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INTERSECTING OROGENIC BELTS ACROSS THE NORTH ATLANTIC*

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ABSTRACT. Most of the rocks now exposed within the Grenville province and other relatively young Precambrian orogenic belts have recently been shown to be recycled parts of older structural provinces that were part of the floor on which younger geosynclinal deposition took place. Orogeny may thus involve the tectonic overprinting of older provinces, by which they acquire new petrologic structures and radiometric characteristics. The concept of overprinting makes it possible to work out the relationships among belts of different ages and makes it plain that most of the granitic rocks of the continental crust are of great antiquity and that they were already granitic before being recycled one or more times. In the Grenville province, for example, quartzofeldspathic crystalline basement has been reworked up to 4 times and accounts for perhaps 90 percent of the granitic rocks exposed. As these granitic rocks do not represent new crustal material generated during the latest orogenic cycle, they cannot be construed as evidence of the large-scale accretion of sialic material to the continental crust.

The hypothesis of continental accretion was initially formulated because of a supposedly parallel distribution of successively younger belts of deformation outward from a continental "nucleus", an arrangement typified by the Churchill, Grenville, Taconic, and Acadian belts around the Superior province in eastern North America. This parallelism is largely illusory. The Grenville front, for example, truncates no less than four older provinces in a thousand miles, transgressing structures in the Southern, Superior, Churchill, and Nain provinces at a high angle. The Grenville province thus naturally contains components of the former extensions of each of these older belts.

If the Canadian structural provinces are linked across the North Atlantic to their equivalent radiometric units in Europe, this type of transgression becomes much more evident. The eastward extension of the Grenville front truncates a further two or three boundaries of older provinces, and the Taconic and Acadian belts, parallel in North America, diverge at right angles as the Caledonian and Hercynian belts in Europe. The entire Grenville and Churchill provinces are traversed by the Caledonian belt, but their extensions reappear on its eastern side in Scandinavia. To illustrate these features the continents on either side of the North Atlantic have been diagrammatically restored to a pre-continental-drift position and the various structural-radiometric provinces that then appear are defined and named.

INTRODUCTION

Recent geological studies of several Paleozoic and Precambrian orogenic belts have shown that most of the granitic rocks exposed within them are reworked segments of older crystalline basement on which later events have been overprinted. Most of the granitic rocks in these complexes appear to have been already granitic before the orogeny began, so that the hypothesis that orogenesis generates a substantial new volume of granitic crustal material (one of the important bases for the concept of continental growth by accretion) seems largely erroneous. At least

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it can no longer be supported by alluding to the granitic rocks in deeply eroded terrains as the products of some process of granitization. The view is widely held that volcanic and sedimentary rocks deep within the geosynclinal pile become granitic or granodioritic by anatexis and granitization, in this manner becoming converted to sialic crust, and so contributing to the granitic terrain that is conventionally pink on geological maps depicting the continental shields. With this argument, the new granitic crustal material is inferred to have the structural (as well as the radiometric) age of the orogeny itself. We now see little or no evidence for this or for the view that the abundance of sial has significantly increased with time.

Instead, orogeny as exemplified by the deeply eroded provinces involves a process whereby parts of one or more preexisting structural provinces are overprinted with new structural, petrologic, and radiometric characteristics that then identify them with the new orgenic belt or province. Study of this tectonic overprinting makes it possible to trace the relationships in space and time among the various structural provinces and orogenic belts. When this is done around the North Atlantic it becomes evident that successively younger orogenic belts converge and diverge, and intersect (or rework) older ones in a complex manner, and that the geosynclinal piles appear to have been developed on the whole not ensimatically but on a basement of preexisting continental crust, which can be inferred to be of great antiquity.

This is not to deny ensimatic development of parts of some organic belts nor a significant contribution of "new rock" added from the mantle to the continental crust during each orogenic cycle, but neither of these processes contributes new crystalline *sial* in any quantity, in the sense of the generation of rocks of broadly granitic composition. Any accretionary growth of the continental crust, therefore, must not be construed as a net addition of granitic material. Indeed, the introduction of large volumes of predominantly basic magma onto and into the continental crust throughout geological time should have resulted in its average composition becoming progressively more basic and thus more like that of the mantle itself. This implies in turn that the compositional differences between the continental crust and the top of the mantle were greatest in the Archaean.

The Grenville province has long been interpreted as the granitic "root' 'of an orogenic belt and generally also as a net addition to the continental crust about 1000 m.y. ago (for example, Jacobs, Russell, and Wilson, 1959; Engel, 1963). Recently it has become clear, however, that the Grenville province has been overprinted on at least 4 older provinces (Stockwell, 1964; Wynne-Edwards, 1969; Douglas, 1969). Most of the rocks now exposed in the Grenville province belong to a reworked basement complex, the belt having been eroded to a depth at which the superincumbent geosynclinal pile (which can be inferred to have been present from the structure and grade of metamorphism) has been all but worn away. The contorted unconformity between the supracrustal rocks and the pre-Grenville Group basement is exposed in many places at the level of the present erosion surface within about 300 m above sea level, so that it has been restored (statistically at least) not far from its pre-geosynclinal position when marine sedimentary deposition began close to sea level (Wynne-Edwards, 1969). Although they have K/Ar ages uniformly close to 950 m.y., the vast tracts of quartzofeldspathic gneisses in the Grenville province, at least in the 34,000 km^2 studied, appear to be largely reworked Archaean rocks, and the proportion of new granitic rocks, in the sense of material acquiring coherence as a crystalline entity for the first time during the Grenville orogeny, probably accounts for less than 5 percent of the rocks exposed. These new rocks represent only a minor increment to the crystalline crust at the time of the Grenville orogeny about 950 m.y. ago. Although some of the younger, less deeply eroded orogenic belts of the Phanerozoic contain large massifs of granitic rocks within the supracrustal sequence, it has yet to be learned what proportion of these was anatectically generated from the supracrustal sequence and what proportion was remobilized from a basement complex. It seems improbable that all these massifs represent new sialic material, if the deeper sections provided by the Grenville province and similar Precambrian belts are any guide.

