Reports

Anorthosite Belts, Continental Drift, and the Anorthosite Event

Abstract. *Most anorthosites lie in two principal belts when plotted on a predrift continental reconstruction. Anorthosite ages in the belts cluster around 1300 ± 200 million years and range from 1100 to 1700 million years. This suggests that anorthosites are the product of a unique cataclysmic event or a thermal event that was normal only during the earth's early history.*

Many models proposed for the primitive earth environment and crustal development have emphasized the similarities of the Precambrian and Phanerozoic rock records. There are, however, differences in the two rock records that can provide some insight into early earth processes, and chief among these is the presence of Adirondack or massif-type anorthosites and their kindred rocks only in the Precambrian. These rocks should not be confused with anorthositic layers in gabbroic or gabbro-peridotite complexes stratified by gravity which are also largely, but not entirely, Precambrian in age. There are over 50 anorthosite massifs in Canada and the United States, and others occur in Colombia, Mexico, the Outer Hebrides, Greenland, Scandinavia, Poland, the U.S.S.R., Africa, Madagascar, India, Brazil, Antarctica, and Australia.

Massif-type anorthosites have certain characteristics (*1*):

1) They form plutons of batholithic proportions that are largely unlayered but appear to be concordant to country rock in Precambrian terranes.

2) They have a uniform mineral composition of over 90 percent plagioclase, generally andesine-labradorite as deformed megacrysts up to 6 feet (1.83 m) in diameter.

3) They are associated with igneous rocks such as noritic gabbros and the charnockite suite and high-pressure, high-temperature metamorphic rocks of the pyroxene granulite facies. Anorthosites do not occur as lavas and rarely as dike rocks.

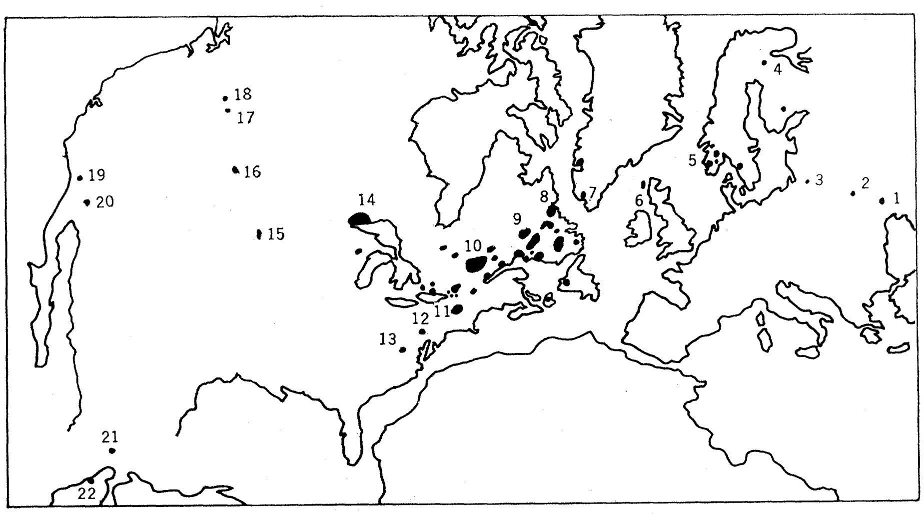

Fig. 1. Anorthosites of the Northern Hemisphere plotted on the North Atlantic reconstruction of Bullard and others (*2*). Anorthosites referred to in the text: 1, Korosten, Ukraine; 2, Korsun–Novomirgorod, Ukraine; 3, Suwalki, Poland; 4, Utsjoki, Finland; 5, southern Norway; 6, South Harris, Outer Hebrides; 7, Gardar, Greenland; 8, Kiglapait-Nain, Labrador; 9, Michikamau, Labrador; 10, Lac St. Jean, Quebec; 11, Adirondacks, New York; 12, Honeybrook, Pennsylvania; 13, Roseland, Virginia; 14, Duluth Minnesota; 15, Cambridge Arch, Nebraska; 16, Laramie Range, Wyoming; 17, Bitterroot Range, Montana; 18, Boehls Butte, St. Joe, Idaho; 19, San Gabriel Range, California; 20, Orocopia Range, California; 21, Pluma Hidalgo, Oaxaca, Mexico; and 22, Sierra de Santa Marta, Colombia.

4) Associated ore minerals are apatite and titanium-iron oxides; sulfides are not abundant.

