Black Giants Anorthosite, New Zealand: A Paleozoic analogue of Archean stratiform anorthosites and implications for the formation of Archean high-grade gneiss terranes

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ABSTRACT

The Black Giants Anorthosite, a mid-Paleozoic (349 ± 5 Ma U-Pb zircon age) layered anorthosite complex in Fiordland, New Zealand, bears striking compositional and lithologic similarities to Archean stratiform anorthosites and, like many of its Archean counterparts, occurs within a high-grade gneiss terrane, preserving a record of metamorphism at mid-crustal depths followed by higher-pressure metamorphism and burial to lower-crustal levels. These and other similarities point to formation of the Black Giants Anorthosite and its Archean equivalents in comparable tectonic environments, most likely a subduction-related magmatic arc which, in the case of Fiordland, resulted from plate convergence along the Pacific margin of Gondwana.

INTRODUCTION

Plate tectonic models for the Archean commonly attract considerable controversy because they accommodate rock assemblages for which there are few obvious analogues in the Phanerzoic rock record. Archean stratiform anorthosite complexes are an important example, the origin and tectonic setting of which have long been problematic (e.g., Windley, 1970; Windley and Smith, 1976; Ashwal, 1993). These anorthosite complexes are characterized by unusually calcic plagioclase (An80–100) and, compared to layered intrusions of Proterozoic and younger age, are deficient in complementary mafic and ultramafic rocks (Windley, 1970; Barton et al., 1979; Phinney et al., 1988; Ashwal, 1993). They are also commonly among the largest and most pristine igneous bodies preserved in Archean high-grade gneiss terranes, and consequently serve as an important source of information about ancient magmatic environments and the geochemistry and isotopic composition of the Archean mantle (see Ashwal, 1993, for review).

However, beyond a few possible analogues identified in ophiolite complexes (Phinney et al., 1988; Ashwal, 1993) and the root zones of subduction-related calc-alkaline batholiths (Windley and Smith, 1976), Phanerozoic equivalents of these anorthosites have yet to be recognized in any great number. Here we report U-Pb zircon ages and other data for a mid-Paleozoic equivalent in Fiordland, New Zealand, hosted by amphibolite facies gneisses representing the lower structural levels of a deeply eroded Paleozoic-Mesozoic magmatic arc. The occurrence of this anorthosite in regionally metamorphosed high-grade gneiss terranes, and consequently serve as an important source of information about ancient magmatic environments and the geochemistry and isotopic composition of the Archean mantle (see Ashwal, 1993, for review).

The Black Giants Anorthosite (Fig. 1) is an incomplete, regionally metamorphosed layered intrusion consisting predominantly of anorthosite, gabbric anorthosite, and amphibolite with subsidiary amounts of interstratified hornblende schist, metatampholite, and metaperidotite (Gibson, 1979a, 1979b, 1982). Contacts with the underlying country rocks (Deep Cove Gneiss and Townley Calc-silicate) are faulted (Fig. 1), and the Black Giants Anorthosite unconformably overlies a thick sequence of regionally extensive paragneisses, marbles, calc-silicate rocks, and minor pelitic schist derived from Cambrian–earliest Ordovician protoliths of shallow-marine origin (Gibson, 1982; Gibson and Ireland, 1996). The upper contact is concordant and juxtaposes the Black Giants Anorthosite against a 1000-m-thick sequence of quartzofeldspathic gneisses, amphibolites, and hornblende-garnet-biotite gneisses (Lyvia Gneiss; Fig. 1) thought to be former volcanic and/or plutonic rocks (Gibson, 1982). Mineral assemblages in these rocks, the Black Giants Anorthosite, and the underlying metasedimentary units are isofacial and formed in response to a common geologic history involving mid-Paleozoic orogenesis followed by further deformation and metamorphism in the late Mesozoic (Gibson et al., 1988; Ireland and Gibson, 1998). The total preserved thickness in the Black Giants Anorthosite is 600–800 m; the strike length is 12 km (Fig. 1), and more than 40 km if isolated outcrops of anorthosite on several neighboring peaks are taken into account (Gibson, 1982). Exhumation of the anorthosite complex and its country rocks was through Early Cretaceous extension combined with late Tertiary transpression on the Alpine fault (Gibson et al., 1988; Ireland and Gibson, 1998).