The distribution of the isotopes of Rb and Sr and in particular the predominance of values of initial ratios of Sr^{87}/Sr^{86} between 0.700 and 0.710 are currently taken as a demonstration of the steady accretion of sial with geological time (Hurley and others, 1962; Hurley and Rand, 1968). Granitic rocks with low initial ratios are thought to be new rocks without a crustal antecedent and to have been derived directly from a regime of low Rb content in the mantle.

Sr/Rb isotopic studies in the Grenville province by Krogh and others suggest that rocks with complex ensialic histories are indeed present but also that a large proportion of granitic rocks have low initial ratios of the order indicated above (Krogh, 1965; Krogh and Davis, 1969). We think that the geological evidence for reworking on a large scale is now so compelling that the "new rock" interpretation placed on some of these bodies and the underlying assumptions of strontium isotopic homogeneity in the mantle and of the processes of isotopic mixing and fractionation in the crust require reexamination. From various investigations, it appears that igneous fractionation, anatexis, metamorphism, carbonate precipitation, and organic fixation are all capable of maintaining a distribution of Sr^{87}/Sr^{86} at or close to 0.705, suggesting that this ratio may be capable of restoration from several sources of common strontium outside the mantle, such as sea water and the dominant gray gneisses of the sialic crust. Armstrong (1968) has already noted the conflict between the Sr-isotope model of continuous evolution of continents and the Pb-isotope model of constant continental volume and has proposed a mechanism of isotopic equilibration of crust and mantle by convection to account for the observed strontium isotope distribution within a roughly constant continental volume. We here provide additional evidence that the continental volume has remained roughly constant, and that the history of orogenesis has been largely one of cannibalism.

The hypothesis of continental growth by accretion is also supported by the premise that orogenic belts tend to be broadly parallel, concentric, and younger outward from a continental nucleus. The importance attached to this "concretionary" pattern, however, has declined since the recent refinement of the hypothesis of continental drift. The concept of parallelism arose from the structural framework of North America. Paleozoic orogenic belts (the Appalachian and Innuitian) bound the Precambrian Shield to the southeast and north, and Mesozoic and Tertiary orogens of the Cordillera and Arctic Islands frame it to the west and northwest. The pattern is apparently still further reinforced by the internal structure of the Shield itself, its Archaean core (the Superior province) being enclosed in a Lower Proterozoic Churchill province and a still younger Grenville province (Stockwell, 1961, 1963a and b, 1964). The part of the North American pattern that suggests continental growth most strongly is to be found on either side of the St. Lawrence River. Here the Grenville province (950 m.y. and older) is followed outward by the parallel Taconic (430 m.y. and older) and Acadian (300 m.y. and older) belts of the Appalachian Mountains.

Reconstruction of these belts across the Atlantic shows that this parallelism has only local significance, and that younger orogenic belts in fact diverge, converge, and intersect with older ones as a general rule. Each new orogeny results in the reworking of older material as a basement complex, parts of such complexes being exposed at present in most of the pre-Mesozoic orogenic belts. The addition of large-scale granitized units to the crust by orogenesis and the parallel distribution of orogenic belts of different ages thus appear to be special rather than general cases.

The new global tectonics of ocean-floor spreading and continental drift make this apparent parallelism less necessary to the accretion hypothesis, because the continental margin may be altered by rifting, each rift boundary then becoming a zone of geosynclinal accumulation and later of accretion. The available evidence from the deeply eroded belts, however, all suggests that any such geosynclinal and orogenic development took place largely on preexisting continental crust.

The general pattern of tectonic overprinting that emerges from this study suggests that the continental crust is of great antiquity. Rather than having been produced in successively younger increments, it must have been reworked, sometimes repeatedly, in different segments at different times. The amount of sialic crust may not have changed appreciably since the end of the Archaean, reworked representatives of this primitive sialic crust being now widely exposed as "fundamental gneiss" in orogenic belts of all ages. These fundamental gneisses carry the radiometric age imprinted on them by their latest reworking, although they may retain some record of their earlier tectonic history.

THE SOURCE OF THE CONTINENTAL CRUST

Rocks of granitic composition appear in the geological record as arkoses, rhyolites, pyroclastics, granites, gneisses, and granulites. They can be produced by a variety of processes, including anatexis and several forms of igneous fractionation. Once formed, however, they can be destroyed only with difficulty, few geological mechanisms being capable of radically altering their compositions. If recrystallized, the rocks reappear as gneisses or granulites, if remelted, as granites, and if reworked again, as still more gneisses or granulites distinguished only by a younger radiometric age. Only prolonged erosion and transportation seem capable of segregating the components of granites in any major way—the silica in sandstone, the alumina in clay, the sodium in the sea, and so on (Wynne-Edwards and Hasan, in manuscript). Its very indestructability therefore should suggest that the bulk of the continental sialic crust might be very old indeed.

Recent reinterpretations of the Grenville province have revealed a pattern of repeated tectonic overprinting (Stockwell, 1964; Wynne-Edwards and others, 1966; Wynne-Edwards, 1969a). The same approach has now been applied over the whole Canadian Shield, in the preparation of the new geological map of Canada (Douglas, 1969a and b). It confirms that about 90 percent of the rocks exposed in all the structural provinces of the Canadian Precambrian date from the Archaean but were reworked at different times. Most of the Canadian continental sialic crust may thus be assumed to have been in existence for most of geological time.