5) Gravity measurements over anorthosite bodies show a substantial negative Bouguer anomaly, which suggests that very little mafic material is associated with them.

Two other characteristics of anorthosite that have been widely overlooked are: (i) anorthosites appear to lie within broad belts when plotted on a reconstruction of the continents before drifting—at least one in primitive Laurasia in the present Northern Hemisphere, and another in Gondwanaland in the Southern Hemisphere; and (ii) apparent ages of anorthosite range from 1100 to 1700 million years, but cluster about 1300 to 1400 million years.

Gravity-stratified complexes, including the Bushveld of South Africa, have anorthosite in layers, but of a different composition than the massif-type anorthosite. The Bushveld type, besides showing a well-developed layered structure, has more Ca and less Si and Na which results in an anorthite-rich plagioclase, has associated chromite and sulfide ores and relatively minor Ti and Fe oxides, can be of any geologic age, and can occur in almost any metamorphic terrane.

The fit of the continents around the North Atlantic at the 500-fathom (about 915 m) line, as calculated by Bullard and others (*2*), was used to plot the assumed original anorthosite positions, relative to today's northern land masses (Fig. 1). The fit of the continents proposed by Du Toit (*3*) for primitive Gondwanaland was used to plot anorthosites of the Southern Hemisphere (Fig. 2). Most of the present-day anorthosite positions were taken from Anderson (*4*).

The Northern Hemisphere anorthosite belt begins in Europe either in northern Finland or in the Ukraine. "Labradorites" have been described in the Ukrainian shield, and anorthosite has been found in wells in northeastern Poland. The belt continues northwest through Sweden and southern Norway, the Outer Hebrides, Greenland, Canada, and the United States, but is difficult to trace west of eastern Canada. There is a suggestion on the map that it bifurcates with one limb continuing west to the anorthositic bodies in the Duluth Gabbro Complex (*5*), and the other southwest to Roseland, Virginia. Anorthosites are found as far west as the

San Gabriel Mountains, and a dislocated counterpart occurs in the Orocopia Range in California.

Another possible belt trends northwest and includes the Cambridge Arch in southwest Nebraska (*6*), the Laramie Range in southeast Wyoming, the Bitterroot Range east of the Idaho batholith in Montana, and the Boehls Butte area west of the Idaho batholith in Idaho.

No anorthosite is known in the eastern United States south of Roseland, Virginia. A potassic anorthosite at Pluma Hidalgo, Oaxaca, Mexico (*7*), however, is remarkably similar to that at Roseland, Virginia. Both have andesine antiperthite megacrysts and abundant rutile. Anorthosite is also found in the Sierra de Santa Marta in northwestern Colombia (*8*). Both the Mexican and Colombian anorthosites are in isolated mountain blocks of Precambrian age whose original positions relative to the Precambrian of the Piedmont belt are unknown.

Remarkably, these anorthosites appear to lie in belts, but the belts are not related to any known Precambrian tectonic directions. If plotted on Fitch's (*9*) reconstruction showing the structural unity of the North Atlantic, most anorthosites lie in the Grenville province but are older than Grenville. However, they also appear in younger provinces as nappes or windows as well as in older provinces. Kranck (*10*) has already pointed out that the Canadian anorthosites do not seem to be related to known directions of Precambrian folding in the Canadian Shield.

On Du Toit's reconstruction of Gondwanaland (*3*), the Southern Hemisphere anorthosite belt (Fig. 2) begins in the west at Capivarito, Brazil, extends east to southern Angola, Tanzania, Madagascar, Queen Maud Land in Antarctica, the Eastern Ghats of India, and possibly into the Musgrave Ranges of Australia. Another belt (not shown) is in eastern Siberia made up of the Dzhugdzhur complex and southern Aldan Shield anorthosites.

Many modern reconstructions place Madagascar opposite Mozambique and Tanzania. The Precambrian stratigraphy of Mozambique and Tanzania, however, does not match that of Madagascar (*11*), but this disparity is overcome by placing Madagascar opposite Kenya and Somalia, as suggested by Du Toit and by the trend of the anorthosite belt. It is difficult to confirm the Madagascar-Somalia fit because of extensive Cenozoic cover in Somalia (*12*).

