REVIEW

GEOSCIENCES

Distribution, cycling and impact of water in the Earth's interior

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ABSTRACT

The Earth's deep interior is a hidden water reservoir on a par with the hydrosphere that is crucial for keeping the Earth as a habitable planet. In particular, nominally anhydrous minerals (NAMs) in the silicate Earth host a significant amount of water by accommodating H point defects in their crystal lattices. Water distribution in the silicate Earth is highly heterogeneous, and the mantle transition zone may contain more water than the upper and lower mantles. Plate subduction transports surface water to various depths, with a series of hydrous minerals and NAMs serving as water carriers. Dehydration of the subducting slab produces liquid phases such as aqueous solutions and hydrous melts as a metasomatic agent of the mantle. Partial melting of the metasomatic mantle domains sparks off arc volcanism, which, along with the volcanism at mid-ocean ridges and hotspots, returns water to the surface and completes the deep water cycle. There appears to have been a steady balance between hydration and dehydration of the mantle at least since the Phanerozoic. Earth's water probably originates from a primordial portion that survived the Moon-forming giant impact, with later delivery by asteroids and comets. Water could play a critical role in initiating plate tectonics. In the modern Earth, the storage and cycling of water profoundly modulates a variety of properties and processes of the Earth's interior, with impacts on surface environments. Notable examples include the hydrolytic weakening effect on mantle convection and plate motion, influences on phase transitions (on the solidus of mantle peridotite in particular) and dehydration embrittlement triggering intermediate- to deep-focus earthquakes. Water can reduce seismic velocity and enhance electrical conductivity, providing remote sensing methods for water distribution in the Earth's interior. Many unresolved issues around the deep water cycle require an integrated approach and concerted efforts from multiple disciplines.

Keywords: water, Earth's interior, mantle, subduction, partial melting

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INTRODUCTION

The Earth is a hydrous planet, and water is the most crucial resource for the emergence and well-being of humankind and other life forms. Although not immediately evident, a huge amount of water, perhaps several times the mass of the entire hydrosphere, is stored in the Earth's interior [1–3]. In particular, the mantle transition zone may be a gigantic water reservoir and contain much more water than the upper and lower mantles [4–6].

Alongside other chemical components, water on Earth's surface is carried by plate subduction into Earth's interior, probably down to the core–mantle boundary. In response to changes in temperature (*T*) and pressure (*P*) along subduction paths, water is redistributed among coexisting mineral phases (including some that are newly formed) in subducting slabs [7–9]. On the other hand, the subducting slabs release some of their water, in the form of liquid phases such as aqueous solutions, hydrous melts and supercritical fluids, into the overlying mantle wedge [10–13]. The hydrated mantle domains are destined to partially melt over time, eventually evolving into volcanism. Volcanic eruptions at arcs along with those at mid-ocean ridges and hotspots return water to the Earth's surface. This grand journey of water transport into and out of the Earth's interior is commonly referred to as the deep water cycle [14].

The storage and cycling of water has far-reaching impacts over geodynamic and geochemical evolution by modulating a variety of properties and processes of the Earth's interior [15–19]. Water probably played an indispensable role in the formation of continental crust [20] and in the initiation of subduction [21]. Dissolved water weakens the mechanical strength of olivine and other mantle minerals, thereby influencing mantle convection and plate tectonics [22–24]. Another well-known fact is that the melting temperatures of silicates are strongly depressed by the presence of water [23,25–27].

The significance of water in the Earth's evolution is increasingly appreciated by Earth scientists from multiple fields. Water in the solid Earth has come to be a frontier and hot topic of research over the past three decades. This review aims to provide a comprehensive yet concise summary of recent progress in our understanding of the speciation, distribution, cycling and impact of water in the Earth's interior.

THE HYDROUS SPECIES

All of the major phases in the Earth's interior take up some water, albeit in different forms. In aqueous solutions, the predominant hydrous species is molecular H_2O along with its dissociated forms (H_3O^+ and OH^-). In silicate melts, it is chiefly molecular H_2O or hydroxyl groups (OH) bonded to Si or other cations [28,29], but pressure of the order of 10 GPa gives rise to more extended structures such as Si–O–H–O–Si [30] and low oxygen fugacity leads to molecular H_2 [31]. In stoichiometrically hydrous minerals such as amphiboles and dense hydrous magnesium silicates (DHMS), OH is an innate component of the crystal lattice [32]. In olivine and other nominally anhydrous minerals (NAMs), which constitute the main body of the bulk silicate Earth, hydrogen generally occurs in point defects and bonds to oxygen to form OH [33,34]. One exception is that the open structure of feldspars can accommodate H_2O molecules [35,36]. Mineral grains may also enclose fluid inclusions or other microscopic hydrous impurities, especially at shallow depths. In the reduced deep mantle, a fraction of hydrogen could dissolve into silicate minerals as molecular H_2 [37]. Hydrogen could be a minor element present in the core as iron hydrides [38,39]. These reduced hydrogen species and rare species such as NH_4^+ are beyond the scope of this review, and will be only gently touched upon below.

Throughout this review, the term water content always refers to the weight fraction of H_2O (in wt% or in ppm) converted from all of the hydrous species in existence. Fourier transform infrared spec-troscopy is by far the most frequently used technique for determination of water content in oxide minerals and glasses [40–42]. Secondary ion mass spectrometry permits submicron spatial resolution [43], but is more technically challenging and is not routinely available. Other methods are even less commonly used at present.

THE RESERVOIRS

Water distribution in the Earth's interior is highly heterogeneous (Table 1; Fig. 1). The upper continental crust is estimated to contain several thousand ppm of water, mainly in hydrous minerals or as fluid inclusions in felsic minerals such as quartz and feldspars [36]. Studies of granulite xenoliths indicate that the lower continental crust is less hydrous, typically with several hundred ppm of water in NAMs [44]. The middle continental crust is generally characterized by the occurrence of amphibole and has water content that is intermediate between the upper and lower continental crusts.

The oceanic crust, composed of mafic igneous rocks and seafloor sediments, is much richer in water than the continental crust. The mafic crust, hydrothermally altered by seawater, contains 1.5 wt% water on average, as pore water or contained in hydrous minerals (including clay minerals) and NAMs [45]. However, the oceanic crust subducted to subarc depths is significantly dehydrated at forearc depths, and is essentially not much different from the continental crust subducted to similar depths with respect to water content [12,61].

Erupted basalts along with the mantle xenoliths they enclose indicate diverse water contents in the upper mantle. Water content of the subcontinental lithospheric mantle spans from almost completely dry to ~250 ppm [41,44,46,62]. The source regions of normal mid-ocean ridge basalts (MORBs), which probably represent a major part of the asthenospheric mantle, are estimated to contain 50–250 ppm water [47–49]. The source regions of ocean island basalts (OIBs), continental flood basalts and enriched MORBs, which may represent a minor portion of the asthenospheric mantle or may be more deeply located, are more hydrous than the normal MORB source, typically with 300–1000 ppm water [50,52,63]. At subduction zones, after being metasomatized by hydrous liquids derived from the subducting slab, the bulk water content of the mantle wedge may rise to a few wt% [53,54].

The major minerals in the transition zone (i.e. wadsleyite and ringwoodite) have long been known to be capable of accommodating a significant amount of water comparable with hydrous minerals

Table 1. Earth's water budget.

	Water content (ppm)	Main forms	Total amount of water (kg)	Relative to the hydrosphere
Hydrosphere	9.6×10^5	Liquid water; ice	1.4×10^{21}	1
Upper continental crust [36]	9×10^3	Hydrous minerals; fluid inclusions	6×10^{19}	0.04
Lower and middle continental crust [44]	$<1 \times 10^3$	NAMs; hydrous minerals	$<2 \times 10^{19}$	0.01
Oceanic crust [45]	1.5×10^4	Pore water; clay minerals; hydrous minerals; NAMs	1×10^{20}	0.07
Subcontinental lithospheric mantle [41,44,46]	<250	NAMs	$<1 \times 10^{19}$	<0.01
MORB source [47–49]	50–250	NAMs	1×10^{20}	0.07
OIB/flood basalt source [50–52]	300–1000	NAMs	$<1 \times 10^{19}$	<0.01
Metasomatic mantle [26,53,54]	$3 \times 10^3 - 4 \times 10^4$	Hydrous minerals; NAMs	$<1 \times 10^{19}$	<0.01
Transition zone [6,55]	1×10^4 ?	NAMs (ringwoodite; wadsleyite)	4.5×10^{21} ?	3 ?
Lower mantle [56–59]	1–4000	NAMs	$3 \times 10^{18} - 1 \times 10^{22}$	0.002–8
Core [39,60]	1×10^4 H?	FeH_x		

[5,64]. However, it was only recently that the first direct evidence, from a diamond-hosted ringwoodite inclusion, confirmed the transition zone to be, at least locally, hydrous [6]. If the inferred ~1 wt% water in ringwoodite was globally representative, the transition zone would be a gigantic water reservoir triple the size of the hydrosphere. However, there is geophysical evidence suggesting that the transition zone can also be locally dry [65].

