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Geologic Evolution of North America

Geologic features suggest that the continent has grown and differentiated through geologic time.

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Among the current and popular hypotheses of continental origins and evolution, two predominate. One postulates a thin crust of continental (granitic) rock formed very early in the earth's history, during relatively rapid differentiation of the earth into core, mantle, and crust (*1*), and subsequent breakup of this primordial granitic crust into continents, migration of the continents, buckling, cycles of erosion, sedimentation, and volcanism.

According to the other hypothesis, the primordial differentiation was less complete—a differentiation of the earth into protocore, protomantle, and oceanic (basaltic) crust. The continents have been derived secondarily, throughout geologic time, by continuing terrestrial differentiation. The essential constituents of the continents, the oceans, and the atmosphere were supplied during secular growth of an iron-rich core, and through partial melting and degassing of the mantle. Volatiles and alkali-aluminum silicates repeatedly moved upward from the mantle in both magma and hydrothermal fluids (*2*). According to this hypothesis the sources of energy have been gravitational, and heat derived from radioactive disintegrations, particularly of short-lived nuclei such as potassium-40 (*3*). There is ample evidence of complementary surficial differentiation, and other such processes may be readily inferred in the absence of direct evidence. They include repeated cycles of weathering and sedimentation, deep burial of sediments, their metamorphism and partial meltings, and permeation of the crust by the resulting granitic melts, especially along great linear mountain belts. The major crustal cycles, it is argued, tend to reoccur at unstable interfaces of any pre-existing continents and oceanic crust. Successive cycles are believed to have resulted in successive sheaths of granite and granitized sediments, welded to the pre-existing, accreting, continental plate (*4*).

In essence, either hypothesis, and each of the innumerable variants of the two, includes the supposition that the relatively thick, infinitely complicated patches of granitic crust result from an efficient differentiation, and from localized, surfical concentration in the continents of alkali-aluminum silicates, the so-called sial. The hypotheses differ mainly with regard to the causes, time or times, processes, and rates of continental differentiation. In this article I discuss briefly some of the geological features, especially of North America, which have both fostered the concept of continental accretion and perplexed all but its most zealous adherents.

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Major Crustal Features

The base of the crust is now defined by the seemingly abrupt Mohorovicic discontinuity in the velocity of elastic waves in the earth (*5*). Above this discontinuity the velocities of V_L (longitudinal) and V_S (shear) waves are less than 7 and 3.5 km/sec, respectively. At the discontinuity in the earth's mantle, V_L and V_S rise abruptly to about 8 and 4.5 km/sec, respectively. The abrupt increase in velocity at the discontinuity seems to reflect the occurrence of rocks that are progressively more dense, more degased, and richer in ferromagnesium silicates. Typical of such "mafic" rocks are the peridotite and eclogite presumed to form the upper mantle. The compositions and interrelations of these rocks in the crust and upper mantle are shown in Table 1 and Fig. 1.

Typically, oceanic crust lies under more than 4000 meters of water and is only 5 to 7 kilometers thick. Dredge hauls, seismic data, and studies of oceanic islands suggest that the predominant rock is basalt, and possibly hydrated peridotite (serpentinite). Over the basalt lies a surprisingly thin blanket of muds and calcareous oozes (1 kilometer thick, or less), in places interfingering with submarine lava and debris flows (*6*).

Near and under most island arcs and their associated trenches, in water from 1500 to 3000 meters deep, the crust thickens to intermediate values of 12 to 25 kilometers (*7*). Most island arcs are dominated by basalt, but peridotite (from the mantle ?) and igneous rocks intermediate between basalt and granite also occur. Most of the older, deeply eroded island arcs have granitic cores, and their primitive sediments include fragments of granite, potassium-rich feldspars, and quartz (*8*).

All of the exposed continental crust and most of the crust that lies under less than 2000 meters of water is from 20 to 60 kilometers thick, averaging about 35 kilometers. In general, the thickness of continental crusts reflects topography; that is, many mountain

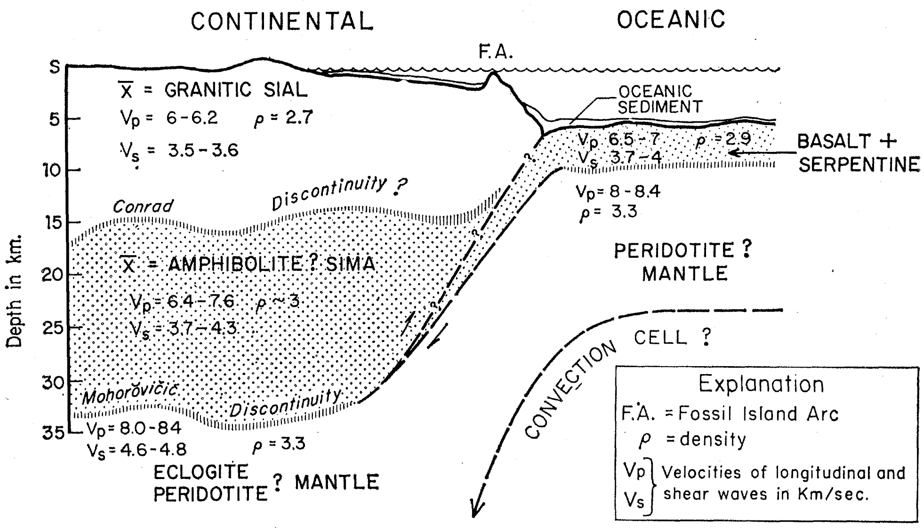

Fig. 1. Generalized vertical section through the earth's crust, showing the inferred relations of the Americas or Asia to the Pacific Ocean.

ranges appear to have roots of crustal rock projecting downward into the mantle, whereas most great basins very crudely define areas of thinner crust (Fig. 1). Apparently the boundary between crust and mantle is not only a seismic discontinuity but also a level of compensation. Columns of crustal rock (or rock plus water) of equal cross-sectional area are of roughly equal mass. The crust seems to float in approximate hydrostatic (isostatic) equilibrium on the mantle (*9*).

The predominant rock of continental crusts is widely referred to as granitic. In most areas where erosion has stripped away the surficial blanket of flat-lying shelf sediments, 30 to 90 percent of the exposed rock is granitic (Table 2). The frequent use of *granitic* as a synonym for *continental* crust probably is valid as a first approximation for the crust to depths of about 12 to 15 kilometers (*5*). But this generalization blurs the fact that parts of the crust as large as 2×10^5 cubic kilometers may consist entirely of rock of a very different type, such as quartzite, basalt, carbonate, or anorthosite. In addition, the finer-scale structural features of the crust are extremely complicated (*10, 11*).

Below 12 to 15 kilometers in the continents, petrogenic theory and geophysical observation suggest, by analogy, rocks of intermediate to basaltic composition occur. The base of the continental crust is presumed to be metamorphosed basalt, and the top of the mantle, eclogite or peridotite (Table 1 and Figure 1).

Antiquity of Continents and Oceans

We find, as noted above, two quite dissimilar kinds of crust—a thin, relatively dense basaltic ocean crust and a much thicker, lighter, granitic crust. The island arcs seem to be a significant, transitional evolutionary feature of intermediate thickness and composition, commonly but not invariably formed at the continental-oceanic interface.

Table 1. Composition and density of common crustal rocks and chondritic meteorite.

Rock type*	Composition (weight percent)											Density
	SiO_2	TiO_2	Al_2O_3	Fe_2O_3	FeO	MnO	MgO	CaO	Na_2O	K_2O	H_2O	
Granite	70.5	0.4	14.1	0.9	2.4	0.06	0.6	1.6	3.6	5.4	0.5	2.7
Quartz diorite	63.2	.6	17.7	1.8	3.2	.1	1.9	4.8	4.2	1.9	.6	2.8
Basalt	48.6	2.8	13.2	2.4	9.2	.2	9.8	10.3	2.4	0.6	.5	2.9
Eclogite	49.3	1.7	14.1	1.5	11.3	1.8	6.1	11.0	2.1	.3	.2	3.3
Peridotite	43.6	0.8	4.0	2.5	9.8	0.2	34.1	3.5	0.6	.2	.7	3.3
Chondritic meteorite†	38.0	.1	2.5	?	12.5	.3	23.8	2.0	1.0	.1	.3	3.6

* Mineralogical composition as follows. Granite: quartz, potassium feldspar, plagioclase, and potassium micas. Quartz diorite: plagioclase, quartz, hornblende, and potassium micas. Basalt: plagioclase, pyroxene, olivine, and iron oxides. Eclogite: sodium pyroxene and garnet. Peridotite: olivine, pyroxene, and iron oxides. Chondritic meteorite: olivine, pyroxene, iron oxides, iron sulfides, and metallic iron. † Also includes Fe, 11.8; FeS, 5.7; and Ni, 1.34.