The high-grade metamorphic terrains of the Proterozoic and Paleozoic belts of the Earth represent relatively deep orogenic sections where the processes of anatexis and granitic remobilization were active, yet relatively little new quartzofeldspathic material was in fact produced within them. The Archaean structural provinces such as the Superior of Canada and part of the Central Gneiss region of Greenland, on the other hand, are overwhelmingly composed of granitic gneisses but for the most part exhibit metamorphism only to the greenschist or middle amphibolite facies, regimes in which wholesale anatexis and remobilization are uncommon. It is therefore unlikely that the reworking of volcanic or sedimentary rocks can have been responsible for the generation of the primitive granitic crust. Some primary form of fractionation associated with the early development and crystallization of the outer Earth shells seems a more probable mechanism for its first development.

THE PATTERN OF OROGENESIS IN NORTH AMERICA AND EUROPE

The broad structural divisions of the Canadian Shield were first recognized by Gill (1949) and Wilson (1949). These tectonic provinces have characteristic lithologic, metamorphic, and structural features that distinguish them as coherent crustal segments, but they acquired more precise definition as plateaux of relatively uniform K/Ar ages, after a systematic program by the Geological Survey of Canada (Stockwell, 1961,

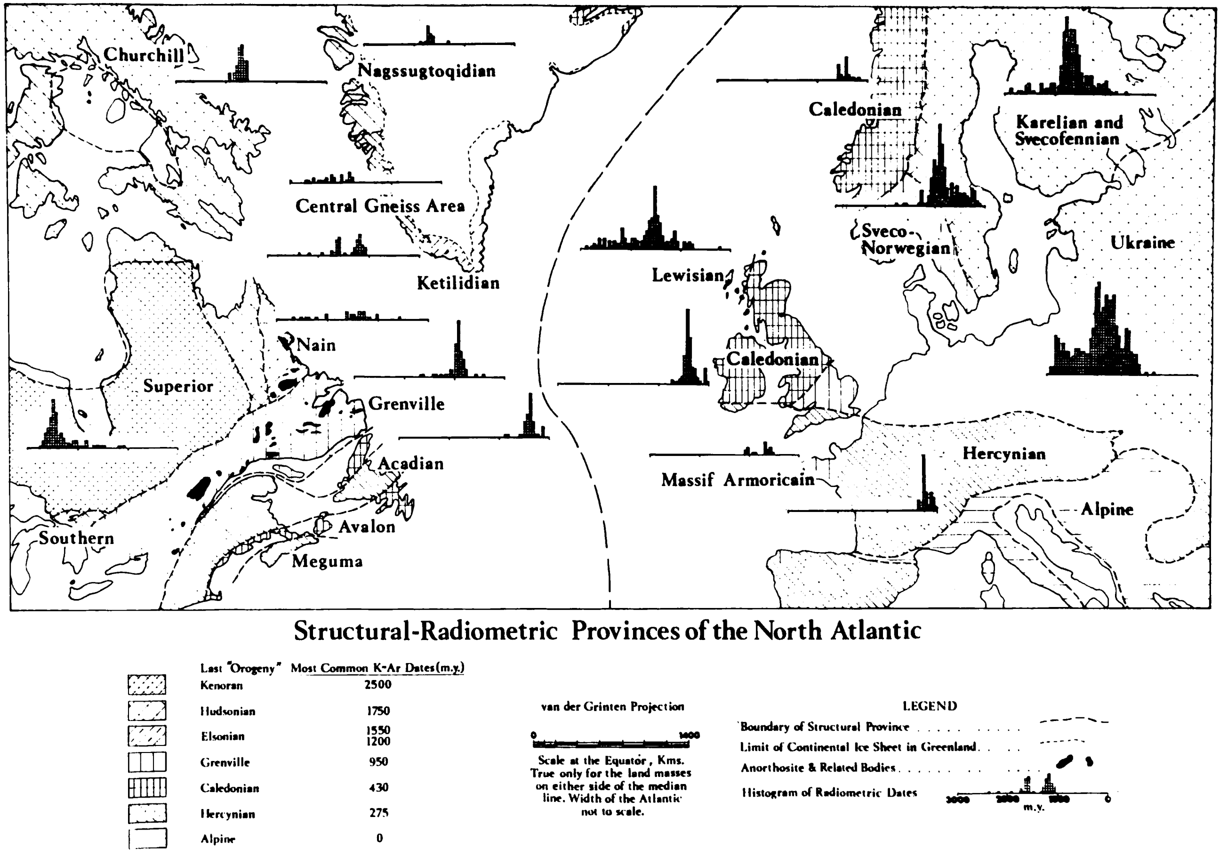

Churchill
Nagssugtoqidian
Central Gneiss Area
Ketilidian
Nain
Superior
Grenville
Acadian
Avalon
Meguma
Southern
Lewisian
Caledonian
Sveco-Norwegian
Karelian and Svecofennian
Ukraine
Caledonian
Massif Armoricain
Hercynian
Alpine
Structural-Radiometric Provinces of the North Atlantic
Last "Orogeny" Most Common K-Ar Dates (m.y.)
Kenoran 2500
Hudsonian 1750
Elsonian 1550 1200
Grenville 950
Caledonian 430
Hercynian 275
Alpine 0
van der Grinten Projection
0 1400
Scale at the Equator, Kms. True only for the land masses on either side of the median line. Width of the Atlantic not to scale.
LEGEND
Boundary of Structural Province
Limit of Continental Ice Sheet in Greenland
Anorthosite & Related Bodies
Histogram of Radiometric Dates
m.y.
0

Fig. 1

1963a and b, 1964). These consistent radiometric dates reflect a point in the cooling history of each orogen at which argon could be retained in crystal structures and may postdate the climax of orogenesis and metamorphism by some appreciable period. In the catazonal parts of the Grenville province, for example, Sr/Rb age determinations are roughly 200 m.y. older than adjacent K/Ar dates. In less metamorphosed belts the gap between determinations by different methods is very much smaller, perhaps reflecting a shorter interval between metamorphism and cooling and exhumation.