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Data repository item 9913 contains additional material related to this article.
Despite the intensity of deformation and metamorphism, relict igneous layering is preserved at all scales (millimeter to meter) within the Black Giants Anorthosite (Gibson, 1979a, 1982), mirroring the situation in other layered intrusions where magmatic differentiation has occurred. Magmatic differentiation is not only evident in the systematic repetition of felsic and mafic layers (Gibson, 1979a, 1982) but also in the change to progressively more Fe-rich bulk compositions with increased stratigraphic height within the intrusion (Gibson, 1979a). Normative-mineral calculations performed on whole-rock chemical analyses show a corresponding shift in normative olivine and pyroxene compositions toward their respective Fe end members (Gibson, 1979a). However, save for a few relict patches of olivine, pyroxene, and dark titaniferous hornblende preserved in some of the more competent, and least-deformed metaperidotites, little remains of the original magmatic mineralogy and textures. Rather, recrystallization is pervasive, and most rocks now comprise varying proportions of calcic plagioclase (An₈₀₋₉₆), pale green tschermakitic-pargasitic hornblende, phlogopite, kyanite, staurolite and rutile; corundum, gedrite, and almandine garnet are less common (Gibson, 1979a, 1979b, 1982). Grain size in the anorthosite layers averages 2–6 mm, although this is largely the result of metamorphic recrystallization, and plagioclase crystals in some rocks may once have been significantly larger. Original grain size is better gauged from the less-strongly deformed metaperidotites, where centimeter-sized plates of pyroxene and hornblende still persist.

**STRUCTURAL AND METAMORPHIC HISTORY**

Like many of its Archean counterparts, the Black Giants Anorthosite is hosted by country rocks that have undergone multiple deformation (D₁–D₃) and high-grade metamorphism (M₁–M₃) (Table 1). D₂ structures predominate in the Black Giants Anorthosite and range from a prominent kyanite lineation contained within the D₂ regional schistosity to kilometer-scale isoclinal folds with variably sheared lower limbs and a conspicuous axial-planar foliation defined by hornblende and phlogopite. These folds originated during kyanite-grade regional metamorphism (M₂) and deform an earlier layer-parallel fabric defined in part by oriented gedrite. Gedrite forms part of the M₁ assemblage (Table 1) and is thought to have developed contemporaneously with low-pressure-high-temperature metamorphism (M₁) in the country rocks, relics of which persist as inclusions in garnet or as complete sillimanite–K-feldspar ± cordierite assemblages (Gibson et al., 1988; Bradshaw, 1989; Ireland and Gibson, 1998). Metamorphic conditions for M₁ are estimated as 4–6 kbar and 640–680 °C (Table 1), whereas kyanite-grade metamorphism (M₂) took place at lower-crustal depths and higher pressures (7–9 kbar) (Gibson, 1979a; Gibson et al., 1988; Bradshaw, 1989; Brown, 1996).

Following D₂ deformation, the Black Giants Anorthosite was intruded by felsic dikes and subjected to subvertical flattening attendant on late Mesozoic extension (D₃), leading to isoclinal folding of the dikes and further tightening of the D₂ folds. Metamorphic mineral assemblages (M₃) in these dikes contain biotite, muscovite, and almandine garnet, thereby permitting an estimation of metamorphic conditions during the initial stages of D₃ extension. Pressure estimates (7–9 kbar; Table 1) for M₃ are identical to those obtaining during M₂, indicating that the Black Giants Anorthosite was still at lower-crustal depths when dike intrusion took place. A magmatic age of 114 ± 2 Ma (2σ) obtained by ion microprobe from one dike (Fig. 2A; sample 94-183) further constrains the age of D₃ extension and associated exhumation to be no earlier than late Mesozoic, by which time the earlier-formed hornblende- and kyanite-bearing assemblages in the anorthosites had been partially overprinted (M₃) by chlorite, clinozoisite, and margarite. Margarite formed through various reactions, including the pressure-sensitive breakdown of coexisting kyanite and clinozoisite (Gibson, 1979b), and originated in response to rapid decompression accompanying the D₃ deformation.

