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The significance of subduction-related accretionary complexes in early Earth processes

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ABSTRACT

The transition from Hadean-style convective overturn, driven by heating from below, and Phanerozoic-style plate tectonics, driven by the sinking of cool lithospheric slabs, was a major turning point in the thermal evolution of the Earth. Prior to this transition the formation of stable, long-lived crust was rare; after this transition, the formation and amalgamation of continental crust became a central theme of tectonic processes. Evidence for Phanerozoic-style plate tectonics includes (1) the formation of oceanic crust at mid-ocean ridge spreading centers, (2) the formation of island arc volcanic and plutonic complexes, and (3) the formation of accretionary mélange complexes during the subduction of oceanic crust. Rock assemblages characteristic of oceanic crust and island arc suites may also be formed during Hadean-style convection, making the recognition of accretionary mélange complexes the most reliable indicator of Phanerozoic-style tectonics. Accretionary mélange complexes result from the juxtaposition of oceanic crust and pelagic sediments in a matrix of arc-derived constituents and may be recognized even after high-grade metamorphic events.

At least three potential Archean mélange complexes have been recognized to date: the Dongwanzi ophiolite mélange of the North China craton, the Schreiber-Hemlo mélange of the Superior province, and the Farmington Canyon complex of the Wyoming province; it has also been proposed that the Isua supracrustals of the Greenland craton represent an accretionary complex, but this proposal has been disputed. Each of these terranes contains lithotectonic elements that could not have formed in a single tectonic setting but are now intimately intermixed. Oceanic components include mafic and ultramafic volcanic rocks, gabbros, harzburgite tectonites, and pelagic sediments (chert); arc components are represented by the mélange matrix, consisting of felsic gneiss with a greywacke composition. These studies of Archean crust show that recognition of accretionary mélange complexes may be a reliable indicator of Phanerozoic-style plate tectonics and that the initiation of recognizable plate-tectonic processes occurred by 3.0 Ga, which coincides with the oldest Phanerozoic-style ophiolite assemblages. This transition may have started as early as 3.8 Ga, which coincides with the end of the terminal lunar bombardment.

Keywords: Archean, Hadean, mélange, ophiolite, early Earth.

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INTRODUCTION

One of the central questions of plate tectonics is when the transition occurred between post-magma ocean Hadean thermal regimes, characterized by high heat flows, chaotic convection, and generalized partial melting of the mantle, and plate-tectonic processes that are recognizably similar to those that occur today. This transition represents a fundamental change in the thermal structure of the planet, from one controlled by the upwelling of mantle plumes to one controlled by the sinking of cold lithospheric plates. Thermal modeling (e.g., Zhong et al., 2000; Bercovici, 2003) shows that convective heat transfer driven by heating from below results in hot material rising in columns, which is thought to be the dominant mode of Hadean heat transfer (Fig. 1). In contrast, Phanerozoic-style plate tectonics is driven by the gravitational sinking of cool, dense lithospheric plates (Carlson, 1981; Hager and O'Connell, 1981; Jurdy and Stefanick, 1991; Anderson, 2001).

The onset of Phanerozoic-style plate tectonics may be marked by the preservation of one or more distinct assemblages: (1) oceanic crust, as represented by ophiolite assemblages or by eclogites that represent subducted oceanic crust, (2) island arc volcanic or plutonic series, or (3) accretionary complexes that contain fragments of oceanic crust and lithosphere in a greywacke or serpentinite matrix mélange. Each of these associations may be preserved in Archean crustal assemblages but not all are equally diagnostic.

The correlation of greenstone belts with oceanic crust requires that the observed stratigraphic sequences represent thin slices of crust ± mantle lithosphere that are repeated by thrust faulting and stacked onto felsic continental crust (e.g., de Wit et al., 1992; de Wit, 1998, 2004; Kusky and Polat, 1999; Hofmann and Kusky, 2004). Evidence for such thin-skin tectonics is controversial in most greenstone belts, and many detailed studies still support autochthonous relations (e.g., intracontinental rifts or ensialic back-arc basins; Lowe, 1994; Bickle et al., 1994; Corcoran and Dostal, 2001; Prendergast, 2004; Mueller et al., 2005). Oceanic crust may also be preserved as eclogite xenoliths brought to the surface by kimberlites or other alkaline lamprophyres. Eclogite xenoliths with chemical and isotopic signatures that require formation and alteration as oceanic crust are well established (e.g., MacGregor and Manton, 1986; Shervais et al., 1988; Neal et al., 1990; Shirey et al., 2001), but similar oceanic crust could form during Hadean-style thermal convection and may not be evidence for Phanerozoic-style plate tectonics.

Archean tonalite-trondhjemite-granodiorite (TTG) gneiss complexes have been correlated with island arc plutonic series formed by slab melting (Drummond and Defant, 1990; Rapp et al., 2003), and it has been proposed that Archean greenstone belts may represent essentially coeval island arc volcanism (e.g., Parman and Grove, 2004; Parman et al., 2001, 2004; Polat and Kerrich, 2001, 2002, 2004). The progression within greenstone belts from ultramafic and mafic volcanism to more felsic, dacitic, and rhyolitic volcanism is now well established and correlates well with current knowledge of island arc suites from the western Pacific (e.g., Hawkins et al., 1984). High-resolution single crystal zircon dating of ash beds intercalated with the greenstone lavas and comparable dates for TTG gneiss complexes show that the TTG suites are generally coeval to slightly younger than the greenstone belts, suggesting a related or consanguineous relationship (e.g., Kröner and Todt, 1988; Kröner et al., 1991; Armstrong et al., 1990; Kamo and Davis, 1994). In each craton, however, there seems to be a

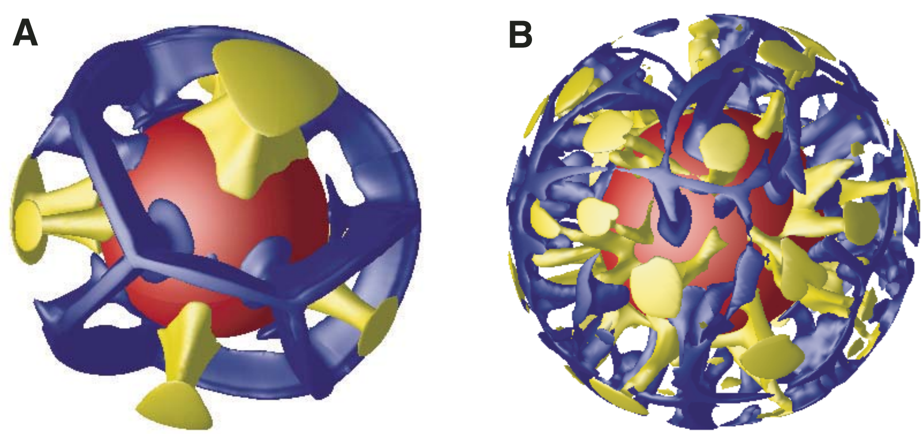

Figure 1. Numerical model of thermal convection driven by heating from below (from Zhong et al., 2000). Red—core, yellow—rising plumes of hot mantle, heated from below by core, blue—sheetlike and columnar zones of convergence and sinking of cooler return flow into mantle. Note that mantle upwelling occurs in plumelike columns, while sinking occurs largely along vertical zones of symmetric convergence. Convergence at triple junctions leads to accumulation of excess lithosphere and sinking in columns. (A) Layered viscosity structure and (B) layered viscosity coupled with temperature dependent viscosity; see Zhong et al., 2000. Reproduced/modified by permission of American Geophysical Union.

nucleus of older granitic gneiss that predates the adjacent greenstones (Ridley et al., 1997).

These correlations are not universally accepted, however (e.g., Arndt et al., 1997a, 1998; Arndt, 2004; Hamilton, 1998), and it is possible for both greenstone belts and TTG suites to form during Hadean convective overturn, prior to the onset of Phanerozoic-style asymmetric subduction. As seen in Figure 1, even during thermal convection driven by heating from below, the sinking of previously created protocrust along symmetric zones of convergence is required. Remelting of this protocrust as it sinks back into the mantle would generate melts similar to the TTG suite, so formation in an island arc setting is not required.

In contrast, subduction zone accretionary complexes are clearly the result of plate-tectonic processes that mimic those we see today and may represent the best evidence for modern-style, asymmetric subduction of lithospheric plates (Kusky and Polat, 1999; Shervais, 2004). In the following sections I develop this thesis in some detail. But first we need to examine Archean stratigraphy and the implications of thermal modeling for Hadean and early Archean tectonics.

ARCHEAN STRATIGRAPHY

The application of plate-tectonic models to the Archean has become more common in recent years, although the correlations are not exact (e.g., de Wit et al., 1992; de Wit, 1998, 2004; Kusky and Polat, 1999; Dirks and Jelsma, 1998; Connelly and Ryan, 1996; Calvert and Ludden, 1999). Much of this debate hinges on the stratigraphy of Archean greenstone belts, their internal structure, and their relationship to the surrounding TTG gneisses.

The oldest intact rock sequences on Earth have been dated at around 3.6–4.03 Ga (DeRonde and de Wit, 1994; Nutman et al., 1993, 1997, 2004; Kusky, 1998; Bowring et al., 1990; Bowring and Williams, 1999), slightly older than the end of the terminal impact cataclysm on the moon at 3.85 Ga (Ryder, 2000). Oxygen isotope analyses and SHRIMP (sensitive high-resolution ion microprobe) dating of detrital zircons from the Jack Hills and Mount Narryer metaquartzites imply that felsic crust reacted with liquid water as early as 4.3 Ga to 4.4 Ga (Wilde et al., 2001; Mojzsis et al., 2001; Peck et al., 2001). This interpretation is tempered by the occurrence of zircons with similar ages in lunar regolith that are clearly not derived from terrestrial-style continental crust (Meyer et al., 1996). Archean TTG suites are compositionally similar to hydrous melts of subducted eclogites (Drummond and Defant, 1990; Martin, 1994; Ridley et al., 1997; Barth et al., 2002; Rapp et al., 2003). However, questions still arise about the processes that formed this felsic crust: was Phanerozoic-style plate tectonics involved, or did they form by complex processes related to rising mantle plumes (Wyman and Kerrich, 2002) or sinking of eclogitic protocrust (Zegers and van Keken, 2001)?

The stratigraphy of older Archean terranes is subject to some controversy. In the classic view, greenstone belts, comprising refractory mafic and ultramafic lava flows and tuffs intercalated with more felsic lavas and shallow marine sedimentary sequences, are deposited unconformably on top of preexisting felsic gneiss complexes (e.g., Kröner, 1985; Bickle et al., 1994; Nisbet and Fowler, 2004; Prendergast, 2004). More recent work suggests two alternatives. The first proposes that greenstone belts represent oceanic crust that was thrust over the TTG gneiss complexes during continental collision events (e.g., Kusky and Kidd, 1992; Kusky, 1998; de Wit, 1998, 2004; Wyman and Kerrich, 2002; Polat and Kerrich, 2001, 2002). These workers interpret TTG assemblages as the product of subduction zone magmatism and the greenstone belts as products of back-arc basin or oceanic plume volcanism. The second alternative proposes that greenstone belts are everywhere slightly older than the TTG suites that intrude them and that both the greenstone belts and their approximately coeval, intrusive TTG suites formed in the same suprasubduction zone setting (Drummond and Defant, 1990; Grove et al., 1999; Parman et al., 2001, 2004; Parman and Grove, 2004; Corcoran et al., 2004).

Clear evidence for plate-tectonic processes typically focuses on finding rock associations that resemble modern oceanic crust or ophiolites or evidence for their subducted remains. Ophiolites are relatively common in the Neoproterozoic (e.g., Stern et al., 2004), but although many greenstone belts have assemblages that have been interpreted as ophiolites, true ophiolite assemblages are rare in the Proterozoic (e.g., 1.95 Ga Jormua ophiolite, Finland; Kontinen, 1987; Peltonen and Kontinen, 2004; 1.73 Ga Payson ophiolite, Arizona; Dann, 1991, 2004; 1.9 Ga Birch Lake assemblage [Flin-Flon belt], Trans-Hudson orogen, Canada; Wyman, 1999; ≈1.8 Ga Buckhorn Creek ophiolite, Colorado; Cavosie and Selverstone, 2003) and almost unknown in the Archean (2.5 Ga Dongwanzi ophiolite; Kusky et al., 2001; Li et al., 2002; 2.8 Ga North Karelian greenstone belt, Russia; Shchipansky et al., 2004; 3.0 Ga Olondo greenstone belt, Tuva; Puchtel, 2004). Other greenstone belts seem not to represent ophiolites, e.g., several terranes of the 2.7 Ga Slave craton (primitive island arc, back-arc basin, and rifted margin terranes; Corcoran et al., 2004; Corcoran and Dostal, 2001; Mueller et al., 2005) and the 3.4 Ga Jamestown "ophiolite" of the Barberton greenstone belt (de Wit et al., 1987; De Ronde and de Wit, 1994) where the sheeted dikes are ≈100 m.y. younger than the volcanic rocks they intrude (Kamo and Davis, 1994).

It is now recognized, however, that most Phanerozoic ophiolites do not represent true oceanic crust formed at mid-ocean ridge spreading centers. Structurally intact Phanerozoic ophiolites form above nascent or reconfigured subduction zones in response to sinking of the subducting slab and extension of the overlying fore-arc and are commonly associated with boninite suite volcanism (e.g., Pearce et al., 1984; Shervais and Kimbrough, 1985; Robinson and Malpas, 1990; Stern and Bloomer, 1992; Pearce, 2003; Shervais, 1990, 2001; Shervais et al., 2004, 2005a). Thus, while ophiolites may be indicative of Phanerozoic-style plate tectonics, they cannot be correlated with the formation of oceanic crust at mid-ocean ridges. True oceanic crust formed at mid-ocean ridge spreading centers is almost invariably destroyed during subduction, although fragments of such crust may be preserved in accretionary complexes (Shervais and Kimbrough, 1987; MacPherson et al., 1990) or recycled as eclogites (Shervais et al., 1988; Helmstaedt and Schulze, 1989). The occurrence of boninitic lavas in several late Archean to early Proterozoic terranes, however, suggests that similar suprasubduction zone processes were active by ca. 2.8 Ga (Polat and Kerrich, 2004; Shchipansky et al., 2004).

Ancient subduction processes may be inferred from eclogite xenoliths with gabbroic or basaltic protoliths and isotopic compositions that reflect ancient seawater alteration (e.g., MacGregor and Manton, 1986; Shervais et al., 1988; Shirey et al., 2001). The chemical and isotopic compositions of these eclogites demonstrate a supracrustal origin as oceanic crust, while their current mineralogy demonstrates that they have been subject to burial deep within the upper mantle. The question remains, however, whether this deep recycling into the mantle occurred in response to Phanerozoic-style asymmetric subduction or during Hadean-style symmetric convergence and subduction, as discussed in the following section.

