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Review Article

Detrital Zircons in Crustal Evolution: A Perspective from the Indian Subcontinent

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Detrital zircons are frequently used for crustal evolutionary studies as they sample vast regions of the continental crust. In the present study, we utilise newly compiled U-Pb detrital zircon data from the Indian subcontinent as well as a compilation of previously reported global data along with Hf isotopes of modern and ancient sediments in order to understand crustal evolution in the Indian subcontinent. The detrital zircon U-Pb age data from the Indian subcontinent show peaks (at 2400–2700, 1600–1900, 850–1200, and 450–550 Ma) that correlate with the formation of major known supercontinents. In addition, two other peaks at 3200–3400 Ma and <100 Ma do not correspond to periods of supercontinent formation. The former peak may represent uneven geographic sample density due to enhanced erosion and exhumation of Archean sources. The distinctly younger (<100 Ma) detrital zircon age peak may represent zircon preservation due to the Himalayan orogeny. The zircon Hf model ages from the Indian subcontinent suggest that the Precambrian crust was the major source of continental crust with younger ages. The conspicuous shift to positive εHf (t) at ca. 3600 Ma from detrital zircons of the Indian subcontinent may underscore a change in geodynamic processes, while the highly negative values post ~3200 Ma may be associated with the crustal reworking. A wavelet analysis of detrital zircons from the Indian and global databases reveals a prominent cyclicity of ~800 Myr and ~350 Myr plausibly representing the supercontinent cycle and its half cycle. An incongruence in power between global and Indian εHf (t) could be due to the local subcontinental geologic processes during the Paleo- to Mesoarchean.

1. Introduction

Detrital zircons (from river sand, sedimentary, and metasedimentary rocks) are frequently used for crustal evolutionary studies as they sample vast regions of the continental crust and experience multiple recycling episodes thereby resulting in thorough mixing of sediments [1–5]. The utility of detrital zircons in deciphering crustal evolution, provenance, tectonics, and paleoclimate has been shown in various studies [1, 6–14]. The U–Th–Pb isotope system from zircons can be used to date the time of crystallization of zircon, the age of a crustal melting event, and occasionally the age of high-grade metamorphism [7, 15]. Additionally, (U-Th)/He or fission track thermochronometry has also been implemented to understand thermal histories [16, 17].

The $^{176}Hf/^{177}Hf$ ratio in zircons is close to the ratio of the melt from which the zircon crystallized. This ratio can be used to calculate the time when the crustal source region, which melted to form the granitic magma from which the zircon crystallized, separated from the mantle (mantle separation age or crustal growth age). The oxygen isotope ratio of the zircon provides a measure of the involvement of low-temperature processes or a measure of the fraction of sediment in the magma source region [18, 19]. The combination of Hf and O isotopes can be used to distinguish between zircons derived from the melting of igneous crust and those derived from the melting of continental crust, which contains a sedimentary component. Further, the zircon grain size has also been used for sediment recycling and provenance studies [20].

The present contribution attempts to address the crustal evolution of the Indian subcontinent using compiled detrital zircon U-Pb and Hf isotope data from ancient and modern sediments. Combined with global detrital zircon datasets, we demonstrate the variability in the evolution of continental crust in the Indian subcontinent.

2. Detrital Zircon in Crustal Evolutionary Studies

A considerable debate revolves around the timing and rate at which the continental crust was generated [21–24]. The proposed continental growth models suggest that (a) the volume of continental crust has constantly increased with time [25], (b) the present volume of continental crust was formed within the first billion years of Earth's history with a quasi-steady-state since then [21], and (c) the growth of the crustal volume was episodic [1, 26–28]. Crustal volumetric growth curves (Figure 1(a)) are based on (a) temperature, such that the continental crust was rapidly generated from a hotter Earth during the Hadean and Archean [29]; (b) age distribution of different rock exposures [30]; (c) rock distribution with different radiometric (Rb-Sr, Nd, and K-Ar) ages [25, 27, 31]; (d) Nd model ages of rocks recently exposed on the surface of the Earth [32]; (e) rapid growth of crust during the late Archean followed by steady-state growth due to island arc volcanism [33]; and (f) age estimation using U-Pb dating combined with Hf and O isotopes in zircon [1, 4, 26, 28, 34]. Additionally, a recent study on the basis of Nd modelling and covariation of U-Pb and Hf isotopes in zircons evokes the continuous crustal generation and destruction model for the Earth's continental crust [35, 36].