The oldest rock complexes of North America and other continents (> 2.5 $\times 10^9$ years) have their closest analogs in the island arcs. This is, of course, one of the main reasons for postulating continental accretion and differentiation from crust of oceanic type and mantle. But before we pursue this matter, brief additional reference should be made to the oceans.

Although the oldest continental fragments are at least 2.5 to 3 billion years old, almost nothing is known of the history of oceanic crust prior to the Cretaceous period (100 million years ago). Actually, 100 million years is the age not of the oceanic crust but of sediments dredged from seamounts rising from the ocean floor. The oldest known basalt from existing oceanic crust was emplaced less than 50 million years ago. Our enormous ignorance of the early history of the oceanic crusts reflects the cost and the logistical problems involved in oceanographic investigations—major impediments to all studies of crustal evolution.

Possibly, there may be little more of early crustal history to read directly from the rocks of the oceans. Many students of mountain building and most contemporary geologists who endorse the theory of continental drift postulate the continuing existence of large convection cells in the mantle to make the mountains and move the continents (*12*). They argue that the measured rates of oceanic sedimentation (1 to 2 cm/1000 years) and the extremely thin skin of sediments in the oceans indicate that the oceanic environment cannot have been stable for more than the last 150 to 200 million years. One suggestion is that the earlier oceanic crusts, with their accumulated record of sedimentary and organic evolution, have been swept laterally against, and reconstituted into, continental margins by convection cells (*13*).

There is, however, considerable evidence that large bodies of sea water have existed for over 3.2 billion years; that they have supported protozoan life for over 2.6 billion years (*14*); and that hypersaline seas evolved in restricted basins at least 1.4 billion years ago (*11, 15*). But this evidence has been extracted by the hammer-carrying geologist, from exposures of the marine rocks deposited, and now exposed, on the continents. Until more sophisticated sampling of the ocean crust has been accomplished—including cores to the Mohorovicic discontinuity—the paleoceanographer must turn to his landlubber colleagues and the more accessible rocks of the continents for source material in writing the history of the sea.

The continents, on the other hand, present a sea of data in which we are constantly in danger of drowning.

The concept of an initially molten earth led field geologists of a generation ago to seek exposures of the primordial chilled crust. They found the continents to consist instead of a complicated, yet recognizable, succession of volcanic-sedimentary and mountain-forming events that culminate in great granite-forming episodes. In the deeply eroded but now stable continental platforms the succession of metamorphosed sediments and volcanics, variously obliterated by younger granites, appeared to reach backward in time almost indefinitely. Because of the overlap of events, the ultimate beginnings of continents seemed to be largely or wholly obliterated.

Hutton, a pioneer British geologist, noted: "In the economy of the World, I can find no traces of a beginning, no prospect of an end."

His conclusion has frequently been echoed by field geologists who have reconnoitered the cores of the continents. But new techniques and new approaches are producing exciting and revealing data. Patterson and his colleagues seem to have established the age of the earth at 4.5 billion years (*16*). The chronologic succession of visible, widespread continental events is either established or closely bracketed in absolute years; parts of the earth that cannot be directly observed and sampled are being measured with increasing accuracy.

Throughout, the concept of continental accretion of North America has survived and flourished. Accretion and secular differentiation of North America from basaltic and more mafic crust and mantle are suggested by three major, complementary features: (i) the striking analogy between the oldest rock complexes in the heart of North America and rocks of the island arcs; (ii) the progressive, secular differentiation of igneous and sedimentary rocks, in successively formed geologic provinces, from rocks typically oceanic in character to rocks more characteristically continental; (iii) the crudely zonal patterns of successive, major, granite-forming and related continent-forming events, as manifest in decipherable rock provinces.

This zonal pattern of rock provinces is broadly generalized in Fig. 2, and is shown in greater detail in Figs. 3 and 4. These maps indicate the decrease in the ages of the designated geologic provinces outward from a central nucleus.

North America, stripped of its thin blanket of younger ($< 0.5 \times 10^9$ years) platform sediments, has a core 6 times older than its margins. As noted previously, the oldest rock complexes in the continental core are those characteristic of island arcs and oceanic margins. Younger provinces include various dilutions of continental

Table 2. Approximate percentages of granitic and pre-existing rocks exposed in geologic provinces of North America. The data are based on point counts of 320 geologic maps, at scales of 1:12,000 to 1:500,000 (see *48*).

Province	Superior-Wyoming; Slave (2.5–3.2×10^9 yr)	Churchill (1.8–2.5×10^9 yr)	Central (1.8–1.4×10^9 yr)	Grenville (1.0–1.8×10^9 yr)	Appalachian; Pacific (0–1.0×10^9 yr)
Basic volcanics	12	6	3	3	5
Felsic volcanics	0.1	0.5	20	4	4
Sedimentary rock	5	18	2	20	46
Peridotite*	0.1	Trace	Trace	Trace	0.1
Diorite and quartz diorite	2	1	0.01	0.01	16
Granitic rock†	76	70	70	66	24
Other	4	4	5	6	5

* Island-arc (Alpine) type. † Includes quartz-monzonite, granodiorite, quartz porphyry, and gneisses pervasively veined by granite.

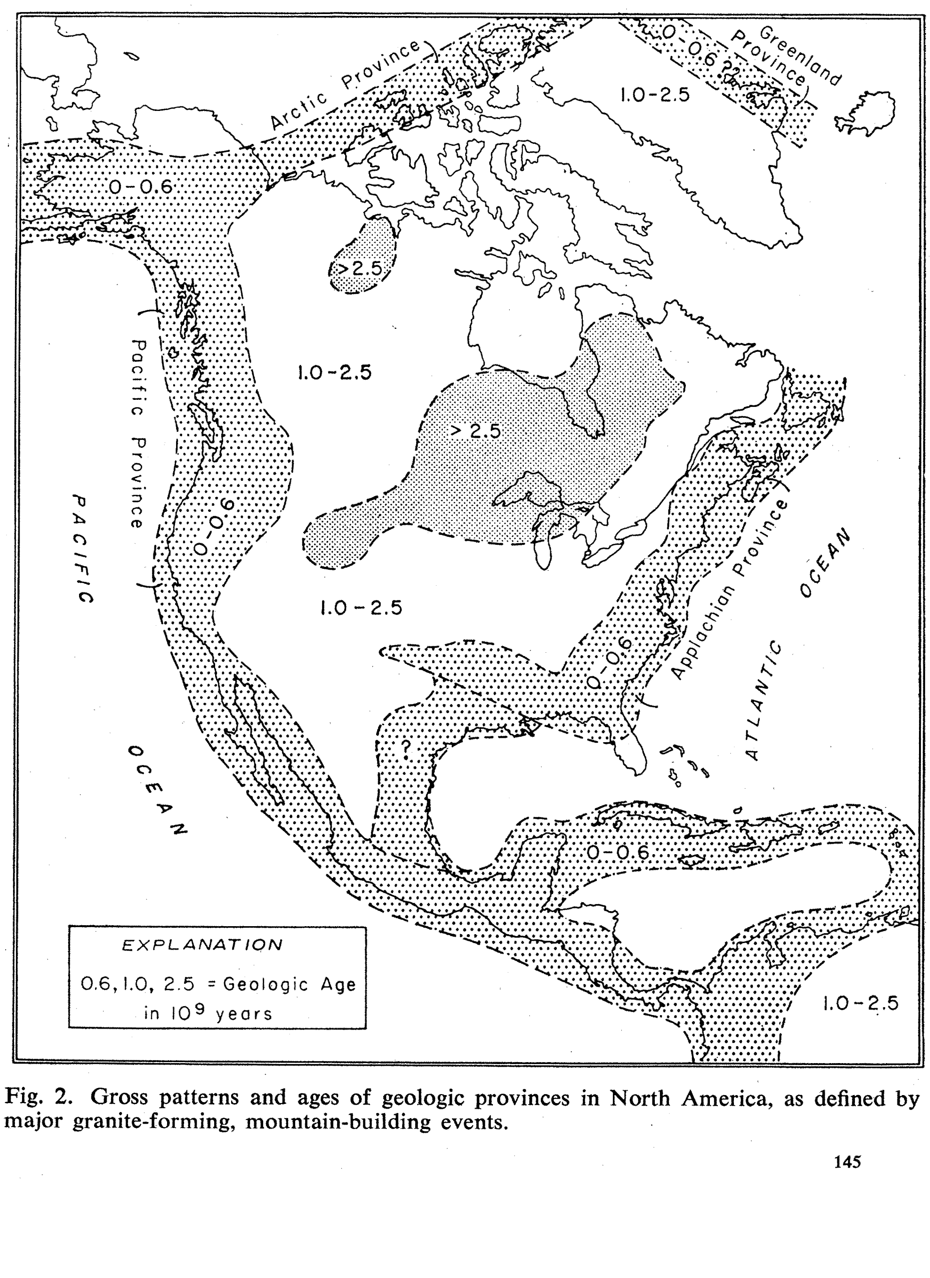

Fig. 2. Gross patterns and ages of geologic provinces in North America, as defined by major granite-forming, mountain-building events.

and oceanic types (Tables 2 and 3). In general, the younger the province, the greater its continental characteristics, as though the successively younger cycles in the outward accretion were increasingly dominated by contributions from the expanding, granitic continent itself. Today's continuing outward spread of North America may be reflected in the accumulation of thick prisms of debris largely of continental type in the Gulf of Mexico (*17*), Baja California (*18*), the Pacific Basin and Range Province (*19*), and other areas.