**GEOCHRONOLOGY**

In addition to the felsic dike (sample 94-183), two other samples from the Black Giants Anorthosite were dated by ion microprobe: a weakly foliated anorthosite (sensu stricto) containing <5% hornblende (sample 94-182) and a lens of mylonitized country rock (kyanite-garnet-hornblende gneiss; sample 94-147) that underwent extensive recrystallization accompanying, or immediately following, magmatic intrusion. An amphibolite dike (sample 94-185) thought to be a manifestation of the same magmatic event that gave rise to the anorthosite was also dated (see following). This amphibolite intrudes 480 Ma granitic orthogneiss at Kellard Point (Fig. 1) and yielded abundant pale pink, sometimes turbid, euhedral to subhedral zircon grains with rounded ends and lengths of 50–100 μm. In contrast, zircon from the two Black Giants samples (16–18 crystals per sample) is coarser

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*Note:* 1—Biotite-garnet thermometry (Ferry and Spear, 1978); 2—Garnet-plagioclase-quartz-Al₂O₃ geobarometry (Newton and Haselton, 1981); 3—Hornblende-garnet thermometry (Graham and Powell, 1984); 4—Garnet-plagioclase biotite-muscovite barometry (Ghent and Stout, 1981); 5—from Gibson (1979b).
the formation of gedrite at the expense of pyroxene and olivine.

with intrusion during the waning stages of M1 metamorphism (D1 deforma-

tion) identical to that of metamorphism in the kyanite-garnet gneiss. Di-
cline-zoned zircon cores are dated as 349 ± 7 Ma age that is identical to age of zircon cores in anorthosite. Only minor Pb loss is apparent. These zircons probably formed during metamorphism attendant on intrusion of host anorthosites. D: Post-M1, pre-M2 amphibolite dike from Kellard Point (94-185). U-Pb data are consistent with mid-Paleozoic intrusion, but most zircons have undergone later Pb loss.

U-Pb zircon ages from the amphibolite dike (sample 94-185) range from 200 to 380 Ma (Fig. 2D) and thus preclude a precise determination of the time of emplacement. Fiordland is host to many such dikes and, although a precise age may not yet be available for them, it is nevertheless ev-

ident from their field relations and the few data reported here (Fig. 2D) that dike intrusion must have occurred between 380 and 330 Ma, and thus in the same time interval as the Black Giants Anorthosite. Several cut across the D1 structures and associated M1 metamorphic fabric, and a significant number have intruded the 350–370 Ma (Oliver, 1980; Bradshaw and Kim-
brough, 1991) granitic orthogneisses of central Fiordland. It is equally clear that dike intrusion must have occurred before 330 Ma, because many amphibolite dikes contain almandine garnet and have been overprinted by the D2 deformation and accompanying 330 Ma kyanite-grade metamorphism (Ireland and Gibson, 1998). It follows that the spread of zircon ages shown in Figure 2D is the result of several different events, including dike intrusion ca. 350–380 Ma followed by metamorphism and substantial resetting of the U-Pb isotopic system during later events. Dike intrusion and emplacement of the Black Giants Anorthosite are thus probably related to a single episode of mid-Paleozoic basaltic magmatism. Moreover, in view of the large num-

ber of dikes intruded, magmatism was most likely extensional in origin. Mid-Paleozoic magmatism and extension have also been documented in the contemporaneous and formerly contiguous, but less-deeply exposed, Lach-
lan fold belt of southeast Australia (Collins and Vernon, 1994; Zen, 1995).