The most controversial issue is the water content of the lower mantle. A number of experimental and computational studies suggest that bridgmanite, the major phase of the lower mantle, could accommodate 0.1–0.4 wt% water [56,57,59]. However, some other workers hold that the high water content found in quenched bridgmanite could be caused by mechanically trapped hydrous inclusions and that the intrinsic water storage capacity of bridgmanite is only a few ppm [58]. Consistent with the view of low water storage capacity of the lower mantle is the finding of H_2O-bearing fluids [66].

For NAMs or rocks, water storage capacity is the maximum amount of water that can be sequestered in the mineral(s) without stabilizing a hydrous fluid or melt phase [27,67]. Only at low temperature and pressure, when the mineral(s) coexist with aqueous solution with water activity ≈ 1, should water

storage capacity be referred to as water solubility. The distinction between water storage capacity and water solubility is illustrated in Fig. 2 for the forsterite–H_2O system. A compilation of experimental studies on the water storage capacity of mantle minerals is available in Yang and Li [68]. These results establish a high bound for actual water content in a solid mantle.

ALONG THE SUBDUCTION PATH

Plate subduction is the predominant mechanism that delivers water into the Earth's interior [12,61]. With the increase of temperature and pressure along the subduction path, the subducting slab undergoes metamorphic dehydration, phase transformations, and even partial melting. Among other parameters, the thermal structure of subduction zones is pivotal in shaping the detailed processes at different depths [12,69,70].

The oceanic plate has stratified water contents. The overlying sedimentary layer, typically less than 1 km thick, is extremely water-rich, with 20–70 wt% H_2O [71]. The water content of the igneous portion decreases from ~10 wt% in the upper extrusive rocks to ~1 wt% in the gabbro layer [45]. The upper
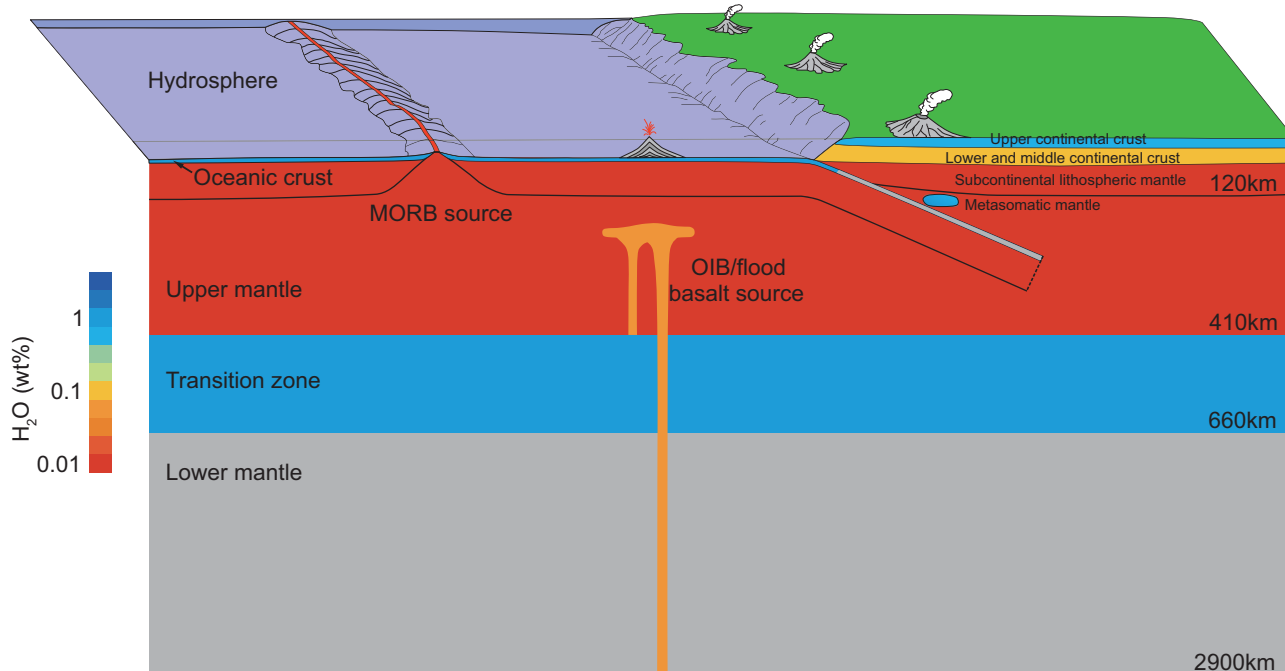
Figure 1. A simplified view of water distribution in the Earth's layered interior by neglecting intralayer heterogeneities, based on the data summarized in Table 1. The lower mantle is coded in grey due to its poorly constrained water content.

several km of lithospheric mantle peridotite can also experience significant hydrothermal alteration [72].

Due to compaction and heating, a significant amount of pore water in the upper oceanic crust is expelled from the slab during the initial stage of subduction. Approaching 300°C and 1 GPa, water is mainly stored in zeolite, prehnite and pumpellyite, and the bulk water content of the upper crust is 6–9 wt% [61,73]. Upon further *P-T* increase to around 600°C and 2.5 GPa (high-pressure blueschist to eclogite facies at the forearc depths, <80 km), the slab continues to dehydrate appreciably (Fig. 3). The major hydrous minerals include chlorite, amphibole, micas, and epidote, with lawsonite only stable for a cold subduction path [12]. Across the amphibole-out boundary, the bulk water content decreases from ~2 wt% to ~1 wt%, corresponding to a volume fraction increase of NAMs from ~50% to >70%.

Along a cold subduction path, the already highly-dehydrated oceanic crust enters a *P-T* regime (500–800°C and 2.5–10 GPa) with dehydration rates notably lower than at previous stages (Fig. 3). Furthermore, both the variety and abundance of hydrous minerals are significantly reduced, with the major phases including lawsonite, zoisite, chloritoid, talc and phengite. Increasing fraction of water is distributed in NAMs, and the bulk water content further drops to only a few 1000 ppm at the subarc (80–160 km) and postarc (>200 km) depths.

If subduction proceeds along a hot path (Fig. 3), the oceanic crust would plunge into the

melting regime (650–950°C and <5 GPa). Zoisite, amphibole and micas are the major water hosts, and the bulk water content remains >1 wt% before melting at *P* < 2.5 GPa (Fig. 3). At higher pressures, amphibole is no longer stable, resulting in a bulk water content of <1 wt% in the crust before melting. Despite the low water content in the crust, dehydration of the underlying peridotite could induce melting of the crust at 1–4 GPa and 650–850°C under water-saturated conditions. At temperatures above
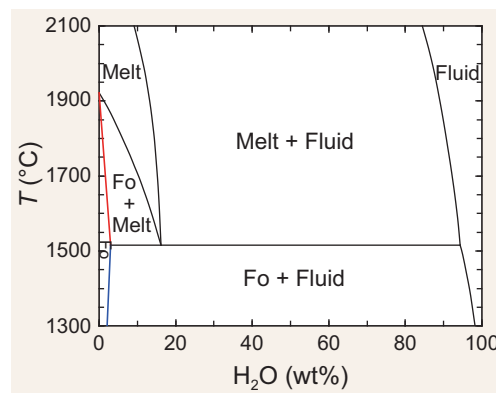

Figure 2. Phase diagram of forsterite (Fo)–H_2O at 1 GPa. The blue curve indicates water solubility in forsterite at low temperatures (saturated by aqueous solution) and the red curve indicates water storage capacity in forsterite at high temperatures (saturated by hydrous melt). These curves are exaggerated toward higher water content for clear demonstration. Modified from Ni *et al.* [27].
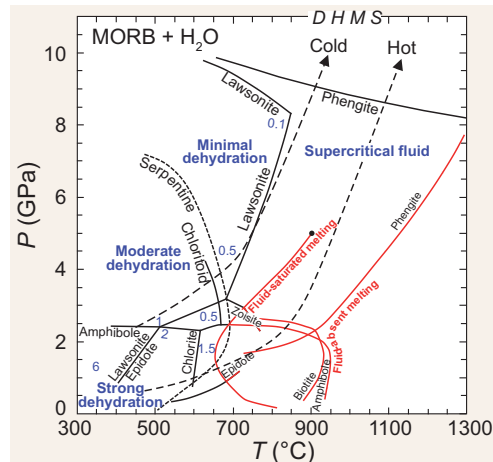
Figure 3. Dehydration and melting regimes of oceanic crust along cold and hot subduction paths (dashed curves with arrow) based on the mineral stability fields in the MORB–H_2O system. The numbers indicate the estimated bulk water content of the oceanic crust in wt%. DHMS (dense hydrous magnesium silicates) form at $P > 10$ GPa. The stability field of serpentine in peridotite is shown for comparison. Modified from Schmidt and Poli [8].

