

Evidence from ophiolites, blueschists, and ultrahigh-pressure metamorphic terranes that the modern episode of subduction tectonics began in Neoproterozoic time

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ABSTRACT

Earth is the only known planet with subduction zones and plate tectonics, and this fact demonstrates that special conditions are required for this mode of planetary heat loss. Sinking of cold, dense lithosphere in subduction zones is the principal plate-driving force, so plate tectonics could not have begun until Earth cooled sufficiently to allow lithosphere to collapse into the underlying asthenosphere. Direct geologic evidence for when the modern episode of subduction tectonics began focuses on the first appearance of ophiolitic graveyards, blueschist facies metamorphic rocks, and ultrahigh-pressure metamorphic terranes. Ophiolites manifest two modes of lithospheric motion expected from subduction tectonics: seafloor spreading and obduction. High-pressure, low-temperature metamorphic blueschists and ultrahigh-pressure terranes indicate subduction and exhumation of oceanic and continental crust, respectively. These lines of evidence indicate that the modern style of subduction tectonics began in Neoproterozoic time. This revolution in the functioning of the solid Earth may have driven wild fluctuations in Earth's climate, described under the "snowball Earth" hypothesis. These conclusions may be controversial, but suggest fruitful avenues for research in geodynamics and paleoclimate.

Keywords: plate tectonics, Neoproterozoic, ophiolites, blueschist, ultrahigh-pressure metamorphism, subduction.

INTRODUCTION

Earth is the only known planet with subduction zones and plate tectonics (Stevenson, 2003), and it is controversial why it is so peculiar. It is also controversial when Earth's modern tectonic regime began: some argue that it began early (Parman et al., 2001; Smithies et al., 2003), and others argue that subduction began in the second half of Earth history (Davies, 1992; Hamilton, 2003). In the following I summarize evidence from subduction proxies—ophiolites, blueschists, and ultrahigh-pressure metamorphic terranes—and conclude that the modern style of subduction tectonics began in Neoproterozoic time. Such a profound tectonic change should also have affected Earth's atmosphere and hydrosphere, and the radical changes documented for Neoproterozoic climate may have been triggered by the Neoproterozoic tectonic revolution.

GEODYNAMIC CONSIDERATIONS

Earth's mantle convection is now driven by the sinking of cold dense lithosphere at subduction zones. Mantle plumes are a subordinate convection mode (Davies and Richards, 1992). Negative buoyancy of the lithosphere results from the small increase in density that silicates undergo as they cool, coupled with

the thickening of the thermally defined lithosphere with age. Lithosphere becomes denser than the underlying asthenosphere within ~20–50 m.y. (Davies, 1992). Of the force needed to drive the plates, ~90% comes from the sinking of subducting lithosphere; the other 10% comes from ridge push (Lithgow-Bertelloni and Richards, 1995). The base of the continents may be accelerated or retarded by circulating asthenosphere (Silver and Holt, 2002), but overall Cenozoic plate motions are well predicted from the distribution of lithosphere age—and thus the mass excess—in subduction zones (Conrad and Lithgow-Bertelloni, 2002, 2004). Mantle tomography shows that subducted lithosphere may sink through the 660 km discontinuity and into the deep mantle (Grand et al., 1997; Kárason and van der Hilst, 2000), demonstrating that aging lithosphere develops a density excess that takes as long to dissipate as to develop. In recognition of this modern understanding of plate-driving forces, Earth's modern tectonic style is best termed "subduction tectonics" (Stern, 2004).

The interior of the early Earth was much hotter than it is today. Many geoscientists assume that this hotter Earth resulted in a more vigorous plate tectonic regime. Given the geo-

dynamic considerations presented here, this assumption should be challenged. It would be more difficult in a hotter Earth to establish the density inversion required for subduction, because the mantle lithosphere should thicken more slowly and the oceanic crust would be much thicker (Pollack, 1997; Sleep, 2000). Sleep (2000) recognized three modes of heat loss in silicate planets: magma ocean, plate tectonics, and stagnant lid. Subduction tectonics can be shut down either by ridge lock, because the Earth's mantle is too cool to melt by adiabatic decompression, or by trench lock, when a hotter mantle generates oceanic crust that is too thick to subduct. Sometime in the past, subduction tectonics was prohibited by trench lock, and sometime in the future it will stop because of ridge lock. Davies (1992) concluded that the Earth did not cool sufficiently to allow the lithosphere to subduct until ca. 1 Ga.

