal to Baie St Paul and probably as far as the mouth of the Saguenay River (Sabourin 1973; Laurin 1970). If some of the gneisses in this zone actually belong in the Grenville Group, as reported, the age of the deformation must be Grenvillian. Elsewhere in the Province, structural trends vary considerably. Large areas display north-northeasterly directions oblique to the present boundaries of the Province (Wynne-Edwards 1972, fig. 2) whereas others trend northwest, as in the 'Ontario Gneiss Segment' for instance. Although some of these directions are certainly of Grenvillian age, others are just as certainly older, and they are better left out of considerations on Grenvillian deformation.

Intrusive activity

The Grenvillian event is well known for the lack of associated syntectonic and late tectonic granitic plutons. Most of the plutonic activity appears to have resulted from remobilization of pre-existing gneisses. For example, in Mont Laurier area (Wynne-Edwards *et al.* 1966) true granitic plutons represent less than 5% of all rock-types. Late tectonic granites are known from various areas (Saguenay region (Frith & Doig 1973), southeastern Ontario) but as a rule they are small, few and far between. It could be that plutonic activity was almost non-existent during the Grenvillian event, or that the presently exposed structural level is deeper than that where discrete plutons normally form. Whereas the latter argument is undoubtedly valid in some regions, it cannot be true everywhere, because granitic plutons are scarce even where structure and metamorphism appear to suggest a high structural level (such as near the Front in Ontario and western Québec).

Some anorthositic and mangeritic plutons were remobilized during the Grenvillian event. From field evidence, some massifs were entirely re-intruded and recrystallized (Borgia anorthosite), others were deformed along their margins only (Lac St Jean), while still others were probably re-intruded as tongues and domes of partly recrystallized material (Morin, Lac Rouvray for instance). Similar considerations seem to apply to some leucocratic members of the suite like the Roberval granite for example (Benoit & Valiquette 1971).

Geochronological data on rocks of the suite in Canada generally confirm this interpretation. Although anorthosites themselves cannot be dated, ages obtained from associated rocks indicate an early period of emplacement around 1450–1500 Ma ago followed by another, later, period around 1100 Ma ago. Remobilization occurred shortly after, around 1000–1100 Ma ago.

Gravity data (Gravity Division map 1974) show that some anorthositic bodies are associated with positive gravity anomalies and others with negative anomalies. The difference in signature is such that it could only be explained by major lithological differences between the two types (J. G. Tanner 1974, personal communication). The simplest explanation is that 'positive' anorthosites are associated with a dense, mafic 'root', whereas 'negative' anorthosites are not. The latter occupy the central and southern parts of the Grenville Province, and the former are concentrated in the eastern part. Studies on the Adirondacks massif (Simmons 1964) the Morin massif (Martignole-Schrijver 1970) and the Lac Rouvray massif (Kehlenbeck 1972) suggest that these bodies are not rooted (or possibly in part only, in the case of the Morin) and form slabs or wedges and tongues in surrounding gneisses. These observations together with reports that some of the 'positive' bodies are little or not deformed at all (Emo 1957; Stevenson 1969) could imply that during the Grenvillian event massifs that now have a negative gravity expression were separated from their mafic roots, remobilized and 'injected' into surrounding gneisses. The style of remobilization should reflect the conditions of pressure and temperature under which this occurred.

Metamorphism

Most of the Grenville Province is in the amphibolite or in the granulite grade of metamorphism but the age of this metamorphism is not known. The absence of extensive regional retrograde metamorphism suggests however that where present, Grenvillian metamorphism must have reached a grade comparable to that reached in earlier events.

'Thermochrons'

Thermochrons are lines of equal K-Ar ages (Harper 1967) considered to indicate, in Precambrian shields, times of cooling below a certain blocking temperature (200–300 °C?) rather than actual age of emplacement of igneous rocks. In the eastern Grenville Province, their configuration shows a general parallelism with the eastern segment of the Front (see the 1000 and 1100 thermochrons, figure 5) implying that the latter acted as a hinge during cooling. This pattern disappears west of Chibougamau, where thermochrons are at a high angle to the Front. The boundary between these two domains of thermochrons is the Chibougamau–

Gatineau lineament. The cooling history of the western Province differed therefore from that of the central and eastern Province. Post-tectonic granites dated by Frith (1971) and by Barton (1971) occur quite close to the 900 Ma thermochron, which confirms that cooling was late in this region, not only because uplift took place slower or later, but because these rocks were actually hotter at a later date than others farther northwest.