Consistent radiometric dates by a single method imply that the rocks from which they came had a common metamorphic or cooling history. They thus provide the best means of identifying coherent Precambrian structural provinces. These provinces are like the younger orogenic belts, in that they are lithologically heterogeneous and are composed of rocks of all ages unified by their common tectonic history into a tectonic entity. The same system of classification by radiometric date can therefore be applied to the Phanerozoic orogenic belts, requiring only that all the unmetamorphosed cover rocks be removed from consideration. If this is done to both sides of the North Atlantic, the results are those of figure 1.

One-third of the age determinations employed in figure 1 are by methods other than K/Ar (table 1). They were included to make the radiometric histogram as complete as possible from the published data and to avoid any bias in their preparation. If further whole-rock Sr/Rb dates were available and were incorporated into a histogram, the distribution curve would become more negatively skewed. If more dates from vein minerals were incorporated, positive skewness could result, but the basic shape of the distribution would still be determined by the preponderance of K/Ar dates related to the main metamorphic events or to their connected cooling stages. The pattern of the histograms can be reproduced from randomly selected segments of the published data, and the grouping of the dates into divisions of 50 m.y. ensures that minor discrepancies will not affect the major results.

Correlations between radiometrically distinctive structural provinces on opposite sides of the Atlantic are at once apparent from figure 1. Age determinations are plotted as histograms employing a common time base with divisions at 0, 1000, 2000, and 3000 m.y. from right to left. Some of the structural subdivisions, such as the British Caledonian, exhibit a single sharp peak, others have a wide variety of dates and several maxima, like the Nain province in Canada or the Scandinavian Karelian and Svecofennian. Some distributions are positively skewed, others negatively. Clearly, therefore, correlation can be made on the range and type of distribution of radiometric ages as well as on the mode. Examples of different types of distributions are shown in figure 2. A wide range of ages reflects incomplete reworking of older crystalline complexes by later events, with the retention of a "metamorphic memory", or in the terms of Armstrong (1966), a "penetration of the metamorphic

TABLE 1

Source of K-Ar and other dates of the structural provinces of Northeast North America and Europe (see fig. 1)

Locality	No. of K-Ar dates	No. of other dates	Commonest date (in m.y.)	Main sources
Canada				
Superior Province	102	—	2500	Stockwell (1961, 1963a, b, 1964)
Churchill Province	55	—	1700	
Nain Province	29	—	1350	
Grenville Province	68	—	950	
Taconic and Acadian Province	48	—	400	
Greenland				
Central gneiss area	17	8	2500-1800	Berthelsen and Noe-Nygaard (1965); Bridgwater (1965); Jørgensen (1968); Larsen and Møller (1968a, b)
Nagssugtoqidian Province	17	—	1750	
Ketilidian Province	33	15	1550-1200	
Fennoscandia				
Karelian and Svecofennian Province	97	164	1750	Parwel and Wickman (1954); Quensel (1957); Gerling and Polkanov (1958); Polkanov and Gerling (1961); Kouvo (1958); Neumann (1960); Magnusson (1960); Kouvo and Kulp (1961); Kulp and Neumann (1961); Wetherill and others (1962); Wickman and others (1963); Welin (1963, 1966); Welin and Blomqvist (1964, 1966); Welin (1966); Kratz, Gerling and Lobach-Zhuchenko (1968)
Sveconorwegian Province	96	104	950	
Caledonian Province	20	3	450	
Russian Platform				
Ukraine	417	15	1950	Polkanov and Gerling (1958); Vinogradov and Tugarinov (1961); Semenenko and others (1968)
The British Isles				
Lewisian Province	97	76	1550	Sabine and Watson (1965, 1966, 1967); Harper 1967; Moorbath and others (1967); Flinn and others (1968); Matthews and Cheeney (1968)
Caledonian Province	376	175	450	
Hercynian Province	87	66	300	
France				
Massif Armoricain	12	6	1000, 700	Leutwein (1968)