Geologic Cycles

Although the provinces delimited in Figs. 2, 3, and 4 are infinitely complicated, each is defined by a series of juxtaposed, variously impinging, and complementary geological "cycles." Most cycles are punctuated by at least one great granite-forming event. The granites tend to be localized along sinuous mountain belts, the sites of maximum crustal instability, and are emplaced at the culmination of one or more major sedimentary or sedimentary-volcanic episodes. The rock products of any cycle reflect the nature and stability of the crust during the cycle. Major stages in the mountain-building cycles are as follows.

1) Erosion of the crustal highs and sedimentation in adjacent crustal troughs, basins, and platforms (the larger crustal troughs, deeply filled with sedimentary and volcanic debris, are called geosynclines).

2) Volcanism, at various intervals and sites, but concentrated and intense during the evolution of most geosynclines.

3) Deformation of the thicker volcanic-sedimentary piles in the geosynclines and recrystallization and partial melting of their depressed keels and of the subjacent mantle.

4) Engulfment of much of the geosynclinal pile by the partial melt, predominantly granitic but ranging in composition from mafic to granitic. This is the major, widely dated, granite-forming "event" on which the "age" assigned each continental province shown in Figs. 2, 3, and 4 is based.

5) Rise of the resulting, commonly elongate, thickened, and granitized mountain range, and its erosion, perhaps as a stage in a new, superimposed or adjacent, crustal cycle. Each cycle results in crustal differentiation, as shown in Fig. 5.

Complementary to the great mountain-building, granite-forming cycles are the rise and fall of adjacent continental platforms and shelves. The depressed portions of these areas acquire widespread blankets of well-sorted and weathered sediments, the so-called platform and shelf sediments. Obviously, the sediments differ in physical and chemical properties according to their source, the agents of transportation, and the sites of deposition, and the entire milieu changes throughout the immediate sedimentary cycle and the encompassing crustal cycle. Consequently, vital clues to crustal history and continental evolution may be drawn from evidence of secular changes in kinds and patterns of sediments and associated volcanics.

Table 3. Estimated compositions of average sediments at three periods during the evolution of North America (see *48*).

Component	Percentage		
	3.2 to 2.5 × 10^9 yr	2.5 to 1.8 × 10^9 yr	0.6 × 10^9 to 0 yr
SiO_2	66.0	65.2	58.8
Al_2O_3	14.5	14.1	13.6
Fe_2O_3	1.4	1.7	3.5
FeO	3.9	2.9	2.1
MgO	2.2	2.3	2.7
CaO	2.8	3.1	6.0
Na_2O	3.0	2.8	1.2
K_2O	1.4	2.6	2.9

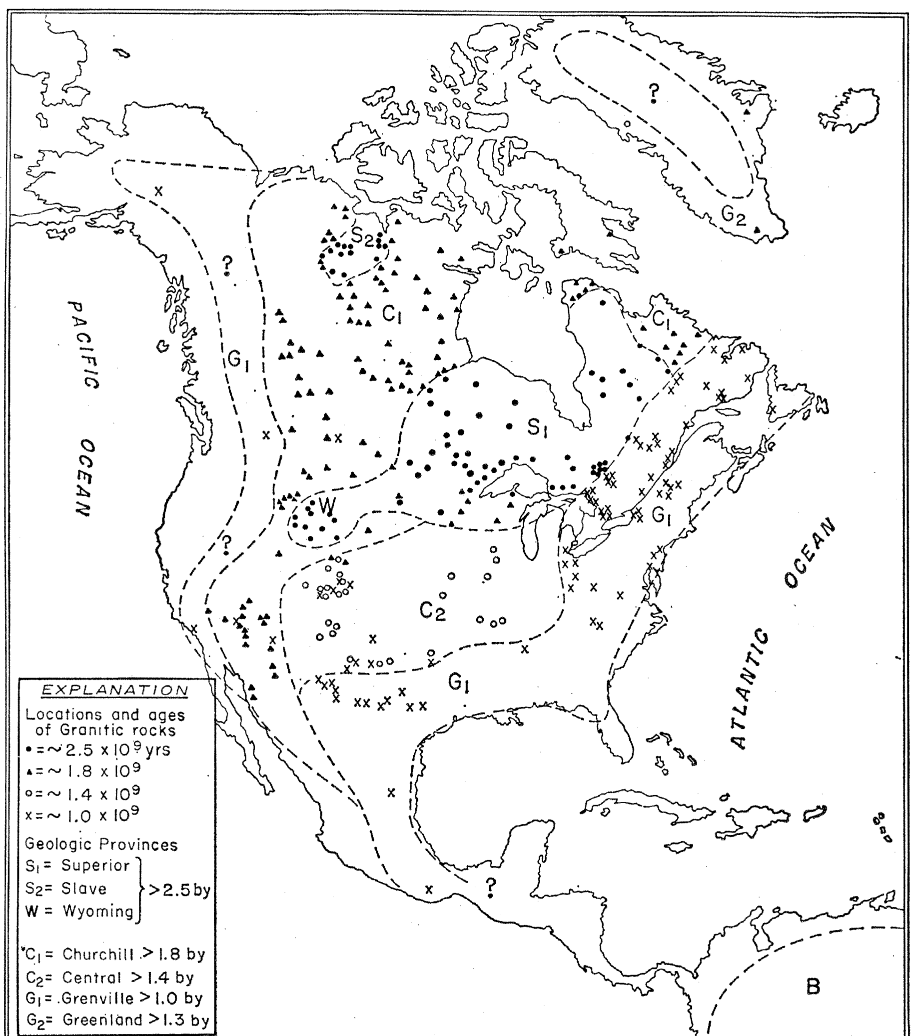

Fig. 3. Localities at which major granite-forming events of a billion or more years ago have been dated. Each point marks the site of one radiometric age determination, or of several closely spaced age determinations. These determinations, together with data from geologic field studies, define the areal extent of Precambrian provinces.

Oldest Continental Rocks

The oldest rocks, and consequently the first clearly recognizable events in North America, are in the Superior-Wyoming and Slave provinces (the latter in the region of Great Slave Lake in Canada) (Figs. 2 and 3). In these areas a major granite-forming event occurred about 2.5 billion years ago (*20*). The granites largely engulf the oldest mappable rocks, a series of volcanic-sedimentary sequences. We have noted that in many respects these volcanic-sedimentary rocks are strikingly like rocks known to form on and adjacent to evolving island arcs. They are made up of basaltic laves, mafic ash falls, slides and slumps of slightly weathered mafic debris, volcanic ejecta, and a primitive sedimentary microbreccia, called graywacke (*21*). There also are peridotites (from the mantle ?) and siliceous iron-bearing sediments.

Some of the volcanic-graywacke suites appear to have their closest analogs in recently emergent volcanic archipelagoes such as the Kurils and Aleutians (*22*). Other suites, while consisting largely of basalt, and graywacke, include fragments of alkali and silica-rich porphyries, and granite. Many of the graywackes also contain minerals common only in granitic (continental) terranes, especially potassium-rich feldspar and micas, zircons, monazites, and abundant quartz (Table 1). There is thus distinct evidence in these ancient sediments of detrital contributions from pre-existing granitic, hence continental, source areas—some sort of protocontinent that formed the nucleus of North America well over 2.5 billion years ago.

The oldest recognizable rocks on other continents are similar island-arc-like complexes (*23*). In describing the ancient Bulawayan complex of South Africa ($> 2.5 \times 10^9$ years old), Macgregor writes (*23*): "The general picture presented by these rocks is one of volcanic islands scattered over an area exceeding 300 miles from north to south and 200 miles from east to west, with gently-sloping volcanic cones of Hawaiian type and explosive andesitic volcanoes rising above the sea, as thick flows of pillowy lava spread out on the ocean floor."

