Oceans of mineral-bound water in earth's lower mantle: Seismic study confirms earlier speculations

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According to well-established views based on several models, water on earth owes its existence to the degassing of the early earth's mantle and to additions from extraterrestrial bodies. Although nearly 70% of the earth's surface is covered by water, the hydrosphere forms only 0.025% of the planet's mass and less than a tenth of the water contained in the mid-ocean ridge magmas and about half of the contents of the enriched mantle[1]. Presently, bulk of the water is locked up in certain minerals in the upper mantle (70–700 km) and presumed to be present in a few high-pressure minerals in the lower mantle (700–2900 km). The latter supposition, born out of laboratory experiments, gained strength through advanced studies on the earth's interior in the decades following the birth of the plate tectonics theory in the 1960s.

Considerable data from several experimental studies, computer-based geodynamic modelling, besides petrological and geochemical investigations on mantle-derived samples have helped understand the physical and chemical changes of the descending plates undergo, particularly about the fate of water carried by them locked up in hydrous minerals. These studies have shown how the latter minerals, quite stable under surface conditions, become unstable when they experience higher pressure and temperature on reaching greater depths. Low-pressure hydrous minerals, like prehnite, chlorite, amphibole and serpentine shed most of their water and get re-structured to stable, denser mineral phases (e.g. amphibolite–eclogite transformation), thus enabling their descent to further depths. The unreleased water within these newly generated, more stable hydrous-phases, like lawsonite, staurolite, chloritoid, zoisite-clinozoisite is transported by the subducting slabs still deeper and are even thought to plunge into the lower mantle, a region previously considered impervious for the descending slabs. In this way, these hydrous phases are assumed to effectively augment the sparse water content in the upper parts of the lower mantle[2–6].

Data from mineral physics experiments, chiefly synthesis at high pressure in the system $MgO–SiO_2–H_2O$, have shown that the subducted lithosphere slabs in the lower mantle can hold as much as 10–18 wt% water in a crystal structure designated Phase D ($Mg_{1.11}Si_{1.09}H_{2.22}O_6$)[7–9]. This Phase D breaks down on reaching lower mantle depths of 1200–1400 km, liberating H_2O. The latter is then absorbed by minerals stable at these depths, like Mg-perovskites and magnesiowüstite at oxygen vacancy sites in their crystal structure arising from the substitution of Si by Al and Fe^{3+}, thereby enriching the upper portions of the lower mantle with huge quantities of water[8,10,11]. Thus in the lower mantle, which is about 60% of the earth's volume and essentially peridotitic in composition (79 wt% Mg-perovskite, 16 wt% magnesiowüstite and 5 wt% Ca-perovskite) with a H_2O content of 0.2 wt%, the total mass of water present works out to a staggering figure – nearly five times that of surface oceans[3,4,10,11]. This could be more if one takes into account the possible contributions from primitive or primordial reservoirs formed in the early earth's magma ocean as well as additions from hydrogen-saturated outer core[12] or chemical impurities-aided point defects in high-pressure polymorphs[13].

Existing views about hydration of the lower mantle are based on several high-pressure experimental studies over the last thirty years. However, no clear field evidence for the entry of water-bearing phases beyond the transition zone (a region from 410 to 700 km depth, marked by olivine–wadsleyite change at 410 km and ringwoodite–perovskite/magnesianwüstite at 700 km)[14] into the lower mantle was reported for a long time. However, the rapid development of seismic tomography in the 1970s and 1980s, imaging the slabs subducting into the upper mantle and penetrating the transition zone into the lower mantle[15], has now strengthened earlier speculations about the role of subducting slabs as efficient carriers of hydrous mineral phases into the earth's deep interior. This mode of entry of water into the lower mantle is supported by a recent contribution through detailed seismic data[3].

The behaviour of seismic waves passing through the earth's interior has contributed much in interpreting the earth's structure. Seismic-wave propagation is influenced by the nature of the medium through which it travels, primarily by the elastic behaviour of the medium, though other properties like scattering, viscosity, grain size and temperature of the medium also affect the propagation. In any anelastic medium (caused by the presence of water, fluids or reduced viscosity), seismic waves lose their energy (frictional loss) and get attenuated or reduced in their amplitude. For example, high attenuation of the waves is noted in the earth's asthenosphere (70–250 km) because this zone is richer in water and has low viscosity relative to the lithosphere lying above this zone[16]. This behaviour of seismic waves passing through water-rich zone forms the basis for the recent search and discovery[3] of 'oceans of water' in the lower mantle. In this study, an indirect evaluation of the 'wetness' of a zone is done based on an attenuation factor Q, which is an expression of the dampening of seismic energy and derived from the number of cycles the oscillating wave takes to reach 4% of its original amplitude. For example, a decrease of the original wave amplitude from a Q value of 300 to a value of 100 is explained as due to increase in the water content of the order of about 10. This study expected appreciable attenuation or decrease in the Q value even with a moderate increase in water content. Such water-rich zones are bound to occur in the deep mantle in view of the earth's long history of subduction process and sinking of the slabs even up to the core–mantle boundary, as revealed by seismic tomography.

