A fluid factory in solid Earth

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ABSTRACT

Global material circulation in our planet from the surface to the bottom of the mantle is controlled by a combination of plate, plume, and "anti–plate" tectonics, where fluids and melts play an active role. Whereas crustal fluids are dominated by CO_2 and H_2O, with subordinate CH_4 and N_2, the volatiles in the lower mantle are speculated to be dominantly CO_2. The process of Archean subduction aided in the sequestration of CO_2 from the ocean-atmosphere system, with the ultimate probable destination being the mantle. When a rising "superplume" hits the tectosphere, the predicted carbonated continental keel would become enriched in CO_2. During the Phanerozoic, the carbonated upper mantle was drastically reduced in size, as speculated from the scarcity of dry, "ultrahot" orogens. Free fluid circulation within Earth is present only in restricted zones, mostly along the plate boundaries and intracontinental rifts, and particularly along subduction zones, where the fluid is mostly water dominated. The propagating water front in the deep mantle in modern Earth may correspond to the apparent increase in pressure through geologic time, which might be one of the reasons for a general lack of ultrahigh-pressure metamorphic belts in the Archean and their prevalence in the Phanerozoic orogenic belts.

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INTRODUCTION

The phenomenon of plate tectonics is a surface manifestation of motion of Earth's lithosphere, and it contributes to the generation of new continental crust that is horizontally transported and eventually destroyed at subduction zones prior to orogenic "suturing." The deep subducted material moves down vertically as a curtain-like sheet and accumulates at 660 km depth, thereafter transforming into large blobs. Some, but not all, of this may descend vertically, reaching to the core-mantle boundary (Zhao et al., 1994; Peacock, 1996; Zhong and Gurnis, 1994; Maruyama et al., 2007, and references therein). Such blobs might be considered to accumulate in "slab graveyards" (Kerr, 1997; Wysession et al., 1998; Sleep, 2003), the presence of which has been recently confirmed on the basis of seismic tomographic studies (e.g., Zhao et al., 2007). Given such a slab graveyard scenario coupled with heating from the core, such material (presumed to be recycled oceanic lithosphere) could be viewed as a potential trigger of, and contributor to, the so-called "superplumes," which rise from the core-mantle interface to the uppermost mantle, penetrate the mantle transition zone, and eventually give rise to "hot spots" (Condie, 2001; Romanowicz and Gung, 2002). Radioactive heat generated in enriched basaltic slab remnants may also contribute to driving such superplumes. Thus, global material circulation may work episodically on a whole-mantle scale as a consequence of material fractionation at both the uppermost regions and the base.

Geophysicists have long recognized the presence of the so-called D double-prime (D″) layer at the base of the mantle (e.g., Kendall and Shearer, 1994), ~200–300 km in thickness, and recent models indicate compositional heterogeneity within this layer. The solidi of mid-ocean-ridge basalt (MORB) and pyrolitic mantle approximate geotherms expected both near the surface and at the base of the mantle, allowing for the production of crustal basaltic and granitic melts at or close to Earth's surface, along with high-density melts (presumably of iron silicates) at the base of the mantle. Continuous formation of such melts is consistent with the presence of an ultralow-velocity zone (ULVZ; e.g., Garnero, 2004) and, in turn, the development through time of continental crust (or anticrust) at the base of the mantle, as proposed by Maruyama et al. (2007). Subducted slabs evidently cannot penetrate the core because of the large density differences among slabs, mantle, and the core.

Thus, the subducted slab material, inferred from seismic tomography, may be plausibly considered to reach the core-mantle boundary. The implications of horizontal movement at the base of the mantle have been referred to as "anti–plate tectonics" and are in many respects analogous to lithospheric plate tectonic processes operating in near-surface regions. Accordingly, through time, it is conjectured that continents gradually develop at or close to the outer Earth surface while concomitant "anticontinents" would be generated at the core-mantle boundary (Maruyama et al., 2007). Thus, as a whole, geodynamic processes can be viewed as a combination of plate, plume, and anti–plate tectonics (Fig. 1). In other words, melts and fluids between the upper- and lowermost levels of the mantle may play a profound role in the process of global material circulation. Here, we propose a "fluid factory" within solid Earth and evaluate some of the recent concepts on fluid distribution in Earth and their implications for tectonic and surface processes.