800–900°C, melting of the crust can occur at subarc depths even under water-undersaturated conditions. Partial melting of the oceanic crust gives rise to adakitic magmatism [74].

If a cold subduction path bypasses the wet solidus of crustal rocks (Fig. 3), which terminates at the second critical endpoint (perhaps 900°C and 5 GPa for the MORB–H_2O system but still controversial [75,76]), the subducting crust can release supercritical fluids with composition and physicochemical properties distinct from aqueous solutions (with >70 wt% H_2O) and hydrous silicate melts (with <30 wt% H_2O) [8,13,77–79].

The above discussion has focused on the oceanic crust. The overlying carbonated sediments could be melted at postarc depths of >200 km, producing hydrous silicate or carbonatite melts [80]. The total mass of water stored in the underlying serpentinized peridotite is difficult to estimate accurately, but may be comparable to that in the oceanic crust [8,72]. Dehydration of the serpentinized peridotite is insignificant below 3–6 GPa, with ∼7 wt% water mainly hosted in serpentine and chlorite. Along the cold subduction path, serpentine breaks down to a series of DHMS (phases A, E, D and superhydrous phase B) at $P > 6$ GPa [32,81], but still up to 5 wt% water could be transported further down toward the transition zone [8]. Along a hot geotherm, serpentine transforms into the 10 Å phase or Mg–sursassite, during which significant dehydration lowers the bulk water content to only ∼0.6 wt%.

Studies of seismic tomography reveal the presence of stagnant slabs in the transition zone below continental edges in the circum-Pacific areas [82–85]. The stagnant slab is thought to lose water to the transition zone and also to the overlying 'big mantle wedge' [86–89]. However, the detailed process of slab-mantle interaction at the transition zone and how this is linked to the origin of continental basalts are still poorly understood.

Some other slabs can subduct to much greater depths in the lower mantle. Water carriers in subducting slabs to the deep mantle are suggested to include superhydrous phase B, phase D, phase Egg, phase δ-H solid solution [32], $(FeH)_{1-x}Ti_xO_2$ [90], FeOOH [91], ringwoodite and other NAMs. Among these phases, ringwoodite, Al-rich phase D, and phase δ-H solid solution probably play more major roles than the others [32,92,93]. Due to the difference in water storage capacity between ringwoodite and lower mantle minerals, dehydration melting could occur at the top of the lower mantle [94,95]. Heating near the core–mantle boundary may lead to the breakdown of phase δ-H and melting of the slab [32]. In addition, Hu *et al.* [91] suggest that FeOOH could decompose to FeO_2 and H_2 at >1800 km depths, remolding the deep water cycle, which is challenged by the discovery of a pyrite-type high-pressure form of FeOOH [96].

A geodynamic model by van Keken *et al.* [70] estimates that globally subducting slabs carry ∼10^{12} kg/year of water into the Earth's interior. One-third of it is lost by 100 km depth (i.e. at the forearc and subarc depths), another one-third is lost by 230 km depth, and the remaining one-third is transported into the Earth's deeper interior.

FROM DEPTHS TO SURFACE

Buoyancy drives the hydrous liquid phases released by the subducting slab to migrate upward, in porous or channeled flow, to the overlying mantle wedge, leading to metasomatism [12,97]. Hydrous minerals in metasomatic mantle domains, with estimated bulk water content of 0.3–4 wt% [53,54], mainly include serpentine, talc, phlogopite and amphibole [8]. The mantle wedge probably starts to melt after a period of storage and heating [12]. Melt inclusion records suggest that water contents in primary mafic melts generally fall in the range of 2–6 wt%, although significantly higher or lower water contents have also been reported [26,98]. Water contents in the melts change continuously along the path of magma evolution and ascent, due to processes such as crustal contamination, magma mixing, and fractional crystallization.

Fractional crystallization of NAMs raises the concentration of volatiles in the melts, which along with pressure decrease leads to volatile saturation and the exsolution of magmatic–hydrothermal fluids, referred to as boiling [99]. At lower temperature and pressure, such hydrothermal fluids may further separate into a brine and a vapor phase, and these fluids play a critical role in the mobilization of metal elements and formation of ore deposits [100]. Alternatively, they may evolve into volcanic gases and reach Earth's surface. Wallace [101] suggests that the global flux of outgassing water through arc volcanism is $\sim 3 \times 10^{11}$ kg/yr, which approximates the amount of water loss by subducting slabs by 100 km depth and indicates a balance between subduction input and eruption output.

Water preserved in the slab beyond the subarc depths experiences more prolonged transport and evolution in the mantle. Some of it could be incorporated in the source regions of OIBs and enriched MORBs [63,102], or could replenish the normal MORB source unobtrusively. Bercovici and Karato [103] posit that due to the contrasting water storage capacities between the transition zone and upper mantle, dehydration melting at their boundary (410 km depth) would deprive the upwelling

mantle of most of its water and form the normal MORB source. The global flux of outgassing water through mid-ocean ridge volcanism is estimated to be $\sim 6 \times 10^{10}$ kg/yr [10], significantly lower than that through arc volcanism. Putting together these estimates of water fluxes [10,70,101], there appears to be more water going into than coming out of the Earth's interior at present. If this inference were true, the surface water reservoir would be shrinking over time. However, these global estimates are associated with large uncertainties. Furthermore, it is probably not appropriate to take the inferred contemporary water inventory as a long-term pattern over geological history.

Besides volcanic eruptions, the exhumation of ultrahigh-pressure metamorphic rocks, which is much more common for continental than for oceanic subduction zones [104,105], provides a direct means to return water from the Earth's interior to the surface [9]. On the other hand, lithospheric delamination also transfers minor amounts of water into the asthenospheric mantle. However, in general, plate subduction and volcanism are by far the most predominant mechanisms for the input and output of water in the deep water cycle, as illustrated in Fig. 4.
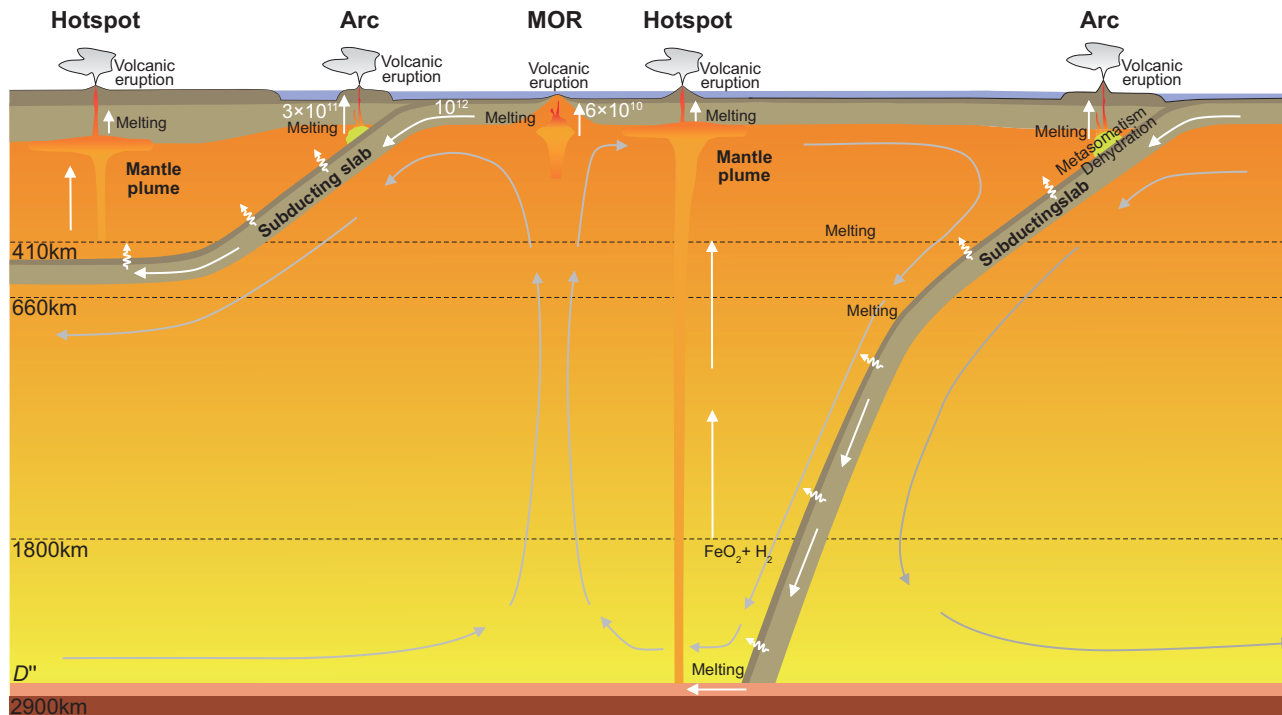

