**TYPES AND CHARACTERISTICS OF TERRESTRIAL ANORTHOSITES;**

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Basalt is the most abundant rock type in the crusts of the terrestrial planets, and for this reason alone it is worthy of study (1). By contrast, anorthosite seems a minor constituent of the solar system, although present in large quantities in certain places such as the lunar crust and the Grenville Province of the Canadian Shield. The fundamental processes involved in the origin of basalt are well understood: it is a mantle-derived partial melt of peridotite. A similar fundamental statement cannot be made about the origin of anorthosite. Anorthositologists cannot yet agree as to a crustal- or mantle-derived origin for the parental melts of their rocks, let alone what the composition of these melts was. Anorthosite, therefore, might be considered even more worthy of study than basalt.

Terrestrial anorthosites are perceived by many as being uniquely Precambrian rocks, most of which formed during a catastrophic anorthosite "event" about one billion years ago. This is a myth. Anorthosite has been produced over the entire span of geologic time, and is forming now. Although many large anorthosite massifs are Proterozoic, their ages range between about 1.0 and 1.7 Ga, and possibly as far back as 2.4 Ga. There is no evidence for a distinct anorthosite event. Other mythology includes the connection between anorthosite formation and granulite facies metamorphism, and the notion that Archean calcic anorthosites are metamorphosed equivalents of layered mafic intrusions such as the Bushveld or Stillwater. We offer the following as a provisional classification of terrestrial anorthosite types.

**1. ARCHEAN MEGACRYSTIC ANORTHOSITES.** These are composed of equidimensional, calcic ($An_{75-90}$), plagioclase megacrysts (1-30 cm across) in a mafic groundmass of broadly basaltic composition (2). Most occurrences are small (<500 $km^2$) and are associated with mafic metavolcanics of Archean greenstone belts to which they are likely genetically related. All metamorphic grades between greenschist and granulite are represented. Examples include Bad Vermilion Lake (Ontario) (greenschist) (3) and Fiskenaesset (West Greenland) (granulite) (4). A few high grade complexes such as Sittampundi (India) and Messina (So. Africa) are associated with marbles, quartzites and schists, possibly suggesting a different geologic setting from those above (5,6). Ultramafic rocks are present in some complexes, but in general the bulk compositions are far more feldspathic than those of typical layered mafic intrusions (7). Some complexes contain concentrations of Fe-Ti oxides and/or chromite. Isotopic and geochemical studies support an origin of these anorthosites as cumulates from mantle-derived mafic melts, but the mechanisms for concentrating large volumes of equant, euhedral, calcic plagioclase megacrysts are uncertain. Many tectonic settings have been proposed (4), but the common association with mafic pillow lavas of greenstone belts suggests an oceanic environment (8).

**2. MASSIF-TYPE ANORTHOSITES.** These are the most voluminous of terrestrial anorthosites, occurring as multiple intrusive complexes of up to 2 x $10^4$ $km^2$ in area, and composing up to 20% of some Proterozoic orogenic belts such as the Grenville Province of the Canadian Shield (9). Many, though not all, have suffered high-grade metamorphism at about 1 Ga, but recent isotopic work (10) shows that primary ages range at least between 1.0 and 1.7 Ga, thus arguing against a distinct, catastrophic anorthosite "event." The rocks are characterized by coarse (up to several m), lathy plagioclase ($An_{40-65}$). Andesine + low-Ca pyroxene and labradorite + olivine types can be distinguished. Mineralogy, geochemistry, and isotopes suggest that these anorthosites are cumulates from mantle-derived melts, but the high Fe/Mg and Na/Ca suggest relatively large degrees of fractionation. Many massifs contain sizeable concentrations of ilmenite and magnetite. Massifs were emplaced into continental crust, which may have acted as a density barrier to rising mantle-derived mafic melts. Flotation cumulates of plagioclase formed, and ascended as mushes to upper crustal emplacement sites. Associated granitic rocks (charnockites and/or rapakivi granites) are not consanguineous, and may have formed by partial melting during and after emplacement (9-11).