THE TECTOSPHERE AS A CO_2 RESERVOIR

The tectosphere, also referred to as continental "keels," is considered to be essentially rigid and cold, representing a chemically distinct raft supporting the bulk of the continental crust (Jordan, 1988). The tectosphere appears to be confined to continental cratonic regions, formed before 2.0 Ga, the origins of which are controversial. However, following its formation during the Archean and early Proterozoic, the volume of the tectosphere is presumed to have been gradually reduced in response to thermal and material erosion. Such effects have been attributed to rising high-temperature plumes during and subsequent to the breakup of primordial supercontinents. Geophysical observations (e.g., Grand, 2002) indicate that by ca. 2.0 Ga,

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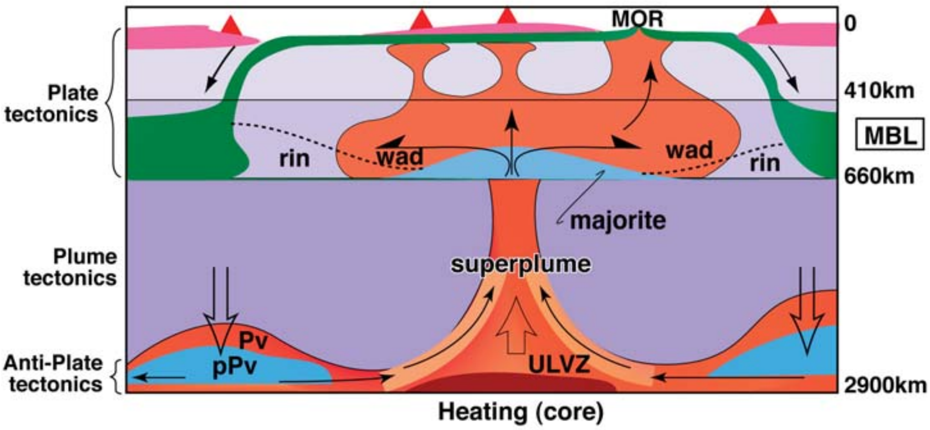

Figure 1. Cartoon illustrating the process of material circulation on a whole-Earth scale controlled by plate, plume, and anti–plate tectonics. MOR—mid-ocean ridge; MBL—mantle boundary layer; ULVZ—ultralow-velocity zone; pPv—post-perovskite; Pv—perovskite; rin and wad indicate stability regions of ringwoodite and wadselyite. See text for discussion.

the thickness of the subcratonic tectosphere probably did not exceed ~300 km. Archean tectosphere remnants have high seismic velocities (indicating lower temperatures) recorded by deep penetration seismic experiments (Zhao, 2004; Zhao et al., 2007), and the distinct compositional difference from suboceanic mantle is corroborated by petrological studies of mantle xenoliths (O'Reilly et al., 1991).

Due to long-term cooling, the Archean mantle was at comparatively lower temperature such that a cold mass would be expected to sink. However, the chemically distinct, buoyant nature of the refractory (melt-depleted) tectosphere appears to have allowed for its development as a thick subcontinental keel; such a model is consistent, for example, with the formation of the Himalayas in response to the collision of India with Eurasia. In this case, a tectosphere-supported Indian microcontinent has clearly intruded over 3000 km into tectosphere-absent sub-Asian mantle, in turn, fragmenting Asia into several microplates (Metcalfe, 2006).

If, as appears likely, the tectosphere is an important reservoir of fluids, the associated subcontinental lithospheric mantle would be distinctly enriched in character, predominantly in CO_2 and incompatible elements (Jordan, 1988). In support of this notion, Santosh and Omori (2008a) correlated the late Archean appearance of ultrahigh-temperature (UHT) granulites (predominantly anhydrous rocks formed under extreme thermal conditions and carrying diagnostic mineral assemblages as well as CO_2-rich fluid inclusions; see Kelsey, 2008; Tsunogae et al., 2008) to the growth of continent and, presumably, carbonated tectosphere.