Fig. 2. Anorthosites of the Southern Hemisphere plotted on the Gondwanaland reconstruction of Du Toit (*3*). Anorthosites referred to in the text: 1, Capivarito, Brazil; 2, southern Angola; 3, Upangwa, Tanzania; 4, Madagascar; 5, Eastern Ghats, India; 6, Musgrave Ranges, Australia; and 7, Queen Maud Land, Antarctica.

Direct dating of anorthosites has generally proven difficult because of low rubidium content. Although some anorthosites have relatively high potassium, almost all have been subject to one or more periods of metamorphism that effectively reset their K^{40} "clocks" to younger dates. Limiting ages can be set in many cases by dating igneous and metamorphic rocks such as charnockites and pyroxene granulites that are closely associated in time with anorthosite and that intrude or are intruded by anorthosite. Direct dating by Sr/Rb- or Pb-isotope techniques has been tried with accessory minerals of pyrogenic origin, including zircon or apatite, or biotite and amphiboles which are more abundant although paragenetically of late or metamorphic origin. When all available dates are compiled, except for some from the U.S.S.R., they concentrate at about 1300 ± 200 million years (Table 1).

The material so dated could only set limits for and not give the actual time of anorthosite emplacement, thus explaining many of the discrepancies in ages. The belt that begins in the Ukraine (Fig. 1), for example, has apparent ages of 1750 million years for the Korosten Complex in the southeast, 1300 to 1500 million years for the Korsun-Novomirgorod, 1250 to 1350 for the Podlasie region in northeastern Poland, and >1000 for the southern Norwegian anorthosites.

Despite our ignorance of significance of anorthosite dates and distribution, there is a large body of evidence bearing on anorthosite origin. Most workers, whether they subscribe to a magmatic, metasomatic, or anatectic origin or all three, agree that high pressure and high temperature are necessary for the formation of anorthosite. Field evidence shows an invariable association with highest metamorphic grade rocks of the granulite facies and the presence of huge plagioclase crystals of intermediate composition, which are molten under dry conditions at about 1400°C. Analytical and experimental data also suggest high pressures and temperatures that can only exist in the lowermost crust or uppermost mantle.

Heath (*13*) reported that initial Sr^{87}/Sr^{86} ratios of anorthosites range from 0.703 to 0.706, or about the same as continental basalt, thus implying an upper mantle–lower crust origin. Taylor (*14*) reported an excess of O^{18} in anorthosites of 5.8 to 7.5 parts per million, which is about equal to basalt and gabbro. Reynolds and others (*15*) found that Adirondack anorthosite had an average K/Rb ratio of about 1500, similar to basaltic achondrites and oceanic tholeiite. As Rb is known to be enriched in the upper part of the crust, this Rb deficiency, as well as the low Sr^{87}, suggests impoverishment in crustal materials. The Roseland anorthosite also has a high K/Rb ratio of about 2000 (*16*).

Buddington (*17*) suggested that a liquid of gabbroic anorthosite composition might have been formed in the uppermost mantle or lowermost crust at a time of abnormally high temperature gradients. Fractional melting of mafic, ultramafic, or gabbroic material with attendant high pressure, including high partial pressures of H_2O and CO_2 could only have taken place at an intermediate time in earth history. According to this hypothesis, the earth has cooled too much since the Precambrian to allow formation of any Phanerozoic anorthosites. Although physical parameters for its formation cannot easily be set, high pressures and temperatures were obviously needed to form anorthosite.

Among explanations for anorthosite formation, ages, and distribution are those based on cataclysm and those based on inferences from the earth's early thermal history.

A cataclysmic event, such as the birth of the earth-moon system which has been set at 500 to 2000 million years by paleontological evidence (*18*) was responsible for a heat pulse that raised the geothermal gradient. The heat pulse was transferred to the earth, and it was both introduced and dissipated over a short period during which the parent anorthositic magma was formed in the lower crust or upper mantle. To judge by the cluster of anorthosite ages about 1300 million

Table 1. Age determinations on anorthosites and related rocks; m.y., million years.