The above expectation of striking water-rich zones in the lower mantle, is now justified by findings from the examination of differential travel time and attenuation in nearly 900 earthquakes that had occurred during a 13-year period (1990–2002). The study found a region of high attenuation in the upper parts of the lower mantle along the east coast of Asia (Figure 1), stretching from the equator to the pole and notably coinciding with the subducted

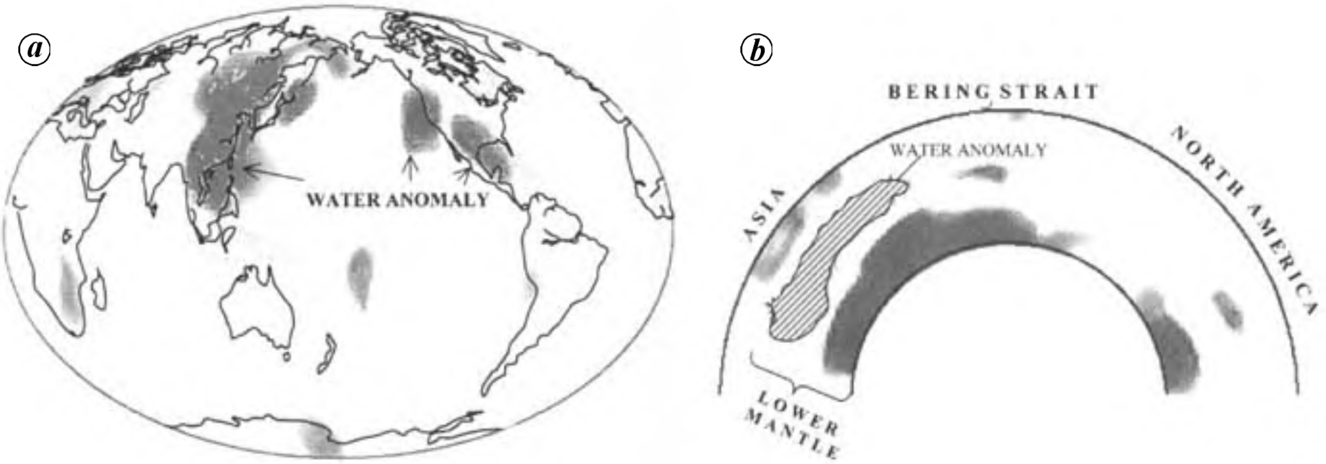

Figure 1. Attenuation anomalies indicating re-hydrated zones within the earth's lower mantle. ***a***, Water-rich zones (grey patches) are found below the East Coast of Asia, North America and Alaska. The large Beijing anomaly beneath the East Coast of Asia is located in the upper portions of the lower mantle. ***b***, Cross-sectional view of the Beijing anomaly detected between depths of 1000–1400 km in the upper parts of lower mantle (adapted from Lawrence and Wysession[3]).

Pacific Oceanic lithosphere from about 700 to 1400 km depth. The Q value here registered a minimum of 95 at about 1000 km depth beneath China, northwest of Beijing (hence called the Beijing anomaly), as against a value ranging between ~311 and 367 for the original unattenuated wave in the subducted lithosphere in the western Pacific and lying below this anomaly. This attenuation is comparable in places to well-studied, water-rich regions in the asthenosphere. Besides, a large anomaly is also noted beneath SE Asia around the Pacific rim to Alaska and also beneath North America. Assuming a small 5% decrease in the original Q value in the Beijing anomaly, and considering the colossal ~108×10^{10} cubic km volume of the lower mantle here, with 0.1 wt% water content, the mass of water available should be exceeding the amount of water in the Arctic Ocean[3].

Before concluding that the Beijing anomaly is caused by water enrichment, other causes that could be instrumental for this were assessed and ruled out. Scattering from small-scale heterogeneity arising from dismembered bits of the subducting slab is one such possibility. However, this is considered improbable, since a reduction in the Q factor from a high of 300 to a low of 100, would require splitting of the subducting lithosphere into several small bits (delamination). This is regarded as hypothetical and highly unlikely, considering the greater rigidity of garnet-bearing oceanic crust compared to the surrounding lower mantle.

Changes in grain-size and viscous drag produce large attenuation – smaller the grain-size, greater is the attenuation. Several of the new mineral phases (e.g. perovskite and periclase) that form in the lower mantle in the wake of the breakdown of hydrous mineral phases dragged down from the transition zone can crystallize as either fine-grained or coarse-grained depending upon their rate of crystallization. They could be fine-grained where the crystallization is rapid as in the $(Mg,Fe)_2SiO_4$ system (spinel to perovskite) or coarse-grained when the crystallization occurred slowly as in the $(Mg,Fe)SiO_2$ system (e.g. garnet to perovskite and magnesiowüstite). However, contrary to crystallization of such new mineral phases normally expected to form on both sides of the subducting slab, the low Q anomaly is observed only on one side – above the subducting lithosphere, where H_2O released by the breakdown of Phase D is known to ascend and accumulate. Besides, most other slabs here, subducting in the lower mantle do not exhibit low Q anomaly surrounding the slab, as one would expect. The absence of such a feature, the study claims, discounts grain size as causing the attenuation anomaly, not to mention the improbability of the transport of such a large volume of material from the transition zone by viscous drag.