Carbonation processes during the Archean would most likely have involved the decomposition of marine carbonates, along with MORB, during subduction-zone metamorphism, with CO_2-bearing fluids being released into the mantle wedge (Santosh and Omori, 2008a). The extended pressure-temperature (*P-T*) stability of carbonates in peridotite would lead to further carbonate precipitation in response to CO_2-rich fluid influx. Regions of carbonated mantle would, moreover, result from the collision and amalgamation of volcanic arc systems, in turn, representing a major CO_2-rich reservoir of the tectosphere. With the advent of relatively cooler conditions in subduction zones by Neoproterozoic time, hydrous minerals would be expected to persist to a greater extent during subduction-zone metamorphism (Maruyama and Okamoto, 2007). The release of water-rich fluids into mantle wedge regions would, in turn, enhance decarbonation reactions in coexisting silicates, resulting in a progressive decrease in the volume of carbonated components in mantle wedge regions. Copious circulation of water in relatively cold subduction zones by ca. 750 Ma (Maruyama and Liou, 2005) more-or-less coincided with mantle decarbonation beneath continental rift zones

In Figure 2, we show a schematic model for CO_2 circulation within the post-Archean Earth system, involving the hydrosphere, atmosphere, carbonated oceanic lithosphere, to metasomatized mantle regions associated with subduction (after Santosh and Omori, 2008a, 2008b). According to this generalized picture, MORB carbonated at spreading axes—and during its lateral transport during seafloor spreading—is eventually decarbonated during subduction at convergent plate boundaries. However, the combined effects of a decrease in ambient P_{CO_2} and the beginning of massive carbonate sedimentation after ca. 2.5 Ga resulted in the formation of hydrated, carbonate-free MORB crust, marking the culmination of carbonation in the mantle wedge. After ca. 640 Ma, hydrated, subducted lithosphere would have reached the mantle transition zone (Maruyama and Okamoto, 2007), thereby triggering the return flow of CO_2 back to the surface as a result of partial melting or subsolidus decarbonation of the subcontinental (carbonated) mantle. Thus, during the Phanerozoic, the relative volume of carbonated upper mantle was drastically reduced. Santosh and Omori (2008a, 2008b) interpreted this to have been a major potential reason for the scarcity of ultrahigh-temperature granulite facies rocks in Phanerozoic orogens.

The incorporation of carbonate into the subcontinental lithosphere by subduction was probably initiated by at least 4 Ga. Hydrothermal carbonate formed at mid-ocean ridges is exemplified by the 3.5 Ga rocks in Pilbara, Western Australia (Van Kranendonk, 2006), and the 3.8 Ga rocks of Isua in Greenland, where subducted, hydrothermally carbonated, oceanic lithosphere has been recorded (Komiya et al., 1999). We contend that these oceanic carbonates were infiltrated into deep mantle regions via a subduction zone, thereby increasing the amount of carbonate in the mantle at the expense of that in the hydrosphere and atmosphere.

The amount of CO_2 computed to have been released by decarbonation within the mantle suggests that the ambient *P-T* conditions were consistent with those estimated from phase equilibria studies related to the formation of high- and ultrahigh-temperature granulite facies rocks (Santosh and Omori, 2008a).We may reasonably conclude that the anomalous thermal conditions required for such mantle decarbonation reactions, along with those associated with the formation of "hot" orogens, could share a common cause, the most likely of which is upwelling mantle plumes. The pattern of distribution of carbonated subcontinental lithosphere (tectosphere) over the world based on S wave (Grand, 2002) seismic tomography shows that the carbonated mantle underlies continental regions characterized by pre–2.0 Ga orogenic belts (Santosh and Omori, 2008b). It is clear that the tectosphere is confined beneath continents, and there are no identifiable examples directly beneath oceanic mantle. The presence of a tectosphere beneath many subcontinental mantle regions is also inferred from the occurrence of carbonate minerals in mantle xenoliths. Santosh and Omori (2008b) used the Proterozoic paleogeography of continents to trace the possible "windows" of CO_2 from mantle to the atmosphere, speculated from the