In summary, it is contrary to our modern understanding of plate-driving forces to argue that a hotter Precambrian Earth favored subduction tectonics. It is more logical to conclude that Earth had to cool sufficiently to allow subduction to begin. The test of this hypothesis should come from the geologic record. This record is examined in following sections.

WHAT RECORDS OF SUBDUCTION SHOULD BE CONSIDERED?

Which kinds of geologic evidence are most compelling? Direct evidence of subduction should be paramount. Specifically, three distinctive petrotectonic associations require subduction: ophiolites, blueschists, and ultrahigh-pressure (UHP) metamorphic terranes. Ophiolites manifest two modes of lithospheric motion expected from subduction tectonics: infinite extension (seafloor spreading) and convergence (required for obduction). A growing proportion of the geologic community acknowledges that many ophiolites form during the earliest stages of subduction and are preserved as forearc basement (Gurnis et al., 2004; Robertson, 2004; Shervais et al., 2004; Stern, 2004). Some ophiolites formed in backarc basins, and these testify indirectly to subduction. The rarest type of ophiolite forms at a mid-ocean ridge, but because seafloor spreading at mid-ocean ridges is driven by subduction, these also testify indirectly that subduction occurred. Where ophiolites form is controversial; fortunately the tectonic setting of ophiolite formation is not important for this analysis because all three tectonic settings for ophiolites require subduction for formation and emplacement.

High-pressure (*P*), low-temperature (*T*) metamorphic rocks, especially blueschists and UHP terranes, also manifest subduction. Blueschists require unusually cold upper mantle geotherms, only found today in subduction zones (van Keken et al., 2002). UHP terranes, especially those forming coesite or diamond (A-type UHP terranes of Maruyama et al., 1996), require that siliceous sediments or continental crust was carried down 100 km or more and then exhumed. UHP terranes most likely form when continental crust is deeply subducted during collision and subsequently exhumed (Liou et al., 2004).

Paleomagnetic data could constrain when the continents first moved independently. However, Scotese (2004) noted that the uncertainty in paleomagnetically determined positions increases rapidly with age and concluded that the pre-late Neoproterozoic paleomagnetic record does not reliably constrain the relative position or motions of the continents. For this reason, paleomagnetic data are not used in the following analysis, although such data may ultimately prove to be a fruitful way to test my conclusions.

If the presence of ophiolites, blueschists, and UHP terranes are diagnostic of subduction, then evaluating when subduction tectonics began can be determined by when these rocks first become common in the geologic record. Erosion can destroy part of this record, especially ophiolites, but blueschists and UHP terranes are metamorphic rocks that are not

likely to be eroded away. It will be shown that the three lines of evidence give a consistent answer, and this result implies that the record is not fatally biased by erosion.

OPHIOLITE GRAVEYARDS

The age distribution of ophiolites has been interpreted to suggest that seafloor spreading began in Late Archean time (Kusky et al., 2001), but Archean ophiolites are controversial and rare. Some ophiolites were generated and emplaced ca. 2.0–1.95 Ga (Kontinen, 1987; Scott et al., 1992), but ophiolites are uncommon in the rest of the Paleoproterozoic and Mesoproterozoic record. Paleoproterozoic ophiolites may represent a short-lived or aborted episode of subduction tectonics, but this is exceptional in the pre-Neoproterozoic record. In general, a few ophiolitic rocks of a given age do not demonstrate establishment of a global and long-lived system of subduction tectonics. It is more important to determine when ophiolites became common, as revealed by abundant and widely distributed ophiolites or ophiolite graveyards.

It was not until almost Neoproterozoic time, ca. 1000 Ma, that unequivocal ophiolites were produced, emplaced, and abundantly preserved. The oldest are the ca. 1030 Ma ophiolites of central Asia (Khain et al., 2002, 2003), which slightly predate the beginning of Neoproterozoic time. Neoproterozoic ophiolites are especially common in northeast Africa and Arabia (Dilek and Ahmed, 2003). Neoproterozoic ophiolites are also abundant in central Asia, graveyard of the paleo-Asian Ocean (Badarch et al., 2002; Khain et al., 2002, 2003). Smaller regions of Neoproterozoic ophiolites are found in the Americas, West Africa, Europe, and China. Since first becoming common in Neoproterozoic time, ophiolites have become hallmarks of our planet (Dilek, 2003). Furthermore, Moores (2002) concluded that ophiolites older than ca. 1 Ga were fundamentally different from younger ophiolites, in particular by having much thicker crust, and thicker oceanic crust impedes subduction (Sleep, 2000). The ophiolite record is thus consistent with geodynamic arguments that Earth wasn't cold enough for subduction to be securely established as the dominant tectonic mode until relatively recently.