HADEAN AND ARCHEAN (?) CRUSTAL PROCESSES

The processes that controlled crustal formation during the Hadean (pre–3.8 Ga; Cloud, 1972) and the Archean (≈3.8–2.5 Ga) remain an area of active debate. It is now generally acknowledged that the earliest Hadean was characterized by core formation and partial melting of the outer mantle (Walter and Trønnes, 2004). The terrestrial magma ocean phase (like the corresponding lunar magma ocean) was probably short-lived and frozen by ≈4.44 Ga, a period we can refer to informally as the Tartarean, after Tartarus (ταρταροω), in Greek mythology the level below Hades where the Titans were held captive. After the Tartarean magma ocean phase, heat flow would have remained high throughout the Hadean and much of the Archean, driving vigorous thermal convection of the mantle by heating from below and forming a large number of small crustal plates (Bickle, 1978; Campbell and Jarvis, 1984; Pollack, 1997). In the following section we examine the implications of this process for Hadean and early Archean tectonics.

Thermal Convection Driven From Below

Physical and numerical models of thermal convection are characterized by plumelike upwellings that bring heat to the surface (Zhong et al., 2000; Bercovici, 2003). These thermal plumes are consistent with models for Archean komatiite formation that suggest oceanic plateaux as modern analogues (Desrochers et al., 1993; Arndt, 2004; Arndt et al., 1997a, 1997b; Wyman and Kerrich, 2002), since these features are thought to represent plume volcanism in an intraoceanic setting (Richards et al., 1989; Campbell et al., 1989; Hill, 1991). If the melting that forms komatiites occurs under dry conditions, mantle potential temperatures of ≈1500 to 1700 °C are implied: hotter than modern plume heads and consistent with an Archean mantle that was hotter than today's, thermally buoyant, and actively convecting (Nisbet et al., 1993; Nisbet and Fowler, 2004).

In contrast, these same physical and numerical models of thermal convection are characterized by the sinking of cooler lithospheric plates along vertical zones of convergence, with material from both sides of the convergence zone sinking back into the hot asthenosphere symmetrically (Fig. 1). Modern, asymmetric convergence, which is driven by the sinking of cold lithospheric plates, is not observed (Zhong et al., 2000; Bercovici, 2003) and may not have occurred in the Hadean or early Archean.

A speculative model for the formation of greenstone belts at the sites of plumelike upwellings from the mantle and their preservation at zones of convergence, along with TTG suite granitoids formed by partial melting of the sinking mafic crust, is shown in Figure 2. This model is based on the pure thermal convection model presented in Figure 1, with hot plumes rising from the core-mantle boundary and melting to form a proto-oceanic crust that is thicker than modern oceanic crust and resembles oceanic plateau crust (e.g., Arndt et al., 1997a). Consistent with the numerical modeling shown in Figure 1, sinking of this proto-oceanic crust at zones of convergence is essentially vertical and symmetric along convection cell walls (Fig. 2).

This model has some interesting implications. First, geometric constraints require that the thick proto-oceanic plateau formed above the rising plume must spread laterally as it moves radially away from the rising plume, in order to preserve crustal volume as the surface area increases (Fig. 2). This spreading will be viscous in the lower crust and brittle in the uppermost crust, where normal faulting should be common. As a result, the preserved crustal thickness should be much thinner than the primary thickness of the plateau (<15% of the original thickness for spreading over two radii of the original plateau). Second, convergence at triple junctions where three cells meet will focus this radial flow back into a single descending "anti-plume"; converging proto-oceanic crust may tend to be preserved here, especially if the position of this triple junction is unstable (Fig. 2). This will preserve the proto-oceanic crust (greenstone belts?) as small, deltoidal blocks, sitting above the triple junction and subject to compressive stress during convergence. Proto-oceanic crust that does sink (i.e., most of it) will be strongly deformed by this convergence and partially melt to form TTG suite magmas that will rise and intrude the overlying greenstone belt. The residue of this melting will be eclogite similar to that formed by subduction processes today.

The implication of this thermal convection model is that even though mafic crust resembling modern oceanic crust, or oceanic plateaux, may have formed, there is no assurance that this crust was destroyed along Phanerozoic-style, asymmetric subduction zones. Sinking of mafic and ultramafic crust along vertical convergence zones would still recycle crustal material back into the mantle, preserving the chemical and isotopic traces of this process and preserving remnants of this mafic

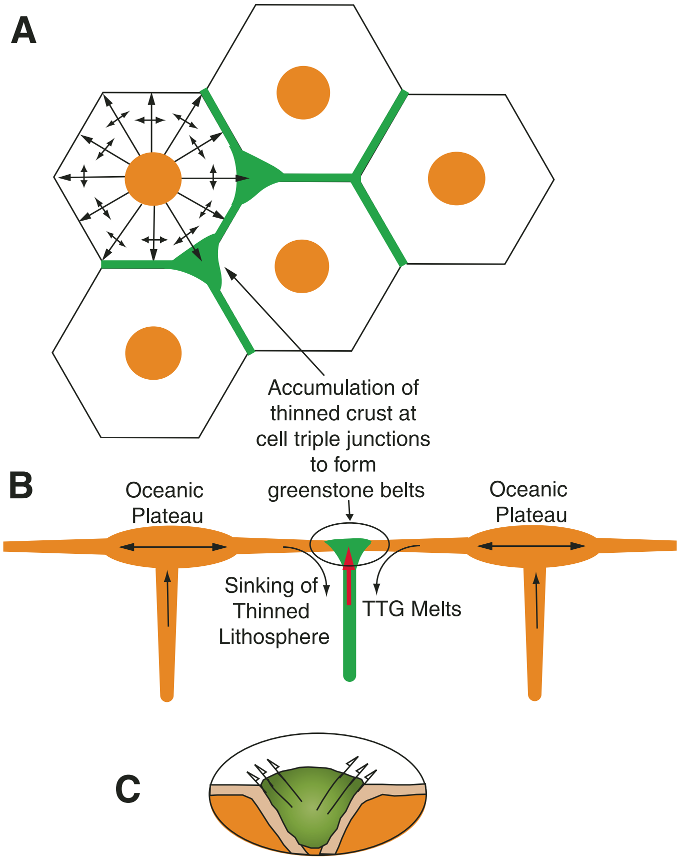

Figure 2. Schematic diagram for origin of greenstone belts and trondhjemite-tonalite-granodiorite (TTG) suites consistent with thermal convection driven by heating from below, showing plan view (A) and cross section (B). Greenstone belts form at upwelling plumes of mantle and spread radially from the plume center toward zones of symmetric convergence and sinking. Greenstone belts most commonly preserved at triple junctions of intersecting convergent zones (detail in inset C). TTG suites represent partial melts of the sinking mafic crust, which typically pools at triple junctions of intersecting convergent zones, intruding the overlying greenstone belts (red arrow).

crust as eclogite. So evidence for the existence and recycling of oceanic-like crust does not conclusively show that modern-style plate tectonics was operative.

The preservation of oceanic crust at symmetric convergence zones is likely to involve significant deformation and thrusting, forming schüppenzones of imbricate thrust slices of oceanic crust that stack older crust onto younger. These thrust complexes would not resemble modern accretionary complexes, however, because there would be no emergent volcanic arc to provide the sediments that dominate modern complexes.

Convection Driven by Sinking Slabs

In contrast, it has been known for some time that Phanerozoic-style plate tectonics is driven by the sinking of cool, dense lithospheric plates, with a small component of push as the plates slide off the uplifted oceanic ridge system—all under the influence of gravity (Carlson, 1981; Hager and O'Connell, 1981; Jurdy and Stefanick, 1991; Anderson, 2001). Oceanic spreading ridges form by the passive upwelling of asthenosphere into the breach created by plate motion, and their only contribution to plate motion is the relief created by the thermal buoyancy of the asthenosphere, which drives the "ridge push" component of plate motion (Carlson, 1981; Hager and O'Connell, 1981; Jurdy and Stefanick, 1991; Anderson, 2001). Oceanic crust formed by this process is thinner than crust created by thermal plumes, but it does not thin by lateral spreading. Island arcs form by hydrous melting of the mantle wedge that forms above the sinking slab.

It has been proposed that komatiites formed by hydrous melting in Archean subduction zones, much like boninites in modern arc settings (Grove et al., 1999; Parman et al., 2001, 2004; Parman and Grove, 2004). This proposal is supported by stratigraphy of Archean greenstone belts, which are dominated by more evolved lavas (basalts, andesites, dacites, rhyolites) and tuffs (commonly silicified to cherts; Lowe, 1994) that resemble primitive arc assemblages in the western Pacific (e.g., Hawkins et al., 1984). Similarly, TTG associations, which dominate the felsic gneiss terranes of Archean cratons, have been correlated with adakitic suites in modern arc terranes, formed by the melting of down-going oceanic crust (Drummond and Defant, 1990; Polat and Kerrich, 2001, 2002). If correct, these models imply that Archean mantle may not have been superheated significantly compared to modern plumes (e.g., Grove and Parman, 2004; Valley et al., 2002). However, komatiites lack negative Nb anomalies and other trace element characteristics of modern arc lavas, so a subduction zone origin is far from clear (e.g., Storey et al., 1991; Arndt, 2004).

PLATE TECTONICS AND ACCRETIONARY PROCESSES

One reliable indicator of Phanerozoic-style plate tectonics is the occurrence of an accretionary prism that includes sediments eroded from the upper, arc-volcanic plate and oceanic crust (mafic volcanic rocks, ultramafic tectonites, and abyssal sediments) from the lower plate (Fig. 3). Such a prism is the clear result of asymmetric subduction, with one plate subducting beneath another, more buoyant plate; subsequent ridge subduction may also be important in modifying the primary assemblage (Shervais et al., 2004, 2005a; Kusky et al., 2004a). In the following discussion we examine first the type example of a Phanerozoic accretionary complex, followed by a well-documented example of a similar rock assemblage overprinted by a major collisional orogeny. Finally, we examine several examples of potential Archean accretionary complexes and their correlation to these well-documented Phanerozoic examples.

It should be noted that not all convergent margins are accretionary. Nonaccreting margins (von Huene and Scholl, 1991) are characterized by subduction erosion that exposes fore-arc basement in the hanging wall of the trench. These mar-

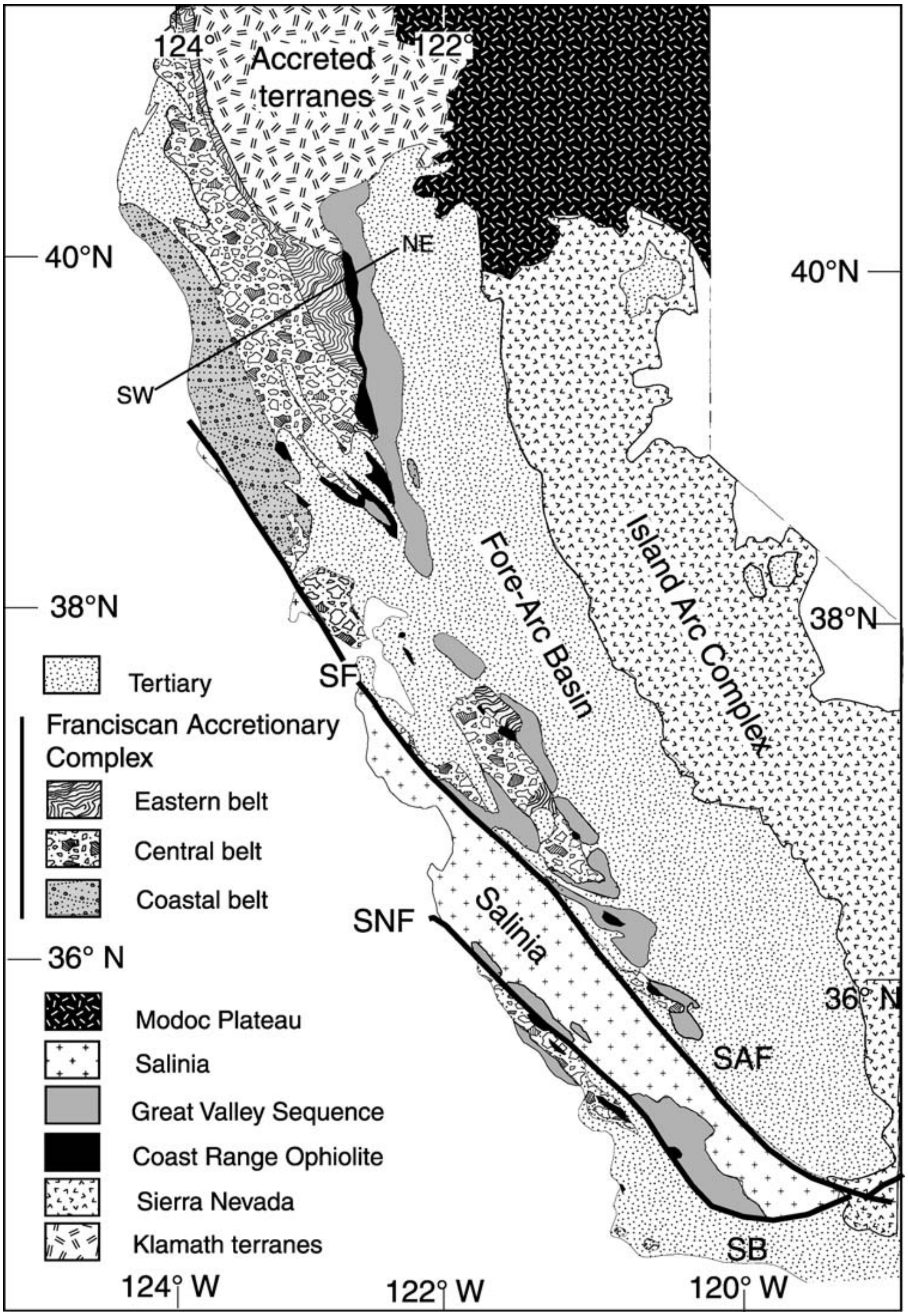

Figure 3. Geologic sketch map showing the distribution of the Franciscan assemblage in California. Eastern, Central, and Coastal belts after Bailey et al. (1964), Blake et al. (1985), and Ernst (1993). The coeval island arc complex and fore-arc basin are labeled, along with accreted terranes of the Klamath Mountains. Arc (Salinia) and Franciscan rocks are repeated west of the San Andreas (SAF) and Sur-Nacimiento (SNF) fault zones. SF—San Francisco, SB—Santa Barbara. Line of section in Figure 4 labeled southwest-northeast.

gins are typically sediment-starved because there are few emergent volcanoes (intraoceanic arcs) or because rivers carry most of the sediment into the back-arc region (continental arcs); what sediment does enter the trench is largely subducted (von Huene and Scholl, 1991). The Mariana-Bonin arc is the type example of a nonaccreting intraoceanic margin, while the Andean arc is the best example of a nonaccreting continental arc margin.