Some of the ancient graywackes include granitic pebbles, or clastic grains of minerals characteristic of granite. In South Africa, pegmatitic granites that cut another pre-existing volcanic-graywacke sequence have been reported to be 3.2 billion years old (*24*). Polkanov and Gerling report an age of 3.5 billion years for a granitic gneiss from the Kola Peninsula (*25*). If these ages prove to be "firm," they establish the existence of granitic rocks—patches of continental crust—no more than a billion years after the origin of the earth.

There is no impelling reason to assume that all continents were nucleated simultaneously, but these data suggest the possibility of at least one, and perhaps several, volcanic-sedimentary cycles in North America preceding those now mapped in the Superior-Wyoming and Slave provinces. The data are consistent with the view that the continents were formed from a predominantly volcanic-basaltic crust not unlike that now found in the Atlantic and Pacific oceans. Initial differentiation could have occurred largely through the weathering of oceanic volcanics, the metamorphism and partial melting of resulting sediments and their basaltic floors, or a combination of these processes superimposed upon a suite of magmatic differentiates (*26*). Granitic rock is erupted by existing Pacific volcanoes, but in relatively small amounts (*27*).

The nature of the initial, granite-forming events remains conjectural. The classic view—that geologic events of the past may be explained by observable, contemporary earth processes and products—requires some modification. The formation of the earth 4.5 billion years ago was a cataclysmic event. So in lesser degree may have been the formation of a first granitic crust.

Astrogeologists may ultimately convince themselves, and others, that the early impaction of giant meteorites fostered or furthered the differentiation of early granitic crust by producing great pools of lava (*28*). Some of the largest mafic lava pools that we observe frozen in the crust (the stratiform sheets) show internal differentiation into more mafic and granitic types (*29*).

Only one province in North America younger than the Superior-Wyoming and Slave provinces—the Pacific province—is dominated by rocks characteristic of, and largely indigenous to, the island arcs and crusts of oceanic type. Pettijohn (*21*), who first emphasized the nature of very old sediments, and

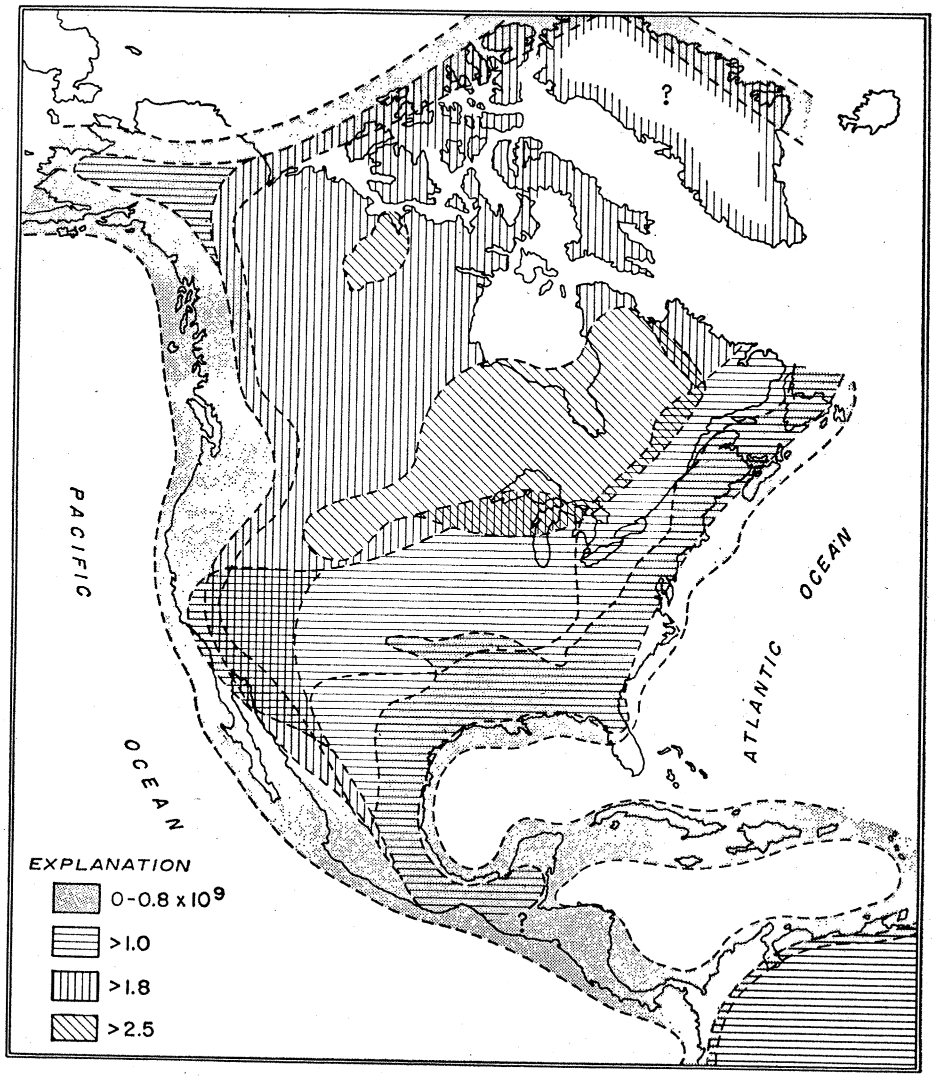

Fig. 4. Some examples of known and readily inferred overlap of successively formed geologic provinces (as defined by major granite-forming events).

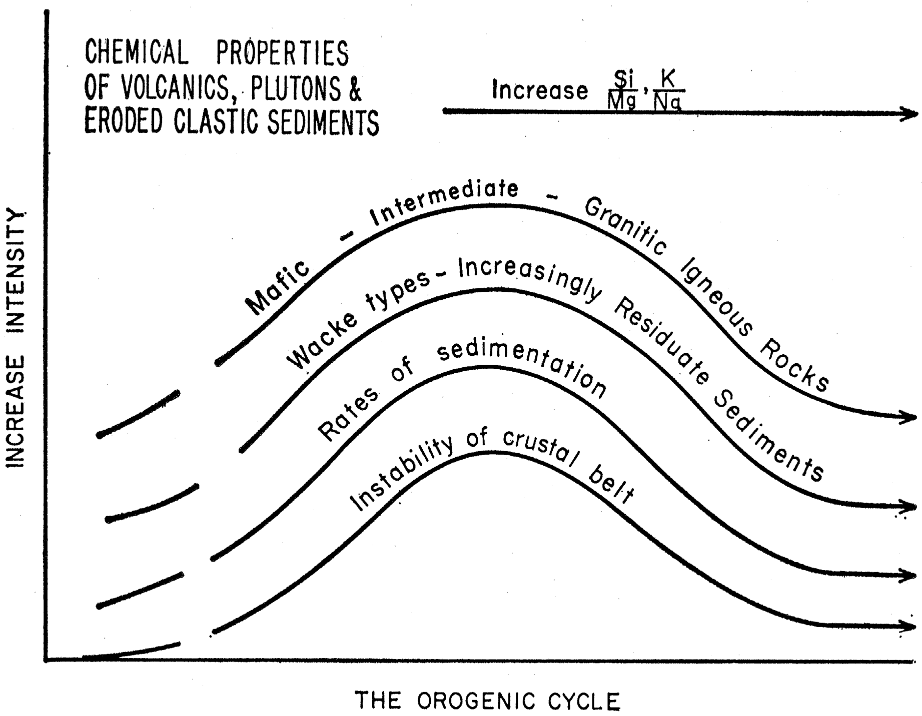

Fig. 5. A diagrammatic representation of geologic events and crustal differentiation during a mountain-building, granite-forming crustal cycle. The horizontal coordinate may reflect spans of 10 to 500 million years.

succeeding workers (*30*) have suggested that the ancient island arcs of the Superior-Wyoming and Slave provinces emerged adjacent to stable shelves and shelf sediments, now effaced by erosion. The argument may be inverted. For in the last 2.5 billion years of geologic time it is the stable continental shelves and their highly differentiated, winnowed blankets of sediments that have best resisted obliteration. The virtual absence of earlier stable shelves on continents suggests that none existed that were equivalent to contemporary shelves in thickness, composition, and stability. Instead, prior to 2.5 billion years ago patches of granitic crust were either (i) very much thinner than later granitic crust or (ii) relatively small in area, hence unable to resist the dynamic and thermal processes that recurred in the underlying mantle.