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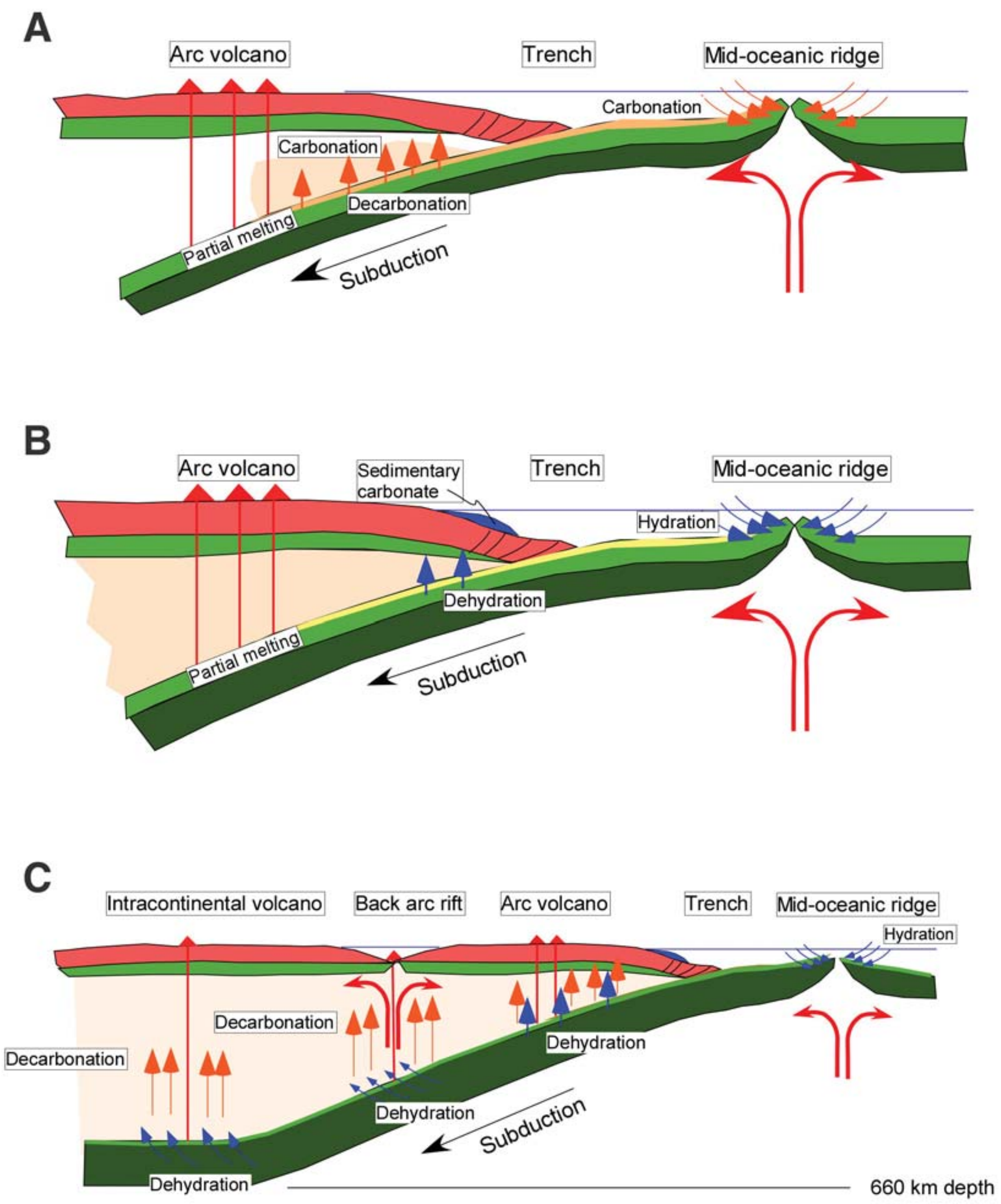

Figure 2. CO_2 circulation mechanism from ocean-atmosphere through carbonated mid-ocean-ridge basalt (MORB) to metasomatized mantle wedge by subduction in the Archean (after Santosh and Omori, 2008b). (A) Archean sequestration of atmospheric-ocean CO_2 into the mantle. (B) Post–2.5 Ga when carbonation of MORB stopped. (C) Deep subduction of H_2O and decarbonation by infiltration after 640 Ma. See text for details.