Phanerozoic Accretionary Complexes

Phanerozoic accretionary complexes include those that are currently active and fossil systems that are both well preserved and well exposed. Currently or recently active systems include the Aleutian trench system (Fruehn et al., 1999), the Java-Sumatra trench system (Hamilton, 1979; Moore and Karig, 1980), the Antilles fore-arc (Moore et al., 1982), off-shore exposures of the Makran (Kukowski et al., 2001), and the Mariana fore-arc (Fryer et al., 2000). Fossil systems include the Lichi mélange in Taiwan (Page and Suppe, 1981), the Chugach-Kodiac mélange in Alaska (Byrne, 1984; Kusky et al., 1997a, 1997b; Kusky et al., 2004a), onshore exposures of the Makran (Platt et al., 1985), and the Franciscan complex of California (Bailey et al., 1964; Cowan, 1978).

The Franciscan complex of California is the classic example of an accretionary complex formed during the subduction of oceanic lithosphere beneath an active arc terrane (Bailey et al., 1964; Hsü, 1968; Ernst, 1993; Wakabayashi, 1999). It encompasses most of the Coast Ranges of central and northern California, cropping out over an area some 700 km long and up to 200 km wide, east of the San Andreas fault; it also crops out over a small area west of the Sur-Nacimiento fault (Fig. 3). The Franciscan complex consists of three tectonic belts, each with its own distinct character and lithologies: the Eastern belt, the Central belt, and the Coastal belt (Bailey et al., 1964). The distribution of these belts is shown in Figure 3, and their relationships in northern California are shown in cross section in Figure 4.

The Eastern belt comprises coherent sheets of blueschist-facies greywacke and basalt up to hundreds of meters thick transposed along low-angle thrust faults, as well as exotic blocks in a chaotic mélange with a metagreywacke matrix (Bailey et al., 1964; Ernst, 1993; Blake and Jones, 1974; Blake and Wentworth, 1999). Eastern belt metasediments have early to mid-Cretaceous depositional ages with mid- to late Cretaceous metamorphic ages (Blake et al., 1982). This entire assemblage is juxtaposed structurally below the mid-Jurassic Coast Range ophiolite and its cover of fore-arc sedimentary rocks

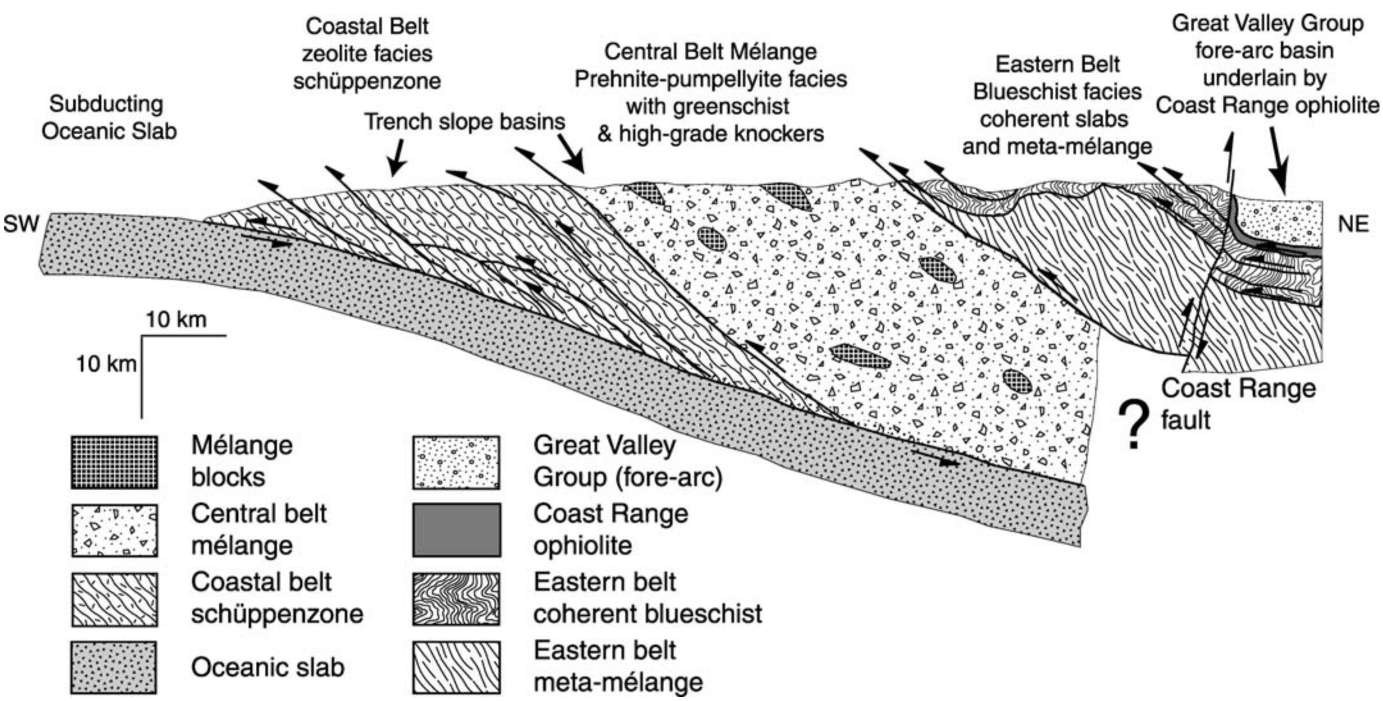

Figure 4. Schematic diagram of Franciscan assemblage accretionary complex, illustrating Phanerozoic-style plate tectonics. Coastal belt represents a schüppenzone of zeolite facies greywackes and shales, largely in coherent tracts but including broken formation. The Central belt of the Franciscan represents the classic mélange terrane, with blocks of low-grade (prehnite-pumpellyite to greenschist facies) greywacke, chert, basalt, diabase, and peridotite, and blocks of high-grade (garnet amphibolite-eclogite-blueschist facies) basalt and greywacke, in a matrix of scaly clay/microgreywacke (or more rarely, serpentinite). Eastern belt of the Franciscan consists of imbricate thrust sheets with coherent tracts of blueschist facies greywacke, schist, and basalt, overlying blueschist facies metamélange. Eastern belt is overlain at depth by Coast Range ophiolite (fore-arc basement) and Great Valley Group (fore-arc basin sediments), but these units are currently juxtaposed along the Neogene Coast Range fault, a high-angle reverse fault. Franciscan relations after Blake et al. (1985); trench side of Coastal belt (which is truncated by the San Andreas fault system) reconstructed from seismic profiles of Japan trench (von Huene and Scholl, 1991).

(Blake et al., 1982; Blake and Jones, 1974; Shervais, 2001; Shervais et al., 2004, 2005a).

The Coastal belt, which lies outboard of the Central and Eastern belts, comprises a schüppenzone of thin, west-verging thrust slices that generally young to the west (Blake et al., 1985). The easternmost thrust slice (Yager terrane) consists of coherent greywacke strata; more westerly terranes are partially to largely disrupted broken formations of arkose, mudstone, conglomerate, and, in the Point Delgado subterrane, basaltic pillow lava and diabase (Blake et al., 1985). The Coastal belt ranges in age from mid-Cretaceous to Miocene (in the King Range terrane; McLaughlin et al., 1982). This belt, which represents the youngest part of the accretionary complex, is characterized by modes that are richer in K-feldspar than older greywackes of the complex, reflecting the unroofing of plutonic rocks in the eastern Sierra arc terrane (Bailey et al., 1964).

The Franciscan central belt forms the classic mélange terrane that is commonly associated with the Franciscan accretionary complex. The central belt contains blocks and knockers of greywacke, greenstone, serpentinite, chert, limestone, blueschist, eclogite, and garnet amphibolite (Bailey et al., 1964; Blake and Jones, 1974; Blake and Wentworth, 1999), as well as large tracts of arkosic wackes interpreted as slope basin deposits (Becker and Cloos, 1985). The mélange matrix is a finely comminuted microgreywacke siltstone/shale that has been strongly sheared to produce the classic argille scagliose texture (Hsü, 1966; Blake and Jones, 1974). Detailed studies of the mélange matrix show that sedimentary processes (olistostromes) are important in some shale-matrix mélanges (Cowan, 1978, 1985), in addition to tectonic disruption by ductile flow (Cloos, 1982).

Serpentinite matrix mélange, which may represent accreted fracture zones, is less common but may represent the primary transport medium for high-grade blocks (Bailey et al., 1964; Coleman, 2000; Hopson and Pessagno, 2005). Serpentinite mélange includes serpentinite broken formation (which consists of massive blocks of serpentinized peridotite enclosed in a matrix of serpentinite schist) as well as true mélange, which consists of exotic blocks of high-grade metamorphic rocks (Figs. 5A and 5B) or greenstone/chert (Figs. 5C and 5D) in a serpentinite schist matrix (Huot and Maury, 2002; Shervais et al., 2005b; Hopson and Pessagno, 2005).

High-grade metamorphic blocks include blueschist, eclogite, amphibolite, and garnet amphibolite (Bailey et al., 1964; Moore and Blake, 1989; Moore, 1984). Many of these blocks are polymetamorphic and preserve evidence of an early high-temperature, medium-pressure assemblage (amphibolite, garnet amphibolite) overprinted by eclogite or blueschist facies assemblages (e.g., Moore and Blake, 1989). These blocks commonly preserve a rind of lower-grade minerals (actinolite, chlorite) with compositions that suggest equilibrium with serpentinite, even when found in shale matrix mélange, implying primary exhumation in serpentinite mélange before being remixed into shale matrix mélange. The rinds are typically polished, striated, and gouged, showing that the blocks formed rigid inclusions within a viscous matrix. Though rare, these high-grade blocks clearly document tectonic mixing of exotic components into matrix components that formed at much lower temperatures and pressures.

The most common tectonic block in most shale-matrix mélange is greywacke. In a few examples, this greywacke sits depositionally on chert-basalt, but more commonly it occurs alone in large, slablike knockers. These greywacke blocks represent either less disrupted material that was parental to the matrix or in some cases slope basin deposits that were deposited on a previously deformed substrate (Cowan, 1978; Becker and Cloos, 1985).

Chert and greenstone are both common knocker lithologies in the Franciscan assemblage. Chert knockers are typically slablike due to their bedding, while the greenstones may include pillow lava, sheet flows, hyaloclastites, or diabase sill complexes (Figs. 5E and 5F). One of the more common knocker assemblages is composite chert-greenstone blocks (Figs. 5C and 5D). These blocks consist of banded cherts deposited on pillowed or massive submarine lavas or intruded by sills of oceanic basalt composition (e.g., Murchey, 1984; Shervais and Kimbrough, 1987; Huot and Maury, 2002). Banded cherts may form decameter-scale lenses intruded by diabase sills (e.g., Aliso Canyon; Shervais and Kimbrough, 1987) or extensive terranes of chert + basalt stacked along thrust faults (e.g., Marin Headlands; Murchey, 1984; Karl, 1984). In parts of the Franciscan composite basalt-chert blocks are stacked in thin thrust sheets (Isozaki and Blake, 1994); similar relations are found in the Japanese accretionary complex (Isozaki et al., 1990, Isozaki, 1997).

Accretionary complexes may be intruded by igneous rocks during ridge collision/subduction events, further complicating their interpretation. This is clearly seen in south-central Alaska, where ridge subduction occurred in the Paleogene (Bradley et al., 2003; Kusky et al., 2003, 2004) and in the Franciscan complex in response to migration of the Farallon triple junction (Johnson and O'Neil, 1984; Cole and Basu, 1995). Some felsic magmas are derived from direct melting of the hot subducting slab, which forms adakites (Sr-rich granites that resemble the Archean TTG suite; Drummond and Defant, 1990). Other magmas include calc-alkaline basalt, trachybasalt, andesite, dacite, and rhyolite (Johnson and O'Neil, 1984; Cole and Basu, 1995).

Effects of Collisional Metamorphism on Accretionary Complexes

What would this assemblage look like if it were metamorphosed to upper amphibolite facies conditions during a continent-continent or arc-continent collision? We have a good model for this process in the Eastern Blue Ridge province of the southern Appalachians, which is separated from the Western Blue Ridge by the Haysville-Fries fault system (Williams and Hatcher, 1983; Adams et al., 1995). The Eastern Blue Ridge province is distinct from amphibolite to granulite facies gneisses of the Western Blue Ridge province (which reflect Grenville-age

Figure 5. Franciscan mélange field photos. (A) Serpentinite matrix mélange near Figueroa Mountain, California. Knockers of diabase and basalt (larger blocks) and high-grade metamorphics (smaller blocks and groups of blocks) are circled for clarity. (B) Knocker of blueschist in serpentinite matrix mélange near Figueroa Mountain, ~30 m across. (C) Large composite knocker of banded chert (top) and diabase (bottom) in shale matrix mélange, Aliso Canyon, California. (D) Banded ribbon chert from composite chert-diabase knocker, Aliso Canyon, California. (E) Smaller (3 m) block of basalt in sheared volcanic matrix, Paskenta, California. (F) Smaller (≈1 m) block of harzburgite in sheared serpentinite-matrix mélange, Paskenta, California.

metamorphism) and more closely resembles rocks of the Inner Piedmont terrane in western South Carolina (Williams and Hatcher, 1983); together the Eastern Blue Ridge province and the Inner Piedmont belt comprise the Jefferson terrane. The Jefferson terrane forms part of the infrastructure of the Alleghenian orogeny, which represents collision of the passive eastern margin of Laurentia with exotic arc terranes and the cratonic margin of Gondwana (Secor et al., 1986; Adams et al., 1995; Adams and Trupe, 1997; Shervais et al., 2003; Dennis et al., 2000, 2004).

The Jefferson terrane consists of biotite-quartz-feldspar gneisses, migmatitic in part, with extensive zones of pegmatite intrusion. Within this groundmass of paragneiss are blocks and slabs of exotic lithologies, including amphibolite, garnet amphibolite, anthophyllite dunite, and eclogite (Ash metamorphic suite, Alligator Back formation; Adams et al., 1995; Adams and Trupe, 1997). Two aspects of this terrane support its origin within an accretionary complex. First is the characteristic association of "oceanic" lithologies (metabasalts, metaserpentinites) within paragneisses derived from immature clastic sediments. In particular, the volumetric dominance of the paragneiss and the irregular distribution of the mafic and ultramafic rocks as blocks and slabs within these paragneisses recall the distribution of exotic blocks in the Franciscan mélange. Second, the occurrence of large slabs of metabasalt with relict eclogite assemblages is consistent with a subduction zone origin, despite later overprinting by amphibolite facies assemblages and retrogression of the primary eclogite phase assemblage (e.g., Willard and Adams, 1994). These slabs resemble garnet amphibolite in the field but preserve relict eclogite assemblages (garnet-omphacite) in the midst of hornblende-rich overprinting. Whole-rock geochemical data and paleo–pressure-temperature work show that these eclogites represent oceanic crust (mid-ocean ridge basalt [MORB]) that was metamorphosed under high pressure–low temperature conditions in a subduction zone long before continental collision (Willard and Adams, 1994; Adams et al., 1995).

