both the scenarios fall far short of the BAU (one in a billion) that is observed.

The problem is that particles with small masses (like s and d quarks) play a crucial role in CP violation in B and K decays. Their masses are negligible at the high temperatures when BAU is created and so their effects are smaller than required. Peskin[11] suggests that if CP violation is discovered in heavy particles (like the Higgs particle, for which a search is on) the strengths of these violations may be strong enough to explain BAU. This is really an admission that there is no viable explanation of BAU with present existing knowledge from B-factories. A realistic scenario for our existence in the universe is still awaited.

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N. Panchapakesan lives at K-110, Hauz Khas, New Delhi 110 016, India.
e-mail: panchu@vsnl.com

The Hadean earth – a veritable hell, or haven for early life? Answer from > 4 billion-year-old zircons

A. V. Sankaran

Of the 4.56 billion years (b.y.) since earth started forming, its history during the first half billion years is hazily understood. For nearly hundred million years of earth's formative period, violent impacts from terrestrial accretion of assorted planetessimals released enormous heat, which in combination with heat from radioactive elements, kept the planet molten and delayed its cooling and initiation of stable crust. Even the few crustal segments that formed at some stage fragmented and invariably foundered into earth's molten interior. This turbulent phase of the formative earth was notable for widespread volcanism, early segregation of iron to form its core, and a catastrophic collision of a massive asteroid leading to formation of moon[1]. This was the state till about 4.45 b.y., after which earth cooled sufficiently for the newly forming crust to remain stable. Infant earth is, therefore, always described as a hot and lifeless planet, a profile so deeply entrenched in the geological literature to inspire an apt name – Hadean (Greek for Hades or hell), first proposed by Preston Cloud[2] in 1976, for the > 3.8 b.y. period. The enigmatic period of first half-billion years (4.56 to 4.15 b.y.) also got a befitting name – 'cryptic' (Figure 1).

Answers as to when earth developed a stable crust and when oceans formed were topics of unending debates for many years. Rock records to help reconstruct the likely scenario of this period, in fact, even that of the subsequent half-billion years, are too poor to provide an authentic account. However, over the last few decades, in the wake of development of sophisticated instrumentation capable of *in situ* analyses of tiny mineral grains or retrieving them from the rock matrix

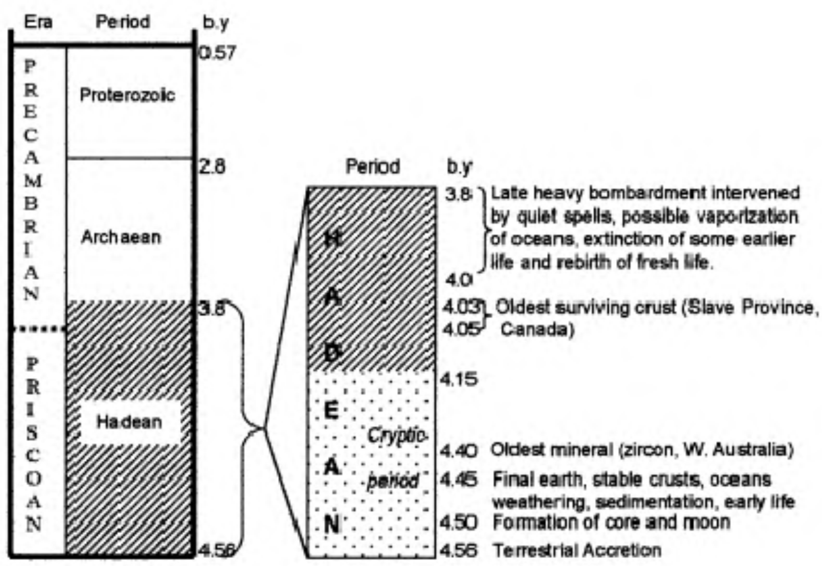

Figure 1. Geologic time scale showing events of the Hadean Era.

for precise geochronological and geochemical analyses, a better picture about earth's 'cryptic' first half-billion years began to unfold. Simultaneously, global efforts for locating oldest surviving crust through detailed geochronological surveys in ancient terrains narrowed down the existing estimates about the time-gap between the beginnings of earth formation and appearance of earliest stable crust. In 1999, surveys conducted in the Acasta Area of the Slave Province in the Canadian Shield led to the discovery of 4.03–4.05 b.y. old metatonalite and metagranodiorite through systematic zircon dating[3–5]. Although these rocks represent the oldest surviving crust discovered so far, brief existence of still older crust has been inferred from 4.3 to 4.4 b.y. zircons of detrital origin in Western Australia, occurring in metamorphosed sediments which must be eroded products of such transient crusts[6–9].