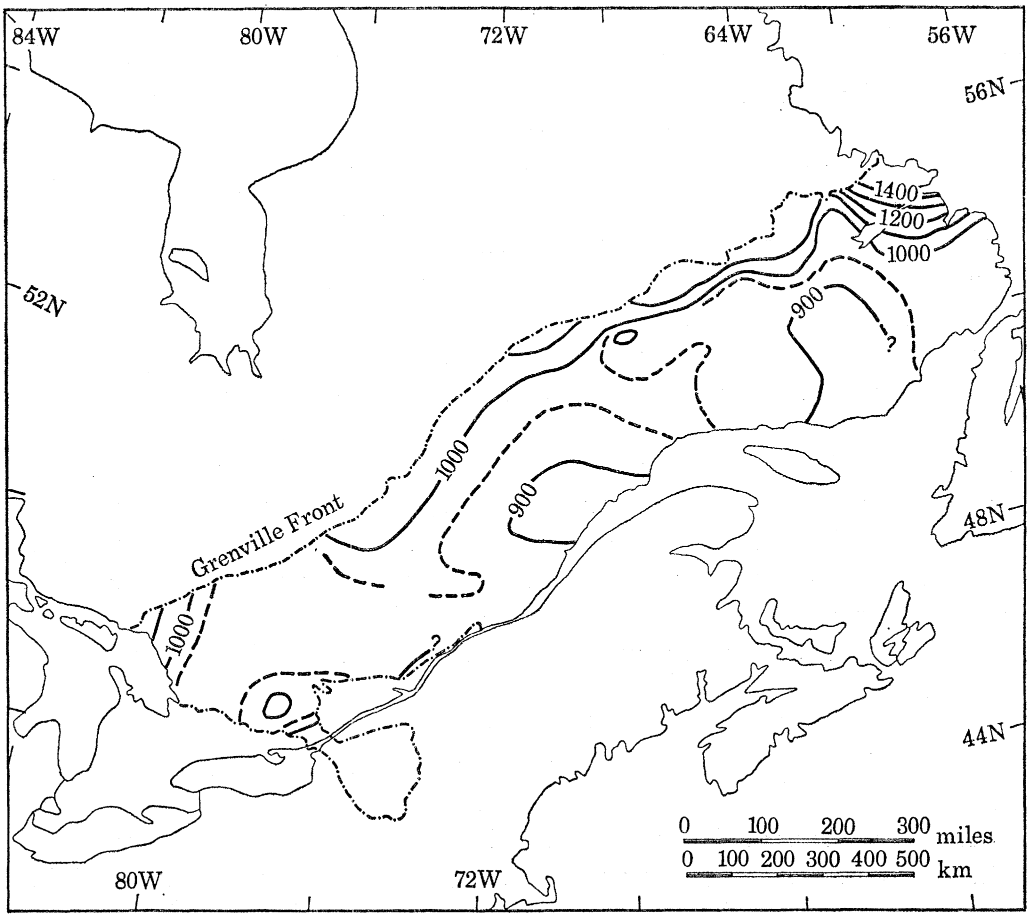

Figure 5. 'Thermochrons' from 96 K-Ar dates on micas.

Interpretation

The Grenville orogeny is thought to be due to continental collision between a North American and an African(?) plate along a northeast trending zone located southeast of the present margin of the Province. Under these conditions major pre-existing structures would be reactivated, but remobilization would decrease from southeast to northwest. As a consequence of continental collision, the Chibougamau–Gatineau lineament, a pre-existing structure, would move again. Rocks situated west of it would have been affected differently from those east of it so that this lineament is, in fact the boundary between a western sub-province and an east-central sub-province.