BLUESCHIST CONUNDRUM

Blueschist is a metamorphosed mafic rock containing abundant sodic amphibole, which is stable under high-*P* and low-*T* conditions (Maruyama et al., 1996). Blueschists are synonymous with B-type UHP terranes of Maruyama et al. (1996) and are characteristic of Pacific-type orogenic belts (Ernst, 2003). The perception that blueschist only forms in subduction zones is based on the association of blueschists with ancient subduction mélanges

and is confirmed by studies of active subduction zones (Abers, 2005; Maekawa et al., 1995; Zhang et al., 2004). The best-studied blueschists, those of the Franciscan and Sanbagawa terranes, appear to have been subducted to depths of 15–70 km before rising back to the surface (Ernst, 2003).

It has been recognized for almost half a century that blueschists are not found in very ancient rocks (de Roever, 1956), and it is now widely acknowledged that the oldest blueschists date from Neoproterozoic time, ca. 800–700 Ma. These are widely distributed in West Africa, India, and western China (Maruyama et al., 1996). Somewhat older (ca. 940 Ma) blueschist may exist in Jiangnan, south China (Shu and Charvet, 1996). One might think that the absence of blueschists from the pre-Neoproterozoic record would long ago have convinced the geoscientific community that the modern episode of subduction tectonics began in Neoproterozoic time, but this is not the case. Instead, the geoscientific community generally agrees that the absence of blueschist from the pre-Neoproterozoic record results from a hotter pre-Neoproterozoic Earth.

The consensus for why blueschists are missing from the first 3.7 b.y. of Earth history must be reevaluated. The “hotter Earth” explanation implies that the ambient mantle thermal structure controls subduction-zone thermal structure, an assumption that is not supported. Subduction-zone thermal structure is controlled by five variables: (1) convergence rate, (2) thermal structure of the subducted plate (a function of slab age), (3) geometry of the subducted slab, (4) rate of shear heating (= shear stress $\times$ convergence rate), and (5) vigor and geometry of flow in the mantle wedge (Peacock, 2003). The first two parameters—convergence rate and slab age—are paramount. These define the subduction-zone thermal parameter (Kirby et al., 1991), which controls subduction-zone thermal structure, as evinced by the maximum depth of earthquakes in a given convergent margin (Molnar et al., 1979). The temperature of ambient mantle and the global geothermal gradient are not thought to be important.

It may be that the hotter early Earth resulted in plates that were thinner than modern plates of a given age, and this would result in a hotter subduction zone where blueschist might not be stable. This possibility can be tested in modern subduction zones, which can be subdivided into those subducting old (older than 65 Ma) cold lithosphere and those subducting young (younger than 40 Ma) warm lithosphere (Peacock and Wang, 1999). Warm subduction may be an appropriate analog for subduction on the early Earth (if this occurred). Low-velocity zones consistent with blueschist fa-

cies subducted crust are inferred seismically (Abers, 2005; Zhang et al., 2004) and petrologically (Maekawa et al., 1995) to exist in cold subduction zones. We need to determine whether blueschists can form in warm subduction zones.

If all pre-Neoproterozoic subduction zones subducted warm young lithosphere, blueschist may not have formed. This explanation is unattractive because subduction of only warm young lithosphere is unlikely. Subduction occurs because gravitationally unstable lithosphere sinks back into the mantle, and young warm lithosphere—associated with thickened oceanic crust—should be buoyant. Somewhere, either down dip or along strike, subduction of young lithosphere must be associated with old, gravitationally unstable lithosphere that can sink. If Earth's lithosphere were sufficiently cold to sink, it should have formed blueschist somewhere.

UHP TERRANES

The term UHP terrane used here is synonymous with A-type UHP terranes (Maruyama et al., 1996), which are characteristic of Alpine-type orogenic belts (Ernst, 2003). Metamorphic assemblages in UHP terranes include coesite and/or diamond and indicate peak conditions of ~700–900 °C and 3–4 GPa (Ernst and Peacock, 1996). Such low-*T*, high-*P* conditions are only found today in subduction zones. UHP terranes represent subduction of continental crust to depths of 100–125 km as a result of continent-continent collision and subsequent exhumation (Liou et al., 2004). Only a few such UHP terranes have been documented, at least eight that are coesite bearing and five that are diamond bearing (Maruyama and Liou, 1998). The oldest, reliably dated UHP locality is the Gourma area of northwest Mali, which contains coesite and was metamorphosed ca. 620 Ma (Jahn et al., 2001). The oldest diamond-bearing UHP terrane is in Kazakhstan, the slightly younger Kokchetav massif, which contains diamond and coesite in a dismembered paragneiss and was metamorphosed at pressures of >4 GPa (>120 km depth) ca. 530 Ma (Maruyama and Liou, 1998). The first evidence for deep subduction of continental crust thus is found in late Neoproterozoic rocks. This implies that the search for pre-Neoproterozoic UHP terranes should be intensified.