presence of tectosphere and the distribution of ultrahigh-temperature metamorphic rocks. They proposed that a substantial amount of Archean mantle-bound CO_2 was released during thermotectonic processes associated with Proterozoic ultrahigh-temperature metamorphic events. The formation of such hot and ultrahot orogens may have represented a critical turning point from carbonated to a decarbonated mantle. However, some ancient non-decarbonated sublithospheric mantle could have nonetheless survived until the present; examples include significant CO_2-rich gas released from the continental East African rift. Such a tectonic setting could be an ideal candidate for present-day CO_2 flushing and ongoing ultrahigh-temperature metamorphism within the lower crust. A more speculative link between subsolidus CO_2 release and melting of "snowball Earth" has also been proposed (cf. Santosh and Omori, 2008b), assuming such CO_2 could have contributed substantially to a global-scale greenhouse effect. This model is in accordance with an earlier proposal of Touret (1992), who considered that the lower continental crust may act as a temporary CO_2 storage during its transfer between the upper mantle and atmosphere. Thus, fluids in Earth may play a crucial role in constraining both interior Earth dynamics and evolution of the surface and near-surface environment.

FLUID DISTRIBUTION IN THE EARTH—SUMMARY

It is well known that surface fluids may penetrate to depths of many kilometers and volatiles may be recycled to mantle depths in subduction zones, leading to processes of devolatilization and revolatilization of the lower crust and upper mantle (Fyfe, 1997). Our knowledge on the nature and distribution of fluids in Earth has largely been restricted to the crustal fluids as studied from fluid-related alteration in sampled rocks, fluid-induced mineral reactions computed from petrologic and phase equilibria studies, direct observation of mineral fluid

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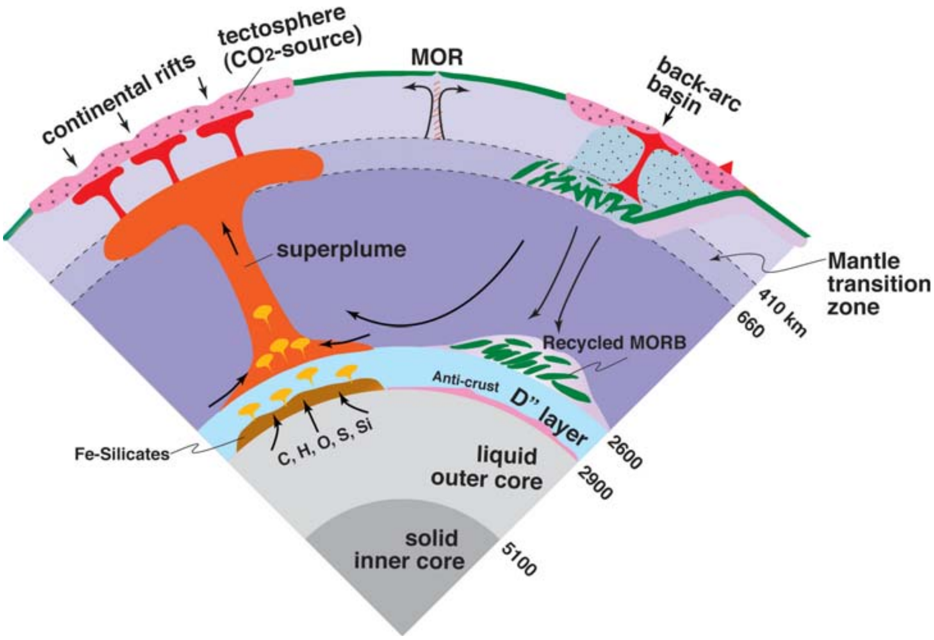

Figure 3. Cartoon illustrating fluid distribution from surface to the central core of Earth. C-O-H-S fluids may constitute up to 10% in the metallic core. The recycled mid-ocean-ridge basalt (MORB) starts from the trench through mantle transition zone and finally down to the core-mantle boundary (CMB). It is then heated up by the outer core, leading to partial melting. The dense iron-rich melts accumulate on the bottom of the D″ layer. The remaining restite MORB with dominant andesitic composition rises upward to form a superplume. The subducted slab from the trench is hydrous, and it is heated up by the surrounding mantle, which releases the water in the mantle wedge and enhances the viscosity. The vertically rising superplume enters into the upper mantle, transforms to horizontal, and branches out into several hot spots. These hot spots cause the rifting of the continent and deliver the mantle fluid to the surface. Surface CO_2 was selectively transported into the mantle in the Hadean to the Archean. After the Neoproterozoic, surface water started to be transported into the mantle transition zones (410–660 km). For the major part of Earth's fluid history, the fluid transport was mostly one way—from the outer core to the surface. The return flow of water started probably only after 750 Ma, although it has not yet entered into the lower mantle.