As mentioned earlier, the U-Pb, Hf, and O isotopes in zircons when combined provide vital information regarding both timing and melt source. U-Pb is a well-documented geochronometer that records the timing of zircon crystallization, while the Lu-Hf and O systems together combine to record the geochemical characteristics of the source. The radiometric ages (K-Ar and Rb-Sr) along with U-Pb detrital zircon ages and Hf/O isotopes elucidate an episodic generation of continental crust (Figure 1(a)) [2, 4, 25, 26, 37, 38]. The major peak clusters for detrital zircon ages at ca. 2500-2700, 1600-1800, 1000-1200, 500-600, and 300 Ma (Figure 1(a)) are commonly observed in the modern and ancient detrital age spectrum [1, 4, 26]. Condie et al. [39] identified two additional peaks 2500 Ma and 2100 Ma while more recently a peak at ca. 3300 Ma was identified in detrital zircons from ancient sediments [14]. These major peak clusters correlate well with the global age peaks and the episodes of major supercontinent formation (Figure 1(a)) [23, 26], while the age minima were suggested to be in agreement with the early stages of supercontinent breakup [26]. A similar conclusion was drawn from the U-Pb and Hf isotopic studies carried out from detrital zircons separated from modern rivers (Mississippi, Congo, Yangtze, and Amazon Rivers) [40] as well as some of the rivers from the African continent [41]. On the basis of U-Pb isotopic data, the studies concluded that the age peaks (at ca. 2700, 1900–2200, 1000–1200, and 400–700 Ma) corresponded to the major episodes of supercontinent assembly. Recently, on the basis of detrital zircon from sedimentary successions, it was suggested that there was continuous growth in the continental crust and zircon age peaks were present throughout geological history [14]. The study further concluded that the age troughs in modern sediments were because of bias in the preservation of the geologic record.

Another school relates the age peaks to short phases of accelerated crustal growth due to superplumes/emplacement of large igneous provinces or periods of accelerated plate motion and subduction, which are separated by periods of inactivity [42–45]. Recently, Phanerozoic zircon ages were scrutinised and studied from two active margins, viz., eastern margin of Australia and the western margin of South America [46]. The study concluded that episodic zircon age distributions correlated with the subduction fluxes signifying that convergence rates play a crucial role in regulating the volume of melting in subduction zone magmatism and in crustal growth [46]. Another study utilised a statistical approach to test episodic crustal growth versus constant growth due to crustal preservation and concluded that the net growth of the continental crust has remained constant since 2 billion years ago [11].

Studies based on detrital zircon U-Pb and Hf-isotopic data have identified episodic juvenile crustal additions versus recycling of older crust [47]. However, zircon U-Pb ages and Hf isotopic characteristics may not be sufficient to fingerprint hybrid or multicomponent additions with time, and therefore, it can be hard to deconvolve the time of actual crust-forming events [48, 49]. This confusion of juvenile versus reworked crust can be addressed by using oxygen isotopes to sort zircons that may contain sedimentary inputs [2]. The oxygen $^{18}O/^{16}O$ ratios are expressed as $\delta^{18}O$ relative to standard mean ocean water (SMOW) wherein $\delta^{18}O$ values ranging from 4.5 to 6.5‰ represent mantle-derived magmas and $\delta^{18}O > 6.5$‰ signify sedimentary recycling [2, 50, 51]. Therefore, using radiogenic isotopes alongside stable isotopes can differentiate whether the zircons have crystallized from juvenile magma during continental crust generation or were reworked from the preexisting crust (Figure 1(b)).

3. Detrital Zircon Record from the Indian Subcontinent

3.1. Database Description and Methods. In the present study, we have compiled and integrated the values of concordant and nearly concordant (from 90% to 110% concordant) U-Pb detrital zircon ages ($n = 17456$; Figure 2) and Hf isotopes ($n = 4934$; Figure 2) from the Indian subcontinent along with U-Pb age data from Puetz and Condie [12] ($n = 9446$). Global U-Pb detrital zircon analysis from Puetz and Condie [12] was further integrated with the published U-Pb detrital zircon data of modern as well as ancient samples (quartzite, conglomerate, sandstone, metapelites, paragneiss, etc.) ($n = 8010$) from India (data available on request). The data within 10% of concordance, common