**3. ANORTHOSITES OF LAYERED MAFIC INTRUSIONS.** Anorthosite and leucogabbroic rocks constitute major fractions of many layered mafic intrusions (LMI). Well known examples include Stillwater (Montana) (12), Bushveld (South Africa) (13), and Dufek (Antarctica) (14). Unlike types 1 and 2, this anorthosite association is not temporally restricted. Anorthosite-bearing LMI can be found of Archean through Tertiary age. Pyroxenes, olivine, and Fe-Ti oxides are common accessory minerals. In general, Fe/Mg and Na/Ca in rocks and minerals increase with stratigraphic height, and the positive slopes produced on En-An diagrams can be attributed to a "normal" fractionation trend. In some LMI such as Dufek, there is a range of plagioclase composition in anorthosites ($An_{50-80}$), related to stratigraphic position (15). In the Stillwater, anorthosites have relatively constant plagioclase compositions ($An_{75-80}$) but constituent mafic silicates vary widely in Fe/Mg, a situation similar to that in lunar anorthositic rocks (16). Anorthositic rocks of LMI are host to a variety of mineral deposits, including platinum group elements, Fe-Ti oxides (some V-bearing), and chromitites. Although

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there is little doubt that LMI crystallized from mantle-derived magmas, the composition of the melt(s) is unknown in detail, as are the relative roles of classical gravitational accumulation, adcumulus growth, infiltration metasomatism, and double diffusive convection in producing the anorthosites.

Some anorthosite-bearing layered intrusions lack large volumes of ultramafic rocks, and therefore have more feldspathic bulk compositions, approaching leuconorite or leucotroctolite. Examples include: Duluth (Minnesota), Kiglapait (Labrador), Mulcahy (Ontario), and Sept Iles (Quebec). Some of these intrusions show other features intermediate between LMI and massif-type complexes, suggesting the possibility of a continuum of processes relating types 2 and 3 (17).

**4. ANORTHOSITES OF OCEANIC SETTINGS.** Anorthosites and a variety of other plutonic rocks including gabbros, troctolites, and Fe-Ti oxide rich samples have been recovered by dredging in the ocean basins. Both mid-ocean ridge and fracture zone settings are represented (18). In those few samples that have been analysed, plagioclase varies between $An_{68}$ and $An_{75}$. Common accessory mafic silicates are olivine and/or clinopyroxene. These rocks are thought to represent cumulates formed by crystallization of basaltic magmas (18,19). Thin (< a few tens of cm) anorthosite layers also compose minor parts of cumulate sequences in ophiolitic complexes, including Bay of Islands (Newfoundland) (20) and Oman (21).

**5. INCLUSIONS IN OTHER IGNEOUS ROCKS.** Anorthosites occur as inclusions in a variety of other igneous rock types, and represent either accumulations of plagioclase from the same magmas as their host (cognate inclusions), or fragments of older anorthosite picked up during ascent (xenolithic inclusions). An example of the former are the Gardar intrusions of South Greenland, where inclusions of up to several thousand $m^2$ in area occur in alkalic basalts (22). Similar inclusions occur in basalts from Hawaii (23) and Iceland (24). A variety of plutonic rocks, including gabbroic and anorthositic types with calcic plagioclase ($An_{85-100}$) are found in calc-alkaline plutons (Peninsular Batholith, Calif., ref. 25) and volcanoes (Soufriere, West Indies, ref. 26). These materials are thought to play an important role in calc-alkaline fractionation trends (25,26). A spectacular example of the xenolithic type is found along the northwestern shore of Lake Superior (Minnesota), where anorthosite ($An_{80}$) xenoliths ranging in size between 1 $km^2$ and 1 $cm^2$ occur in the Beaver Bay diabase (27). Xenoliths of anorthosite also occur in granitoid plutonic complexes (28).

**6. OTHER TYPES.** Several isolated anorthosite occurrences defy the above classification scheme. The Boehl's Butte (Idaho) and Bitterroot (Montana) anorthosites include a variety of compositional types ($An_{25-100}$), and occur as lenses in Proterozoic schists and quartzites. They have been suggested to represent refractory residues produced during crustal anatexis (29), and if so, are the only anorthosites known that have not crystallized directly from a silicate melt. In the Air massif of West Africa, anorthosites (avg. $An_{60}$) occur as a major component of Paleozoic hypabyssal ring complexes, and show spectacular radially symmetrical crystal orientation (30). These occurrences are worthy of further study.

We thus distinguish six types of anorthosite on earth; lunar (and Mercurian?) anorthosites represent a seventh type (**EXTRATERRESTRIAL**). Just as there are seven kinds of ambiguity (31), there appear to be seven kinds of anorthosite.

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