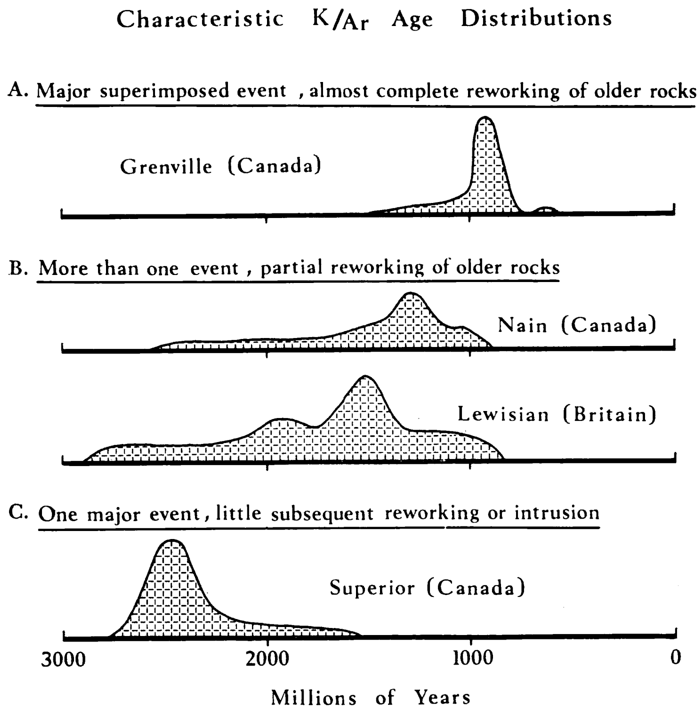


Fig. 2

veil". Heterogeneous provinces of this type, with a similar range of dates, are the Nain and Lewisian (fig. 2B). Negative skewness (mode younger than mean), such as that shown by the Grenville province (fig. 2A) and the Churchill province, implies wholesale reworking of older rocks, with traces of metamorphic memory. Positive skewness (mode older than mean) or normal distribution imply little or no crystalline history before the main event and only minor disturbances after. Examples are the Superior province (fig. 2C) in which the Kenoran orogeny (2500 m.y.) appears to have been the earliest and only major event and the Paleozoic orogens, such as the Scottish Caledonian, the Maritime Acadian, and the European Hercynian, in which older crystalline basement complexes are not yet widely exposed and orogeny at the present level of erosion has affected only the supracrustal section.

Viewed on the same scale as the Precambrian events, as in the age histograms of figure 1, the Paleozoic orogenies for the most part appear simple rather than compound, the polyphase deformation and metamorphism within them being part of a single cycle. Although there may be significant differences in the timing and scale of these phases from place to place as witnessed by the stratigraphic and structural record, general correlations can be made with confidence from one orogenic belt to another on opposite sides of the Atlantic Ocean on the basis of the range and distribution of the radiometric age determinations.

The radiometrically-defined structural provinces are best classified by the last orogenic event that affected them, which usually coincides with a pronounced radiometric age peak in the relevant histogram. The date of this peak is related to the date at which the whole of the province became cratonic and ceased to be tectonically active. The oldest crustal segment by this classification is the Superior province in Canada, last affected by the Kenoran orogeny at about 2500 m.y. The small number of dates published for the Central Gneiss area of southwestern Greenland have a similar distribution (as do those for the Western Nain province in Labrador). These Central Gneisses are thought to comprise a pre-Ketilidian basement (Berthelsen and Noe-Nygaard, 1965).

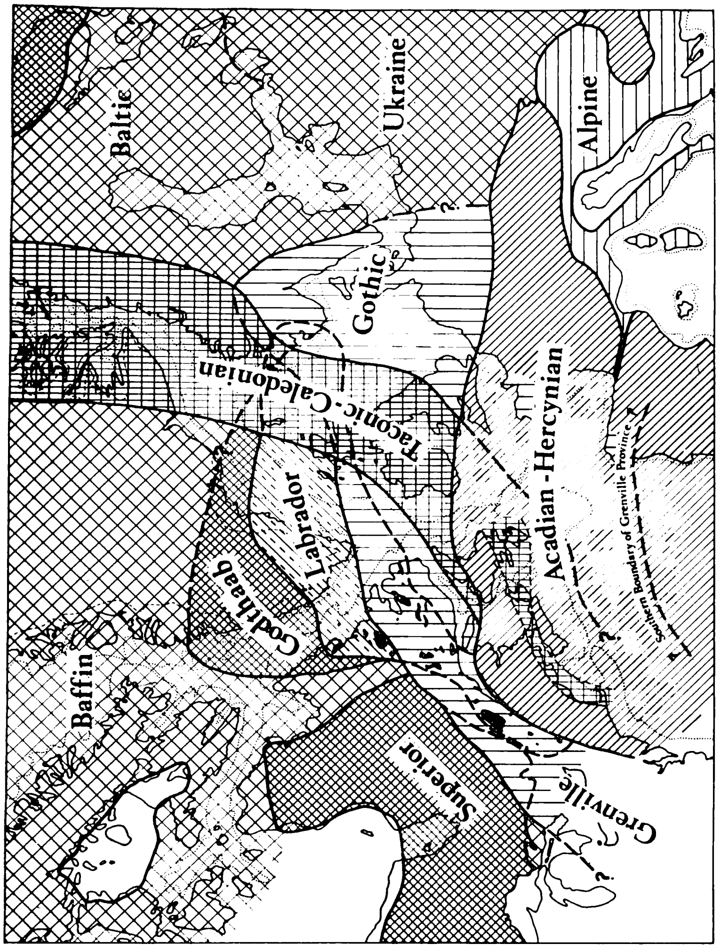
Similar and even older Archaean dates are preserved in several of the other provinces, such as the Lewisian of Britain and the Karelian and Svecofennian of the Baltic Shield, but in these there has been later (and in some cases repeated) reworking of these rocks. The Proterozoic orogens fall into three main classes in which the last major events took place at about 1750, 1400, and 950 m.y., corresponding to the Hudsonian, Elsonian, and Grenville orogenies in Canada (Stockwell, 1964). The pre-Hudsonian provinces in eastern Canada are the Southern and Churchill, the latter embracing Baffin Island and the Labrador trough, and the Churchill province has a simple peak at 1750 m.y. but is negatively skewed, suggesting the presence of reworked Archaean rocks. The Nagssugtoquides (Ramberg, 1956) of western Greenland north of latitude 66 give a similar age distribution—an obvious correlation. Although the range of recorded ages is much greater in the Baltic Shield, the Karelian and Svecofennian provinces of Scandinavia and the Ukraine province of Russia have their major peak at 1750 m.y. and have been placed in the same category for this reason. In the Baltic Shield, orogenies of this date have been identified as the Svecofennide or the Karelide (Magnusson, 1960; Polkanov and Gerling, 1961).

