The internal structure and geochemistry of many Phanerozoic ophiolites show a complex pattern of igneous accretion that involved multiple stages and sources of melt evolution and life cycles in suprasubduction zone (SSZ) environments (Shervais, 2001; Dilek and Flower, 2003). Some of the most extensively studied Tethyan ophiolites appear to have developed, for example, in arc-forearc settings within restricted marginal basins, which were nested in older, preexisting oceans (Ishikawa et al., 2002; Dilek et al., 2008). The subduction of the ocean floor in these older basins, combined with slab rollback processes, facilitated ophiolite development in the extending upper plate within relatively short time spans (<10 m.y.). The SSZ ophiolites generated during these arc-trench rollback cycles commonly have structurally and geochemically heterogeneous crustal components attesting to the progressive evolution of their mantle melt sources. We discuss here that SSZ ophiolites, albeit with different internal structure and stratigraphy, are part of Archean greenstone belts, suggesting the operation of plate tectonic–like processes as early as 3.8 Ga in the Archean.

The Middle Jurassic Mirdita ophiolite (MO) in northern Albania contains a ~12-km-thick oceanic lithosphere with SSZ affinity. Different dike generations and lava units within the sheeted dike complex and in the extrusive sequence of the MO show a geochemical progression from older mid-oceanic ridge basalts (MORB) and basaltic andesites to younger dikes and lavas with compositions of basaltic andesite, dacite, and rhyolite. These more evolved rocks display island arc tholeiite (IAT) signatures characterized by progressive depletion in increasingly incompatible elements. Even younger dikes and lavas higher in the sequence have boninitic compositions, suggesting that their magmas were produced from partial melting of highly depleted, ultra-refractory harzburgites (Dilek et al., 2008). These late-stage dike and lava rocks show enrichment in the most-incompatible elements that likely resulted from subduction-derived fluids and from partial melting of subducted sediments (Plank and Langmuir, 1998).

The ~12–15-km-thick Cretaceous Semail ophiolite in Oman has a pseudostratigraphy reminiscent of fast-spreading modern oceanic lithosphere. Similar to the other SSZ Tethyan ophiolites, the Semail ophiolite also shows multiple stages of igneous accretion of its crustal units with different geochemical fingerprints (Alabaster et al., 1982). The layered gabbros, the majority of the sheeted dikes, and the basalts and pillow lavas of the lower extrusive sequence (Geotimes Unit) appear to have had common parental magmas with MORB-like geochemistry (Alabaster et al., 1982; Godard et al., 2003). These MORB-like plutonic and sheeted dike rocks are intruded by late-stage calc-alkaline plutons, and the basaltic Geotimes unit is overlain by pillowed to massive lava flows with basaltic andesite, dacite, and rhyolite compositions, making up the younger Lasail and Alley Units. The youngest dikes and lavas in the Alley Unit, some of the late-stage ultramafic intrusions in the lower crust, and harzburgitic host peridotites with orthopyroxene dikes all have boninitic compositions, representing refractory magma series derived from high degrees of partial melting of a depleted mantle source (Ishikawa et al., 2002; Tamura and Arai, 2006). These geological and geochemical features indicate a progressive evolution of the Semail magmas from initial MORB-like to IAT tholeiites to boninites over time.

SSZ ophiolites with similar crustal architecture and geochemical features as in the Tethyan ophiolites are common in the Neoproterozoic, for example, in the Neoproterozoic record (Kusky, 2004). Whether the Archean record of Earth’s crustal evolution includes SSZ ophiolites, however, remains a fundamental question because of its strong implications for the operation of modern plate tectonics in deeptime. The Archean greenstone belts, which contain widespread mafic-ultramafic rock assemblages, are likely candidates for including ophiolites. Some researchers, however, interpret them as anastomosing networks of synforms consisting of dense lavas that were caught up between diapiric batholiths and associated felsic crust (Hamilton, 2003). The origin of voluminous Archean komatiite-tholeiitic basalt association has been attributed to anomalously hot mantle plumes and much higher mantle temperatures and melting conditions than those in the Phanerozoic (Herzberg, 2004; Smithies et al., 2005). Such conditions in the Archean Earth are thought to have created crust that was far too hot, weak, and mobile to behave as rigid plates and to permit rise of dense melts (Hamilton, 2003).

Based on their geochemical similarities to Phanerozoic boninites, however, recent studies suggest subduction zone origin of some of the Archean komatiites (Parman et al., 2001). Furthermore, garnet-albite-bearing mineral assemblages from the mid-Archean Barberton greenstone-granitoid terrain reveal pressures of 1.2–1.5 GPa at temperatures of 600–650 °C, and signal high-pressure, low-temperature metamorphic conditions reminiscent of modern subduction zones (Moyen et al., 2006). This discovery suggests that lithospheric subduction was operating as early as 3.2 Ga. The reported occurrence of boninites, picrites, adakites, Mg-andesites, and Nb-enriched basalts, all subduction related, in the 3.8–2.5 Ga greenstone belts also supports the operation of modern convergent margin tectonics in the Archean (Smithies et al., 2007).