The east-central sub-province

Remobilization is maximum in a belt running from the Adirondacks to Sept-Iles. It decreases from there to the northwest and to the northeast. At collision time this belt was probably opposite the zone of early and maximum impact whereas the extreme eastern province was facing a zone of late impact or even a re-entrant in the other continent (Dewey & Bird 1970; Dewey & Burke 1973, 1974). In the region of maximum reactivation, structural trends are northeast, but farther northwest they are increasingly influenced by the older north–northeast direction of the Chibougamau–Gatineau lineament. Anorthosites are remobilized and some form wedges thrust to the northwest and to the west (Wynne-Edwards 1972; Kehlenbeck 1972). Emplacement of true magmatic granites is restricted to the Saguenay region, possibly because of immediate proximity to the zone of maximum reactivation.

This east-central sub-province is limited to the northwest and to the west by the Chibougamau–Gatineau lineament that grades into the frontal fault zone, itself semi-continuous almost to the Labrador Sea. Movement along the Front was marked by brittle deformation, and occurred in part at least, in the greenschist facies. This segment of the Front was therefore deformed at a higher structural level than regions located farther south where the style of deformation is more ductile, a sure indication of deeper structural levels. The present topographic surface cuts obliquely across deeper structural levels ('étages tectoniques') from north to south. Along the Front, deformation is maximum opposite sedimentary basins (Mistassini-Otish, Labrador Trough, Seal Lake graben) but weaker elsewhere, suggesting that compression was only strong enough for gneisses to be thrust onto sediments along the edge of pre-existing basins but not upon other gneisses. Besides this variation in style that was controlled by pre-existing lithologies and structures, it would appear that thrust and lateral transport to the northwest was more important in the Mistassini sector, and decreased to the northeast. One may thus envisage the whole east-central sub-province as one block that pivoted around a point near the Grenville Front on the Labrador Coast and moved farthest north and northwest in its western part, where remobilization was most intense (see also Fahrig, Christie & Schwarz 1974).

The western sub-province

The Grenville Province west of the Chibougamau–Gatineau lineament is formed mainly of southeast-trending quartzo-feldspathic gneisses, limited to the southeast by the Bancroft–Renfrew lineament. Structural trends of rocks of the Grenville Group turn from northeast in the south to north-northeast in the north. They reflect the overall pattern of deformation along the eastern margin of the sub-province. To the north, rocks of the Group are squeezed between older granitic gneisses of the two sub-provinces. The structural grain is controlled by the position of the Chibougamau–Gatineau lineament, that runs north–south. To the south, the effects of this lineament are weaker, and because reactivation was more intense, the north-easterly trend of the proposed suture line dominates the structural framework.

Farther northwest, quartzo-feldspathic gneisses are only moderately affected, in part because of their greater distance from reactivation zones, and in part because their prior structures are almost at right angles to the new ones, and therefore difficult to refold. Thin, northwesterly trending, infolded strips of Grenville Group marbles (along Coulonge River and elsewhere) imply that rejuvenation of the old craton preferentially followed its ancient structural lines.

In Ontario the Grenville Front zone displays well developed northeasterly trends that are mostly older than the Grenvillian event, as indicated by the age of minerals in movement zones (Krogh & Davis 1969). They were rejuvenated about 1000 Ma ago.

In Québec, movement along the Front varies from moderate in the west to nil in the north-eastern corner of the sub-province. During the Grenvillian orogeny, presumed relative