inclusions, and geophysical techniques such as electrical conductivity (see Santosh and Omori, 2008a, and references therein; Santosh et al., 2008; Tsunogae et al., 2008). Inferences concerning the nature of fluids in deeper portions of Earth have been made on the basis of data from exhumed ultrahigh-pressure (UHP) metamorphic rocks and mantle-derived magmas and xenoliths. These studies indicated that the upper crustal fluids are generally dominated by H_2O, with subordinate CO_2, CH_4, and N_2, whereas the lower crustal fluids are mostly CO_2-rich (cf. Touret, 2005; Santosh, 2003). The magmatic, metasomatic, and metamorphic fluid factories in various tectonic settings might have played a major role in the geochemical and tectonic evolution of Earth.

A cartoon in Figure 3 speculates about the distribution and transport of fluids in solid Earth. According to this scenario, free fluid circulation occurs in restricted zones, mostly associated with plate boundaries, particularly convergent margins. Here, the fluid is mostly water-dominated, and the mantle transition zone (~410–660 km) effectively serves as a huge water tank, with the capacity to store ~5 times the volume of modern oceans in dense hydrous silicates. However, circulating fluid is nonetheless probably less than 1% water at Earth's surface (Maruyama and Okamoto, 2007).

In divergent tectonic zones, fluids are mostly mantle-derived, along with lesser contributions of recycled water. In the lower mantle, the volatiles may be considered to be dominantly CO_2, together with light elements (C, O, H, S) derived ultimately from Earth's core (Javoy, 1997; Frezzotti and Peccerillo, 2007). These components are presumed to escape to shallower levels facilitated by "superplumes" that link the core to Earth's surface. If high-temperature, adiabatic upwelling (plumes) or mantle decompression beneath divergent plate margins impinges on the tectosphere, small CO_2-rich melt fractions would be candidate parent melts for relatively rare magma types such as carbonatites, kimberlites, and lamproites. Thus, assuming the lower crust to be enriched in CO_2 rather than water, the "hot" and "ultrahot" orogens constituting associated phenomenon reflect anomalous high-temperature metamorphic conditions (>900 °C) approaching H_2O-undersaturated solidus conditions (more on this to be published in a forthcoming paper by Santosh et al.).

According to these arguments, subduction-related volcanic arcs allowed the transfer of CO_2 from hydrospheric and atmospheric reservoirs to the Archean mantle to be sequestered as a volumetrically significant mantle component. Such a carbonated mantle might have been one of the major constituents of the tectosphere. If CO_2 distribution was relatively homogeneous, it probably represented less than 0.1 wt% of the whole. However, the distribution of the CO_2 derived by subduction would be expected to be heterogeneous, generating CO_2-enriched zones or "pockets" in the mantle, which would subsequently reinfiltrate the crust. However, mantle carbonation is likely to have been largely confined to the Archean, if continental growth were rapid rather than an incremental process (Rino et al., 2004, 2008), given the apparently sudden appearance of sedimentary carbonate in the early Proterozoic (Veizer et al., 1989), implying corresponding behavior of CO_2 in Phanerozoic oceans.

The behavior of H_2O differs significantly from that of CO_2 within Earth's interior (the former serves as an effective lubricant). H_2O-rich fluid was available only in near-surface regions, and the highly inflected geothermal gradients prevailing in the Archean precluded hydrous fluids from becoming a dominant factor until fairly mature stages of Earth evolution. During the Phanerozoic, H_2O-dominated subducting slab–derived fluids became a significant factor down to depths of ~660 km. The propagating H_2O "front" in deeper mantle may correspond to the apparent increase in pressure through geologic time. Thus, we might speculate that although UHP metamorphic rocks might have formed in the Archean, they were seldom exhumed to the surface, and they remained as relict eclogitic MORB fragments in the mantle, only traces of which may have reached the surface in the form of xenoliths in kimberlites.

The apparent paucity of UHP metamorphic belts in the Archean as compared to their common occurrence in denuded Phanerozoic orogens has been attributed to secular cooling in ambient subduction-related thermal conditions (Brown, 2007). Alternately, this could also be related to the history of fluid circulation in the evolution of Earth.

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