Zircon (Zr_2SiO_4) occurs as a common accessory mineral in granitoids, syenites, carbonatites and a few mafic rocks and it also forms during metamorphism of sediments. It is a mineral that resists destruction during weathering and accumulates along with sediments as a detrital mineral. Being geochemically robust, unaffected by post-crystallization metamorphism, the mineral retains its minor and trace elements – particularly the radioactive elements like U, Th and their radiogenic product Pb, a feature ideal for getting reliable dates. Apart from their use in dating, their minor and trace element contents have proved useful in tracing the mineral's petrogenesis – whether it crystallized from a primary magma melt, or a melt, derived for example, through dehydration of recycled or subducted early continental slabs. Now, two groups of investigators from Australia, England and United States have applied zircon's geochemistry to comprehend the state of earth during Hadean times and their interesting conclusions may call for a revision of our understanding of this era. Their studies[7,8] probing the isotope geochemistry of some of the > 4.0 b.y. zircons, the sole survivors of short-lived early crusts, have shown that this era was actually cool and not hot and hellish and that oceans had also formed and conditions were favourable for heralding life on earth[7,10–12].

The zircons that have spawned the unorthodox view of a relatively cool Hadean earth hail from metamorphosed sediments of the Jack Hills area, Yilgarn Craton, Western Australia, the same place that two decades back had provided the ~ 4276 m.y. old zircons, the detrital remnants of still older crust[6]. Over the last few years, detailed investigations in this area have resulted in the location of a metaconglomerate rich in heavy detrital minerals like zircon, Cr-spinel and fuchsite. Dating of these zircons by the two teams has revealed that they belong to ages ranging between 3.9 and 4.4 b.y., suggesting that they may have come from separate source rocks of different ages though none of these rocks exist now[7,8]. Dating of one zircon from this assembly, relatively free from inclusions and other complexities, gave $^{207}Pb/^{206}Pb$ age of 4404 ± 8 m.y., making it the oldest recognized terrestrial mineral[7], 95 m.y. older than the oldest reported earlier[6].

Quite a few inferences have emerged from geochronology of the West Australian zircons. The detrital origin of these early Hadean zircons is strong evidence that their primitive parent rocks must have remained stable and exposed long enough to undergo weathering. The transport of the zircons liberated from these rocks along with other sediments implies availability of running water as well as basins for their sedimentation. For these processes to operate, water should remain in liquid form and for this, earth must have cooled quite rapidly within a short geological span to temperatures below 100°C. Further, the fact that zircons generally are products of hydrated granitoid magmatism lends support for inferring presence of water (oceans) or water introduced to shallow mantle environment, for example by recycling or subduction of hydrated oceanic crust[12,13]. These logical deductions about the geology of the Hadean earth have now been confirmed through evaluation of oxygen isotopes in the > 4 b.y. zircons.

The degree of fractionation of the isotopes of oxygen – ^{16}O, ^{17}O and ^{18}O, is used to interpret past temperatures on earth's surface and also in studies to differentiate whether a granitoid is of mantle source or metasedimentary or derived through hybrid interactions. Zircons are known to maintain their magmatic oxygen isotopes unaffected by any subsequent metamorphic episodes unlike other minerals like quartz or feldspar[11,14]. Certain interesting geochemical trends observed with respect to $\delta^{18}O$ values in zircons have now helped to reconstruct the Hadean earth scenario. It is observed that the $\delta^{18}O$ within the zircons from Archaean magmas average close to that of earth's primitive mantle (5.3‰ ± 0.3‰) (refs 15–17), and it gets enhanced when the zircons crystallize from melts carrying crustal contamination such as fluids from subducting oceanic crust, or melts of subducted sediments or other such influxes[14]. Such inputs are highly likely in rocks formed during younger geological times (< 2 b.y.), in a more evolved earth, than during less evolved Archaean earth[14,18]. This is demonstrated in the Canadian Shield where comparisons of zircons of different ages derived from different igneous processes and histories have shown that grains of the younger Proterozoic age display enhanced $\delta^{18}O$ (8.2‰ ± 1.7‰) compared to their counterparts (5.7‰ ± 0.6‰) from older Archaean times[12,14,18]. One of the two teams investigating the Jack Hills zircons reported high $\delta^{18}O$ values (6‰–8‰) for the 4.4 b.y. zircon[7,10,12], while another team found in the 3.98 to 4.28 b.y. group of zircons occurring here, the $\delta^{18}O$ ranged between 5.4‰ and 15‰ (ref. 8). The high values match with zircons (of younger age) known to have had hydrated crustal input to the parent melt and justifiably the teams have concluded that these high $\delta^{18}O$ values in the Jack Hills zircons are signatures of strong crustal contamination.