Figure 4. Earth's deep water cycle (delineated in white arrows). Plate subduction and volcanic eruptions (at subduction zones, mid-ocean ridges and hotspots) are the predominant mechanisms of ingassing and outgassing of water, respectively. The numbers indicate water fluxes in kg/yr. About one-third of water in subducted slabs is recycled at subduction zones through dehydration and melting. The other two-thirds arrive at >100 km depths and may replenish the source regions of OIBs, MORBs and continental basalts. Some slabs may become stagnant near the 660 km discontinuity and lose water to the transition zone and the overlying mantle. Some other slabs can subduct to the lower mantle, and the water they carry may be partly converted to H_2 beyond 1800 km depth. Mantle convection is shown in grey arrows. MOR, mid-oceanic ridge.

FROM EARLY EARTH TO THE PRESENT

The above discussion concentrates on the conditions and processes in the modern Earth, in which plate tectonics has operated at least since the Phernozoic. The early Earth was much different. It was once believed that the Moon-forming giant impact ∼4.5 Gyr ago deprived the Earth almost completely of its primordial water, forming dry terrestrial and lunar magma oceans, and that most water was added to the Earth during the 'later vaneer' period by asteroids and comets [106]. However, there is growing evidence indicating that water loss during the giant impact was incomplete (especially if water oceans had not formed before the impact) and that the Earth had already developed water oceans by 4.4 Gyr ago [107–109]. Whether the shallow part of the terrestrial magma ocean was oxidized or reduced, water vapor was always a major component in the early atmosphere, and exchange of water between the magma ocean and the atmosphere was intensive [110,111]. Some water was likely lost to space at an early stage, but this process did not last long [112] as the geomagnetic field was established. Because much more water can be dissolved in melt than in minerals, crystallization would expel water to the atmosphere, whereas melting would resorb water into the mantle [16,113], in contrast with the modern Earth in which melting leads to dehydration of the mantle instead.

After the solidification of the magma ocean and condensation of water oceans, water vapor, alongside other greenhouse gases (e.g. CO_2, CH_4 and NH_3), probably prevented the water oceans from being frozen by low solar luminosity [114,115]. In the traditional 'mantle degassing' (one-way process) model, the more primitive Hadean or Archean mantle should be more hydrous than the present mantle. However, even in the absence of plate tectonics, water could still be recycled to the mantle through other mechanisms, such as crustal delamination [116]. Furthermore, there are few geological records that suggest any major change in sea level, at least since the Phanerozoic. Therefore, a balance between water influx and outflux, and hence a balance for water storage between the surface and internal reservoirs, were probably established early in the Earth's history [16]. Water in the early Earth is believed to have played a critical role in initiating plate tectonics [21], perhaps some 3.0 Gyr ago [117]. Ever since then, the deep water cycle has been intimately coupled with plate tectonics, but it should have taken some time for plate tectonics to fully evolve to the modern style as observed today.

INFLUENCES OF WATER STORAGE AND CYCLING

The Earth's deep water cycle is more than simply a passive consequence of plate tectonics. As mentioned above, the initiation of subduction was probably promoted by lubrication by water [21]. The global workings of the modern Earth's interior are still being profoundly impacted by the storage and cycling of water [18,19].

Effect on rheological strength of minerals

Water dissolved in NAMs reduces their rheological strength (Fig. 5), referred to as the hydrolytic weakening effect [122], although there is debate over the magnitude of this effect [23,119,120,123]. Mantle convection and plate motion are generally believed to be significantly influenced by this effect, and the boundary between the asthenosphere and the lithosphere may simply reflect a viscosity contrast caused by different water contents [16,22,24,124]. The base of the cratonic mantle lithosphere may be hydrated by hydrous liquid phases derived from the subducting oceanic slab, leading to its weakening and thinning [41,46,125,126]. A related phenomenon is the pressure-dependent effect of water on the olivine fabrics and, consequently, on the seismic anisotropy of the upper mantle [124,127].
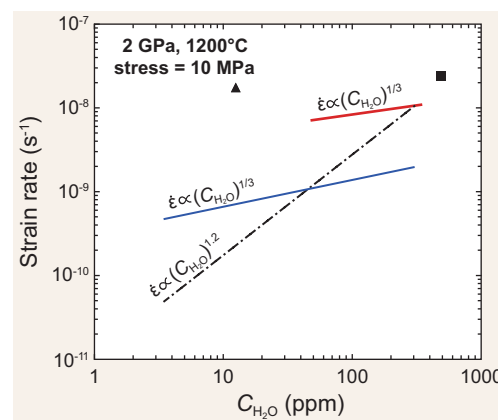

Figure 5. The increase of strain rate with water content in olivine (pure forsterite or Fo_{90}) based on different experimental studies using single crystal (red line: [118]; blue line: [119]; triangle: [120]) or polycrystalline (black dashed line: [121]; square: [24]) olivine, normalized to 2 GPa, 1200°C and a differential stress of 10 MPa.
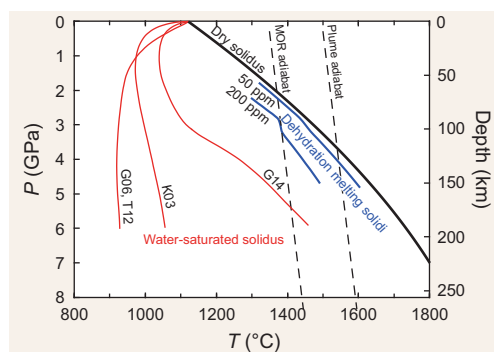
Figure 6. Effect of water on depressing the solidus (melting temperature) of mantle peridotite. Under water-undersaturated conditions, corresponding to mid-ocean ridges and mantle plumes (with their adiabatic geotherms shown in dashed lines), melting temperature decreases with increasing water content in the mantle (blue curves) [129,135]. There is huge disparity with water-saturated solidus (red curves), corresponding to subduction zone setting (K03: [131]; G06: [132]; T12: [133]; G14: [134]).

Effect on melting and other phase transitions

As a highly incompatible component, water dissolves more easily in silicate melts relative to minerals, thereby lowering the solidus of rocks and enhancing melting [27,128,129]. The effect of water on melting is the most obvious at subduction zones, such as flush melting of the oceanic crust and dehydration melting of the metasomatic mantle domains. Although volcanism at mid-ocean ridges is caused by decompression and that at hotspots is associated with thermal anomalies, in both cases water in mantle minerals increases the onset depth and degree of melting [14,130]. The effect of water on the solidus of peridotite at low water activity is relatively well constrained [129], but there are huge discrepancies between different experimental studies on water-saturated systems [131–134], as illustrated in Fig. 6.

Different zones of the mantle have contrasting water storage capacities. When mantle rocks migrate from a zone with high water storage capacity to another zone with low water storage capacity, the excessive water that cannot be accommodated in the mineral crystal structure induces partial melting [136]. This could occur at the lithosphere–asthenosphere boundary [137], at the base of the upper mantle [103], and at the base of the transition zone [95].

Magmatic evolution is also influenced by water, such as lowering the density and crystallization temperature of hydrous melts and altering the crystallization sequence [138–140]. Water also affects

mineral phase transition, thereby thickening seismic discontinuities [141–143].

Effects on elastic properties of minerals and seismic velocity

Water has a disproportionately large effect on the elastic properties and density of minerals, and hence on seismic velocities (V_P and V_S) and V_P/V_S ratio [144–147], which is probably due to the formation of cation vacancies [148]. A number of velocity anomalies in the upper mantle and in the transition zone cannot be explained by lateral temperature variation alone, and are suggested to be associated with the effect of water (e.g. [149–152]). Based on experimental and computational data for olivine polymorphs, the most abundant minerals in the mantle until the 660 km discontinuity, modeling results suggest that water could cause up to a 0.7% reduction in the velocity of the upper mantle and up to a 4.7% reduction in the transition zone [145] (Fig. 7). In the transition zone, the addition of water has a greater effect on the sound velocities of wadsleyite than for ringwoodite.