Eclogite and high-pressure granulite facies rocks in the central Carolina terrane represent MORB dikes emplaced into the basement of the Carolina arc terrane where they were subject to high-pressure, medium-temperature metamorphism during an arc-arc collision (Dennis et al., 2000, 2004; Shervais et al., 2003). These rocks are not strictly analogous to the Blue Ridge eclogites but did suffer a similar amphibolite facies retrograde overprint during a collisional orogeny similar to the Alleghenian orogeny (Shervais et al., 2003). In the Carolina eclogites, garnet preserves extreme zoning that can be mapped chemically with the microprobe to establish which garnet composition was in equilibrium with which assemblage. Sodic pyroxene (omphacite) has been completely replaced by diopside-albite symplectites that reflect increased temperature and lowered pressure during thermal equilibration of the subducted lithosphere (Shervais et al., 2003). These diopside-albite symplectites are characteristic of retrograde eclogite assemblages and can be recombined using image analysis techniques to recover the composition of the primary omphacite. The resulting compositions can be used to calculate the pressure-temperature history of the former eclogites, despite amphibolite and even granulite facies overprints (Shervais et al., 2003).

Archean Accretionary Complexes

Recognition of Archean accretionary complexes is complicated by the protracted history of metamorphism and tectonism that commonly characterizes rock assemblages formed on active plate boundaries (e.g., Kusky and Polat, 1999). These rocks are more likely to be overprinted by both high-pressure and high-temperature metamorphic events than rocks formed in continental interiors or even arc volcanic suites formed above the same subduction zone (being on the upper plate, volcanic arcs rarely subduct and are commonly preserved even in major continental collision zones; e.g., the Kohistan-Ladakh arc terrane in the western Himalaya; Shah and Shervais, 1999). Nonetheless, by recognizing the effects of these later tectonic and metamorphic events, it is possible to interpret the original history of these rock assemblages in terms of modern plate-tectonic theory.

Possibly our best evidence for Archean plate tectonics at this time is found in three potential accretionary mélange complexes: the 2.5 Ga Dongwanzi ophiolite mélange in the north China craton (Kusky et al., 2001, 2004b; Li et al., 2002), the 2.7 Ga Schreiber-Hemlo greenstone belt in the Superior province of Canada (Polat et al., 1998; Polat and Kerrich, 1999), and the 2.6 Ga Farmington Canyon complex in north-central Utah (Shervais, 2004). The 3.8 Ga Isua Supergroup of Greenland (Komiya et al., 1999, 2004) may provide a fourth example that is significantly older, but its interpretation as an accretionary complex has been disputed (Myers, 2001, 2004).

Dongwanzi Ophiolite Mélange

The Dongwanzi ophiolite mélange crops out in the Zunhua structural belt, a continuation of the late Archean Central orogenic belt of the North China craton (Li et al., 2002). This late Archean mobile belt consists of gneiss, greenstone belts, and mafic/ultramafic complexes that represent in part an ophiolitic mélange (Kusky et al., 2001, 2004b; Li et al., 2002; Huson et al., 2004; Huang et al., 2004). The mélange resembles the Eastern Blue Ridge province in many respects, consisting of mafic-ultramafic plutonic rocks (cumulates and harzburgite tectonites with podiform chromite), dike complex, pillow lava, and banded iron formations (≈chert) in a mélange matrix of foliated and sheared biotite gneiss (Li et al., 2002; Kusky et al., 2001, 2004b). More than 1000 ultramafic boudins have been recognized in the Zunhua belt (Li et al., 2002; Kusky et al., 2004b), an association that is difficult to reconcile with the biotite gneiss country rock except as blocks in mélange.

Within or adjacent to this mélange is the Dongwanzi ophiolite, the best example to date of a true Archean ophiolite (Kusky et al., 2001, 2004b). This ophiolite fragment is ≈50 km long and 10 km wide. It is located near the eastern margin of the Zunhua structural belt, along the leading edge of the orogen (Kusky et al., 2001). To the west are found greenstones and TTG rocks that may represent the associated volcanic arc complex, along with retrograde eclogites and high-pressure granulites of the Hengshan belt (Li et al., 2002). The Dongwanzi ophiolite mélange is interpreted as an accretionary prism formed along an active continental margin that was subsequently trapped during collision of the western and eastern blocks of the North China craton and metamorphosed to amphibolite facies.

Schreiber-Hemlo Greenstone Belt

The late Archean (≈2670–2750 Ma) Schreiber-Hemlo greenstone belt of the Superior province crops out along the north shore of Lake Superior in southern Ontario, Canada, over an area ~90 km long and 10–20 km wide (Polat et al., 1998, 1999; Wyman et al., 2002). Metamorphic grade ranges from lower greenschist facies in the western (Schreiber) area to lower amphibolite facies in the eastern (Hemlo) region (Pan and Fleet, 1993). Volcanic rocks include oceanic plateaux assemblages (tholeiitic basalts, komatiites) and oceanic island arc assemblages (basalts, andesites, dacites with arc tholeiite or calc-alkaline compositions). Sedimentary rocks are siliciclastic turbidites interpreted as trench deposits (Polat et al., 1998; Polat and Kerrich, 1999). All of these rock assemblages have been intruded by arc-derived tonalite-trondhjemite-granodiorite plutons that are only slightly younger than the host rocks.

As described by Polat and coworkers (Polat et al., 1998; Polat and Kerrich, 1999, 2001, 2002, 2004), the oceanic plateau basalts, island arc volcanics, and siliciclastic trench turbidites were tectonically juxtaposed before and during intrusion of the TTG suite. All of the subduction-related igneous and sedimentary rocks are characterized by LREE–enrichment (light rare earth elements) and by distinct negative Ti, Zr, and Nb anomalies on primitive-mantle normalized spider diagrams, whereas the oceanic plateau basalts have relatively flat REE (rare earth element) patterns and lack negative anomalies in the primitive-mantle normalized high-field strength elements (Polat et al., 1998; Polat and Kerrich, 1999, 2001, 2002, 2004).

For the most part these distinct assemblages appear to form a schüppenzone of large, km-scale fault-bounded blocks, with little mixing between adjacent regimes. Locally, blocks of material exotic to the surrounding matrix are recognized, including arc rhyolites in a matrix of sheared ocean plateau tholeiite and blocks of gabbro, tonalite, and volcanic rock in a matrix of sheared and foliated shale or wacke (Polat et al., 1998; Polat and Kerrich, 1999). In some cases these rocks may represent boudinaged dikes and not true exotic mélange blocks; in others their exotic nature seems more clear. Native blocks are also recognized, including komatiite, gabbro, or chert in sheared ocean plateau tholeiite, forming a broken formation. Exotic and native blocks range in size from a few meters to decameters.

Polat and coworkers (Polat et al., 1998, 1999; Polat and Kerrich, 1999, 2001, 2002) interpret these relationships to represent formation (and deformation) within an accretionary complex in a convergent margin, subduction zone setting. They recognize that much of the deformation observed probably formed along the contacts of adjacent thrust sheets and by the progressive layer-parallel extension of more rigid horizons within the sheared matrix.

Despite the apparent occurrence of both mélange and broken formations, there are some significant differences between the Schrieber-Hemlo greenstone belt and Phanerozoic accretionary complexes. The primary difference is the predominance of arc-derived igneous lithologies: modern accretionary complexes are dominated by siliciclastic sediments derived by erosion from the adjacent island arc, but tectonic blocks of arc volcanic or plutonic rocks are rare to nonexistent (Bailey et al., 1964; MacPherson et al., 1990; Shervais and Kimbrough, 1987). Igneous rocks within Phanerozoic accretionary complexes are almost all derived from the subducting oceanic plate, along with blocks of chert and limestone that are exotic to the trench depositional setting. Another difference is the dominance of large, fault-bounded blocks of volcanic and plutonic rocks derived from the subducting ocean crust as well as from the arc: in modern accretionary complexes these rocks are subordinate to the more common shale or greywacke matrix. Large basalt-chert terranes may occur (e.g., Marin Headlands terrane, California), but these are relatively rare. Since many komatiite sequences are now interpreted as primitive arc volcanics, it seems possible that rather than an accretionary complex, the Schreiber-Hemlo greenstone belt may represent an island arc terrane deformed during a continent-continent collision, comparable to the Kohistan arc terrane in northern Pakistan (Coward et al., 1982; Shah and Shervais, 1999). Alternatively, it may represent a nonaccreting convergent margin similar to the Mariana-Bonin fore-arc, which exposes older arc basement in the hanging wall of the trench (Hawkins et al., 1984).

The Farmington Canyon Complex

The late Archean (≈2.6 Ga) Farmington Canyon complex of northern Utah, which lies on the southwestern margin of the Wyoming province, has been interpreted to represent a passive margin sedimentary wedge that was metamorphosed to amphibolite facies conditions in the middle Proterozoic (Bryant 1988a, 1988b; Nelson et al., 2002). The Archean age of this complex (≈2.6 to possibly 3.0 Ga) is based on inheritance in zircon U/Pb systematics, old Nd model ages, and high Sr initial ratios in orthogneiss (Hedge et al., 1983). The complex was intruded by granitic gneiss and metamorphosed ca. 1.8 Ga (Hedge et al., 1983). Nelson et al. (2002) date the complex at ca. 1800 Ma using the monazite Th-Pb microprobe technique; they suggest the older ages may reflect the age of the sediment provenance and not its formation age. However, the monazite ages are coincident with the metamorphism and granite intrusion dated by Hedge et al. (1983) and may simply reflect mid-Proterozoic metamorphism.

The southern Farmington Canyon complex consists largely of migmatitic quartzo-feldspathic gneiss (Fig. 6A) containing isolated blocks and slabs of (1) mafic metavolcanics (amphibolite, pyroxene amphibolite, garnet amphibolite), (2) ultramafic metavolcanics (now serpentine-anthophyllite), and (3) quartzite. The migmatitic gneiss has a chemical composition similar to greywacke (Bryant, 1988a, 1988b), consistent with its formation from a Franciscan-style greywacke mélange matrix. There is some variability in its appearance, and some areas may represent coherent slope basin deposits of more arkosic wackes, analogous to the Cambria slab in the Franciscan complex. The gneisses and amphibolites are strongly deformed and may be

Figure 6. Farmington Canyon complex mélange field photos. (A) Migmatitic felsic gneiss, interpreted to represent metamorphosed matrix of greywacke matrix mélange. (B) Large knocker of banded chert, cut by amphibolite dikes, in Farmington Canyon; compare banding with Franciscan ribbon chert in Figure 4. (C) Close-up of banding in metachert, near Ogden, Utah. (D) Composite knocker of amphibolite (upper part of outcrop) and metachert (lower part of outcrop), Centerville Canyon; white line marks approximate contact. (E) Garnet amphibolite with large garnets surrounded by plagioclase-hornblende rims formed in response to decreased pressure or elevated temperature, Sessions Mountains, Utah. (F) Composite knocker of komatiite (under hammer), amphibolite (halfway up slope), and chert (top of slope) in Farmington Canyon complex near Ogden, Utah.

mylonitic in places; these rocks are crosscut by undeformed granite pegmatites with sharp discordant contacts that represent much younger anorogenic melts (Shervais, 2004).

Quartzite in the southern Farmington Canyon complex may represent metachert rather than an epiclastic quartzite (Shervais, 2004). These quartzites lack clastic sedimentary structures, and bedding is suggested by color variations and micaceous horizons (commonly the Cr-mica fuchsite) that mimic bedding features in chert (Figs. 6B and 6C). A banded chert protolith is suggested for some outcrops based on the intercalation of quartzite beds 5–20 cm thick with schist layers 1–2 cm thick (Fig. 6B). Chert and amphibolite typically occur in the same block (Fig. 6D), suggesting an oceanic crust sediment-basement contact or sills that intrude oceanic sediments off axis (e.g., Shervais and Kimbrough, 1987; Figs. 5C and 5D).

Amphibolite lenses in the Farmington Canyon complex range up to 200 m long and 50 m wide and are similar in size to volcanic blocks in the Franciscan assemblage (e.g., Bailey et al., 1964). Mineral assemblages include plagioclase and hornblende ± clinopyroxene, garnet, and quartz. Garnet porphyroblasts up to 4 cm across in amphibolite are commonly mantled by a low-pressure, high-temperature symplectite of plagioclase and hornblende (±pyroxene) that implies a clockwise pressure-temperature-time path (Fig. 6E). The common association of amphibolite with "quartzite" (metachert) in composite bodies is similar to the basalt-chert assemblage in the Franciscan complex (Figs. 6B and 6C).

Ultramafic lenses in the Farmington Canyon complex consist of serpentine, pyroxenes, anthophyllite, and other mafic minerals and are commonly associated with amphibolite or hornblende-plagioclase gneiss and quartzite (Yonkee et al., 2000). The largest lenses, up to 80 m × 20 m, lie in a matrix of felsic layered gneiss in contact with lenses of metachert (Fig. 6F). The association of ultramafic rocks with metachert implies that the ultramafics represent metavolcanic assemblages (e.g., komatiite) rather than the mantle tectonites that are common in the Franciscan complex.

The combination of old Nd model ages and Archean inherited zircon components implies that this accretionary complex formed on the southwestern margin of the Wyoming province in conjunction with a coeval continental margin arc that may be represented in part by the northern portion of the Farmington Canyon complex (orthogneiss, migmatite, pegmatite). This continental margin arc apparently collided with the Santaquin arc in the mid-Proterozoic (e.g., Nelson et al., 2002).

The Isua Supracrustals

The Isua supracrustals (Bridgwater et al., 1976) represent some of the oldest supracrustal rocks preserved on earth, with U/Pb zircon dates of 3.71–3.85 Ga (Bridgwater et al., 1976; Nutman et al., 1993, 1997, 2001, 2004). Detailed mapping demonstrates a range in metamorphic grade from epidote amphibolite in the southern zone to greenschist/amphibolite transition in the northern zone. Rocks of the northern zone are not only lower in metamorphic grade but are generally less deformed as well (Komiya et al., 1999, 2004; Nutman et al., 1996; Myers, 2001, 2004).

Komiya et al. (1999) interpret the lower half of the northern zone as mélange that consists of angular to subround blocks of greenstone (including well-preserved to flattened pillow lavas) in a matrix of sheared mudstone. The upper half of the northern unit comprises several thin thrust sheets of basalt (pillow lava ± hyaloclastite) overlain by metachert or banded iron formation. The southern unit is a schüppenzone of thin thrust sheets that forms duplex structures along layer parallel faults (Komiya et al., 1999). The thrust sheets generally comprise pillow basalt and chert overlain by turbidites of mafic wackes, arkose, mudstones, calcareous sandy shale, and minor conglomerate (Fedo, 2000). The southern and northern units are separated by a middle unit that consists dominantly of chert with overlying turbidite, similar to the sediments that rest on pillow basalt in the southern unit (Komiya et al., 1999).

In contrast, Myers (2001, 2004) interprets the entire sequence as a schüppenzone of mafic volcanics and chert. He suggests that the "mafic wackes, arkose, and mudstones" of Komiya et al. (1999) are in fact sheared volcanics and that the carbonates are metasomatic in origin, not sediments (Rosing et al., 1996). In addition, Nutman et al. (1996) have shown that rocks within the supracrustal belt span an age range of ≈100 Ma. If this interpretation is correct, then the Isua greenstones cannot be interpreted as a Phanerozoic-style accretionary complex; it does, however, resemble what we might expect to form during Hadean-style symmetric convergence.