DISCUSSION

In common with many Archean anorthosites (Windley, 1970, 1973; Barton et al., 1979; Ashwal, 1993), the Black Giants Anorthosite is multi-

ply-deformed and occurs within a high-grade gneiss terrane. Other similarities include its sheet-like form, a comparable degree of internal stratifica-
tion, and emplacement of the parental magma at shallow crustal depths (Weaver et al., 1981; Ashwal, 1993) before high-grade metamorphism and subsequent burial to deeper crustal levels. It is also compositionally and lithologically indistinguishable from many stratiform Archean anorthosites: its plagioclase is in the same compositional range (An90–100), and there is a predominance of felsic over mafic and ultramafic lithologies (cf. Ashwal, 1993). Their respective mineralogies also appear to have been very similar before metamorphism with both olivine and pyroxene represented in the original magmatic assemblages. The parental basaltic magma for the Black Giants Anorthosite may even have been hydrous, like that of the Fiskeneset set intrusion (Greenland) (Windley et al., 1973), as evidenced by the persis-

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tence of original titaniferous hornblende in some of the less strongly deformed metapelite.

Archean anorthosites have been compared to anorthosites in the root zones of exposed Early Cretaceous calc-alkalic batholiths (Windley and Smith, 1976). Formation in an oceanic tectonic setting has also been considered (Weaver et al., 1981; Ashwal, 1993), although this interpretation is clearly inappropriate for the Black Giants Anorthosite and several Archean anorthosites such as the Messina and Sittampundi complexes (Barton et al., 1979; Ramadurai et al., 1975), all three of which were intruded into shallow-marine continental-shelf sequences. An oceanic setting for the Black Giants Anorthosite is also difficult to reconcile with the large volume of granite intruded into the Fiordland graniteneighbours from both after and after intrusion of the anorthosite. Mid-Paleozoic granite intrusion in Fiordland resulted from plate convergence and subduction along the Pacific margin of Gondwana, and occurred intermittently from 480 to 320 Ma (Gibson and Ireland, 1996; Ireland and Gibson, 1998). Moreover, both tonalite and granodiorite are well represented in Fiordland (Gibson, 1982; Bradshaw and Kimbrough, 1991), mirroring the compositional range of granites in some Phanerozoic magmatic arcs and many older Archean terranes (Windley and Smith, 1976). The tectonic setting of Fiordland in mid-Paleozoic time was probably not unlike the situation prevailing today in the Andes and North American Cordillera. In these two regions, subduction-related calc-alkalic magmatism was superseded by rifting and backarc extension (Coney and Harms, 1984; Petford and Atherton, 1995). The Black Giants Anorthosite postdates the main phase of mid-Paleozoic calc-alkalic magmatism in western New Zealand at 360–370 Ma (Ireland and Gibson, 1998; Muir et al., 1996) and was most likely intruded into continental crust undergoing extension as a result of thermal weakening induced by the earlier magmatism and associated low-pressure–high-temperature metamorphism. Emplacement into an extensional environment is also supported by the style of metamorphism and volume of contemporaneous mafic dike injection. The complex was then metamorphosed and buried to lower crustal depths before exhumation in late Mesozoic time following the onset of continental extension associated with opening of the Tasman sea (Gibson et al., 1988). Several Archean anorthosites (e.g., Messina; Barton et al., 1979) exhibit a comparable history of mid-crustal emplacement and metamorphism before deep burial and subsequent exhumation, and most likely formed in an equally active tectonic environment. They also probably formed in a subduction-related magmatic arc setting, thereby lending strong support to previous suggestions (Windley and Smith, 1976) that convergent plate margins are a plausible tectonic setting for the formation of many Archean anorthosites and Archean high-grade gneiss terrains in general.

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