Whatever the primordial facts, the contemporary vista suggests that it is impossible for basalt-graywacke suites of the Superior-Wyoming and Slave type to evolve on a well-defined continent, 20th-century model. The average composition of the crust on emergent North America between 2.8 and 3 billion years ago (prior to the emplacement of granite) was far closer to that of basalt than the crust of North America is today (Table 2). Similarly, the sediments of the Superior-Wyoming and Slave provinces are very different in composition from the sediments formed on North America in the last 600 million years (Table 3). There has been continental growth and differentiation. This does not mean that there have been no temporary reversals or partial foundering of granitic crust. But the gross trend has important implications for studies of geochemical cycles and the so-called geochemical balance, in which the compositions of the average modern sediments, of the average contemporary crust, and so on, are commonly employed as secular constants (*31*).

The age of the Superior-Wyoming and Slave provinces is defined by waves of granitic rocks that largely engulfed the volcanic-graywacke complexes some 2.5 billion years ago. These granitic rocks constitute three-fourths of these provinces as they are now mapped. Geophysical data indicate that they persist to depths of at least 12 to 15 kilometers in the crust. Downward-projecting keels of the graywacke-volcanic complexes appear to reach a depth equivalent to the width of the exposed complex (*32*).

Actually, only a small fraction of the so-called granitic rocks are, strictly speaking, granite. The "granitic" terranes include abundant diorites, quartz diorites, and granodiorite—that is, deep-seated rocks intermediate in composition between granitic and mafic types (Table 1). In most localities these rocks appear to have been emplaced in sequence, the most mafic first, followed by the more granitic types. Characteristically, diorites and quartz diorites are largely indigenous to volcanic-graywacke terranes and are among the first deep-seated igneous rocks emplaced in such terranes. The fact that granitic rocks are so abundant and widespread in the Superior-Wyoming and Slave provinces at the 2.5-billion-year level suggests that many of these granites are regenerated, partial melts from pre-existing crust of intermediate character, formed either in preceding cycles or through cataclysmic events.

The granite-forming event of 2.5 billion years ago is significant in that it indicates the development for the first time in North America, and presumably on other continents, of a thick, stable, and resistant granitic crust. Thereafter, this crust (the Superior-Wyoming and Slave provinces) persisted either above sea level or as a partially immersed but stable platform. Observations of mass and crustal buoyancy suggest that for 2.5 billion years the continental crust of the Superior-Wyoming and Slave provinces has been at least 20 to 25 kilometers thick.

It is tempting to speculate on the initial areal extent of the 2.5-billion-year continental crust. Almost surely the Superior-Wyoming and Slave provinces were more extensive than is now apparent. This is readily inferred from

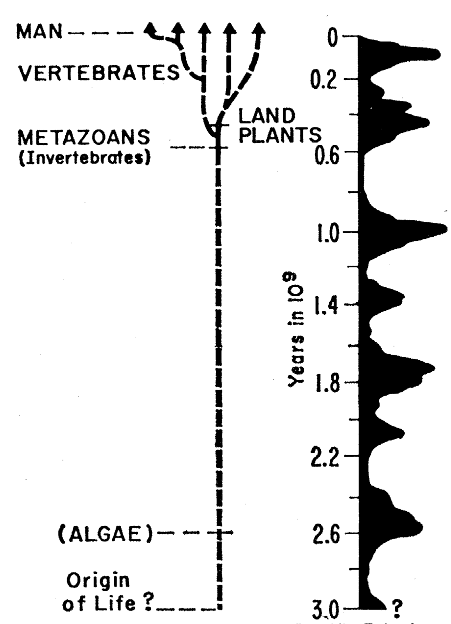

Fig. 6. A schematic representation of organic evolution and the occurrence of major granite-forming episodes of North America.

studies of younger provinces. All of these overlap pre-existing provinces by 20 percent, to as much as 60 percent (Fig. 4). Specifically, the succession of volcanic-sedimentary and granite-forming events that define the Appalachian province (0.2 to 0.8 $\times$ 10^9 years) overlap the Grenville province ($\sim$ 1 $\times$ 10^9 years) by about 60 percent (Fig. 4). Similarly, in the western part of North America there is wide overlap and near-obliteration of older provinces by a succession of younger provinces dated at 0.1, 0.4, 1.0, and 1.8 billion years ago.

Other features which suggest that the Superior-Wyoming and Slave provinces were formerly more extensive than they are now include (i) their broad but stubby forms, and (ii) the angular intersections of their mountain belts with those of enveloping provinces. In general, the younger the mountain belt and province, the more elongate the form. These relations suggest that the fossilized mountain belts that form the older provinces have been sliced off and reincorporated in succeeding mountain-building, granite-forming episodes.

Recent detailed mapping of the edges of the Superior-Wyoming and Slave provinces supports this inference. Blurred vestiges of rocks of the Superior province can be traced southeast across the "Grenville front" into the much younger ($\sim$ 1.0 $\times$ 10^9 years) Grenville province, where they are all but obliterated by superimposed events (*33*). Recent work also suggests that the Superior and Slave provinces were originally either joined or were separated by only a very narrow belt of island arc or oceanic-type crust. Hence, the relict Superior-Wyoming and Slave provinces tell us that 2.5 billion years ago thick granitic crust comprised an area at least 20 percent that of present-day North America. But the data suggest that the extent of (thinner ?) granitic crust may have been greater—equivalent to perhaps one-fourth or more of the present area of the continent.

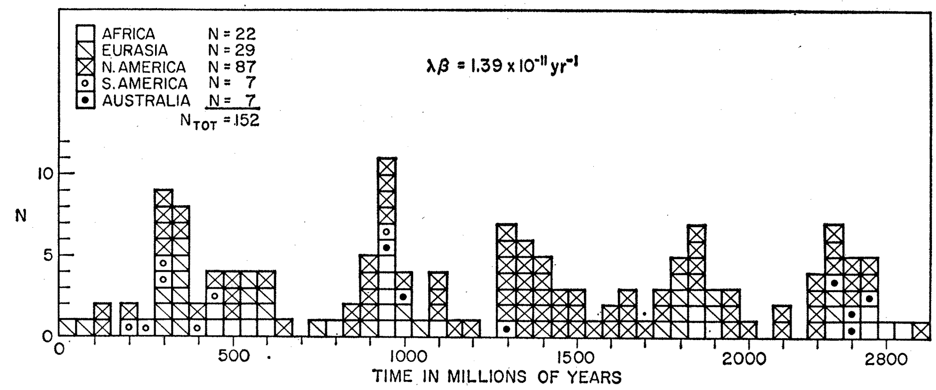

Fig. 7. Distribution in time and by continent of 152 rubidium-strontium age determinations which indicate the world-wide episodic nature of granite-forming events. The blocks are separated by a time comparable to the error of the measurement. Plots of hundreds of A^{40}/K^{40}, lead-lead, and uranium-thorium-lead age determinations show correlative peaks (see *50* and Fig. 6). [From Aldrich, Wetherill, Bass, Tilton, and Davis (*51*)]

Succeeding Provinces and Events

The evolution of successive geologic provinces in North America is characterized by several features. (i) Most of the volcanic-sedimentary series show a progressive increase in the increments of continental debris, much of it extensively weathered and differentiated. (ii) The pre-existing provinces behave as stable, neutral, or slightly negative plates and basins into which well-sorted clastics and chemical and biochemical precipitates are deposited as broad, thin blankets. (iii) The associated volcanics include higher percentages of alkali and silica-rich types than the volcanics of pre-existing provinces. These generalizations are drawn from data in Tables 2 and 3 obtained through point counts of some 320 maps of areas in the several provinces.

Although the data in Tables 2 and 3 are crude approximations, the trends are obvious. For example, in the Churchill province, which partially encircles and partly separates the Superior-Wyoming and Slave provinces, the pregranitic volcanic-sedimentary complexes include abundant graywacke and pillowed basalt. But lavas and tuffs of intermediate and rhyolitic (granitic) composition are common and widespread. Arkoses—that is, sandstones largely composed of disintegrated granites—appear in many sedimentary sequences. So do carbonate layers and well-sorted, cross-bedded quartz-rich sandstones, although they commonly constitute only a small fraction of the total sedimentary record (*34*).

During the evolution of the Churchill province (1.8 to 2.5 $\times$ 10^9 years ago), epicontinental seas covered large areas of the Superior-Wyoming and Slave provinces. In these seas, in large shallow basins, the first known blankets of shelf sediments formed (*35*). These include well-sorted cross-bedded quartzose sandstones, potassium-rich shales, and carbonate sediments. A feature of these old carbonate sediments in North America and other continents is the rare appearance of fossil algal reefs and colonies. Indeed, one algal limestone in South Africa predates the emplacement of granite 2.4 billion years ago. There are, however, no unequivocal examples of metazoan fossils prior to about 600 million years ago (Fig. 6). Successive widespread incursions of shallow seas across beveled provinces of North America and other continents have left in their sediments the great heritage of fossil life and the outlines of organic evolution.