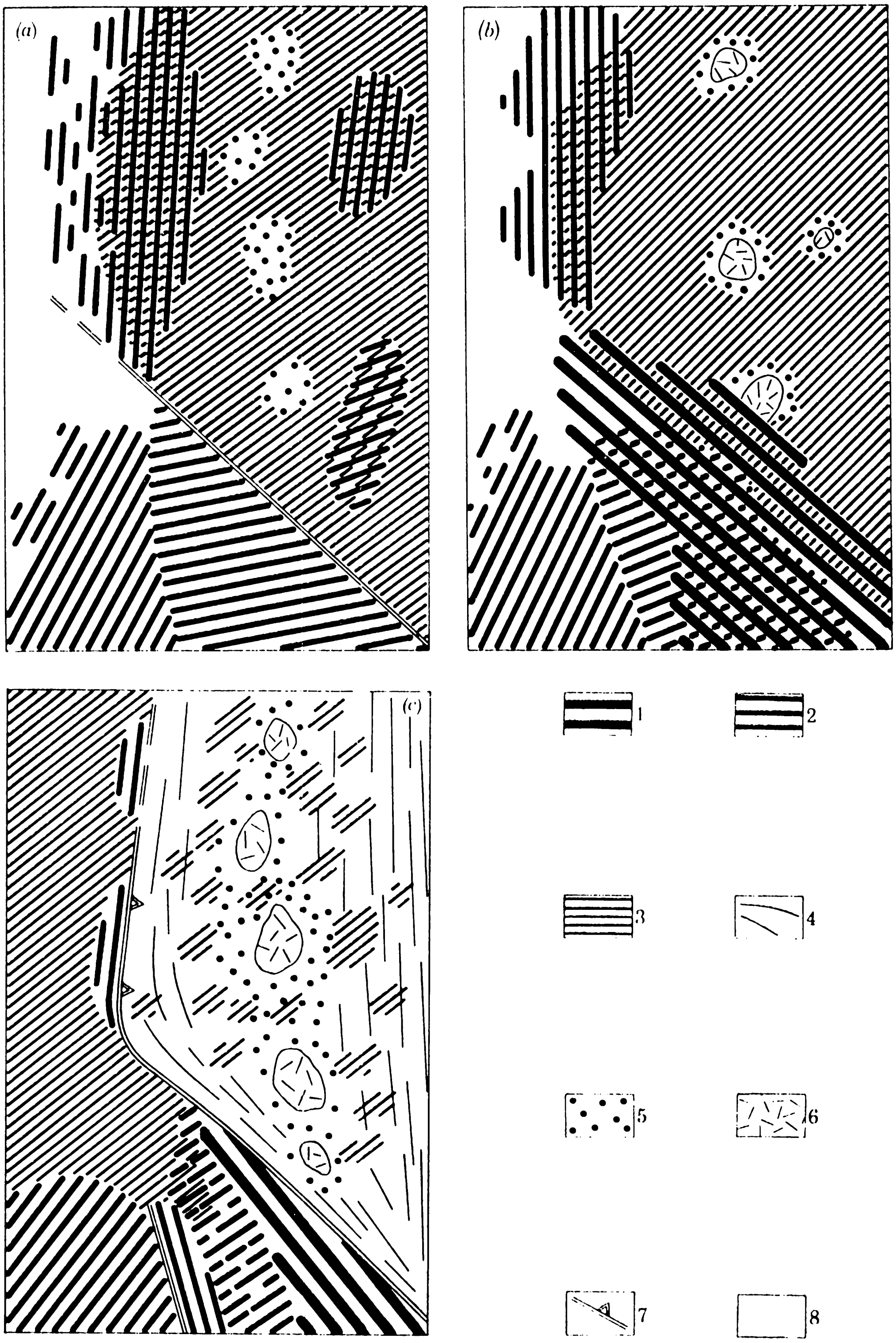

FIGURE 6. Model of possible evolution of the southern part of the Grenville Province. (*a*) About 1400 Ma ago. Archean basement northeast of the Chibougamau–Gatineau lineament is partly covered by Aphebian metasediments and granulite aureoles of anorthosite massifs are just being eroded. Areas southwest of the lineament are occupied by thick Aphebian metasediments. Trends of patterns symbolize trends of folds. (*b*) About 1300 Ma ago. The Grenville Group is being deposited in the area of the lineament, possibly in an aulacogene. Anorthosites are being eroded. (*c*) about 1000 Ma ago. The Chibougamau–Gatineau lineament is reactivated. Northeast of it the Archean basement and the anorthosites are remobilized. New trends are superposed on the older ones. Southwest of the lineament remobilization follows pre-existing trends, the Grenville Front separates remobilized material from unaffected regions to the southeast. The reactivated Chibougamau–Gatineau lineament joins the northern part of the Grenville Front. 1, Helikian Grenvlile Group; 2, Aphebian rocks; 3, Archean rocks; 4, superimposed Grenvillian trends; 5, granulitic aureoles surrounding anorthosites; 6, anorthositic intrusions; 7, Chibougamau–Gatineau lineament and northern part of the Grenville Front; 8, area of older rocks strongly reactivated by the Grenvillian event.

movement of the western sub-province relative to the north American craton seems to have decreased from southwest to northeast, as if this part of the Front moved like giant scissors pivoting around Chibougamau. The segment of the Front located immediately west of Chibougamau (Lac Surprise area) would thus have been close to the 'pivot' and would have been spared major deformation. The geometry of the region suggests that if compression came from the southeast, the Gatineau–Chibougamau lineament would absorb most of the available energy and would protect the Lac Surprise area from major deformation (figure 6).