All these provinces have a vestigial record of older events and evidence of younger ones as well. The Ukraine province in particular has peaks at 2800, 2450, 1750, and 1400 m.y., which have been respectively identified as the Katarchaean, Saamides, Svecofennides, and Gothides (or Jotnian) (see Magnusson, 1960; Polkanov and Gerling, 1961; Simonen, 1960). The dates suggest that there was a pre-Kenoran crystalline period in this region, as yet undetected in Canada, and later events corresponding to the Kenoran, Hudsonian, and Elsonian. Additional events have been proposed at 1640 m.y. (the date for the Rapakivi granites) and at 2000 m.y., the latter date being that of the Belomorian complex (Gerling and Polkanov, 1958). The continuous intervening spectrum of radiometric dates in these provinces may reflect their continuous evolution punctuated by the identified major episodes, or more probably, the results of the redistribution of the parent and daughter elements in partially reworked rocks. No doubt these broad Baltic provinces could be further subdivided into more homogeneous radiometric domains, but the histograms demonstrate that significant events can be detected in spite of problems of partial argon loss, orogenic overprinting, and so on.

The next youngest Precambrian provinces ceased their important development in the range 1200 to 1550 m.y., corresponding to the period of the Elsonian orogeny of Stockwell (1961, 1963a and b, 1964). This event appears to have been related to the emplacement of the large massifs of anorthosite in eastern Canada and the Gardar intrusions in Greenland (Berthelsen and Noe-Nygaard, 1965, p. 137) but did not involve the complete reworking of older rocks. The Nain province in Canada and the Ketilidian province of Greenland thus exhibit a range of K/Ar dates from Archaean (2500 m.y. and older) to about 1100 m.y. The similar distribution of dates suggests that the two provinces should be correlated, and that at least part of the exposed gneisses within them originated in the Archaean.

The Lewisian of the Scottish Hebrides and Highlands has a similar range of dates. There is an alternation of small domains of Scourian (2500 m.y.) and Laxfordian (1600 m.y.) dates, which suggests a correlation with the Kenoran and Elsonian events in the Nain province of Canada. An Inverian event at 2200 m.y. has also been identified, and a few 950 m.y.-old dates have been recorded from the southern part of the exposure. Events equivalent to the Grenville orogeny in Canada may thus also have been felt in the southern part of the Lewisian gneiss complex.

The Grenville province of Canada has a sharply defined radiometric peak at 950 m.y., with only a small degree of negative skewness (or "metamorphic memory"), which we ascribe to the complete reworking of older rocks during catazonal metamorphism. The negative skewness will, however, be much increased as more Sr/Rb dates are published (for example, Krogh, 1965). Deformation in supracrustal rocks in the basement of the Greenland Caledonian fold belt has been ascribed by Haller (1961) to a Carolidian orogeny which may have the same age as the Grenville orogeny. There may be further traces of this event, as noted above, in the southern part of the Lewisian province of Britain. Charnian strata exposed in Charnwood Forest in England may have been deposited about this time (Anderson, 1965, p. 85 and 99). Recent dates reported by Leutwein (1968) from the massif Armoricain in Brittany are concentrated at 1000 and at 700 m.y. and may reflect the Grenville orogeny in the basement rocks of the Hercynian. The main occurrence of these dates in Europe, however, is within the Sveconorwegian province of southern Norway and Sweden (Kratz, Gerling, and Lobach-Zhuchenko, 1968). Here, as in the Grenville province, there is a pronounced radiometric age peak at 950 m.y., but one here accompanied by positive skewness. The younger dates probably reflect some reworking and argon loss produced by the Caledonian orogeny to the north and west. Signs of an older event at about 1200 m.y. may be related to the



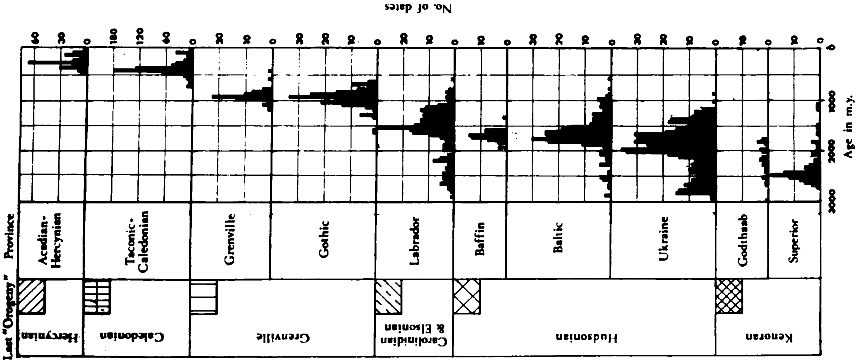
Structural-Radiometric Provinces of the North Atlantic

LEGEND

Boundary of Structural Provinces known, assumed
Limit of Continental Ice Sheet in Greenland
Limit of Continental Shelf at 100 Fathoms
Anorthosite & Related Bodies

Scale at Equator, Kms.
van der Grinten Projection

Fig. 3



emplacement of the Egersund and other anorthosite complexes, an event comparable to the Canadian Elsonian at the same time.