Basalts in the Isua greenstone belt include both MORB and ocean island basalt (OIB)–like compositions. The Isua MORB is enriched in FeO compared to modern MORB and was derived from a fractionated mantle (light rare earth element/heavy rare earth element rations < 1 [heavy rare earth elements]) with a potential temperature ~1480 °C (Komiya et al., 2004). The Isua OIB has a flat REE pattern, suggesting derivation from a primitive source. The occurrence of true oceanic basalts in the Isua greenstone belt, rather than the arclike volcanics characteristic of other greenstone belts, is consistent with modern settings in which true oceanic basalts are found in accretionary complexes, not ophiolites, which represent arc volcanism. It is also consistent with Hadean-style convergence.

DISCUSSION

The recognition of subduction-related accretionary complexes hinges largely on our ability to identify assemblages of rocks that could not have formed together in a single tectonic or depositional setting and must represent tectonic mixtures of widely divergent rock types. The juxtaposition of discrete blocks of oceanic lithologies that could not form on a passive margin with a mélange matrix derived from proximal, arc-dominated sources comprises first-order evidence in support of the accretionary complex model. The occurrence of chert blocks in microgreywacke mélange matrix also seems to require physical mixing of rocks from distinct depositional settings and may be proof enough for an accretionary origin. Confirmation of this interpretation requires the discovery of relict high-pressure assemblages that document formation in a collisional or subduction environment.

Hadean tectonics was likely dominated by upwelling thermal plumes and symmetric sinking of opposing lithospheric plates, consistent with models of thermal convection driven by heating from below (e.g., Fig. 1). Geometric constraints require that any crust generated above these rising plumes (presumably thick, plateaulike accumulations of mantle-derived basalts and komatiites; Arndt, 1994, 2004; Arndt et al., 1997a) must be thinned rapidly by lateral spreading as the crust expands radially from the plume-centered plateau (Fig. 2). This continual thinning of the crust will promote rapid cooling and thickening of the underlying mantle lithosphere, which will also thin by lateral spreading as it expands radially from the plateau. The crust generated above the rising plumes may accumulate and be preserved at zones of symmetric convergence, especially at triple-plate junctions where excess crust is forced into a descending "anti-plume" (Fig. 2).

The occurrence of subduction-related accretionary complexes among Archean rocks ranging in age from 2.5 Ga to 2.7 Ga, as discussed above, suggests that Phanerozoic-style plate tectonics was operational by the late Archean. If the Isua rocks are indeed a mélange, then such tectonics may have commenced as early as 3.8 Ga. This conclusion is reinforced by the occurrence of Phanerozoic-style ophiolites with boninitic volcanism in rocks ranging in age from 3.0 to 2.8 Ga (Puchtel, 2004; Shchipansky et al., 2004). This is consistent with the proposal that Archean greenstone belts represent primitive island arc terranes (Grove et al., 1999; Parman et al., 2001, 2004; Parman and Grove, 2004).

The time period between 3.8 Ga and 3.0 Ga appears to represent a transition from Hadean-style tectonics to late Archean Phanerozoic-style plate tectonics. There are no clear examples of Phanerozoic-style accretionary complexes or ophiolites older than 3.0 Ga, but some mid-Archean greenstone belts resemble primitive island arc terranes (e.g., Grove et al., 1999). One scenario for how this transition may have occurred is shown in Figure 7: greenstone-granite terranes accumulate at triple junctions between convergent plates (Fig. 7A); waning plume volcanism on one plate allows the adjacent plate to expand as the convergence zone shifts toward the waning plume (Fig. 7B); finally, the expanding plate begins to sink under the hotter, more buoyant shrinking plate to form an asymmetric convergent boundary (Fig. 7C). The expanding plate will be denser because it is farther from its parent plume and because thinning of the overlying crust on the expanding plate will enhance cooling and thickening of its subjacent mantle lithosphere. The onset of asymmetric convergence will induce passive upwelling of the asthenosphere along linear rifts, transforming the radially expanding plumes into ridge-centered plumes on oceanic spreading centers.

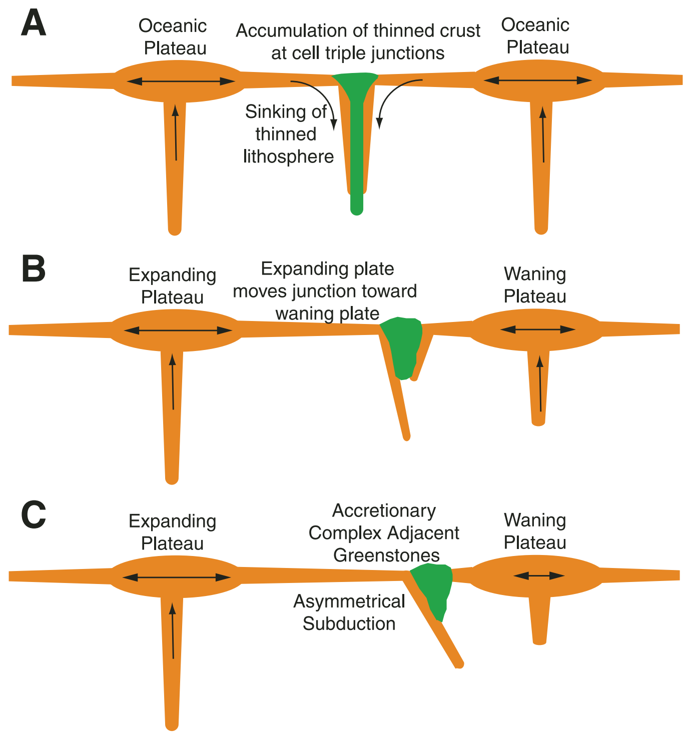

Figure 7. Schematic model for transition from Hadean-style tectonics to late Archean Phanerozoic-style plate tectonics: (A) Greenstone-granite terranes accumulate at triple junctions between convergent plates; (B) waning plume volcanism on one plate allows the adjacent plate to expand as the convergence zone shifts toward the waning plume; (C) finally, the expanding plate begins to sink under the hotter, more buoyant shrinking plate to form an asymmetrical convergent boundary. The expanding plate (left side) is denser because it is farther from its parent plume and because thinning of the overlying crust on the expanding plate enhances cooling and thickening of its subjacent mantle lithosphere. The onset of asymmetrical convergence (C) will induce passive upwelling of the asthenosphere along linear rifts, transforming the radially expanding plumes into ridge-centered plumes on oceanic spreading centers.

The accumulating evidence for Phanerozoic-style plate tectonics during the late Archean implies that cooling of Earth's mantle during the Hadean, subsequent to the Tartarean magma ocean and core formation, was relatively efficient and rapid. This efficient heat loss may have been driven in part by basin-forming impacts during the terminal bombardment around 3.9–3.8 Ga. The resulting decrease in geothermal gradient and development of a stable thermal boundary layer on the surface allowed the accumulation of sufficient liquid water to cool oceanic lithosphere hydrothermally and promote Phanerozoic-style asymmetric subduction, passive upwelling of asthenosphere, and the formation of accretionary subduction complexes that mixed arc-derived clastic sediments with exotic fragments of oceanic crust.

The loss of heat in response to this continuous thinning of the thermal boundary layer during vigorous convection was apparently rapid enough to cool Earth's surface below 100 °C by ca. 3.8 Ga when we first observe pillow lava and water-laid sediments (e.g., Komiya et al., 1999; Bolhar et al., 2004) and possibly sooner. Wilde et al. (2001) and Mojzsis et al. (2001) have argued that the oxygen isotopic compositions in some primordial detrital zircons require liquid water soon after planetary accretion, as early as 4.4 Ga. Valley et al. (2002) use these same data to argue for a cool early Earth with "continental" type crust by 4.4 Ga; however, they also suggest formation in a "tectonic environment similar to Iceland today" (Valley et al., 2002, p. 352). Since Iceland may represent our best analogue for plume-related oceanic plateaux in the Hadean, this tectonic setting is consistent with Hadean crustal processes discussed earlier. And studies of zircons from lunar regolith breccias show that granitic rocks need not be abundant for zircon to be preserved and concentrated (Meyer et al., 1996).

CONCLUSIONS

Phanerozoic-style plate tectonics may be recognized in Proterozoic and Archean rock assemblages by the occurrence of (1) oceanic crust or ophiolites, (2) island arc volcanic or plutonic suites, or (3) accretionary complexes formed in asymmetric subduction zones. However, rock assemblages similar to those formed at mid-ocean ridges or in island arcs may also form during Hadean-style convective overturn. In contrast, subduction zone accretionary complexes result from the physical juxtaposition of rock assemblages formed in different tectonic settings, making them unique to Phanerozoic-style plate tectonics. Recognition of these assemblages in the Archean rock record is thus *prima facie* evidence for Phanerozoic-style plate tectonics. This evidence is reinforced by the occurrence of boninites in the 2.8 Ga North Karelian ophiolites (Shchipansky et al., 2004) and by Phanerozoic-style island arc assemblages in the 2.7 Ga Slave province (Corcoran et al., 2004).

The increasing evidence for Archean subduction accretionary complexes implies a fundamental change in the thermal structure of the planet between 3.0 and 3.8 Ga that resulted in a mantle potential temperature only slightly higher than that observed today. If the Isua Supergroup is an accretionary complex and marks the onset of rigid lithosphere like today's, the transition from Hadean-style thermal convection driven by heating from below to Phanerozoic-style tectonics driven by cooling and sinking of lithospheric slabs appears to be coincident with the end of the late meteorite bombardment at ca. 3.8 Ga (Ryder, 2000). An older transition may be suggested by oxygen isotopes in primordial zircons, but evidence for a fractionated mantle at 4.4 Ga is debated (e.g., Amelin et al., 1999; Peck et al., 2001). The presence of liquid water on Earth's surface does not require lower mantle potential temperatures, but it does limit how high those temperatures may have been.

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REFERENCES CITED

Adams, M.G., and Trupe, C.H., 1997, Conditions and timing of metamorphism in the Blue Ridge thrust complex, northwestern North Carolina and eastern Tennessee, *in* Stewart, K.G., Adams, M.G., and Trupe, C.H., eds., Paleozoic Structure, Metamorphism, and Tectonics of the Blue Ridge of Western North Carolina: Durham, North Carolina, Duke University, Carolina Geological Society 1997 Field Trip Guidebook, p. 33–48.

Adams, M.G., Stewart, K.G., Trupe, C.H., and Willard, R.A., 1995, Tectonic significance of high-pressure metamorphic rocks and dextral strike-slip faulting in the southern Appalachians, *in* Hibbard, J., van Staal, C., Cawood, P., and Colman-Sadd, S., eds., New Perspectives in the Appalachian-Caledonian Orogen: Geological Association of Canada Special Paper 41, p. 21–42.

Amelin, Y., Lee, D.C., Halliday, A.N., and Pidgeon, R.T., 1999, Nature of the Earth's earliest crust from hafnium isotopes in single detrital zircons: Nature, v. 399, p. 252–255, doi: 10.1038/20426.

Anderson, D., 2001, Top-down tectonics?: Science, v. 293, p. 2016–2018, doi: 10.1126/science.1065448.

Armstrong, R.A., Compston, W., de Witt, M.J., and Williams, I.S., 1990, The stratigraphy of the 3.5–3.2 Ga Barberton Greenstone Belt revisited: A single zircon ion microprobe study: Earth and Planetary Science Letters, v. 101, p. 90–106, doi: 10.1016/0012–821X(90)90127-J.

Arndt, N.T., 1994, Archean komatiites, *in* Condie, K.C., ed., Archean Crustal Evolution: Amsterdam, Elsevier, p. 11–44.

Arndt, N.T., 2004, Komatiites, kimberlites and boninites: Journal of Geophysical Research, v. 108, no. B6, p. 2293, doi: 10.1029/2002JB002157.

Arndt, N.T., Albarede, F., and Nisbet, E.G., 1997a, Mafic and ultramafic magmatism, *in* de Witt, M., and Ashwal, L.D., eds., Greenstone Belts: Oxford Monographs in Geology and Geophysics 35, p. 233–254.

Arndt, N.T., Kerr, A.C., and Tarney, J., 1997b, Dynamic melting in plume heads: The formation of Gorgona komatiites and basalts: Earth and Planetary Science Letters, v. 146, p. 289–301, doi: 10.1016/S0012–821X(96)00219–1.

Arndt, N.T., Albarède, F., Cheadle, M., Ginibre, C., Herzberg, C., Jenner, G., Chauvel, C., and Lahaye, Y., 1998, Were komatiites wet?: Geology, v. 26, p. 739–742, doi: 10.1130/0091–7613(1998)026<0739:WKW>2.3.CO;2.

Bailey, E.H., Irwin, W.P., and Jones, D.L., 1964, Franciscan and related rocks, and their significance in the geology of western California: Bulletin 183—California: Division of Mines and Geology, v. 183, p. 1–177.

Barth, M.G., Foley, S.F., and Horn, I., 2002, Partial melting in Archean subduction zones: Constraints from experimentally determined trace element partition coefficients between eclogitic minerals and tonalitic melts under upper mantle conditions: Precambrian Research, v. 113, no. 3-4, p. 323–340, doi: 10.1016/S0301–9268(01)00216–9.

Becker, D.G., and Cloos, M., 1985, Mélange diapirs into the Cambria Slab; a Franciscan trench slope basin near Cambria, California: The Journal of Geology, v. 93, no. 2, p. 101–110.

Bercovici, D., 2003, The generation of plate tectonics from mantle convection: Earth and Planetary Science Letters, v. 205, p. 107–121, doi: 10.1016/S0012–821X(02)01009–9.

Bickle, M.J., 1978, Heat loss from the Earth: A constraint on Archaean tectonics from the relation between geothermal gradients and the rate of heat production: Earth and Planetary Science Letters, v. 40, p. 301–315, doi: 10.1016/0012–821X(78)90155–3.

Bickle, M.J., Nisbet, E.G., and Martin, A., 1994, Archean greenstone belts are not oceanic crust: The Journal of Geology, v. 102, p. 121–138.

Blake, M.C., Jr., and Jones, D.L., 1974, Origin of Franciscan mélanges in northern California, *in* Modern and Ancient Geosynclinal Sedimentation; Problems of palinspastic restoration: Tulsa, Oklahoma, Society of Economic Paleontologists and Mineralogists Special Publication 19, p. 345–357.

Blake, M.C., Jr., and Wentworth, C.M., 1999, Structure and metamorphism of the Franciscan Complex, Mt. Hamilton area, Northern California: International Geology Review, v. 41, no. 5, p. 417–424.

Blake, M.C., Jr., Jayko, A.S., and Howell, D.G., 1982, Sedimentation, metamorphism and tectonic accretion of the Franciscan assemblage of Northern California, *in* Leggett, J., ed., Trench-forearc geology; sedimentation and tectonics on modern and ancient active plate margins: Geological Society [London] Special Publication 10, p. 433–438.