The thermochron pattern definitely shows that the Grenville Front of the western sub-province was not a hinge zone. The pattern of cooling is not clear but could have been associated with a broad domal uplift centered northwest of Renfrew.

Conclusion

In summary, the model that is being proposed for the evolution of the Grenville Province during Helikian times implies three stages (figure 6).

(1) The first (around 1450–1500 Ma ago) is the emplacement in a pre-existing sialic basement of anorthositic rocks surrounded by granulitic aureoles. Relative uplift of the east-central Grenville Province along a zone of movement called here the Chibougamau–Gatineau lineament took place at an undetermined time after this, but prior to deposition of the Grenville Group. Once it was in existence, this lineament was going to control part of the subsequent structural evolution of the area, in much the same way as the pre-existing western segment of the Grenville Front farther west.

(2) Around 1300 Ma ago major rifting occurred southeast of the present Grenville Province, opening a proto-Atlantic ocean along northeasterly trending fractures. This rifting was accompanied by the opening of the Seal Lake graben, by intrusion of dyke swarms, and by formation of an aulacogen along the side of the Chibougamau–Gatineau lineament. Depositional history of the Grenville Group reflects block-faulting, volcanism and subsidence along northeasterly trends. A chain of nepheline-bearing alkalic rocks marks one rim of the aulacogen. No record of an oceanic crust has been found but the sialic basement was possibly mobilized and re-emplaced in the form of trondhjemitic plutons.

(3) The Grenvillian event, around 1100 Ma ago reflects closing of the proto-Atlantic ocean and continental collision. The Grenville Province was reactivated and deformed according to two key rules, namely that reactivation decreases away from the collision zone, and that deformation uses pre-existing structural discontinuities. To understand the evolution of the region, it is necessary to remember also that the present level of erosion represents a complex and oblique section across various structural levels of the province.

The Chibougamau–Gatineau lineament separates an eastern sub-province from a western one. Reactivation was maximum along the present St Lawrence River where northeasterly structural trends are dominant and where late-tectonic granitic plutons have been emplaced. It decreased to the north and to the northwest, to the Grenville Front, where deformation was mainly brittle, at a higher structural level. Movement along the Chibougamau–Gatineau lineament protected from intense deformation the areas situated northwest of it, particularly around Lac Surprise. Depending on their geographical location, massifs of anorthosite were remobilized at varying degrees. As a rule, the degree of remobilization corresponds closely to the intensity of reactivation in the gneisses. It is most pronounced along the St Lawrence river southwest of Baie Comeau and decreases to the north and to the east.

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In the western sub-province, the Grenville Group is highly deformed and is squeezed between the two rims of the former aulacogen. Deformation of the older gneisses is less intense because their pre-existing structural grain runs at a high angle to the new one, which is itself controlled by the position of the former aulacogen. The Grenville Front zone moved like scissors, movement was maximum near Sudbury and decreased to the northeast.

The overall final cooling of the Province read from thermochron maps shows that the eastern Front was the only part of it that was a hinge zone during the final stages of the Grenvillian event. The western Front bears no relation to the cooling history.

Except for prevalent K-Ar ages of 1000 ± 100 Ma, the unifying characteristics of the Grenville Province have long eluded precise definition (Wynne-Edwards 1964). Reasons are that the Province is a reactivated complex where deformation was partly controlled by pre-existing structures and where reactivation decreased away from the present southeastern edge of the Province. Because the Province has been cut along various oblique sections by the present topographic surface, its evolution is not readily visualized.

The Grenvillian event is the earliest manifestation of the Wilson cycle in the North Atlantic which has therefore opened three times, around 1300 Ma, 700 Ma and 200 Ma ago.

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