The granite-forming events that culminated in the development of the Churchill province about 1.8 billion years ago extended into Greenland and as far southwest as the Gulf of California (Fig. 3). It is not clear whether the Churchill province ever enveloped the Superior-Wyoming and Slave provinces on the southeast, nor are the relative extents and interrelations of the Churchill and Central provinces well understood. But it does seem clear that by 1.8 billion years ago the Churchill province was nearly 1.5 times larger than the relict Superior-Wyoming and Slave provinces; that it almost encircled them; and that, with them, it comprised an area almost half that of present-day North America. The data also support the conclusion that the Churchill province was much larger in extent than it is today.

The Central province is poorly exposed, but much of what we see in rare outcrops and scattered drill holes seems unique and exciting. Bass has noted the seeming predominance of intermediate-to-rhyolitic volcanics and of potassium-rich granite in which there is little evidence of solid-state deformation (*36*). Most granites of other provinces are deformed, presumably by mountain-making forces that accompanied their emplacement. Other unique aspects of many parts of the Central province are the scarcity of sedimentary rocks and the date of the major, granite-forming event, about 1.4 billion years ago (*37*). This great magmatic event and the much more recent Pacific event interrupt a series of granitic episodes that apparently otherwise occurred with some regularity every 600 to 800 million years (Figs. 6 and 7).

The data suggest that about 1.4 billion years ago the entire central and southwestern part of the United States was a gigantic puddle or blister of granitic magma, with perhaps a very thin sedimentary skin.

If the Central province evolved through differentiation at a continental-oceanic interface, the magmatic processes were uniquely efficient and complete. Possibly much of the Central province represents a re-fusion and further differentiation of a pre-existing continental crust at least 1.8 billion years ago.

The Grenville province is developed along the entire eastern and southern parts of North America (Fig. 3). There it seems to form a great sheath extending from Labrador to Mexico (*38*). It may also appear in the southern part of Greenland and extend southward into Central America. Its pre-granitic, volcanic-sedimentary sequences vary widely in composition. The best known, in southeastern Ontario (*39*), southwest Quebec (*33*), and New York include thick clean carbonate beds, quartzites, and—at least locally—an evaporite sequence with gypsum (*11*). Anorthosites, igneous-looking rocks composed largely of plagioclase feldspar, form scattered massifs of highly controversial origin.

During the evolution of the Grenville province, algae flourished in widespread shallow shelf seas that invaded parts of the Central, Churchill, and Superior-Wyoming and Slave provinces. Carbonate formations are thus widespread in both the geosynclinal and the shelf sediments. Indeed, with quartzites and potassium-rich shales, they commonly predominate over sediments of the microbreccia-graywacke type (Table 3). Dolomite [$CaMg(CO_3)_2$] predominated over limestone ($CaCO_3$) at this time, but the ratio was reversed about 500 million years ago (Table 4). The average sediment thus shows an increase in well-weathered and sorted types over primitive graywacke types, with increases in the ratios of potassium to sodium, of ferric iron oxide to ferrous iron oxides, of calcium to magnesium, of calcite to dolomite, and of carbonates to clastics in which there are free carbon and sulfides (Table 3).

The granite-forming episode that climaxed the Grenville era emplaced potassium-rich silicate fluids throughout at least 20 percent of North America. A major unresolved question is whether an analog to the Grenville event occurred in western North America. A tenuous association of granite (dated 1×10^9 years) at Pikes Peak and geologic features near Los Angeles and in southeastern Alaska suggest Grenville granite-forming events and sediments at these places (*40*). But the succeeding, complex series of sedimentary-volcanic and granite-forming events along the entire western coast have all but obliterated the earlier record. This is true to a lesser extent in eastern North America. Geochronologic sleuthing indicates that there the Appalachian province is built largely upon the Grenville (*41* and Fig. 4). The encircling patterns of these young Appalachian, Pacific, and Greenlandian provinces are perhaps the most striking example of province overprinting, and of the instability of the continental edges, during the last 600 million years (Figs. 2, 4).

The relatively young Appalachian, Pacific, and Greenlandian provinces are known in considerable detail, and the constituent rocks are described at length in most textbooks of historical geology and stratigraphy. Several of their broad features are especially pertinent here. (i) They form very young, elongate sheaths to the continents. (ii) They are built in part on pre-existing older provinces but include constituents from fringing island arcs (*42*) or other positive crustal blocks not now apparent (*43*). (iii) Both the Appalachian and the Greenlandian provinces appear to have once projected outward beyond the existing continental crust into the oceanic basin (Fig. 2). This suggests that continents may have pulled apart, or that mobile belts extended from one continent to another across the ocean floor (*44*).

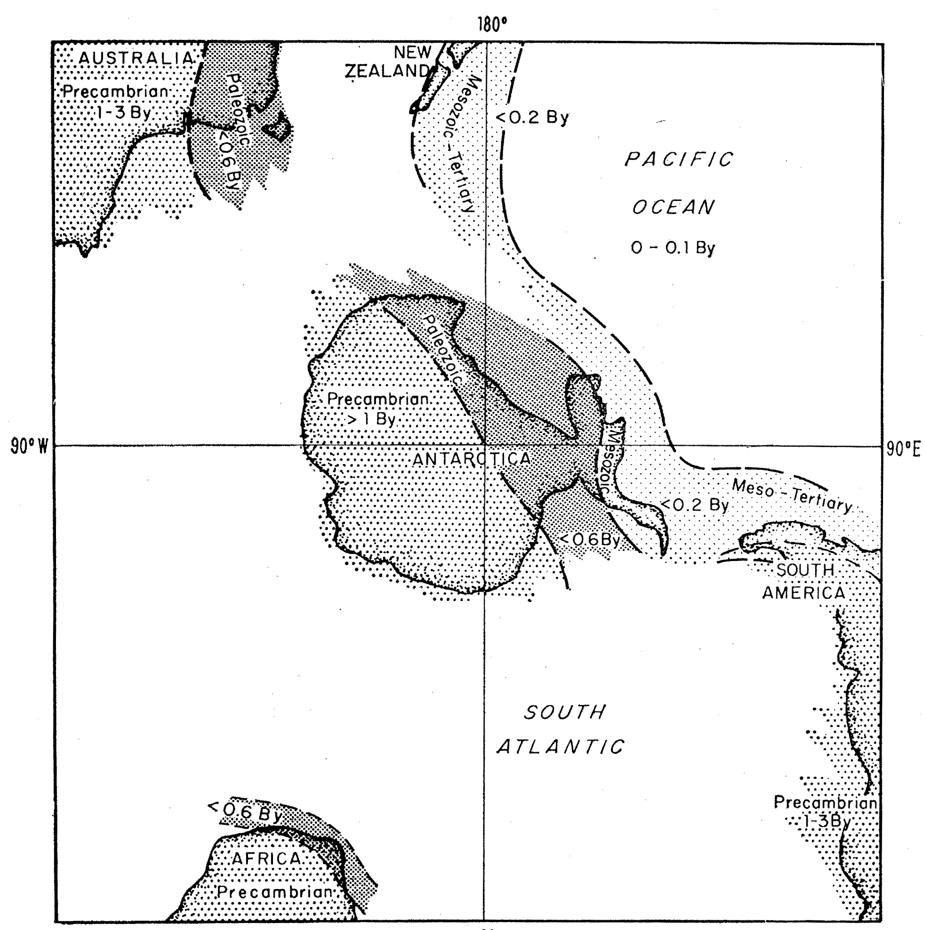

Fig. 8. A polar map showing in generalized form the unidirectional patterns of successive mountain- and granite-forming episodes in Australia-New Zealand, Antarctica, Africa, and South America.

Other Continents and Continental Drift

There are grounds for postulating the continental accretion of North America, but what of the patterns of provinces and mountain belts on other continents? The data seem too fragmentary to justify extended speculation. One thing is clear. Young, evolving (?) island arcs and mountain belts are by no means ubiquitous at continental-oceanic margins. They are found throughout much of the Pacific, the Carribbean, and the Arctic and Antarctic oceans. In contrast, the perimeters of the Atlantic and Indian oceans largely lack island arcs and young coastal mountains. Parts of the granitic, continental crusts of Greenland, India, western Australia, and eastern South America—a billion or more years old—appear to merge abruptly into thin, basaltic, oceanic crust (Fig. 8).