Blake, M.C., Jr., Jayko, A.S., and McLaughlin, R.J., 1985, Tectonostratigraphic terranes of the Northern Coast Ranges, California, *in* Howell, D.G., ed., Tectonostratigraphic terranes of the Circum-Pacific Region: Houston, Texas, Circum-Pacific Council for Energy and Mineral Resources, p. 159–171.

Bolhar, R., Kamber, B.S., Moorbath, S., Fedo, C.M., and Whitehouse, M.J., 2004, Characterisation of early Archean chemical sediments by trace element signatures: Earth and Planetary Science Letters, v. 222, p. 43–60, doi: 10.1016/j.epsl.2004.02.016.

Bowring, S.A., and Williams, I.A., 1999, Priscoan (4.00–4.03 Ga) orthogneisses from northwestern Canada: Contributions to Mineralogy and Petrology, v. 134, p. 3–16, doi: 10.1007/s004100050465.

Bowring, S.A., Housh, T.B., and Isachsen, C.E., 1990, The Acasta gneisses: Remnant of Earth's early crust, *in* Newsome, H., and Jones, J., eds., Origin of the Earth: Oxford, UK, Oxford University Press, p. 319–343.

Bradley, D.C., Kusky, T.M., Haeussler, P., Rowley, D.C., Goldfarb, R., and Nelson, S., 2003, Geologic signature of early ridge subduction in the accretionary wedge, forearc basin, and magmatic arc of south-central Alaska, *in* Sisson, V.B., Roeske, S., and Pavlis, T.L., eds., Geology of a transpressional orogen developed during a ridge-trench interaction along the North Pacific Margin: Geological Society of America Special Paper 371, p. 19–50.

Bridgwater, D., Keto, L., McGregor, V.R., and Myers, J.S., 1976, Archaean gneiss complex of Greenland, *in* Escher, A., and Watt, W.S., eds., Geology of Greenland: Copenhagen, Grønlands Geologiske Undersøgelse, p. 18–75.

Bryant, B., 1988a, Geology of the Farmington Canyon Complex, Wasatch Mountains, Utah: U.S. Geological Survey Professional Paper 1476, 54 p.

Bryant, B., 1988b, Evolution and early Proterozoic history of the margin of the Archean continent in Utah, *in* Ernst, W.G., ed., Metamorphism and crustal evolution of the Western United States, Rubey Volume 7: Englewood Cliffs, New Jersey, Prentice-Hall, p 431–445.

Byrne, T., 1984, Early deformation in mélange terranes of the Ghost Rocks formation, Kodiak Islands, Alaska, *in* Raymond, L.A., ed., Mélanges: Their nature, origin, and significance: Geological Society of America Special Paper 198, p. 21–51.

Calvert, A.J., and Ludden, J.N., 1999, Archean continental assembly in the southeastern Superior province of Canada: Tectonics, v. 18, no. 3, p. 412–429, doi: 10.1029/1999TC900006.

Campbell, I.H., and Jarvis, G.T., 1984, Mantle convection and early crustal evolution: Precambrian Research, v. 26, p. 15–56, doi: 10.1016/0301–9268(84)90016–0.

Campbell, I.H., Hill, R.E.T., and Griffiths, R.W., 1989, Melting in an Archaean mantle plume: Heads it's basalts, tails it's komatiites: Nature, v. 339, p. 697–699, doi: 10.1038/339697a0.

Carlson, R.L., 1981, Boundary forces and plate tectonics: Geophysical Research Letters, v. 8, p. 958–961.

Cavosie, A., and Selverstone, J., 2003, Early Proterozoic oceanic crust in the northern Colorado Front Range: Implications for crustal growth and initiation of basement faults: Tectonics, v. 22, p. 1–23.

Cloos, M., 1982, Flow mélanges; numerical modeling and geologic constraints on their origin in the Franciscan subduction complex, California: Geological Society of America Bulletin, v. 93, no. 4, p. 330–344, doi: 10.1130/0016–7606(1982)93<330:FMNMAG>2.0.CO;2.

Cloud, P., 1972, A working model of the primitive Earth: American Journal of Science, v. 272, no. 6, p. 537–548.

Cole, R.B., and Basu, A.R., 1995, Nd-Sr isotopic geochemistry and tectonics of ridge subduction and middle Cenozoic volcanism in western California: Geological Society of America Bulletin, v. 107, no. 2, p. 167–179, doi: 10.1130/0016–7606(1995)107<0167:NSIGAT>2.3.CO;2.

Coleman, R.G., 2000, Prospecting for ophiolites along the California continental margin, *in* Dilek, Y., Moores, E., Elthon, D., and Nicolas, A., eds., Ophiolites and oceanic crust: Geological Society of America Special Paper 349, p. 351–364.

Connelly, J.N., and Ryan, B., 1996, Late Archean evolution of the Nain Province, Nain, Labrador: Imprint of a collision: Canadian Journal of Earth Sciences, v. 33, no. 9, p. 1325–1342.

Corcoran, P.L., and Dostal, J., 2001, Development of an ancient back-arc basin overlying continental crust: The Archean Peltier Formation, Northwest Territories, Canada: The Journal of Geology, v. 109, p. 329–348, doi: 10.1086/319976.

Corcoran, P.L., Mueller, W.U., and Kusky, T.M., 2004, Inferred ophiolites in the Archean Slave Craton, *in* Kusky, T.M., ed., Precambrian Ophiolites and Related Rocks, Developments in Precambrian Geology, v. 13: Amsterdam, Elsevier, p. 363–404.

Cowan, D.S., 1978, Origin of blueschist-bearing chaotic rocks in the Franciscan Complex, San Simeon, California: Geological Society of America Bulletin, v. 89, no. 9, p. 1415–1423, doi: 10.1130/0016–7606(1978)89<1415:OOBCRI>2.0.CO;2.

Cowan, D.S., 1985, Structural styles in Mesozoic and Cenozoic mélanges in the western Cordillera of North America: Geological Society of America Bulletin, v. 96, p. 451–462, doi: 10.1130/0016–7606(1985)96<451:SSIMAC>2.0.CO;2.

Coward, M.P., Jan, M.Q., Rex, D., Tarney, J., Thirwall, M., and Windley, B.F., 1982, Geotectonic framework of Himalaya of northern Pakistan: Journal of the Geological Society of London, v. 139, p. 299–308.

Dann, J.C., 1991, Early Proterozoic ophiolite, central Arizona: Geology, v. 19, p. 590–593, doi: 10.1130/0091–7613(1991)019<0590:EPOCA>2.3.CO;2.

Dann, J.C., 2004, The 1.73 Ga Payson ophiolite, Arizona, USA, *in* Kusky, T.M., ed., Precambrian Ophiolites and Related Rocks, Developments in Precambrian Geology, v. 13: Amsterdam, Elsevier, p. 73–94.

De Ronde, C.E.J., and de Wit, M.J., 1994, Tectonic history of the Barberton greenstone belt, South Africa: 490 million years of Archean crustal evolution: Tectonics, v. 13, no. 4, p. 983–1005, doi: 10.1029/94TC00353.

de Wit, M.J., 1998, On Archean granites, greenstones, cratons and tectonics: Does the evidence demand a verdict?: Precambrian Research, v. 91, no. 1-2, p. 181–226, doi: 10.1016/S0301–9268(98)00043–6.

de Wit, M.J., 2004, Archean greenstone belts do contain fragments of ophiolites, *in* Kusky, T.M., ed., Precambrian Ophiolites and Related Rocks, Developments in Precambrian Geology, v. 13: Amsterdam, Elsevier, p. 599–614.

de Wit, M.J., Hart, R.J., and Hart, R.A., 1987, The Jamestown ophiolite complex, Barberton mountain belt: A section through 3.5 Ga ocean crust: Journal of African Earth Sciences, v. 6, p. 681–730, doi: 10.1016/0899–5362(87)90007–8.

de Wit, M.J., Roering, C., Hart, R.J., Armstrong, R.A., de Ronde, C.E.J., Green, R.W.E., Tredoux, M., Peberdy, E., and Hart, R.A., 1992, Formation of an Archaean continent: Nature, v. 357, p. 553–562, doi: 10.1038/357553a0.

Dennis, A.J., Shervais, J.W., and Secor, D.T., Jr., 2000, Newberry, South Carolina Eclogite: Structural setting and style of occurrence, *in* Wyeth, A., ed., A Compendium of Field Trips of South Carolina Geology: Columbia, South Carolina Department of Natural Resources, Geological Survey, p. 29–38.

Dennis, A.J., Shervais, J.W., Mauldin, J., and Maher, H.D., Jr., 2004, Petrology and geochemistry of Neoproterozoic volcanic arc terranes beneath the Atlantic Coastal Plain, Savannah River Site, South Carolina: Geological Society of America Bulletin, v. 116, p. 572–593, doi: 10.1130/B25240.1.

Desrochers, J.-P., Hubert, C., Ludden, J.N., and Pilote, P., 1993, Accretion of Archean oceanic plateau fragments in the Abitibi Greenstone Belt, Canada: Geology, v. 21, p. 451–454, doi: 10.1130/0091–7613(1993)021<0451:AOAOPF>2.3.CO;2.

Dirks, P.H.G.M., and Jelsma, H.A., 1998, Horizontal accretion and stabilization of the Archean Zimbabwe Craton: Geology, v. 26, p. 11–14, doi: 10.1130/0091–7613(1998)026<0011:HAASOT>2.3.CO;2.

Drummond, M., and Defant, M., 1990, A model for trondhjemite-tonalite-dacite genesis and crustal growth via slab melting: Archean to modern comparison: Journal of Geophysical Research, v. 95, no. B13, p. 21,503–21,521.

Ernst, W.G., 1993, Metamorphism of Franciscan tectonostratigraphic assemblage, Pacheco Pass area, east-central Diablo Range, California Coast Ranges: Geological Society of America Bulletin, v. 105, no. 5, p. 618–636, doi: 10.1130/0016–7606(1993)105<0618:MOFTAP>2.3.CO;2.

Fedo, C.M., 2000, Setting and origin for problematic rocks from the >3.7 Ga Isua greenstone belt, southern West Greenland, Earth's oldest coarse clastic sediments: Precambrian Research, v. 101, p. 69–78.

Fruehn, J., von Huene, R., and Fisher, M.A., 1999, Accretion in the wake of terrane collision; the Neogene accretionary wedge off Kenai Peninsula, Alaska: Tectonics, v. 18, no. 2, p. 263–277.

Fryer, P., Lockwood, J.P., Becker, N., Phipps, S., and Todd, C.S., 2000, Significance of serpentine mud volcanism in convergent margins, *in* Dilek, Y., Moores, E.M., Don, M.E., and Adolphe, N., eds., Ophiolites and oceanic crust: New insights from field studies and the Ocean Drilling Program: Geological Society of America Special Paper 349, p. 35–51.

Grove, T.L., and Parman, S.W., 2004, Thermal evolution of the Earth as recorded by komatiites: Earth and Planetary Science Letters, v. 219, p. 173–187, doi: 10.1016/S0012–821X(04)00002–0.

Grove, T.L., Parman, S.W., and Dann, J.C., 1999, Conditions of magma generation for Archean komatiites from the Barberton Mountainland, South Africa, *in* Fei, Y., Bertka, C.M., and Mysen, B.O., eds., Mantle petrology: Field observations and high-pressure experimentation; A tribute to Francis R. (Joe) Boyd: Geochemical Society Special Publication 6, p. 155–167.

Hager, B., and O'Connell, R., 1981, A simple global model of plate dynamics and mantle convection: Journal of Geophysical Research, v. 86, p. 4843–4867.

Hamilton, W.B., 1979, Tectonics of the Indonesian region: U.S. Geological Survey Professional Paper 1078, 345 p.

Hamilton, W.B., 1998, Archean magmatism and deformation were not products of plate tectonics: Precambrian Research, v. 91, no. 1-2, p. 143–179, doi: 10.1016/S0301–9268(98)00042–4.

Hawkins, J.W., Bloomer, S.H., Evans, C.A., and Melchior, J.T., 1984, Evolution of intra-oceanic arc-trench systems, *in* Carlson, R.L., and Kobayashi, K., eds., Geodynamics of back-arc regions: Tectonophysics, p. 175–205.

Hedge, C.E., Sacey, J.S., and Bryant, B., 1983, Geochronology of the Farmington Canyon complex, Wasatch Mountains, Utah, *in* Miller, D.M., ed., Tectonic and stratigraphic studies of the eastern Great Basin: Geological Society of America Memoir 157, p. 37–44.

Helmstaedt, H., and Schulze, D.J., 1989, Southern African kimberlites and their mantle sample: Implications for Archean tectonics and lithosphere evolution, *in* Boyd, F.R., and Meyer, H.O.A., eds., Kimberlites and Related Rocks: Carleton, Blackwell, p. 358–368.

Hill, R.I., 1991, Starting plumes and continental breakup: Earth and Planetary Science Letters, v. 104, p. 398–416, doi: 10.1016/0012–821X(91)90218–7.

Hofmann, A., and Kusky, T., 2004, The Belingwe Greenstone Belt: Ensialic or Oceanic?, *in* Kusky, T.M., ed., Precambrian Ophiolites and Related Rocks, Developments in Precambrian Geology, v. 13: Amsterdam, Elsevier, p. 487–538.

Hopson, C.A., and Pessagno, E.A., 2005, Tehama-Colusa Serpentinite mélange: A remnant of Franciscan Jurassic oceanic lithosphere: Northern California, International Geology Review, v. 47, p. 65–100.

Hsü, K.J., 1966, Franciscan rocks of the Santa Lucia range, California, and the Argille scagliose of the Apennines, Italy; a comparison in style of deformation: Geological Society of America Special Paper 87, p. 210–211.

Hsü, K.J., 1968, Principles of mélanges and their bearing on the Franciscan-Knoxville paradox: Geological Society of America Bulletin, v. 79, no. 8, p. 1063–1074.

Huang, X., Jianghai, L., Kusky, T.M., and Chen, Z., 2004, Microstructures of the Zunhua 2.50 Ga Podiform Chromite, North China Craton and implications for the deformation and rheology of the Archean oceanic lithospheric mantle, *in* Kusky, T.M., ed., Precambrian Ophiolites and Related Rocks, Developments in Precambrian Geology, v. 13: Amsterdam, Elsevier, p. 321–338.

Huot, F., and Maury, R.C., 2002, The Round Mountain serpentinite mélange, northern Coast Ranges of California: An association of backarc and arc-related tectonic units: Geological Society of America Bulletin, v. 114, no. 1, p. 109–123.

Huson, R., Kusky, T.M., and Li, J.H., 2004, Geochemical and petrographic characteristics of the Central Belt of the Archean Dongwanzi Ophiolite Complex, *in* Kusky, T.M., ed., Precambrian Ophiolites and Related Rocks, Developments in Precambrian Geology, v. 13: Amsterdam, Elsevier, p. 283–322.

Isozaki, Y., 1997, Jurassic accretion tectonics of Japan: The Island Arc, v. 6, p. 25–51.