The above conclusion agrees with theoretically calculated $\delta^{18}O$ values of (7‰–11‰) (ref. 8) using oxygen isotope fractionation factor (–2‰) between zircon and its host granites[19]. These values are considered strong indication of input of 'recycled crustal material that had interacted with liquid water under surface or near surface condition'[8]. A similar view has come about from Hf-isotopic study of zircon from this craton which point to its crystallization by the remelting of significantly older per-aluminous granitoid[8,20] crust. These are claimed to be clinching proofs for existence of stable crusts which were subjected to weathering, diagenesis or reworking to generate sediments and that these processes were active even earlier than 4.4 b.y. (Cryptic period 4.56–4.15 b.y.). The magnitude of water and rock reactions to produce high $\delta^{18}O$ observed would suggest presence of liquid water or stable oceans within first 50 million years of earth formation.

The above conclusions were arrived after elimination of other possibilities that may lead to high $\delta^{18}O$ such as extraterrestrial origin through accreting objects for the zircons, fractional crystallization of the parent melt at 4.4 b.y. or through exchange with steam rather than liquid water[12]. However, it is argued that the observed features in this zircon such as zoning and high REE enrichment, particularly LREE[10,21] are unlikely to generate such high $\delta^{18}O$ values of 8‰–10‰. Further, they are more compatible with the zircon generated in granitic melt derived from partial melting of pre-existing crust and not from extraterrestrial source. Interaction with steam, instead of liquid water, is also discounted as temperature for such a state for H_2O (> 374°C) is much higher than indicated by the $\delta^{18}O$ in the zircons[12]. Presence of SiO_2 inclusions indicating quartz-saturated magma and similarity of this 4.4 b.y. zircon with other zircons in the same rock preclude the other alternative scenarios[12].

The concept of a cool Hadean earth with liquid water or oceans, however, may yet appear inconceivable against the backdrop of bombardment of highly energetic meteorites and consequent high thermal state of earth expected. However, recent evaluation of rate of bombardment from the time of onset of earth accretion has shown that this declined rapidly and accretion was completed by 4.45 b.y. and earth became cool sufficiently and remained so till about 4.0 b.y. (refs 22, 23). The studies show further that there was another spell of late heavy bombardment (LHB) believed to have been triggered by processes in the outer solar system or through deflection of asteroids and original minor satellites of earth or through re-accretion of debris ejected during the lunar cataclysmic event, which could have turned earth once again to a hot place, vapourizing oceans and triggering igneous and hydrothermal processes[12,24]. The > 4 b.y. Jack Hills zircons obviously are products from the tranquil period prior to LHB and their high $\delta^{18}O$ positively confirm interaction of their parent early protoliths with liquid water.

The existence of liquid water bodies such as oceans by 4.4 b.y. suggests strong possibilities for presence of biosphere much earlier than hitherto thought. This has a great impact on our knowledge about beginnings of life in our planet inasmuch as such a veneer of water is absolutely essential for its origin and evolution[8]. The indications for existence of such ancient life are already reported from water-laid sediments such as the >3850 m.y. banded-iron-formations (BIF) of the Akilia Island, Greenland[25,26] and discovery of 3500 m.y. microfossils from Western Australia[27]. These discoveries may point to favourable protected environments (e.g. ocean bottom hydrothermal environment) serving as a virtual haven for possible biological processes and for primitive life between 4.4 and 3.9 b.y. Hadean times[12,13,25,28]. Although a subsequent spell of late heavy bombardment may have affected life, it could have also brought in fresh seeds of life. It is believed that this spell was not an 'era of continuous massive impacts but most likely dominated by quiet conditions punctuated by relatively infrequent episodes of extreme thermal shock'[21] and could still have harboured sanctuaries for survival of life. Under these conditions, it is possible that the ocean bottom primitive life may have been annihilated and re-evolved more than once[7], and these bouts may perhaps represent early events of meteorite-triggered mass extinction and evolution.

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A. V. Sankaran lives at No. 10, P & T Colony, I Cross, II Block, RT Nagar, Bangalore 560 032, India
e-mail: sankaran@bgl.vsnl.net.in