Lower Paleozoic orogenic provinces around the North Atlantic are the Taconic of the Appalachians and the Caledonian belts of Britain, Norway, and East Greenland. Radiometric dates for these are most abundant in Britain, where they form a simple peak at 450 m.y. A range of distinguishable episodes between 420 and 475 m.y. has in fact been postulated (Giletti, Moorbath, and Lambert, 1961; Miller and Brown, 1964). Dates for the Norwegian Caledonian and for the Taconic part of the Appalachian belt are similar, again concentrated at about 450 m.y. Determinations in the Appalachians are complicated, however, by the abundance of unmetamorphosed cover rocks and by the overlapping of the Acadian and Taconic structural elements. The Acadian forms a median fold belt in the Maritime provinces (Neale and others, 1961; Poole, 1967) of Upper Paleozoic age, at approximately 300 m.y., but radiometric data are few. In Europe, however, the Upper Paleozoic belt is distinctly separated from the Lower, the Hercynian orogeny trending eastward through France into Central Europe, and the Caledonian trending northward in Scandinavia. Hercynian radiometric dates in Europe are strongly concentrated at about 275 m.y.

RECONSTRUCTION ACROSS THE NORTH ATLANTIC

It is apparent from the foregoing survey that most of the structural provinces can be correlated across the North Atlantic. Reconstructions to a pre-continental drift configuration have previously been published by Miller (1965) and Dearnley (1966), both being broadly similar to figure 3, in which the continents have been fitted together along the 100 fathom line. The object of figure 3 is not to substaniate the theory of continental drift, for in fact correlations can be established across the Atlantic independent of any subsequent relative drift of the continents, but to emphasize the highly discordant, cross-cutting arrangement of orogenic belts of different ages.

The provinces identified in figure 3 that are made up of more than one continental crustal unit have been given new names so as to preserve the original sense of the names that have already applied to each segment. They are listed in table 2. In figure 3 histograms of radiometric dates for the new combined provinces have been plotted and arranged in the chronological order of their pronounced peaks. These peaks are at roughly 2500, 2000, 1750, 1450, 900, 450, and 300 m.y., corresponding to the Kenoran, Belomorian, Hudsonian, Elsonian, Grenville, Caledonian, and Hercynian "orogenies". Each of the new provinces, whether Phanerozoic or Precambrian, produces a coherent distribution of dates, with a pronounced radiometric peak, just like the original provinces of the Canadian Shield defined by Stockwell.

The pre-Kenoran (2500 m.y. or older) provinces are the Superior of Canada and the Godthaab of Greenland and Labrador, separated only by the Labrador trough of deformed Lower Proterozoic rocks belonging

TABLE 2

Structural-radiometric provinces across the North Atlantic

New Province*	Former subdivisions	Commonest radiometric date in m.y. (last major tectonic overprint)	Orogeny
Superior	Superior	2500	Kenoran
Godthaab	Western Nain (Canada) Central Gneiss (Greenland)	2500 2200	
Ukraine	Ukraine	2000 1750	(Belomorian?) Hudsonian
Baltic	Karelian Svecofennian	1750	(Karelian and Svecofennian)
Baffin	Churchill (Canada) Nagssugtoqidian (Greenland)	1750	
Labrador	Eastern Nain (Canada) Ketilidian (Greenland) Lewisian (Scotland)	1550-1200	Elsonian (Laxfordian) (Gardar)
Gothic	Gothide (Sweden, Norway)	950	Grenville
Grenville	Grenville (Canada)	950	(Jotnian, Gothide, Carolinide?)
Taconic-Caledonian	Taconic (Canada and U.S.A.) Caledonian (Britain, Norway, Greenland)	450	Caledonian (Taconic)
Acadian-Hercynian	Acadian (Canada and U.S.A.) Hercynian (Britain, France, Central Europe)	300	Hercynian (Acadian)

* New names have been chosen for the combined provinces of figure 3 so that the names of the original provinces will retain their first definition.

to the pre-Hudsonian Baffin province (the Churchill province in Canada). The pattern suggests that the Superior and Godthaab were once one and the same province, on which developed the superimposed younger supracrustal belt of the Labrador trough. The pre-Hudson (1750 m.y. or older) provinces are the Baffin, Baltic, and Ukraine. These form a very broad northern belt interrupted only by the Caledonian orogen of Greenland and Norway. The pattern suggests that the Caledonian was constructed on this pre-Hudsonian basement at a high angle to its structural trend.

The Labrador province is the sole pre-Elsonian (1200 m.y. or older) region defined as such, although relicts of this event are present in the Grenville province (Wynne-Edwards, 1969a) and perhaps also in parts of the Baltic and Ukraine provinces. The Labrador province includes the eastern Nain province of the Canadian seaboard, the Ketilidian province of southern Greenland, and the Lewisian gneiss complex of

Britain. Anorthosite masses occur in each of these regions. The former boundaries of the Labrador province have been extended to embrace the anorthosite massifs of the Grenville province and southern Norway, regions in which the anorthosites and other rocks have been reworked by the younger Grenville orogeny. The Labrador province and its reworked extensions can thus be defined by the distribution of anorthosite masses, by the prevalence of radiometric dates in the range 1200 to 1500 m.y., corresponding to the Elsonian, and by the characteristic scatter of age determination from about 2800 to 1100 m.y. These features are strong indications that the Elsonian event was mainly expressed by the emplacement of enormous masses of anorthosite and related rocks over a period of several hundred million years, and that the accompanying metamorphism and reworking of the dominantly Archaean country rocks was insufficient to reset the radiometric clocks completely. The reworked parts of the Labrador province may extend still further under the Caledonian belt northward and eastward into the Baltic Shield, and under the Appalachians and Central Plains southwestward and westward in the buried Precambrian of the United States—for masses of anorthosite have been described from both of these regions.

The configuration of the orogens of figure 3 shows plainly that the Grenville province of Canada and the Gothides of southern Scandinavia were once part of a single orogen that has been divided by the construction of the Caledonian belt upon it. The radiometric pattern in the two portions is the same, with a pronounced peak at 950 m.y.