Effect on electrical conductivity of minerals and melts

Compared to seismic velocity, electrical conductivity is even more sensitive to the presence of water [153]. This is the case with both minerals and silicate melts [154–156]. The electrical conductivity of olivine is enhanced by an order of magnitude by several hundred ppm water [68,157],
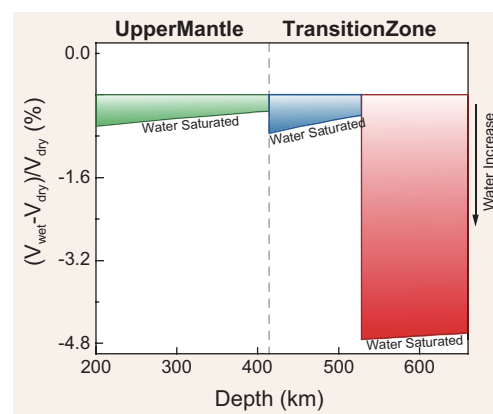

Figure 7. Effect of water on the seismic velocity (V) of the upper mantle and transition zone, based on experimental results for olivine polymorphs and a pyrolite model. The shaded regions are for water content ranging from nil to the water storage capacity of olivine polymorphs. The effects on P- and S-waves are similar [145] and are therefore not distinguished.
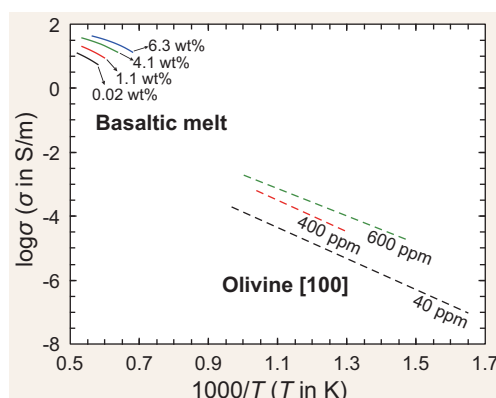
Figure 8. Effect of water on electrical conductivity of olivine [100] at 1 GPa and that of basaltic melt at 2 GPa. Based on experimental data in Yang [157] and Ni *et al.* [158].

and that of basaltic melt is enhanced by an order of magnitude by ∼6 wt% water [158,159] (Fig. 8). However, the mechanisms of hydration effects are totally different. For minerals, it involves the transport of protons [154], but for silicate melts it is caused by enhanced mobility of cations associated with a viscosity decrease [155,160], as well as the participation of OH as charge carrier [161,162]. The effects of water on electrical conductivity and on seismic velocity can be used for remote-sensing of water distribution and hydrous melting in the Earth's interior by magnetotellurics and seismology [65,153,158,163].

Properties of hydrous phases

The above discussion deals with several prominent hydration effects on NAMs and silicate melts. It is equally important to know the physicochemical properties of innate hydrous phases, namely aqueous solutions and hydrous minerals, particularly their density, elastic properties [147,164–167] and electrical conductivity [159,168]. Such information is crucial for correct interpretations of seismological and magnetotelluric data and for the identification of water-rich zones in the Earth's interior. Furthermore, the breakdown of hydrous minerals during subduction causes the development of brittle fractures [169], which may be an important mechanism for intermediate- to deep-focus earthquakes [170–172].

OUTLOOK

While research progress over the past three decades has roughly described the distribution (Fig. 1), cycling (Fig. 4) and impact (Figs 5–8) of water in the Earth's interior, the following big questions still need to be answered.

(1) How hydrous are the mantle transition zone and the lower mantle? How are their water contents influenced by whole-mantle convection over geological time?
(2) Where are the solidi of basalt and peridotite under water-saturated conditions? How common is partial melting of the subducting oceanic crust at different depths?
(3) What are the *P-T* conditions for the formation of supercritical fluids? How important is the role played by supercritical fluids at subduction zones?
(4) What are the major carriers of water in subducting slabs at various depths? How do slabs exchange water with the mantle at different depths? How is the slab signal passed to OIBs and continental basalts?
(5) How abundant are H_2 and other reduced hydrogen species in the deep mantle and the core?
(6) How significant is the effect of water on mantle rheology and on the elastic and electrical properties of the lower mantle phases?
(7) Does melting really occur at the lithosphere–asthenosphere, upper mantle–transition zone and transition zone–lower mantle boundaries due to contrasting water storage capacity? What is the influence of melting on the deep water cycle?
(8) How much of Earth's water is primordial (i.e. has survived the giant impact)?
(9) How have water distribution and cycling evolved from the early Earth to the present?

To resolve these critical issues around the deep water cycle, an integrated approach and concerted efforts are required from geochemical, geophysical and geodynamic studies. Research progress in these fields will greatly advance our understanding of the working mechanisms of the Earth's interior and their consequences on surface environments.

REFERENCES

1. Williams Q and Hemley RJ. Hydrogen in the deep earth. *Annu Rev Earth Planet Sci* 2001; **29**: 365–418.

2. Ohtani E. Water in the mantle. *Elements* 2005; **1**: 25–30.

3. Peslier A, Schönbächler M and Busemann H *et al.* Water in the Earth's interior: distribution and origin. *Space Sci Rev* 2017; **212**: 743–810.

4. Smyth JR. A crystallographic model for hydrous wadsleyite (β-Mg_2SiO_4): an ocean in the Earth's interior? *Am Mineral* 1994; **79**: 1021–4.

5. Inoue T, Yurimoto H and Kudoh Y. Hydrous modified spinel, $Mg_{1.75}SiH_{0.5}O_4$: A new water reservoir in the mantle transition region. *Geophys Res Lett* 1995; **22**: 117–20.

6. Pearson DG, Brenker FE and Nestola F *et al.* Hydrous mantle transition zone indicated by ringwoodite included within diamond. *Nature* 2014; **507**: 221–4.

7. Poli S and Schmidt MW. H_2O transport and release in subduction zones: Experimental constraints on basaltic and andesitic systems. *J Geophys Res* 1995; **100**: 22299–314.

8. Schmidt MW and Poli S. Devolatilization during subduction. In: Holland HD and Turekian KK (eds). *Treatise on Geochemistry*. Amsterdam: Elsevier Science, 2014, 669–701.

9. Zheng Y and Hermann J. Geochemistry of continental subduction-zone fluids. *Earth Planets Space* 2014; **66**: 93.

10. Peacock SA. Fluid processes in subduction zones. *Science* 1990; **248**: 329–37.

11. Iwamori H. Transportation of H_2O and melting in subduction zones. *Earth Planet Sc Lett* 1998; **160**: 65–80.

12. Zheng Y, Chen R and Xu Z *et al.* The transport of water in subduction zones. *Sci China Earth Sci* 2016; **59**: 651–82.

13. Ni H, Zhang L and Xiong X *et al.* Supercritical fluids at subduction zones: evidence, formation condition, and physicochemical properties. *Earth-Sci Rev* 2017; **167**: 62–71.

14. Hirschmann MM. Water, melting, and the deep earth H_2O cycle. *Annu Rev Earth Planet Sci* 2006; **34**: 629–53.

15. Regenauer-Lieb K. Water and geodynamics. *Rev Mineral Geochem* 2006; **62**: 451–73.

16. Hirschmann M and Kohlstedt D. Water in Earth's mantle. *Phys Today* 2012; **65**: 40–5.

17. Keppler H. Volatiles under high pressure. In: Karato S (ed.). *Physics and Chemistry of the Deep Earth*. Hoboken: Wiley-Blackwell, 2013, 3–37.

18. Nakagawa T, Nakakuki T and Iwamori H. Water circulation and global mantle dynamics: insight from numerical modeling. *Geochem Geophys Geosyst* 2015; **16**: 1449–64.

19. Karato S. Water in the evolution of Earth and other terrestrial planets. In: Schubert G (ed.). *Treatise on Geophysics*. Amsterdam: Elsevier, 2015, 105–44.

20. Campbell IH and Taylor SR. No water, no granites - no oceans, no continents. *Geophys Res Lett* 1983; **10**: 1061–4.

21. Regenauer-Lieb K. The Initiation of Subduction: Criticality by Addition of Water? *Science* 2001; **294**: 578–80.

22. Mackwell SJ, Kohlstedt DL and Paterson MS. The role of water in the deformation of olivine single crystals. *J Geophys Res* 1985; **90**: 11319–33.

23. Hirth G and Kohlstedt DL. Water in the oceanic upper mantle: implications for rheology, melt extraction and the evolution of the lithosphere. *Earth Planet Sc Lett* 1996; **144**: 93–108.

24. Kohlstedt DL. The role of water in high-temperature rock deformation. *Rev Mineral Geochem* 2006; **62**: 377–96.

25. Tatsumi Y. Migration of fluid phases and genesis of basalt magmas in subduction zones. *J Geophys Res* 1989; **94**: 4697–707.