Site	Age (m.y.)	Notes
	Africa – Asia – Australia	
Southern Angola (*22*)	1260 ± 90	By Nicolaysen on muscovite in pegmatite with Rb/Sr. Considered minimum age for anorthosite.
Upangwa, Tanzania (*23*)	1712 ± 70	K/Ar date on muscovite (1720) and biotite (1705) from leucocratic gneiss at Igawa; considered correlative with Ubendian. Anorthosite complex about 100 km away is also part of Ubendian system. Dating is thus tenuous.
Eastern Ghats, India (*24*)	1300–1520	Emplacement of charnockites using whole-rock Rb/Sr ages.
Musgrave Ranges, Australia (*25*)	1390 ± 130	Nine pyroxene granulites for Rb/Sr isochron.
Stanovoi Region (*26*) Aldan shield, Siberia (*26*)	< 1800–2000 > 1550–1600	Intrusion of anorthosites and syenites.
Dzhugdzhur Massif, Siberia (*27*)	2250 ± 150	Pb^{207}/Pb^{206} on two apatites from anorthosite, 2260 and 2240 m.y.; Pb^{206}/U^{238}, 1580 and 1650 m.y.; Pb^{207}/U^{235}, 1900 and 1930 m.y.; 2250 m.y. is from Concordia plot.
Anabar Massif. Siberia (*28*)	1734	K/Ar on hornblende from gabbro anorthosite Irkutsk.
	North America – South America	
St. Joe (Boehls Butte), Idaho (*29*)	1200	Age of sill amphibolite considered comagmatic with anorthosite.
San Gabriel Range, California (*30*)	⩾ 1200	Pb/U on zircon from cross-cutting pegmatite.
Laramie Range, Wyoming (*31*)	> 1335 ± 30 < 1715 ± 60	Sherman granite (1335) intrudes anorthosite which in turn intrudes gneiss complex (1715). Whole-rock Rb/Sr isochrons.
Cambridge Arch, Nebraska (*6*)	> 1170, < 1700 prob. 1300–1360	1170 is age of cataclasis, 1700 is age of basement rock; 1300–1360 is thermal event.
Duluth Gabbro Complex, Minnesota (*32*)	1115 ± 15	Pb/U concordia on zircon concentrates.
Canada (*33*)	1370	Date of Elsonian orogeny and anorthosite emplacement.
Adirondacks, New York (*34*)	1125 ± 10	Pb/U ages on zircon.
Roseland, Virginia (*35*)	1100	Date on charnockitic rock about 110 km northeast of Roseland, considered equivalent to charnockite at Roseland (*16*). Pb/U ages on zircon are from 1070–1150; Rb/Sr and K/Ar on biotite are 890 and 800.
Michikamau, Labrador (*36*)	1400 ± 80	K/Ar on biotite in cross-cutting granite gave 1360 ± 80 and on intruded metasedimentary rocks 1520 ± 85.
Kiglapait, Labrador (*37*)	1480 ± 50	K/Ar on biotite in granodiorite intrusive.
Sierra de Santa Marta, Colombia (*38*)	1380	Rb/Sr isochron on Dibulla gneiss, granulite facies.
Gardar, Greenland (*39*)	1150–1335	K/Ar on biotite from granite and on phlogopite-talc from ultrabasic rocks.
and (*40*)	1250–1300	Anorthosite xenoliths in Narrsaq gabbro of Mid-Gardar period of dike formation. Anorthosite itself gave 1025 on K/Ar in biotite and 1075 on K/Ar in augite which represents a later thermal event.
	Europe	
South Harris, Outer Hebrides (*41*)	1450 ± 30 1530 ± 30	Date is Sr/Rb on biotite from pegmatite intruding metagabbro about 300 m from metagabbro-anorthosite gneiss contact.
Southern Norway (*42*)	> 1000	Emplacement of para-anatectic anorthosites and cogenetic rocks.
Podlasie region, Poland (*43*)	1250–1350	Charnockitic localities not given, but this is same region as the anorthosite of Suwalki.
Korosten Complex, Ukraine (*44*)	1750	Gabbro and rapakivi granites; "Labradorites" grade into both.
Korsun—Novomirgorod, Ukraine (*44*)	1300–1500	Alkaline gabbro and granite. "Labradorites" grade into monzonites and gabbros.

years, the thermal event must have only occurred once.

Another cataclysm is meteorite impact, suggested by the Sudbury lopolith, a possible astrobleme just to the north of the anorthosite belt in Canada. This may have triggered the rise of anorthosite diapirs and is tied in to the explanations below. The Sudbury lopolith has been dated at about 1700 million years (*19*).