Isozaki, Y., and Blake, M.C., 1994, Biostratigraphic constraints on formation and timing of accretion in a subduction complex, an example from the Franciscan complex in northern California: The Journal of Geology, v. 102, p. 283–296.

Isozaki, Y., Maruyama, S., and Furuoka, F., 1990, Accreted oceanic materials in Japan: Tectonophysics, v. 181, p. 179–205, doi: 10.1016/0040–1951(90)90016–2.

Johnson, C.M., and O'Neil, J.R., 1984, Triple junction magmatism: A geochemical study of Neogene volcanic rocks in western California: Earth and Planetary Science Letters, v. 71, p. 241–262, doi: 10.1016/0012–821X(84)90090–6.

Jurdy, D., and Stefanick, M., 1991, The forces driving the plates: Constraints from kinematics and stress observations: Philosophical Transactions of the Royal Society of London, ser. A, v. 337, p. 127–138.

Kamo, S.L., and Davis, D.W., 1994, Reassessment of Archean crustal development in the Barberton Mountain Land, South Africa, based on U-Pb dating: Tectonics, v. 13, no. 1, p. 167–192, doi: 10.1029/93TC02254.

Karl, S.M., 1984, Sedimentologic, diagenetic, and geochemical analysis of upper Mesozoic ribbon cherts from the Franciscan assemblage at the Marin Headlands, California, *in* Blake, C., Jr., ed., Franciscan geology of Northern California: Field Trip Guidebook 43: Los Angeles, Pacific Section, Society of Economic Paleontologists and Mineralogists, p. 71–88.

Komiya, T., Maruyama, S., Masuda, T., Nohda, S., Hayashi, M., and Okamoto, K., 1999, Plate tectonics at 3.8–3.7 Ga: Field evidence from the Isua accretionary complex, Southern West Greenland: The Journal of Geology, v. 107, p. 515–554, doi: 10.1086/314371.

Komiya, T., Maruyama, S., Hirata, T., Yurimoto, H., and Nohda, S., 2004, Geochemistry of the oldest MORB and OIB in the Isua supracrustal belt, southern west Greenland: Implications for the composition and temperature of early Archean upper mantle: The Island Arc, v. 13, p. 47, doi: 10.1111/j.1440–1738.2003.00416.x.

Kontinen, A., 1987, An early Proterozoic ophiolite: The Jourma mafic-ultramafic complex, northeastern Finland: Precambrian Research, v. 35, p. 313–341, doi: 10.1016/0301–9268(87)90061–1.

Kröner, A., 1985, Evolution of the Archean continental crust: Annual Review of Earth and Planetary Sciences, v. 13, p. 49–74, doi: 10.1146/annurev.ea.13.050185.000405.

Kröner, A., and Todt, W., 1988, Single zircon dating constraining the maximum age of the Barberton Greenstone Belt, Southern Africa: Journal of Geophysical Research, v. 93, no. b12, p. 15,329–15,337.

Kröner, A., Byerly, G.R., and Lowe, D.R., 1991, Chronology of early Archaean granite-greenstone evolution in the Barberton Mountain Land, South Africa, based on precise dating by single zircon evaporation: Earth and Planetary Science Letters, v. 103, p. 41–54, doi: 10.1016/0012–821X(91)90148-B.

Kukowski, N., Schillhorn, T., Huhn, K., von Rad, U., Husen, S., and Flueh, E.R., 2001, Morphotectonics and mechanics of the central Makran accretionary wedge off Pakistan: Marine Geology, v. 173, p. 1–19, doi: 10.1016/S0025–3227(00)00167–5.

Kusky, T.M., 1998, Tectonic setting and terrane accretion of the Archean Zimbabwe craton: Geology, v. 26, p. 163–166, doi: 10.1130/0091–7613(1998)026<0163:TSATAO>2.3.CO;2.

Kusky, T.M., and Kidd, W.S.F., 1992, Remnants of an Archean oceanic plateau, Belingwe greenstone belt, Zimbabwe: Geology, v. 20, p. 43–46, doi: 10.1130/0091–7613(1992)020<0043:ROAAOP>2.3.CO;2.

Kusky, T.M., and Polat, A., 1999, Growth of granite-greenstone terranes at convergent margins, and stabilization of Archean cratons: Tectonophysics, v. 305, p. 43–73, doi: 10.1016/S0040–1951(99)00014–1.

Kusky, T.M., Bradley, D.C., Haeussler, P., and Karl, S., 1997a, Controls on accretion of flysch and mélange belts at convergent margins: Evidence from the Chugach Bay thrust and Iceworm mélange, Chugach Terrane, Alaska: Tectonics, v. 16, p. 855–878, doi: 10.1029/97TC02780.

Kusky, T.M., Bradley, D.C., and Haeussler, P., 1997b, Progressive deformation of the Chugach accretionary complex, Alaska, during a Paleogene ridge-trench encounter: Journal of Structural Geology, v. 19, p. 139–157, doi: 10.1016/S0191–8141(96)00084–3.

Kusky, T.M., Li, J.-H., and Tucker, R.D., 2001, The Archean Dongwanzi ophiolite complex, North China craton: 2.505-billion-year-old oceanic crust and mantle: Science, v. 292, no. 5519, p. 1142–1145, doi: 10.1126/science.1059426.

Kusky, T.M., Bradley, D.C., Donley, D.T., Rowley, D., and Haeussler, P., 2003, Controls on intrusion of near-trench magmas of the Sanak-Baranof belt, Alaska, during Paleogene ridge subduction, and consequences for forearc evolution, *in* Sisson, V.B., Roeske, S., and Pavlis, T.L., eds., Geology of a transpressional orogen developed during a ridge-trench interaction along the North Pacific Margin: Geological Society of America Special Paper 371, p. 269–292.

Kusky, T.M., Ganley, R., Lytwyn, J., and Polat, A., 2004a, The Resurrection Peninsula Ophiolite, Mélange and Accreted Flysch Belts of Southern Alaska as an Analog for Trench-Forearc Systems in Precambrian Orogens, *in* Kusky, T.M., ed., Precambrian Ophiolites and Related Rocks, Developments in Precambrian Geology, v. 13: Amsterdam, Elsevier, p. 627–674.

Kusky, T.M., Jainghai, L., Glass, A., and Huang, X.N., 2004b, Origin and Emplacement of Archean Ophiolites of the Central Orogenic Belt, North China Craton, *in* Kusky, T.M., ed., Precambrian Ophiolites and Related Rocks, Developments in Precambrian Geology, v. 13: Amsterdam, Elsevier, p. 223–274.

Li, J.H., Kusky, T.M., and Huang, X., 2002, Archean podiform chromitites and mantle tectonites in ophiolitic mélange, North China Craton; a record of early oceanic mantle processes: GSA Today, v. 12, no. 7, p. 4–11, doi: 10.1130/1052–5173(2002)012<0004:APCAMT>2.0.CO;2.

Lowe, D.R., 1994, Accretionary history of the Archean Barberton Greenstone Belt (3.55–3.22 Ga), southern Africa: Geology, v. 22, p. 1099–1102, doi: 10.1130/0091–7613(1994)022<1099:AHOTAB>2.3.CO;2.

MacGregor, I.D., and Manton, W.I., 1986, Roberts Victor eclogites: Ancient oceanic crust: Journal of Geophysical Research, v. 91, p. 14,063–14,079.

MacPherson, G.J., Phipps, S.P., and Grossman, J.N., 1990, Diverse sources for igneous blocks in Franciscan mélanges, California Coast Ranges: The Journal of Geology, v. 98, no. 6, p. 845–862.

Martin, H., 1994, The Archean grey gneisses and the genesis of continental crust: *in* Condie, K.C., ed., Archean Crustal Evolution: Amsterdam, Elsevier, v. 11, p. 205–259.

McLaughlin, R.J., Blake, M.C., Jr., and Jones, D.L., 1982, Franciscan mélange in central northern California, Geological Survey research 1982: U.S. Geological Survey Professional Paper P1275, 70 p.

Meyer, C., Williams, I.S., and Compston, W., 1996, Uranium-lead ages for lunar zircons; evidence for a prolonged period of granophyre formation from 4.32 to 3.88 Ga: Meteoritics, v. 31, no. 3, p. 370–387.

Mojzsis, S.J., Harrison, T.M., and Pidgeon, R.T., 2001, Oxygen-isotope evidence from ancient zircons for liquid water at the Earth's surface 4,300 Myr ago: Nature, v. 409, p. 178–182, doi: 10.1038/35051557.

Moore, D.E., 1984, Metamorphic history of a high-grade blueschist exotic block from the Franciscan Complex, California: Journal of Petrology, v. 25, no. 1, p. 126–150.

Moore, D.E., and Blake, M.C., Jr., 1989, New evidence for polyphase metamorphism of glaucophane schist and eclogite exotic blocks in the Franciscan Complex, California and Oregon: Journal of Metamorphic Geology, v. 7, no. 2, p. 211–228.

Moore, G.F., and Karig, D.E., 1980, Structural geology of Nias Island, Indonesia: Implications for subduction zone tectonics: American Journal of Science, v. 280, p. 193–223.

Moore, J.C., Biju, D.B., Bergen, J.A., Blackinton, G., Claypool, G.E., Cowan, D.S., Duennebier, F., Guerra, R.T., Hemleben, C.H.J., Hussong, D., Marlow, M.S., Natland, J.H., Pudsey, C.J., Renz, G.W., Tardy-M, Willis, M.E., Wilson, D., and Wright, A.A., 1982, Offscraping and underthrusting of sediment at the deformation front of the Barbados Ridge; Deep Sea Drilling Project Leg 78A: Geological Society of America Bulletin, v. 93, p. 1065–1077.

Mueller, W.U., Corcoran, P.L., and Pickett, C., 2005, Mesoarchean Continental Breakup: Evolution and Inferences from the >2.8 Ga Slave Craton–Cover Succession, Canada: The Journal of Geology, v. 113, p. 23–45, doi: 10.1086/425967.

Murchey, B.L., 1984, Biostratigraphy and lithostratigraphy of chert in the Franciscan Complex, Marin Headlands, California, *in* Blake, C., Jr., ed., Franciscan geology of Northern California: Field Trip Guidebook 43, Pacific Section, SEPM: Los Angeles, California, Society of Economic Paleontologists and Mineralogists, Pacific Section, p. 51–70.

Myers, J.S., 2001, Protoliths of the 3.8–3.7 Ga Isua greenstone belt: West Greenland: Precambrian Research, v. 105, p. 129–141, doi: 10.1016/S0301–9268(00)00108-X.

Myers, J.S., 2004, Isua illusions: Illusive tectonic, sedimentary, volcanic and organic features of the >3.8 – >3.7 Ga Isua greenstone belt, south-west Greenland, *in* Eriksson, P., Altermann, W., Nelson, D., Mueller, W., and Catuneau, O., eds., The Precambrian Earth: Tempos and Events: Amsterdam, Elsevier, p. 66–74.

Neal, C.R., Taylor, L.A., Davidson, J.P., Holden, P., Halliday, A.N., Paces, J.B., Clayton, R.N., and Mayeda, T.K., 1990, Eclogites with oceanic crustal and mantle signatures from the Bellsbank kimberlite, South Africa, Part 2: Sr, Nd, and O isotope chemistry: Earth and Planetary Science Letters, v. 99, p. 362–379, doi: 10.1016/0012–821X(90)90140-S.

Nelson, S.T., Harris, R.A., Dorais, M.J., Heizler, M., Constenius, K., and Barnett, D.A., 2002, Basement complexes in the Wasatch Fault, Utah, provide new limits on crustal accretion: Geology, v. 30, p. 831–834, doi: 10.1130/0091–7613(2002)030<0831:BCITWF>2.0.CO;2.

Nisbet, E.G., and Fowler, M., 2004, The origin and earliest history of the Earth, *in* Holland, H., and Turekian, K., eds., Treatise of Geochemistry, Volume 8, Biogeochemistry: Amsterdam, Elsevier, p. 1–39.

Nisbet, E.G., Cheadle, M.J., Arndt, N.T., and Bickle, M.J., 1993, Constraining the potential temperature of the Archaean mantle: A review of the evidence from komatiites: Lithos, v. 30, p. 291–307, doi: 10.1016/0024–4937(93)90042-B.

Nutman, A.P., Friend, C.R.L., Kinny, P.D., and McGregor, V.R., 1993, Anatomy of an early Archean gneiss complex: 3900 to 3600 Ma crustal evolution in southern West Greenland: Geology, v. 21, p. 415–418, doi: 10.1130/0091–7613(1993)021<0415:AOAEAG>2.3.CO;2.

Nutman, A.P., McGregor, V.R., Friend, C.R.L., Bennett, V.C., and Kinny, P.D., 1996, The Itsaq Gneiss Complex of southern West Greenland; the world's most extensive record of early crustal evolution (3900–3600 Ma): Precambrian Research, v. 78, p. 1–39.

Nutman, A.P., Mojzsis, S.J., Friend, C.R.L., and McGregor, V.R., 1997, Recognition of >3850 Ma waterlaid sediments in West Greenland and their significance for the early Archean Earth: Geochimica et Cosmochimica Acta, v. 61, p. 2475–2484.

Nutman, A.P., Friend, C.R.L., and Bennett, V.C., 2001, Review of the oldest (4400–3600 Ma) geological record: Glimpses of the beginning: Episodes, v. 24, p. 93–101.

Nutman, A.P., Friend, C.R.L., Bennett, V.C., and McGregor, V.R., 2004, Dating of the Ameralik dyke swarms of the Nuuk district, southern West Greenland: Mafic intrusion events starting from c. 3510 Ma: Journal of the Geological Society of London, v. 161, p. 421–430.

Page, B.M., and Suppe, J., 1981, The Pliocene Lichi mélange of Taiwan; its plate-tectonic and olistostromal origin: American Journal of Science, v. 281, no. 3, p. 193–227.

Pan, Y., and Fleet, M.E., 1993, Polymetamorphism in the Archean Hemlo-Heron Bay greenstone belt, Superior Province; P-T variations and implications for tectonic evolution: Canadian Journal of Earth Sciences, v. 30, p. 985–996.

Parman, S.W., and Grove, T.L., 2004, Petrology and geochemistry of Barberton komatiites and basaltic komatiites: Evidence of Archean fore-arc magmatism, *in* Kusky, T.M., ed., Precambrian Ophiolites and Related Rocks, Developments in Precambrian Geology, v. 13: Amsterdam, Elsevier, p. 539–565.

Parman, S.W., Grove, T.L., and Dann, J.C., 2001, The production of Barberton komatiites in an Archean subduction zone: Geophysical Research Letters, v. 28, no. 13, p. 2513–2516, doi: 10.1029/2000GL012713.

Parman, S.W., Grove, T.L., Dann, J.C., and de Wit, M.J., 2004, A subduction origin for komatiite and cratonic lithospheric mantle: South African Journal of Geology, v. 107, no. 1-2, p. 107–118.

Pearce, J.A., 2003, Supra-subduction zone ophiolites; the search for modern analogues, *in* Dilek, Y., and Newcomb, S., eds., Ophiolite concept and the evolution of geological thought: Geological Society of America Special Paper 373, p. 269–293.