This fact, together with the near-fit of some continental outlines, extensive but not entirely convincing paleoclimatological and paleomagnetic data, and the interruptions of mountain belts and old sial at the edges of the continents, has kept Wegener's hypothesis of continental drift alive and kicking (*12, 13*). There is clearly a crude fit between the edges of the continents that face the Atlantic, and between those that face the Indian Ocean. This has prompted some geologists to suggest that the present continents dispersed from a common supercontinent and drifted across the present Atlantic and Indian oceans. The time-of-drift that fits best with diverse geologic events and data is about 150 to 200 million years ago (*13*). But it is difficult to reconcile the interpretations of continental drift and continental accretion. If North America broke away from Europe and Africa and drifted west less than 200 million years ago, we would expect accretion to be largely unidirectional from east to west. Otherwise, the Grenville and Appalachian mountain belts must have evolved in the heartland of the parent continent prior to the drift.

There appear to be examples of unidirectional continental accretion, and some of these may be reconciled with the postulated drift. One example is the Australian-Antarctic region indicated in Fig. 8. Geologists familiar with the Australia-New Zealand region have frequently postulated the "eastward migration of geosynclines," and of the continental-oceanic interface. The evidence is suggestive (*45*), although there seem to be serious objections (*46*).

Several possible rates of continental growth are implied by the data. A plot of the relict areas of each province (including the known overlap) against time suggests a linear growth rate (Fig. 9). Hurley and his colleagues have argued that a linear rate of continental growth also is borne out by comparisons of the ratio Sr^{87}/Sr^{86} with the geological age of granitic rocks (*47*). They estimate an average growth rate of about 7000 square kilometers per million years, operative over most of geologic time. Their geochemical calculations are suggestive but not conclusive. Wide deviations from linearity are consistent with the data at hand; these include waxing and waning periods of continental growth and the previously noted explosive early growth, with recurrent, lesser granite-forming episodes every 300 to 800 million years.

Summary

The oldest decipherable rock complexes within continents (more than 2.5 billion years old) are largely basaltic volcanics and graywacke. Recent and modern analogs are the island arcs formed along and adjacent to the unstable interface of continental and oceanic crusts. The major interfacial reactions (orogenies) incorporate preexisting sial, oceanic crust, and mantle into crust of a more continental type. Incipient stages of continental evolution, more than 3 billion years ago, re-

Table 4. Estimated secular variation in the composition of carbonate sediments and in the ratio of carbonates to clastics (see *48*).

Clastics/ carbonate	Dolomite $[CaMg(CO_3)_2]$/ limestone $(CaCO_3)$	Age (yr × 10^9)
1000:1	3:1	1.8
30:1	3:2	1.0–1.8
15:1	1:4	0.6

main obscure. They may involve either a cataclysmic granite-forming event or a succession of volcanic-sedimentary and granite-forming cycles. Intermediate and recent stages of continental evolution, as indicated by data for North America, involve accretion of numerous crustal interfaces with fragments of adjacent continental crust and their partial melting, reinjection, elevation, unroofing, and stabilization. Areas of relict provinces defined by ages of granites suggest that continental growth is approximately linear. But the advanced differentiation found in many provinces and the known overlaps permit wide deviation from linearity in the direction of a more explosive early or intermediate growth.

Mountain-building, granite-forming events instrumental in continental evolution are episodic, possibly periodic on a worldwide scale.

The trend of continental evolution, although episodic and at least intermittently reversible, involves increases in (i) the ratio of thickened, stable continent to unstable island arc and ocean; (ii) the ratio of continental volume to eroded sediments; (iii) the ratio of residuate sediments to graywacke; and

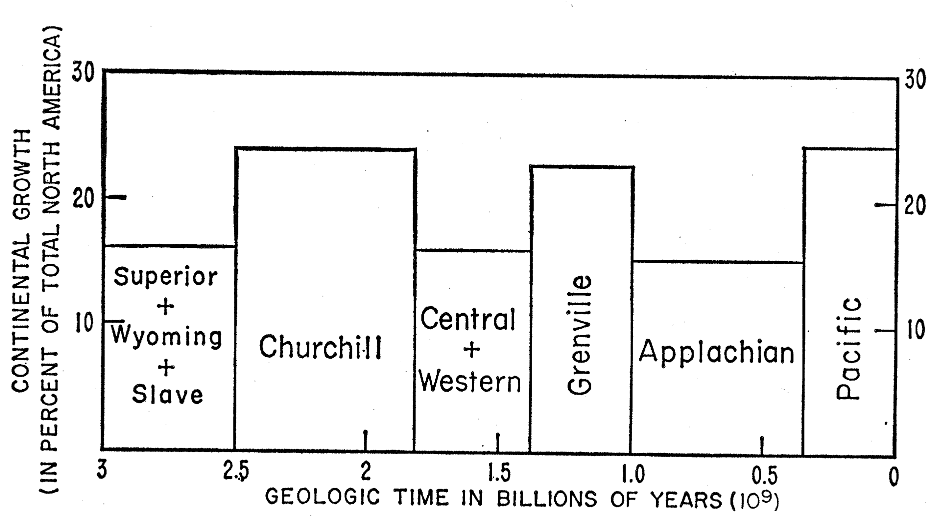

Fig. 9. Graphic representation of the crudely linear rate of continental growth indicated by the known extent and overlap of successively formed geologic provinces. Geologic evidence permits extensive variation from this pattern.

(iv) the ratio of biochemical precipitates to clastics.

Secular changes in the composition of average sediment on, and eroded from, continents include increases in the ratios of ferric to ferrous iron oxide, potassium to sodium, and calcium to magnesium. Specific sediments exhibit little secular change in composition but show critical changes in proportions and in the geography of their environments. Secular distributions on North America of arc-type ultrabasics, pillow basalts, quartz diorites, and other rocks largely indigenous to crustal interfaces and oceanic crust form a series of crudely arcuate zones. These migrate outward with time from the continental core to the present continental margins (*48, 49*).