26. Grove TL, Till CB and Krawczynski MJ. The role of H_2O in subduction zone magmatism. *Annu Rev Earth Planet Sci* 2012; **40**: 413–39.

27. Ni H, Zhang L and Guo X. Water and partial melting of Earth's mantle. *Sci China Earth Sci* 2016; **59**: 720–30.

28. Stolper E. The speciation of water in silicate melts. *Geochim Cosmochim Ac* 1982; **46**: 2609–20.

29. Zhang Y and Ni H. Diffusion of H, C, and O components in silicate melts. *Rev Mineral Geochem* 2010; **72**: 171–225.

30. Mookherjee M, Stixrude L and Karki B. Hydrous silicate melt at high pressure. *Nature* 2008; **452**: 983–6.

31. Hirschmann MM, Withers AC and Ardia P *et al.* Solubility of molecular hydrogen in silicate melts and consequences for volatile evolution of terrestrial planets. *Earth Planet Sc Lett* 2012; **345–348**: 38–48.

32. Ohtani E. Hydrous minerals and the storage of water in the deep mantle. *Chem Geol* 2015; **418**: 6–15.

33. Bell DR and Rossman GR. Water in Earth's mantle: the role of nominally anhydrous minerals *Science* 1992; **255**: 1391–7.

34. Smyth JR. Hydrogen in high pressure silicate and oxide mineral structures. *Rev Mineral Geochem* 2006; **62**: 85–115.

35. Hofmeister AM and Rossman GR. A spectroscopic study of irradiation coloring of amazonite: structurally hydrous, Pb-bearing feldspar. *Am Mineral* 1985; **70**: 794–804.

36. Johnson EA. Water in nominally anhydrous crustal minerals: speciation, concentration, and geologic significance. *Rev Mineral Geochem* 2006; **62**: 117–54.

37. Yang X, Keppler H and Li Y. Molecular hydrogen in mantle minerals. *Geochem Persp Let* 2016; **2**: 160–8.

38. Fukai Y. The iron-water reaction and the evolution of the Earth. *Nature* 1984; **308**: 174–5.

39. Murphy CA. Hydrogen in the Earth's core. In: Terasaki H and Rebecca A (eds). *Deep Earth: Physics and Chemistry of the Lower Mantle and Core*. Hoboken: Wiley, 2016, 253–64.

40. Rossman GR. Analytical methods for measuring water in nominally anhydrous minerals. *Rev Mineral Geochem* 2006; **62**: 1–28.

41. Hui H, Xu Y and Pan M. On water in nominally anhydrous minerals from mantle peridotites and magmatic rocks. *Sci China Earth Sci* 2016; **59**: 1157–72.

42. Sheng Y, Gong B and Li W *et al.* Methodological progress in trace amounts of structural water in nominally anhydrous minerals. *Sci China Earth Sci* 2016; **59**: 901–9.

43. Hauri E, Wang J and Dixon JE *et al.* SIMS analysis of volatiles in silicate glasses. *Chem Geol* 2002; **183**: 99–114.

44. Xia Q, Liu J and Kovács I *et al.* Water in the upper mantle and deep crust of eastern China: concentration, distribution and implications. *Natl Sci Rev* 2017, doi:10.1093/nsr/nwx016.

45. Staudigel H. Chemical fluxes from hydrothermal alteration of the oceanic crust. In: Holland HD and Turekian KK (eds). *Treatise on Geochemistry*. Amsterdam: Elsevier Science, 2014, 583–606.

46. Xu Z, Gong B and Zhao Z. The water content and hydrogen isotope composition of continental lithospheric mantle and mantle-derived mafic igneous rocks in eastern China. *Sci China Earth Sci* 2016; **59**: 910–26.

47. Michael P. Regionally distinctive sources of depleted MORB: evidence from trace elements and H_2O. *Earth Planet Sc Lett* 1995; **131**: 301–20.

48. Saal AE, Hauri EH and Langmuir CH *et al.* Vapour undersaturation in primitive mid-ocean-ridge basalt and the volatile content of Earth's upper mantle. *Nature* 2002; **419**: 451–5.

49. Workman RK and Hart SR. Major and trace element composition of the depleted MORB mantle (DMM). *Earth Planet Sc Lett* 2005; **231**: 53–72.

50. Sobolev AV and Chaussidon M. H_2O concentrations in primary melts from supra-subduction zones and mid-ocean ridges: implications for H_2O storage and recycling in the mantle. *Earth Planet Sc Lett* 1996; **137**: 45–55.

51. Aubaud C, Pineau F and Hekinian R *et al.* Carbon and hydrogen isotope constraints on degassing of CO_2 and H_2O in submarine lavas from the Pitcairn hotspot (South Pacific). *Geophys Res Lett* 2006; **33**: L02308.

52. Xia Q, Bi Y and Li P *et al.* High water content in primitive continental flood basalts. *Sci Rep* 2016; **6**: 25416.

53. Carlson RL and Miller DJ. Mantle wedge water contents estimated from seismic velocities in partially serpentinized peridotites. *Geophys Res Lett* 2003; **30**: 1250.

54. Kelley KA, Plank T and Newman S *et al.* Mantle melting as a function of water content beneath the Mariana arc. *J Petrol* 2010; **51**: 1711–38.

55. Fei H, Yamazaki D and Sakurai M *et al.* A nearly water-saturated mantle transition zone inferred from mineral viscosity. *Sci Adv* 2017; **3**: e1603024.

56. Murakami M, Hirose K and Yurimoto H *et al.* Water in Earth's lower mantle. *Science* 2002; **295**: 1885–7.

57. Litasov K, Ohtani E and Langenhorst F *et al.* Water solubility in Mg-perovskites and water storage capacity in the lower mantle. *Earth Planet Sc Lett* 2003; **211**: 189–203.

58. Bolfan-Casanova N, Keppler H and Rubie DC. Water partitioning at 600 km depth and evidence for very low water solubility in magnesium silicate perovskite. *Geophys Res Lett* 2003; **30**: 1905.

59. Hernández ER, Alfè D and Brodholt J. The incorporation of water into lower-mantle perovskites: a first-principles study. *Earth Planet Sc Lett* 2013; **364**: 37–43.

60. Stevenson DJ. Hydrogen in the Earth's core. *Nature* 1977; **268**: 130–1.

61. Schmidt MW and Poli S. Experimentally based water budgets for dehydrating slabs and consequences for arc magma generation. *Earth Planet Sc Lett* 1998; **163**: 361–79.

62. Demouchy S and Bolfan-Casanova N. Distribution and transport of hydrogen in the lithospheric mantle: a review. *Lithos* 2016; **240–243**: 402–25.

63. Dixon JE, Leist L and Langmuir C *et al.* Recycled dehydrated lithosphere observed in plume-influenced mid-ocean-ridge basalt. *Nature* 2002; **420**: 385–9.

64. Kohlstedt DL, Keppler H and Rubie DC. Solubility of water in the α, β and γ phases of $(Mg,Fe)_2SiO_4$. *Contrib Mineral Petr* 1996; **123**: 345–57.

65. Utada H, Koyama T and Obayashi M *et al.* A joint interpretation of electromagnetic and seismic tomography models suggests the mantle transition zone below Europe is dry. *Earth Planet Sc Lett* 2009; **281**: 249–57.

66. Palot M, Jacobsen SD and Townsend JP *et al.* Evidence for H_2O-bearing fluids in the lower mantle from diamond inclusion. *Lithos* 2016; **265**: 237–43.

67. Hirschmann MM, Aubaud C and Withers AC. Storage capacity of H_2O in nominally anhydrous minerals in the upper mantle. *Earth Planet Sc Lett* 2005; **236**: 167–81.

68. Yang X and Li Y. High-P/T experimental studies and water in the silicate mantle. *Sci China Earth Sci* 2016; **59**: 683–95.

69. Peacock SM. Thermal and petrologic structure of subduction zones. *Geoph Monogr Ser* 1996; **96**: 119–33.

70. Van Keken PE, Hacker BR and Syracuse EM *et al.* Subduction factory: 4. Depth-dependent flux of H_2O from subducting slabs worldwide. *J Geophys Res* 2011; **116**: B01401.

71. Plank T. The chemical composition of subducting sediments. In: Holland HD and Turekian KK (eds). *Treatise on Geochemistry*. Amsterdam: Elsevier Science, 2014, 607–29.

72. Hacker BR. H_2O subduction beyond arcs. *Geochem Geophys Geosyst* 2008; **9**: Q03001.

73. Peacock SM. The importance of blueschist $\rightarrow$ eclogite dehydration reactions in subducting oceanic crust. *Geol Soc Am Bull* 1993; **105**: 684–94.