Pearce, J.A., Lippard, S.J., and Roberts, S., 1984, Characteristics and tectonic significance of supra-subduction zone ophiolites, *in* Kokelaar, B.P., and Howells, M.F., eds., Marginal basin geology: Geological Society [London] Special Publication 16, p. 74–94.

Peck, W.H., Valley, J.W., Wilde, S.A., and Graham, C.M., 2001, Oxygen isotope ratios and rare earth elements in 3.3 to 4.4 Ga zircons: Ion microprobe evidence for high 18O continental crust and oceans in the early Archean: Geochimica et Cosmochimica Acta, v. 65, no. 22, p. 4215–4229, doi: 10.1016/S0016–7037(01)00711–6.

Peltonen, P., and Kontinen, A., 2004, The Jormua Ophiolite: A mafic-ultramafic complex from an ancient ocean-continent transition zone, *in* Kusky, T.M., ed., Precambrian Ophiolites and Related Rocks, Developments in Precambrian Geology, v. 13: Amsterdam, Elsevier, p. 35–72.

Platt, J.P., 1986, Dynamics of orogenic wedges and the uplift of high-pressure metamorphic rocks: Geological Society of America Bulletin, v. 97, no. 9, p. 1037–1053, doi: 10.1130/0016–7606(1986)97<1037:DOOWAT>2.0.CO;2.

Platt, J.P., Leggett, J.K., Young, J., Raza, H., and Alam, S., 1985, Large-scale sediment underplating in the Makran accretionary prism: Southwest Pakistan: Geology, v. 13, p. 507–511.

Polat, A., and Kerrich, R., 1999, Formation of an Archean tectonic mélange in the Schreiber-Hemlo greenstone belt, Superior Province, Canada: Implications for Archean subduction-accretion process: Tectonics, v. 18, p. 733–755, doi: 10.1029/1999TC900032.

Polat, A., and Kerrich, R., 2001, Magnesian andesites, Nb-enriched basalt-andesites, and adakites from late-Archean 2.7 Ga Wawa greenstone belts, Superior Province, Canada: Implications for late Archean subduction zone petrologenetic processes: Contributions to Mineralogy and Petrology, v. 141, no. 1, p. 36–52.

Polat, A., and Kerrich, R., 2002, Nd-isotope systematics of ~2.7 Ga adakites, magnesian andesites, and arc basalts, Superior Province: Evidence for shallow crustal recycling at Archean subduction zones: Earth and Planetary Science Letters, v. 202, no. 2, p. 345–360, doi: 10.1016/S0012–821X(02)00806–3.

Polat, A., and Kerrich, R., 2004, Precambrian arc associations: Boninites, adakites, magnesian andesites, and Nb-enriched basalts, *in* Kusky, T.M., ed., Precambrian Ophiolites and Related Rocks, Developments in Precambrian Geology, v. 13: Amsterdam, Elsevier, p. 567–598.

Polat, A., Kerrich, R., and Wyman, D.A., 1998, The late Archean Schreiber-Hemlo and White River–Dayohessarah greenstone belts, Superior Province: collages of oceanic plateaus, oceanic arcs, and subduction-accretion complexes: Tectonophysics, v. 289, p. 295–326, doi: 10.1016/S0040–1951(98)00002-X.

Polat, A., Kerrich, R., and Wyman, D.A., 1999, Geochemical diversity in oceanic komatites and basalts from the late Archean Wawa greenstone belt, Superior Province, Canada: Trace element and Nd isotopic evidence for a heterogeneous mantle: Precambrian Research, v. 94, p. 139–173, doi: 10.1016/S0301–9268(98)00110–7.

Pollack, H.N., 1997, Thermal Characteristics of the Archaean, *in* deWit, M., and Ashwal, L.D., eds., Greenstone Belts: Oxford Monographs in Geology and Geophysics, v. 35, p. 223–232.

Prendergast, M.D., 2004, The Bulawayan Supergroup: A late Archaean passive margin-related large igneous province in the Zimbabwe craton: Journal of Geological Society of London, v. 161, p. 431–445.

Puchtel, I.S., 2004, 3.0 Ga Olondo Greenstone Belt in the Aldan Shield, E. Siberia, *in* Kusky, T.M., ed., Precambrian Ophiolites and Related Rocks, Developments in Precambrian Geology, v. 13: Amsterdam, Elsevier, p. 405–424.

Rapp, R.P., Shimizu, N., and Norman, M.D., 2003, Growth of early continental crust by partial melting of eclogite: Nature, v. 425, p. 605–609, doi: 10.1038/nature02031.

Richards, M., Duncan, R., and Courtillot, V., 1989, Flood basalts and hot-spot tracks: Plume heads and tails: Science, v. 246, p. 103–107.

Ridley, J.R., Vearncombe, J.R., and Jelsma, H.A., 1997, Relations between greenstone belts and associated granitoids, *in* deWit, M., and Ashwal, L.D., eds., Greenstone Belts: Oxford Monographs in Geology and Geophysics, v. 35, p. 376–397.

Robinson, P.T., and Malpas, J., 1990, The Troodos ophiolite: New perspective on its origin and emplacement, *in* Malpas, J., Moores, E., Panayiotou, A., and Xenophontos, C., eds., Ophiolites; oceanic crustal analogues: Proceedings of the symposium "Troodos 1987," Nicosia, Cyprus, Geological Survey Department, p. 13–26.

Rosing, M.T., Rose, N.M., Bridgwater, D., and Thomsen, H.S., 1996, Earliest part of Earth's stratigraphic record: A reappraisal of the >3.7 Ga Isua (Greenland) supracrustal sequence: Geology, v. 24, p. 43–46, doi: 10.1130/0091–7613(1996)024<0043:EPOESS>2.3.CO;2.

Ryder, G., 2000, Glass beads tell a tale of lunar bombardment: Science, v. 287, p. 1768–1769.

Secor, D.T., Snoke, A.W., Bramlett, K.W., Costello, O.P., and Kimbrell, O.P., 1986, Character of the Alleghanian orogeny in the southern Appalachians, Part I, Alleghanian deformation in the eastern Piedmont of South Carolina: Geological Society of America Bulletin, v. 97, p. 1314–1328.

Shah, M.T., and Shervais, J.W., 1999, The Dir-Utror metavolcanic sequence, Kohistan arc terrane, northern Pakistan: Journal of Asian Earth Sciences, v. 17, no. 4, p. 459–475, doi: 10.1016/S1367–9120(99)00009–7.

Shchipansky, A.A., Samsonov, A.V., Bibikova, E.V., Babarina, I.I., Konilov, A.N., Krylov, K.A., Slabunov, A.I., and Bogina, M.M., 2004, 2.8 Ga Boninite-Hosting partial suprasubduction zone ophiolite sequences from the North Karelian Greenstone Belt, NE Baltic Shield, Russia, *in* Kusky, T.M., ed., Precambrian Ophiolites and Related Rocks, Developments in Precambrian Geology, v. 13: Amsterdam, Elsevier, p. 425–486.

Shervais, J.W., 1990, Island arc and ocean crust ophiolites: Contrasts in the petrology, geochemistry, and tectonic style of ophiolite assemblages in the California Coast Ranges, *in* Malpas, J., Moores, E., Panayiotou, A., and Xenophontos, C., eds., Ophiolites: Oceanic Crustal Analogues: Nicosia, Cyprus, Geological Survey Department, Proceedings of the Symposium Troodos 1987, p. 507–520.

Shervais, J.W., 2001, Birth, death, and resurrection: The life cycle of supra-subduction zone ophiolites: Geochemistry, Geophysics, Geosystems, v. 2, no. 2000GC000080, 20,925 words, 8 fig., 3 tables.

Shervais, J.W., 2004, Is the southern Farmington Canyon complex a late Archean/early Proterozoic accretionary complex? *in* Reimold, W.U., and Hofmann, A., eds., Abstract volume, Field Forum on Processes on the Early Earth, Kaapvaal Craton, Geological Society of South Africa, Johannesburg, SA, 4–9 July 2004, p. 88–89.

Shervais, J.W., and Kimbrough, D.L., 1985, Geochemical evidence for the tectonic setting of the Coast Range ophiolite; a composite island arc-oceanic crust terrane in western California: Geology, v. 13, no. 1, p. 35–38, doi: 10.1130/0091–7613(1985)13<35:GEFTTS>2.0.CO;2.

Shervais, J.W., and Kimbrough, D.L., 1987, Alkaline and transitional subalkaline metabasalts in the Franciscan complex mélange, *in* Morris, E.M., and Pasteris, J.D., eds., Mantle metasomatism and alkaline magmatism: Geological Society of America Special Paper 215, p. 167–182.

Shervais, J.W., Taylor, L.A., Lugmair, G.W., Clayton, R.N., Mayeda, T.K., and Korotev, R.L., 1988, Early Proterozoic oceanic crust and the evolution of sub-continental mantle: Eclogites and related rocks from southern Africa: Geological Society of America Bulletin, v. 100, p. 411–423, doi: 10.1130/0016–7606(1988)100<0411:EPOCAT>2.3.CO;2.

Shervais, J.W., Dennis, A.J., McGee, J.J., and Secor, D.T., 2003, Deep in the heart of Dixie: Pre-Alleghanian eclogite and HP granulite metamorphism in the Carolina terrane, South Carolina, USA: Journal of Metamorphic Geology, v. 21, no. 1, p. 65–80, doi: 10.1046/j.1525–1314.2003.00416.x.

Shervais, J.W., Kimbrough, D.L., Renne, P.R., Hanan, B.B., Murchey, B., Snow, C.A., Zoglman-Schuman, M.M., and Beaman, J., 2004, Multi-stage origin of the Coast Range Ophiolite, California: Implications for the life cycle of supra-subduction zone ophiolites: International Geology Review, v. 46, no. 4, p. 289–315.

Shervais, J.W., Murchey, B., Kimbrough, D.L., Renne, P., and Hanan, B.B., 2005a, Radioisotopic and biostratigraphic age relations in the Coast Range Ophiolite, Northern California: Implications for the tectonic evolution of the Western Cordillera: Geological Society of America Bulletin, v. 117, no. 5/6, p. 633–653.

Shervais, J.W., Kolesar, P., and Andreasen, K., 2005b, A field and chemical study of serpentinization—Stonyford, California: Chemical flux and mass balance: International Geology Review, v. 47, p. 1–23.

Shirey, S.B., Gurney, J.J., Pearson, D.G., Harris, J.W., Wiechert, U., Carlson, R.W., Richardson, S.H., and Menzies, A., 2001, Archean emplacement of eclogitic components into the lithospheric mantle during formation of the Kaapvaal craton: Geophysical Research Letters, v. 28, no. 13, p. 2509–2512, doi: 10.1029/2000GL012589.

Stern, R.J., and Bloomer, S.H., 1992, Subduction zone infancy; examples from the Eocene Izu-Bonin-Mariana and Jurassic California arcs: Geological Society of America Bulletin, v. 104, no. 12, p. 1621–1636, doi: 10.1130/0016–7606(1992)104<1621:SZIEFT>2.3.CO;2.

Stern, R.J., Johnson, P.R., Kroner, A., and Yibas, B., 2004, Neoproterozoic ophiolites of the Arabian Shield: Field Relations and Structure, *in* Kusky, T.M., ed., Precambrian Ophiolites and Related Rocks, Developments in Precambrian Geology, v. 13: Amsterdam, Elsevier, p. 95–128.

Storey, M., Mahoney, J.J., Kroenke, L.W., and Saunders, A.D., 1991, Are oceanic plateaus sites of komatiite formation?: Geology, v. 19, p. 376–379, doi: 10.1130/0091–7613(1991)019<0376:AOPSOK>2.3.CO;2.

Valley, J.W., Peck, W.H., King, E.M., and Wilde, S.A., 2002, A cool early Earth: Geology, v. 30, p. 351–354, doi: 10.1130/0091–7613(2002)030<0351:ACEE>2.0.CO;2.

von Huene, R., and Scholl, D.W., 1991, Observations at convergent margins concerning sediment subduction, subduction erosion, and the growth of continental crust: Reviews of Geophysics, v. 29, p. 279–316.

Wakabayashi, J., 1999, The Franciscan; California's classic subduction complex, *in* Moores, E.M, Sloan, D., and Stout, D., eds., Classic Cordilleran concepts; a view from California: Geological Society America Special Paper 338, p. 111–121.

Walter, M.J., and Trønnes, R.G., 2004, Early Earth differentiation: Earth and Planetary Science Letters, v. 225, p. 253–269, doi: 10.1016/j.epsl.2004.07.008.

Wilde, S.A., Valley, J.W., Peck, W.H., and Graham, C.M., 2001, Evidence from detrital zircons for the existence of continental crust and oceans on the Earth 4.4 Gyr ago: Nature, v. 409, p. 175–178, doi: 10.1038/35051550.

Willard, R.A., and Adams, M.G., 1994, Newly discovered eclogite in the southern Appalachian orogen, northwestern North Carolina: Earth and Planetary Science Letters, v. 123, p. 61–70, doi: 10.1016/0012–821X(94)90257–7.

Williams, H., and Hatcher, R.D., Jr., 1983, Appalachian suspect terranes, *in* Hatcher, R.D., Jr., Williams, H., and Zietz, I., eds., Contributions to the tectonics and geophysics of mountain chains: Geological Society of America Memoir 158, p. 33–53.

Wyman, D.A., 1999, Paleoproterozoic boninites in an ophiolite-like setting, Trans-Hudson orogen, Canada: Geology, v. 27, p. 455–458, doi: 10.1130/0091–7613(1999)027<0455:PBIAOL>2.3.CO;2.

Wyman, D.A., and Kerrich, R., 2002, Formation of Archean continental lithospheric roots: The role of mantle plumes: Geology, v. 30, p. 543–546.

Wyman, D.A., Kerrich, R., and Polat, A., 2002, Assembly of Archean cratonic mantle lithosphere and crust: Plume-arc interaction in the Abitibi-Wawa subduction-accretion complex: Precambrian Research, v. 115, p. 37–62, doi: 10.1016/S0301–9268(02)00005–0.

Yonkee, W.A., Willis, G.C., and Doelling, H.H., 2000, Petrology of Precambrian rocks of the Farmington Canyon complex, Antelope Island, Utah, *in* King, J.K., and Willis, G.C., eds., The geology of Antelope Island, Davis County, Utah: Utah Geological and Mineral Survey, Miscellaneous Publication MP-00-1, 163 p.

Zegers, T.E., and van Keken, P.E., 2001, Middle Archean continent formation by crustal delamination: Geology, v. 29, p. 1083–1086, doi: 10.1130/0091–7613(2001)029<1083:MACFBC>2.0.CO;2.

Zhong, S., Zuber, M., Moresi, L., and Gurnis, M., 2000, Role of temperature-dependent viscosity and surface plates in spherical shell models of mantle convection: Journal of Geophysical Research, v. 105, p. 11,063–11,082, doi: 10.1029/2000JB900003.

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