Given the occurrence of subduction-related volcanic rocks and metamorphic assemblages in the Archean geology, SSZ ophiolites should be found within greenstone belts. A careful examination of some of the Archean greenstone belts indeed shows that they represent highly deformed and dismantled SSZ ophiolites. Eo-to-Mesoproterozoic greenstone belts in southwest Greenland (e.g., 3800–3700 Ma Isua, ca. ~3075 Ma Ivisaartoq, 3070 Ma Ujarassuit) are composed mainly of metavolcanic rocks, metagabbros, and ultramafic rocks associated with metapelites, chert, banded iron formation (BIF), and felsic rocks. The Isua greenstone belt contains a sheeted dike complex locally grading upward into pillow lavas (Furnes et al., 2007). Both the sheeted dikes and pillow lavas in Isua display similar concentrations of incompatible elements and their ratios, suggesting that they are coegenetic. Compositionally, volcanic rocks in both the Isua and Ivisaartoq greenstone belts are dominantly tholeiitic basals, boninites, and picrites, with minor intermediate to felsic volcanic rocks (Polat et al., 2008). Trace element characteristics of the Archean metavolcanics are comparable to those of the ultramafic to mafic volcanic rocks occurring in modern subduction systems (e.g., Izu-Bonin-Mariana) and in the Phanerozoic ophiolites, displaying similar geochemical trends as discussed earlier.

These examples demonstrate that a hybrid mixture of MORB-like and arc-like element sig-
natures is a characteristic feature of Phanerozoic and Archean ophiolite sequences. This pattern reflects repeated melting of a MORB mantle source in a subarc-forearc wedge that has been modified by fluids released from subducting oceanic slab and sediment-derived melts. Our generic model for a SSZ origin of the Archean and Phanerozoic oceanic crust depicts melt generation, mixing, and differentiation at different pressure ranges in multiple levels within the sub-forearc mantle wedge (Fig. 1). Aggregation of melts results in melt production and modification in the mantle melt column, whose evolution is strongly affected by the return mantle flow that is driven by slab rollback and the arc-wedge corner flow (Dilek et al., 2008, and references therein). Slab rollback is faster than the convergence rates results in upper plate extension leading to seafloor spreading, proto-arc rifting, and formation of sheeted dike complexes. Late-stage boninitic magmas evolve from partial melting of relatively hot, hydrous, and ultra-refractory peridotite in the rapidly evolving suprasubduction mantle wedge.

Although Phanerozoic and Archean ophiolites may represent remnants of ancient oceanic lithosphere evolved in discrete, pre-collision subduction rollback cycles, Archean ophiolites differ from their Phanerozoic counterparts in their internal structure and chemostratigraphy. The occurrence of komatiites in Archean greenstone belts presents compelling evidence for a hotter mantle. Higher potential mantle temperatures are likely to have caused higher degrees of partial melting, resulting in the formation of thicker oceanic crust (>20 km) in the Archean than at present (~5–10 km). Nisbet and Fowler (1983) argued that Archean oceanic crust had an ultramafic (komatitic-picritic) bulk composition that formed at elevated temperatures (>1500 °C). In the Mesoarchean Ivisaaq greenstone belts, high MgO, Ni, and Cr concentrations and Mg-numbers in clinopyroxene cumulates and high-Mg pillow lavas are consistent with island arc picritic compositions (Polat et al., 2008). Ultramafic rocks and gabbros occur as sills in pillow lava sequences, and some gabbros are associated with anorthosite bodies and inclusions. Anorthosites commonly have higher initial εNd values than those of their gabbroic host rocks, suggesting different mantle-melt sources for their origin (Polat et al., 2008).

However, anorthosites and picritic lavas are isotopically comparable, indicating a petrogenetic link between them.

We suggest that typical Archean oceanic crust might have included a lower layer of anorthosites, gabbros, and mafic lavas with ultramafic sills and an upper layer of gabbro-dioritic sills, rare sheeted dikes, basaltic-to-picritic lavas, high-Mg andesites and IAT volcanics, and dunitic-to-wehlritic sills (Fig. 1). The lower layer represents the first stage of oceanic crust formation during the initial stages of subduction, whereas the upper layer characterizes the products of adiabatically upwelling ultramafic picritic melts intruding into the overlying volcanic rocks as sills and dikes at later stages of subduction in the presence of slab rollback-induced extension. The rare occurrence of or the lack of sheeted dikes can be explained by much higher spreading rates and higher mantle temperatures in the Archean than at present or in the Phanerozoic (Bickle, 1986; Hargraves, 1986). These conditions would hinder inelastic deformation facilitating fracture formation and propagation that is necessary for dike emplacement in a brittle stress regime.

The occurrence of SSZ ophiolites in the 3.8 Ga crust suggests that Phanerozoic-type seafloor spreading and subduction zone processes were operating at this time, and that hydrothermal cooling beneath spreading centers and sinking of rigid lithospheric slabs via subduction were already established by then. If so, this inferred plate tectonic regime in the Eoarchean marks a significant shift from the earlier thermal regime (Hadean-style thermal convection) of Earth.

REFERENCES CITED