Zones of higher temperature can attenuate seismic waves and create an anomaly, but their influence also is ruled out for the Beijing anomaly. It is argued that subduction processes have been operating for the last 200 million years and this must have transported such a large volume of relatively cold oceanic crusts that the warming up of the lower mantle is not possible. Another source for the existence of islands of relatively higher temperature could be the hot ascending megaplumes, as noticed in the Pacific and African plates. However, in the vicinity of the Beijing anomaly no plume-like structures are seen that could be the source of heat transfer. Apart from this, it is not possible to create such a large, horizontal thermal anomaly extending from the equator to the pole, on top of a subduction zone. Above all, no low-velocity anomaly as one would expect in the seismic waves transiting through increased temperature zone is observed. A comparison of the seismic wave speeds and attenuation (Q and v as functions of water and velocity) for nearly 900 earthquakes examined, rejects increased temperature as the cause for the anomaly beneath eastern Asia[3].

The increased concentration of water is therefore considered the most likely cause for the observed East Asian low Q anomaly and the influence of heterogeneity, grain size, viscous drag and elevated temperature, if prevalent, are expected to be insignificant. The study concludes that the lithosphere that subducted beneath the East Coast of Asia must have remained cold enough, a pre-requisite for carrying the hydrous mineral Phase D in a stable manner[8], and they must have served as an efficient aqueduct transporting water continuously into the lower mantle. A doubt, nevertheless, arises as to why rehydration, similar to the one that produced the Beijing anomaly does not occur in other slabs subducting to similar depths. The answer for this, according to the study, may either be due to small volume hydrous phases initially present, or the slab may not have been cold enough to carry these phases to lower mantle depths. Locating the 'missing water' in the earth's interior, particularly in the lower mantle, is indeed a breakthrough, but some are yet apprehensive about the uncertainties that usually haunt geophysical interpretations of data from the remote reaches of the earth's interior[1].

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Combating antibiotic resistance in bacteria: Selection between sensitive and resistant bacterial populations in drug combination treatment

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Imagine a physically disabled patient with a nosocomial septic arthritis due to *Staphylococcus aureus*. The cure is defied because the normal bacterial microflora of the human body is now insensitive to the available antibiotics. Mutations arise in the mobile genetic elements (transposons) harboured by the bacteria. The transposon DNA might code for (a) 'efflux' pumps that eject the antibiotics from cells, (b) genes might give rise to enzymes that degrade the antibiotics, or (c) genes that chemically alter and inactivate the drugs.

Rather than treatment with a single antibiotic, will a combination of some available antibiotics be effective against the resistant mutant than the normal (wild type) bacteria? The results of research carried out by the systems biologist, Roy Kishony and his graduate students at Harvard Medical School, USA, using the model organism *Escherichia coli*, predict that a combination of some available antibiotics in different combinations promotes the growth of the resistant and wild type bacteria (normal strain) differently. Whereas sensitive and resistant strains respond similarly to a given drug, there is a region of drug combination in which only the sensitive strain grows, i.e. a combination that actually selects against the resistant mutant rather than the wild type[1]. When a bacterium mutant becomes resistant to a particular antibiotic, its behaviour to another antibiotic can be different: the wild type bacteria despite being more sensitive to the individual drugs outcompete the resistant mutant bacteria. The combination drugs must of course be in the right concentrations.

The antibiotic doxycycline (DOX) inhibits protein synthesis and is used to treat a variety of bacterial infections. The authors studied the effects of this antibiotic in combination with erythromycin and ciprofloxacin, on selection of resistant and sensitive test bacterium by tagging the DOX-sensitive and DOX-resistant types using yellow or green fluorescing proteins respectively, and monitoring bacterial luminescence using a FACS (fluorescence activated cell sorter) machine as a measure of their growth rates. Further, they measured growth rates as a function of two-dimensional drug concentrations and found synergy with DOX and erythromycin, and suppression with DOX and ciprofloxacin. As expected, the DOX-resistant mutant out-competed the wild type under DOX treatment and when DOX was given with erythromycin. Remarkably, in the presence of ciprofloxacin, DOX generated selection against its own resistant mutant allele! For example, when 0.1 μg ml^{-1} DOX was added to 7.5 ng ml^{-1} ciprofloxacin. The authors emphasize that 'our work is limited to sublethal drug concentrations, in a controlled environment *in vitro* and that any possible therapeutic implications from these findings are beyond its scope'. However, these findings would lead to research into 'new treatment strategies employing antimicrobial combinations with improved selection against resistance'.

The antibiotic interactions that select against resistance may offer a powerful method to leverage the efficacy of therapeutic agents. This paper raises important issues: Is our present concept of resistance falsified? Does the origin of resistant bacterial cells involve epigenetic changes in addition to genetic change? How does combination drug therapy tip the balance against resistance, i.e. the erstwhile sensitive bacteria outcompeting those that evolve resistance under applied selective pressures? Are the principles in selection of bacteria also applicable to normal human cells in tumours?

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