DISCUSSION

The temporal distribution of ophiolites, blueschists, and UHP terranes is consistent with the hypothesis that the modern episode of subduction tectonics began in Neoproterozoic time. This hypothesis cannot be proved, but further work in key areas should move the discussion forward. There are at least two intriguing corollaries of this hypothesis.

The first concerns when each of the three subduction-related petrotectional assemblages first appears, and the second considers the impact of Neoproterozoic tectonic changes on climatic and biological oscillations.

The three independent lines of evidence—ophiolites, blueschists, and UHP terranes—agree that subduction tectonics began about Neoproterozoic time, but did these related manifestations begin synchronously? The oldest of each are not the same age—the oldest ophiolites, ca. 1.03 Ga, are significantly older than the oldest blueschists, ca. 800 Ma, and these are older than the oldest-known UHP terranes. Such a progression is expected from our understanding of the subduction-driven Wilson-supercontinent tectonic cycle and specifically from the sequence beginning with Rodinia break-up and culminating in the amalgamation of a late Neoproterozoic supercontinent. Ophiolites appear first, as subduction begins owing to lithospheric collapse. Next, blueschists appear as collisions of oceanic plateaus, and arcs jam subduction zones and allow subducted blueschist facies oceanic crust to be exhumed. UHP terranes form last, when continents collide. Terminal collisions are accompanied by the deep subduction of continental crust (Liou et al., 2004), which rebound to the surface when convergence ends. The sequence ophiolites → blueschists → UHP terranes is predicted when the global subduction tectonic regime is established, and that is what is observed in the Neoproterozoic rock record. This sequence of events is also consistent with the record of the seawater $^{87}\text{Sr}/^{86}\text{Sr}$ preserved in carbonates, which rose dramatically ca. 600 Ma (Jacobsen and Kaufman, 1999). The $^{87}\text{Sr}/^{86}\text{Sr}$ record provides independent confirmation of Ediacaran continental collision by showing that large tracts of continental crust were shedding radiogenic (high $^{87}\text{Sr}/^{86}\text{Sr}$) detritus into the oceans.

The second point to emphasize is that a revolution in the solid Earth system of this magnitude must have profoundly affected the exterior Earth system. Such wild climatic fluctuations are documented for this time. Neoproterozoic climate changed from intervals when perhaps the entire planet's surface was frozen, to sweltering greenhouses, and back again. The carbon isotope record, faithful monitor of the biomass, also fluctuated wildly (Jacobsen and Kaufman, 1999). These oscillations are discussed as the “snowball Earth hypothesis” (Hoffman et al., 2002). What initiated climatic instability in the Neoproterozoic is not known, but it may have been a response to the initiation of subduction tectonics. Explosive volcanism would have increased dramatically as volcanic arcs first built above subduction zones, injecting tephra, sulfur dioxide, and other gases into the strato-

sphere. Ash in the stratosphere may cool the planet briefly, but sulfur gases would have a longer effect via sulfuric acid aerosols (Röbäck, 2003). The primary chilling was volcanogenic. As an analog, Northern Hemisphere explosive volcanism increased dramatically during late Pliocene time, and this may have triggered Northern Hemisphere glaciation (Prueher and Rea, 2001).

Chilling may have also resulted from decreasing CO_2 in the atmosphere related to Rodinia breakup and indirectly to lithospheric collapse. Continental fragmentation increased runoff and hence consumption of carbon dioxide through continental weathering (Donnadieu et al., 2004). Rodinia breakup also witnessed the eruption of flood basalts, increasing the weatherability of the land and consumption of atmospheric CO_2 (Godderis et al., 2003). Both processes would tend to boost continental silicate weathering, consume atmospheric CO_2 , and help chill Earth.

CLOSING REMARKS

The hypothesis that the modern episode of subduction tectonics began in Neoproterozoic time is bound to be controversial. Nevertheless, evaluating this hypothesis and exploring its implications for Neoproterozoic climate and life will provide stimulating opportunities for interdisciplinary research into the fascinating Neoproterozoic Earth system. Resolving this controversy also will provide new avenues for understanding fundamental geodynamic questions, including what are the driving forces of plate tectonics and how does subduction begin?

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