The Grenville front is the northwestern boundary of the Grenville province. It is a major linear tectonic feature that separates high-grade metamorphic rocks of the Grenville province from low-grade metamorphic rocks to the northwest having older K/Ar radiometric ages. In different places along its length it appears as a metamorphic transition, a fault, or a mylonite zone (Wynne-Edwards, 1964, 1967). On a regional scale the Grenville front is an interface between older ages and the 950 m.y. old K/Ar dates related to the Grenville orogeny and can be traced by these means. It is a highly discordant boundary. Followed northeastward from Lake Huron it cuts across the Southern province (1750 m.y. and older), the Superior province (2500 m.y. and older), the Churchill province at the Labrador trough (1750 m.y. and older), and the Nain province (1200 m.y. and older) at a high angle to the structures of each. Where last seen at the Atlantic coast, it represents an interface between dates of 950 m.y. and those of 1200 m.y. and older. The Grenville front apparently misses southern Greenland, where the Gardar intrusions are undeformed, but may be represented in the southernmost parts of the Lewisian gneiss complex where a few dates of about 950 m.y. have been obtained. At this point it must pass under the Caledonian front (the Moine thrust). It reappears across the Caledonian belt in Sweden, where there is a further interface, this time between 950 m.y.-old dates and 1750 m.y.-old dates, between the Gothides and Svecofennides (fig. 3). This boundary has been drawn tentatively along a prominent tectonic feature in the Gothides of Sweden and can be taken to represent the re-emergence of the Grenville front from beneath the Caledonian belt.

The definition of orogenic fronts in such radiometric terms can usefully be extended to the boundaries of other provinces of different age. The Caledonian front can be defined as the northwesterly interface between dates of about 450 m.y. and older ones. In Canada this front is "Logan's line" in the St. Lawrence River valley, where the Appalachian fold belt abuts against the Grenville province. Where next seen to the northeast, the Caledonian front is represented by the Moine thrust in Scotland, here abutting on the Lewisian gneiss complex of the Labrador province (fig. 3). This is an older province than the Grenville. Plainly the Caledonian front has crossed the Grenville front in the interval between these two exposures. The Grenville front, as noted above, can be correlated with the Gothide front in Scandinavia, demonstrating that the whole Caledonian belt has crossed the Grenville front between the British Isles and Sweden.

The next youngest front is the Acadian in North America and the Hercynian in Europe, representing the northern limit of dates of about 300 m.y. The Acadian Front is parallel to and overlapping with the Taconic front in the northern United States, a divergence between the two perhaps becoming apparent only in Newfoundland. In the British Isles, however, this divergence becomes extreme, the Hercynian front striking eastward through the southwest of Ireland and England, the Caledonian Front striking north-northeast in Western Scotland and east Greenland. The northern front of the Hercynian belt in Europe is largely obscured by cover rocks and must be inferred. Its approximate position is shown in figure 3, following Holmes (1965, p. 1117).

The result of these recombinations across the North Atlantic is quite different from that anticipated from a study of North America alone. The parallel disposition of the Grenville, Taconic, and Acadian belts in eastern North America, so suggestive of continental growth, turns out to be a configuration of only local significance. The Grenville front intersects at least five older fronts along its length, and the Caledonian belt steps right across the Grenville province and its front, first onto the Labrador province, possibly next onto the Godthaab, and finally onto the Baltic province of Scandinavia. The Taconic and Acadian belts diverge ever more sharply to become the Caledonian and Hercynian belts of Europe. The pattern of the reworking of older provinces as the basement complexes of younger ones emerges as a general rule.

Plainly, most of the orogenic belts on either side of the North Atlantic were built upon old continental crustal material, freely overlapping or intersecting older structural trends, and did not in any sense represent net accretions around a primitive nucleus. Old crustal material has thus been repeatedly reworked. The implication, as seen in figure 3, is that only minor parts of the primitive crust escaped this reworking in post-Archaean time.

The modern development of the hypothesis of ocean-floor spreading (for example, Hess, 1962) strongly suggests that orogenesis and continental drift are directly related, the deformation of the Cordillera along the Pacific margin of North America, for example, being one expression of the opening of the Atlantic, and the pattern on the Atlantic ocean floor another. The development need not, however, necessarily have been related to continental margins, as seen by narrow younger orogenic belts that subdivide larger older ones (for example the Superior and Godthaab divided by the Labrador trough; the Grenville and Gothic divided by the Caledonian), but when properly understood and classified, the nature and distribution of orogenic belts may provide a complete record of migration of continental crustal segments, in the manner suggested by Dearnley (1966) and Zwart (1967, 1969).

CONCLUSIONS

The conclusions from this reassessment of the pattern of orogenic belts around the North Atlantic are:

1. That the range and distribution of radiometric dates provide a reliable means of correlation of orogenic belts and of gauging the extent to which their basement complexes are exposed, in spite of minor local and regional variations in the number of age determinations, the method used, and the amount of structural reworking;

2. That almost all the sialic continental crust is of great antiquity, having originated in the Archaean. Major portions of it have been tectonically overprinted at different times, often repeatedly, in the basement complexes of later orogenic belts. These basement complexes are now widely exposed in the Precambrian orogens. The younger structural provinces around the North Atlantic have for the most part been constructed on preexisting older structural provinces and on continental rather than on oceanic crust. The pattern of reworking and tectonic overprinting is detectable and should furnish a nearly continuous record of continental movement in time and space.

3. That a parallel distribution of successively younger orogenic belts outward from a continental nucleus is abnormal and not general. The view that orogenesis produces continental growth rests largely on the arrangement in this fashion of the Grenville province and the Appalachians in eastern North America, but this distribution becomes highly discordant when followed eastward.

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