74. Defant MJ and Drummond MS. Derivation of some modern arc magmas by melting of young subducted lithosphere. *Nature* 1990; **347**: 662–5.

75. Kessel R, Ulmer P and Pettke T *et al.* The water-basalt system at 4 to 6 GPa: phase relations and second critical endpoint in a K-free eclogite at 700 to 1400 °C. *Earth Plan Sc Lett* 2005; **237**: 873–92.

76. Mibe K, Kawamoto T and Matsukage KN *et al.* Slab melting versus slab dehydration in subduction-zone magmatism. *Proc Natl Acad Sci USA* 2011; **108**: 8177–82.

77. Shen AH and Keppler H. Direct observation of complete miscibility in the albite-H_2O system. *Nature* 1997; **385**: 710–2.

78. Hermann J, Spandler C and Hack A *et al.* Aqueous fluids and hydrous melts in high-pressure and ultra-high pressure rocks: implications for element transfer in subduction zones. *Lithos* 2006; **92**: 399–417.

79. Zheng Y, Xia Q and Chen R *et al.* Partial melting, fluid supercriticality and element mobility in ultrahigh-pressure metamorphic rocks during continental collision. *Earth-Sci Rev* 2011; **104**: 342–74.

80. Grassi D and Schmidt MW. Melting of carbonated pelites at 8-13 GPa: generating K-rich carbonatites for mantle metasomatism. *Contrib Mineral Petr* 2011; **162**: 169–91.

81. Frost DJ. The stability of hydrous mantle phases. *Rev Mineral Geochem* 2006; **62**: 243–71.

82. Okino K, Ando M and Kaneshima S *et al.* The horizontally lying slab. *Geophys Res Lett* 1989; **16**:1059–62.

83. Fukao Y, Obayashi M and Inoue H *et al.* Subducting slabs stagnant in the mantle transition zone. *J Geophys Res* 1992; **97**: 4809–22.

84. Fukao Y, Obayashi M and Nakakuki T *et al.* Stagnant slab: a review. *Annu Rev Earth Planet Sci* 2009; **37**: 19–46.

85. Huang J and Zhao D. High-resolution mantle tomography of China and surrounding regions. *J Geophys Res* 2006; **111**: B09305.

86. Zhao D and Ohtani E. Deep slab subduction and dehydration and their geodynamic consequences: evidence from seismology and mineral physics. *Gondwana Res* 2009; **16**: 401–13.

87. Kuritani T, Ohtani E and Kimura J. Intensive hydration of the mantle transition zone beneath China caused by ancient slab stagnation. *Nat Geosci* 2011; **4**: 713–6.

88. Xu Y, Zhang H and Qiu H *et al.* Oceanic crust components in continental basalts from Shuangliao, Northeast China: derived from the mantle transition zone? *Chem Geol* 2012; **328**: 168–84.

89. Wang X, Wilde SA and Li Q *et al.* Continental flood basalts derived from the hydrous mantle transition zone. *Nat Comms* 2015; **6**: 7700.

90. Nishihara Y and Matsukage KN. Iron-titanium oxyhydroxides as water carriers in the Earth's deep mantle. *Am Mineral* 2016; **101**: 919–27.

91. Hu Q, Kim DY and Yang W *et al.* FeO$_2$ and FeOOH under deep lower-mantle conditions and Earth's oxygen-hydrogen cycles. *Nature* 2016; **531**: 241–4.

92. Nishi M, Irifune T and Tsuchiya J *et al.* Stability of hydrous silicate at high pressures and water transport to the deep lower mantle. *Nat Geosci* 2014; **7**: 224–7.

93. Pamato MG, Myhill R and Boffa Ballaran T *et al.* Lower-mantle water reservoir implied by the extreme stability of a hydrous aluminosilicate. *Nat Geosci* 2015; **8**: 75–79.

94. Richard G, Monnereau M and Rabinowicz M. Slab dehydration and fluid migration at the base of the upper mantle: implications for deep earthquake mechanisms. *Geophys J Inter* 2007; **168**: 1291–304.

95. Schmandt B, Jacobsen SD and Becker TW *et al.* Dehydration melting at the top of the lower mantle. *Science* 2014; **344**: 1265–8.

96. Nishi M, Kuwayama Y and Tsuchiya J *et al.* The pyrite-type high-pressure form of FeOOH. *Nature* 2017; **547**: 205–8.

97. Manning C. The chemistry of subduction-zone fluids. *Earth Planet Sc Lett* 2004; **223**: 1–16.

98. Plank T, Kelley KA and Zimmer MM *et al.* Why do mafic arc magmas contain ~4wt% water on average? *Earth Plan Sc Lett* 2013; **364**: 168–79.

99. Sharma R and Srivastava PK. Hydrothermal fluids of magmatic origin. In: Kumar S and Narain Singh R (eds). *Modelling of Magmatic and Allied Processes.* Basel; Springer International Publishing, 2014, 181–208.

100. Richards JP. Magmatic to hydrothermal metal fluxes in convergent and collided margins. *Ore Geol Rev* 2011; **40**: 1–26.

101. Wallace PJ. Volatiles in subduction zone magmas: concentrations and fluxes based on melt inclusion and volcanic gas data. *J Volcanol Geoth Res* 2005; **140**: 217–40.

102. Hofmann AW and White WM. Mantle plumes from ancient oceanic crust. *Earth Plan Sc Lett* 1982; **57**: 421–36.

103. Bercovici D and Karato S. Whole-mantle convection and the transition-zone water filter. *Nature* 2003; **425**: 39–44.

104. Zheng Y. Metamorphic chemical geodynamics in continental subduction zones. *Chem Geol* 2012; **328**: 5–48.

105. Zheng YF and Chen YX. Continental versus oceanic subduction zones. *Natl Sci Rev* 2016; **3**: 495–519.

106. Albarède F. Volatile accretion history of the terrestrial planets and dynamic implications. *Nature* 2009; **461**: 1227–33.

107. Watson EB and Harrison TM. Zircon thermometer reveals minimum melting conditions on earliest Earth. *Science* 2005; **308**: 841–4.

108. Genda H and Abe Y. Enhanced atmospheric loss on protoplanets at the giant impact phase in the presence of oceans. *Nature* 2005; **433**: 842–4.

109. Marty B. The origins and concentrations of water, carbon, nitrogen and noble gases on Earth. *Earth Plan Sc Lett* 2012; **313–314**: 56–66.

110. Elkins-Tanton LT. Magma oceans in the inner solar system. *Annu Rev Earth Planet Sci* 2012; **40**: 113–39.

111. Hirschmann MM. Magma ocean influence on early atmosphere mass and composition. *Earth Plan Sc Lett* 2012; **341–344**: 48–57.

112. Marty B. Water in the early Earth. *Rev Mineral Geochem* 2006; **62**: 421–50.

113. Abe Y, Ohtani E and Okuchi T. Water in the early Earth. In: Canup RM and Righter K (eds). *Origin of the Earth and Moon.* Tucson: University of Arizona Press, 2000, 413–33.

114. Sagan C and Mullen G. Earth and Mars: evolution of atmospheres and surface temperatures. *Science* 1972; **177**: 52–56.

115. Kasting J. Earth's early atmosphere. *Science* 1993; **259**: 920–6.

116. Johnson TE, Brown M and Kaus BJP *et al.* Delamination and recycling of Archaean crust caused by gravitational instabilities. *Nat Geosci* 2014; **7**: 47–52.

117. Shirey SB and Richardson SH. Start of the Wilson cycle at 3 Ga shown by diamonds from subcontinental mantle. *Science* 2011; **333**: 434–6.

118. Costa F and Chakraborty S. The effect of water on Si and O diffusion rates in olivine and implications for transport properties and processes in the upper mantle. *Phys Earth Planet Int* 2008; **166**: 11–29.

119. Fei H, Wiedenbeck M and Yamazaki D *et al.* Small effect of water on upper-mantle rheology based on silicon self-diffusion coefficients. *Nature* 2013; **498**: 213–5.

120. Tielke JA, Zimmerman ME and Kohlstedt DL. Hydrolytic weakening in olivine single crystals. *J Geophys Res Solid Earth* 2017; **122**: 3465–79.

121. Karato S and Jung H. Effects of pressure on high-temperature dislocation creep in olivine. *Philos Mag* 2003; **83**: 401–14.

122. Griggs DT and Blacic JD. Quartz: anomalous weakness of synthetic crystals. *Science* 1965; **147**: 292–5.

123. Mei S and Kohlstedt DL. Influence of water on plastic deformation of olivine aggregates: 2. Dislocation creep regime. *J Geophys Res* 2000; **105**: 21471–81.