References and Notes

1. L. R. Deer, *Advan. Sci.* **15**, 39 (1958); F. A. Vening Meinesz, *Geol. Mijnbouw* **1952**, 373 (1952).
2. W. W. Rubey, *Bull. Geol. Soc. Am.* **62**, 1111 (1951); *Geol. Soc. Am. Spec. Papers No. 62* (1955), p. 631.
3. F. Birch, *Nuclear Geology* (Wiley, New York, 1954), p. 148; *Bull. Geol. Soc. Am.* **69**, 483 (1958); G. J. F. MacDonald, in *Researches in Geochemistry*, P. H. Abelson, Ed. (Wiley, New York, 1959), p. 476.
4. J. T. Wilson, *The Earth as a Planet* (Univ. of Chicago Press, Chicago, 1954), p. 204.
5. F. Press, *Science* **133**, 1455 (1961); B. Gutenberg, *Geol. Soc. Am. Spec. Papers No. 62* (1955), p. 19.
6. R. W. Raitt, *Bull. Geol. Soc. Am.* **67**, 1623 (1956); J. Ewing and M. Ewing, *ibid.* **70**, 291 (1957); B. C. Heezen, in *Continental Drift*, S. K. Runcorn, Ed. (Academic Press, New York, 1962), vol. 3, p. 235.
7. M. Talwani, G. Sutton, J. Worzel, *J. Geophys. Res.* **64**, 1545 (1959); C. B. Officer, J. I. Ewing, R. S. Edwards, H. R. Johnson, *Bull. Geol. Soc. Am.* **68**, 359 (1957); R. D. Adams, *New Zealand J. Geol. Geophys.* **5**, 74 (1962).
8. Australian Petroleum Company, *J. Geol. Soc. Australia* **8**, No. 1, 10 (1961); P. Liechti, F. W. Roe, N. S. Haile, *Geol. Surv. Borneo* **1**, 217 (1960); R. G. Schmidt, *U.S. Geol. Surv. Profess. Papers No. 280-B* (1957).
9. W. A. Heiskanen and F. A. Vening Meinesz, *The Earth and Its Gravity Field* (McGraw-Hill, New York, 1958); G. P. Woolard, *J. Geophys. Res.* **64**, 1521 (1959).
10. L. Noble, *Bull. Geol. Soc. Am.* **52**, 941 (1941).
11. J. S. Brown and A. E. J. Engel, *ibid.* **67**, 1599 (1956)
12. F. A. Vening Meinesz, in *Continental Drift*, S. K. Runcorn, Ed. (Academic Press, New York, 1962), p. 145; T. Chamalaun and P. H. Roberts, *ibid.*, p. 177.
13. H. H. Hess, in *Petrologic Studies: A Volume in Honor of A. F. Buddington* (Geological Society of America, New York, 1962), p. 599.
14. A. A. Macgregor, *Trans. Geol. Soc. S. Africa* **43**, 9 (1940); A. Holmes, *Nature* **173**, 612 (1954); L. T. Aldrich, G. W. Wetherill, G. L. Davis, *Geochim. Cosmochim. Acta* **10**, 238 (1956).
15. R. G. Blackadar and J. A. Frazer, *Geol. Survey Can. Paper No. 60-8* (1960), p. 6.
16. C. Patterson, *Geochim. Cosmochim. Acta* **10**, 230 (1956); see, also, recent measurements which, according to Gerling and his colleagues, indicate an age of the earth of at least 6.5 billion years [E. K. Gerling, Y. A. Shukolyukov, T. V. Koltsova, I. I. Mateeva, S. Z. Yakovleva, *Geokhimiya* **1962**, No. 11, 931 (1962)].
17. J. I. Ewing, J. L. Worzel, M. Ewing, *J. Geophys. Res.* **67**, 2509 (1962); F. P. Shepard, F. B. Phleger, T. H. Van Andel, "Recent Sediments, Northwest Gulf of Mexico," *Publ. Am. Assoc. Petrol. Geologists* (1960).
18. W. Hamilton, *Bull. Geol. Soc. Am.* **72**, 1307 (1961); T. H. Van Andel, personal communication.
19. F. P. Shepard and K. O. Emery, *Geol. Soc. Am. Spec. Papers No. 31* (1941); K. O. Emery, *Bull. Geol. Soc. Am.* **63**, 1105 (1952).
20. J. A. Lowdon, *Geol. Surv. Can. Paper No. 61-17* (1961); P. W. Gast, J. L. Kulp, L. E. Long, *Ann. N.Y. Acad. Sci.* **91**, 1574 (1958); S. S. Goldich, A. O. Nier, H. Baadsgaard, J. H. Hoffman, H. W. Krueger, *Minn. Geol. Surv. Bull.* **41** (1961).
21. F. J. Pettijohn, *Bull. Geol. Soc. Am.* **54**, 925 (1943).
22. F. M. Byers, Jr., *U.S. Geol. Surv. Bull.* **1028-L**, 267 (1959); R. R. Coats, in "The Crust of the Pacific Basin," *Am. Geophys. Union Monogr. No. 6* (1962), p. 92; A. V. Goryatchev, *ibid.*, p. 41; V. F. Yerokhov, *Proc. Acad. Sci. USSR Earth Sci. Sect.* **130**, 1, (1960).
23. A. A. Macgregor, *Trans. Geol. Soc. S. Africa* **54**, 35 (1951); A. F. Wilson, *J. Roy. Soc. W. Australia* **41**, 57 (1958); C. S. Pichamuthu, *J. Geol. Soc. India* **3**, 106 (1962); A. Simonen, *Bull. Comm. Geol. Finlande* 160 (1953).
24. L. O. Nicholaysen, in *Petrologic Studies: A Volume in Honor of A. F. Buddington* (Geological Society of America, New York, 1962), p. 571; H. L. Allsopp, *J. Geophys. Res.* **65**, 1499 (1961).
25. A. A. Polkanov and E. R. Gerling, *Tr. Lab. Geol. Dokembriya, Akad. Nauk SSSR No. 15* (1961).
26. N. L. Bowen, *The Evolution of Igneous Rocks* (Princeton Univ. Press, Princeton, N.J., 1928).
27. M. N. Peterson and E. D. Goldberg, *J. Geophys. Res.* **67**, 3477 (1962).
28. H. C. Urey, *Geochim. Cosmochim. Acta* **1**, 209 (1951); R. Dietz, *J. Geol.* **69**, 499 (1961); —, *ibid.* **70**, 502 (1962); J. J. Gilvarry, *Nature* **188**, 886 (1960).
29. A. F. Buddington, *Am. Mineralogist* **28**, 119 (1940); H. H. Hess, *Geol. Soc. Am. Mem.* **80** (1960); A. L. Hall, *Geol. Surv. S. Africa Mem.* **28** (1932); L. R. Wager and W. A. Deer, *Medd. Groenland* **105**, 1 (1939).
30. T. A. Clark and C. W. Stearn, *The Geologic Evolution of North America* (Ronald Press, New York, 1960), p. 264.
31. V. M. Goldschmidt, *Geochemistry* (Oxford Univ. Press, New York, 1954), p. 47; F. E. Wickman, *Geochim. Cosmochim. Acta* **5**, 97 (1954).
32. M. J. S. Innes, *Dominion Obs. Publ. No. 6* (1960).
33. F. F. Osborne and M. Morin, *Roy. Soc. Can. Spec. Paper No. 4* (1962), p. 118. T. C. Phemister, *Intern. Geol. Congr. 21st Copenhagen 1960* (1960) p. 108.
34. H. S. Armstrong, *Intern. Geol. Congr. 21st Copenhagen 1960* (1960), p. 7; H. D. B. Wilson and W. C. Brisbin, *Roy. Soc. Can. Spec. Paper No. 4* (1962), p. 60.
35. C. H. Stockwell, *Roy. Soc. Can. Spec. paper No. 4* (1962), p. 6.
36. M. N. Bass, verbal discussions; *Missouri Geol. Surv. Water Resources, Repts. Invest. No. 26* (1961).
37. G. R. Tilton, G. W. Wetherill, G. L. Davis, *J. Geophys. Res.* **67**, 40 (1962); L. R. Aldrich, G. W. Wetherill, G. L. Davis, *Bull. Geol. Soc. Am.* **68**, 655 (1957).
38. C. Fries, Jr., E. Schmitter, P. E. Damon, D. E. Livingston, *Bull. Inst. Geol. Univ. Nacl. Mex.* **64**, 45 (1962).
39. A. E. J. Engel and C. G. Engel, *Bull. Geol. Soc. Am.* **64**, 1013 (1953); "Grenville Problem," *Roy. Soc. Can. Spec. Paper No. 2* (1956).
40. L. T. Silver, personal communication; G. J. Wasserburg, paper presented at annual meetings of the Geological Society of America, Houston (1962).
41. G. R. Tilton, G. W. Wetherill, G. L. Davis, M. N. Bass, *J. Geophys. Res.* **65**, 4173 (1960); L. E. Long and J. L. Kulp, *Bull. Geol. Soc. Am.* **73**, 969 (1962).
42. G. M. Kay, *Geol. Soc. Am. Mem.* **48**, (1951).
43. F. J. Pettijohn, *Intern. Geol. Congr. 21st Copenhagen 1960* (1960), p. 452.
44. G. Gastil, *ibid.*, p. 162.
45. J. F. Everndon and J. A. Richards, *J. Geol. Soc. Australia* **9**, 1 (1962); G. A. Joplin, *ibid.*, p. 52; G. J. Wasserburg, H. Craig, H. W. Menard, A. E. J. Engel, C. G. Engel, *J. Geol.*, in press; H. H. Hess, *Geol. Soc. Am. Spec. Paper No. 62* (1955), p. 398.
46. J. C. Standard, *Bull. Geol. Soc. Am.* **72**, 1783 (1961).
47. P. M. Hurley, H. Hughes, G. Faure, H. W. Fairbairn, W. H. Pinson, *J. Geophys. Res.* **67**, 5315 (1962).
48. Data presented in this discussion and in Tables 2–4 are drawn from hundreds of papers and maps published in the geological literature, mainly in the last two decades. Most of these papers and maps appeared in publications of the Geological Survey of Canada and the U.S. Geological Survey; in provincial and state surveys; and in the *Bulletin of the Geological Society of America*.
49. Two excellent (unpublished) bibliographies have been compiled, on (i) continental rocks and (ii) age studies, by E. G. Lidiak, R. E. Dennison, and W. R. Muehlberger [Advanced Research Projects Agency publ. ARPA Proj. 8100, University of Texas (1963)], and a bibliography of geochronology has been compiled by Geochron Laboratories, Inc., Cambridge, Mass. (1960). The unsung hero of the saga of continental evolution is the field geologist. I am indebted to him and to all those on whose work I have drawn. My research is supported in part by the National Science Foundation (Earth Sciences grant 19643). M. Bass, G. Goles, and W. Munk kindly read the manuscript and offered constructive comments.
50. G. Gastil, *Am. J. Sci.* **258**, 5 (1960).
51. L. T. Aldrich, G. W. Wetherill, M. N. Bass, G. R. Tilton, G. L. Davis, *Ann. Rept. Carnegie Inst. Wash. No. 210* (1960).