Anorthosite formation and emplacement might have been a normal event for an early time in earth history when a higher geothermal gradient existed than at present. Water and other volatiles were also being outgassed from the mantle and lower crust then and could have been trapped for a period long enough to assist in forming parent anorthositic magma. Under water pressures of 5 kb or more, plagioclase components tend to be enriched in a liquid of simplified basaltic compositions (as a diopside-anorthite system) that might be typical of the upper mantle. The eutectic temperature is also lowered, from 1274° to 1095°C, and the eutectic composition shifted from 42 to 73 percent anorthite (*20*). When outgassing resumed anorthosite would tend to rise diapirlike because of its density (± 2.73), and anorthosite plutons would be emplaced. Large-scale granitic and rhyolitic activity that took place just south of the anorthosite belt, from eastern New Mexico to western Ohio about 1200 to 1400 million years ago (*6*) may also be related to this anorthosite event.

If anorthosite plutons did arise diapir-like only during a limited period in the Precambrian, there may be a significant discontinuous layer still present in the continental crust, probably corresponding to the Conrad discontinuity (*21*).

Whether or not any explanation offered here proves acceptable, the fact that anorthosites are limited in time and space requires an explanation.

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Generation and Maintenance of Gradients in Taxonomic Diversity

Abstract. *Latitudinal gradients in diversity of organisms represent an equilibrium distribution for at least the last 270×10^6 years. Faunas endemic to tropical regions evolved significantly faster than extra-tropical faunas. The latitude-dependent difference in rates of evolution also represents an equilibrium condition for at least the last 270×10^6 years and has consequences for paleontological correlation of rocks because the attainable resolution depends on rate of evolution and will thus be greater in tropic regions than in extra-tropical ones.*

Latitudinal gradients in taxonomic diversity of organisms have recently been accorded attention by geologists because of their implications about past environments and possible continental movements. For such geological studies it is sufficient to know that an empirical relationship exists between diversity of organisms and latitude. The associated problem of identifying mechanisms by which diversity gradients are generated and maintained is biological rather than geological. It appears, however, that the perspective of geological time, permitting consideration of the evolutionary history of organisms, may constrain the number of possible mechanisms.

Strong diversity gradients sloping poleward from the equator are characteristic for widely distributed, large groups of living organisms having a good distribution potential. Such gradients characterize diversity among genera and families, as well as among species (*1*). The fact that gradients are strongly expressed among higher taxa suggests but does not prove that they have existed for a long time. In considering the equilibrium condition of this biological pattern the realm of geology is entered, for the problem is dependent on the scale of geological time.

The equilibrium condition of this pattern can be tested by examining the diversity of well preserved, adequately collected, and extensively studied fossil groups. We have chosen for this purpose two widely distributed invertebrate groups, Permian brachiopods and Cretaceous planktonic foraminifera.

In the region for which we have data (Northern Hemisphere) for the Maestrichtian interval of the Cretaceous (about 70 to 80×10^6 years B.P.) a typical diversity gradient existed among species of Cretaceous planktonic foraminifera (Fig. 1). This gradient existed despite the fact that climatic belts in the Cretaceous apparently were ill-defined, and world climate was milder than at present with a concomitant reduction in slope of the

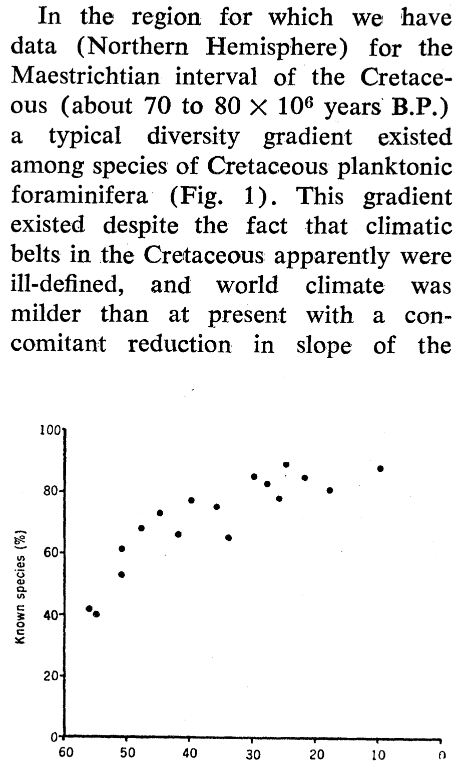

Fig. 1. Diversity among species of Maestrichtian planktonic foraminifera in the Northern Hemisphere as percent of total number of species known plotted against latitude. The gradient in diversity is similar to that typically found in living organisms.