124. Jung H. Water-induced fabric transitions in olivine. *Science* 2001; **293**: 1460–3.

125. Dixon JE, Dixon TH and Bell DR *et al.* Lateral variation in upper mantle viscosity: role of water. *Earth Plan Sc Lett* 2004; **222**: 451–67.

126. Xia Q, Liu J and Liu S *et al.* High water content in Mesozoic primitive basalts of the North China Craton and implications on the destruction of cratonic mantle lithosphere. *Earth Plan Sc Lett* 2013; **361**: 85–97.

127. Wang Q. Homologous temperature of olivine: implications for creep of the upper mantle and fabric transitions in olivine. *Sci China Earth Sci* 2016; **59**: 1138–56.

128. Kohn SC and Grant KJ. The partitioning of water between nominally anhydrous minerals and silicate melts. *Rev Mineral Geochem* 2006; **62**: 231–41.

129. Hirschmann MM, Tenner T and Aubaud C *et al.* Dehydration melting of nominally anhydrous mantle: the primacy of partitioning. *Phys Earth Planet* 2009; **176**: 54–68.

130. Aubaud C, Hauri EH and Hirschmann MM. Hydrogen partition coefficients between nominally anhydrous minerals and basaltic melts. *Geophys Res Lett* 2004; **31**: L20611.

131. Katz RF, Spiegelman M and Langmuir CH. A new parameterization of hydrous mantle melting. *Geochem Geophys Geosyst* 2003; **4**: 2002GC000433.

132. Grove T, Chatterjee N and Parman S *et al.* The influence of H$_2$O on mantle wedge melting. *Earth Plan Sc Lett* 2006; **249**: 74–89.

133. Till CB, Grove TL and Withers AC. The beginnings of hydrous mantle wedge melting. *Contrib Mineral Petr* 2012; **163**: 669–88.

134. Green DH, Hibberson WO and Rosenthal A *et al.* Experimental study of the influence of water on melting and phase assemblages in the upper mantle. *J Petrol* 2014; **55**: 2067–96.

135. Hirschmann MM. Mantle solidus: experimental constraints and the effects of peridotite composition. *Geochem Geophys Geosyst* 2000; **1**: 2000GC000070.

136. Ohtani E, Litasov K and Hosoya T *et al.* Water transport into the deep mantle and formation of a hydrous transition zone. *Phys Earth Planet Int* 2004; **143–144**: 255–69.

137. Mierdel K, Keppler H and Smyth JR *et al.* Water solubility in aluminous orthopyroxene and the origin of Earth's asthenosphere. *Science* 2007; **315**: 364–8.

138. Gaetani GA, Grove TL and Bryan WB. The influence of water on the petrogenesis of subductionrelated igneous rocks. *Nature* 1993; **365**: 332–4.

139. Moore G and Carmichael ISE. The hydrous phase equilibria (to 3 kbar) of an andesite and basaltic andesite from western Mexico: constraints on water content and conditions of phenocryst growth. *Contrib Mineral Petr* 1998; **130**: 304–19.

140. Ochs FA and Lange RA. The density of hydrous magmatic liquids. *Science* 1999; **283**: 1314–7.

141. Wood BJ. The effect of H_2O on the 410-kilometer seismic discontinuity. *Science* 1995; **268**: 74–6.

142. Smyth JR and Frost DJ. The effect of water on the 410-km discontinuity: an experimental study. *Geophys Res Lett* 2002; **29**: 123–1.

143. Ohtani E and Litasov KD. The effect of water on mantle phase transitions. *Rev Mineral Geochem* 2006; **62**: 397–420.

144. Jacobsen SD. Effect of water on the equation of state of nominally anhydrous minerals. *Rev Mineral Geochem* 2006; **62**: 321–42.

145. Mao Z and Li X. Effect of hydration on the elasticity of mantle minerals and its geophysical implications. *Sci China Earth Sci* 2016; **59**: 873–88.

146. Wu Z and Wang W. First-principles calculations of elasticity of minerals at high temperature and pressure. *Sci China Earth Sci* 2016; **59**: 1107–37.

147. Ye Y. Hydration effects on crystal structures and equations of state for silicate minerals in the subducting slabs and mantle transition zone. *Sci China Earth Sci* 2016; **59**: 707–19.

148. Gavrilenko P, Ballaran TB and Keppler H. The effect of Al and water on the compressibility of diopside. *Am Mineral* 2010; **95**: 608–16.

149. Nolet G and Zielhuis A. Low S velocities under the Tornquist-Teisseyre zone: Evidence for water injection into the transition zone by subduction. *J Geophys Res* 1994; **99**: 15813–20.

150. van der Meijde M, Marone F and Giardini D. Seismic evidence for water deep in Earth's upper mantle. *Science* 2003; **300**: 1556–8.

151. van der Lee S, Regenauer-Lieb K and Yuen DA. The role of water in connecting past and future episodes of subduction. *Earth Plan Sc Lett* 2008; **273**: 15–27.

152. Li J, Wang X and Wang X *et al.* P and SH velocity structure in the upper mantle beneath Northeast China: evidence for a stagnant slab in hydrous mantle transition zone. *Earth Plan Sc Lett* 2013; **367**: 71–81.

153. Karato S. Water distribution across the mantle transition zone and its implications for global material circulation. *Earth Plan Sc Lett* 2011; **301**: 413–23.

154. Karato S. The role of hydrogen in the electrical conductivity of the upper mantle. *Nature* 1990; **347**: 272–3.

155. Gaillard F. Laboratory measurements of electrical conductivity of hydrous and dry silicic melts under pressure. *Earth Plan Sc Lett* 2004; **218**: 215–28.

156. Wang D, Mookherjee M and Xu Y *et al.* The effect of water on the electrical conductivity of olivine. *Nature* 2006; **443**: 977–80.

157. Yang X. Orientation-related electrical conductivity of hydrous olivine, clinopyroxene and plagioclase and implications for the structure of the lower continental crust and uppermost mantle. *Earth Plan Sc Lett* 2012; **317–318**: 241–50.

158. Ni H, Keppler H and Behrens H. Electrical conductivity of hydrous basaltic melts: implications for partial melting in the upper mantle. *Contrib Mineral Petr* 2011; **162**: 637–50.

159. Guo X, Chen Q and Ni H. Electrical conductivity of hydrous silicate melts and aqueous fluids: measurement and applications. *Sci China Earth Sci* 2016; **59**: 889–900.

160. Ni H, Hui H and Steinle-Neumann G. Transport properties of silicate melts. *Rev Geophys* 2015; **53**: 715–44.

161. Zhang L, Guo X and Wang Q *et al.* Diffusion of hydrous species in model basaltic melt. *Geochim Cosmochim Ac* 2017; **215**: 377–86.

162. Guo X, Li B and Ni HW. Electrical conductivity of hydrous andesitic melts pertinent to subduction zones. *J Geophys Res* 2017; **122**: 1777–88.

163. Karato S-I. Remote sensing of hydrogen in Earth's mantle. *Rev Mineral Geochem* 2006; **62**: 343–75.

164. Mookherjee M and Stixrude L. Structure and elasticity of serpentine at high-pressure *Earth Plan Sc Lett* 2009; **279**: 11–19.

165. Chantel J, Mookherjee M and Frost DJ. The elasticity of lawsonite at high pressure and the origin of low velocity layers in subduction zones. *Earth Plan Sc Lett* 2012; **349–350**: 116–25.

166. Li X, Mao Z and Sun N *et al.* Elasticity of single-crystal superhydrous phase B at simultaneous high pressure-temperature conditions. *Geophys Res Lett* 2016; **43**: 8458–65.

167. Zhang Z, Zhang C and Geng M. Equations of state for aqueous solutions under mantle conditions. *Sci China Earth Sci* 2016; **59**: 1095–106.

168. Guo X. Experimental study of the electrical conductivity of hydrous minerals in the crust and the mantle under high pressure and high temperature. *Sci China Earth Sci* 2016; **59**: 696–706.

169. Raleigh CB and Paterson MS. Experimental deformation of serpentinite and its tectonic implications. *J Geophys Res* 1965; **70**: 3965–85.

170. Jung H, Green HW and Dobrzhinetskaya LF. Intermediate-depth earthquake faulting by dehydration embrittlement with negative volume change. *Nature* 2004; **428**: 545–9.

171. Zhang J, Green HW and Bozhilov K *et al.* Faulting induced by precipitation of water at grain boundaries in hot subducting oceanic crust. *Nature* 2004; **428**: 633–6.

172. Wang J, Zhao D and Yao Z. Seismic anisotropy evidence for dehydration embrittlement triggering intermediate-depth earthquakes. *Sci Rep* 2017; **7**: 2613.