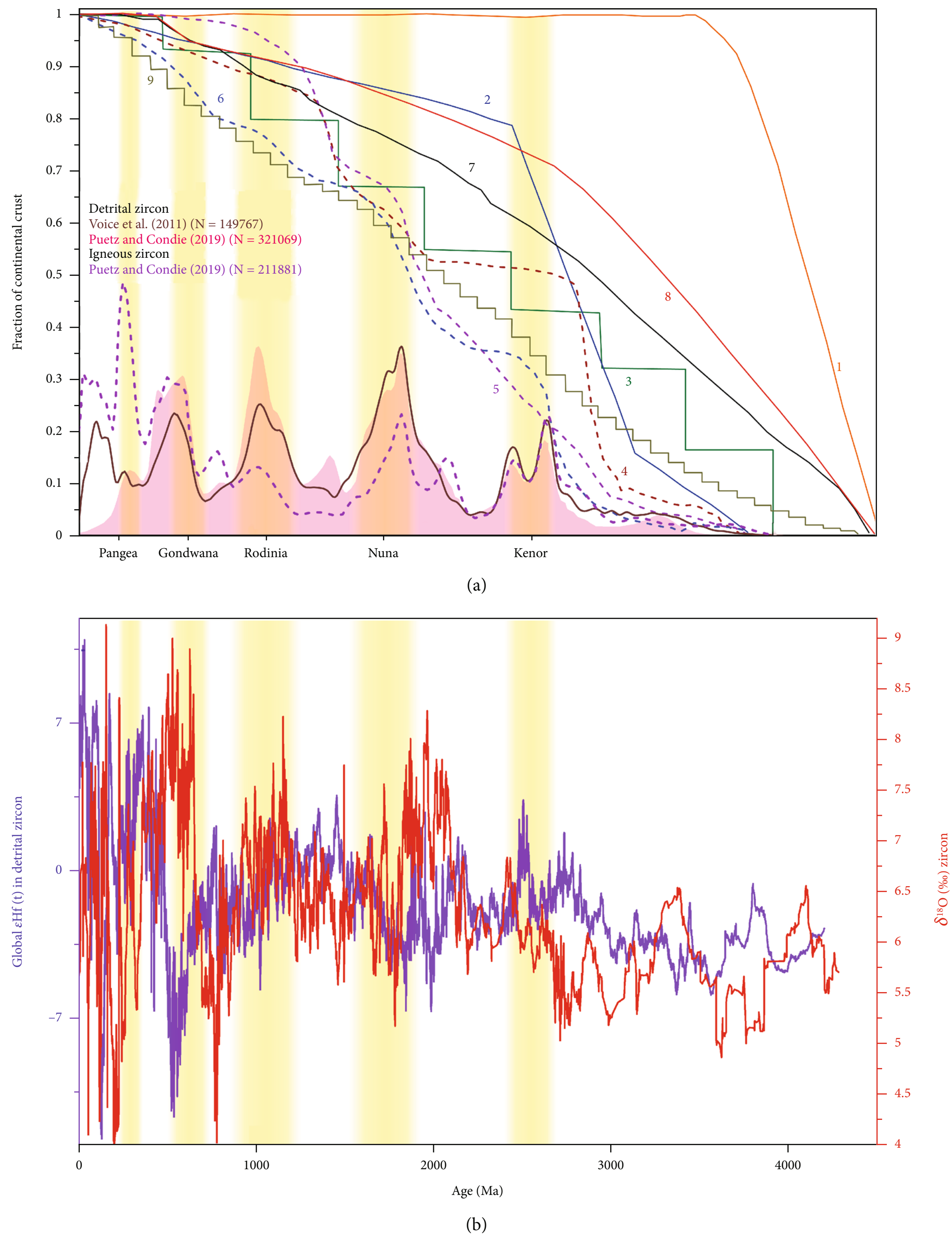

Figure 1: (a) Various published models for the growth of continental crust along with detrital zircon U-Pb age (crystallization ages) peaks [4, 12]: 1, [29]; 2, [110]; 3, [32]; 4, [27]; 5, [28]; 6, [26]; 7, [1]; 8, [34]; 9, [35]. (b) The red curve represents moving average (51 R. Avg.; $n = \sim 6200$) of $\delta^{18}O$ analysis from zircons vs. crystallization age [59], and the blue curve is the running average (121 R. Avg.; $n = \sim 42{,}460$) of εHf (t) [56]. The yellow bands depict the ages of supercontinent assembly [61, 111–115].

Pb correction, and with $^{206}Pb/^{204}Pb$ ratio for common Pb noncorrected data greater than ~3000 or f206 < 1 were selected and plotted as kernel density estimation age spectra using Isoplot R [52] and Python codes on Jupyter Notebook. In contributions where no information on $^{206}Pb/^{204}Pb$ or f206 was provided, it was assumed that acceptable values were used for publications. Ages from $^{207}Pb/^{206}Pb$ were used for grains older than 1500 Ma, while $^{206}Pb/^{238}U$ ages were used for younger grains [53]. With respect to Hf isotopes, the compiled data have measured

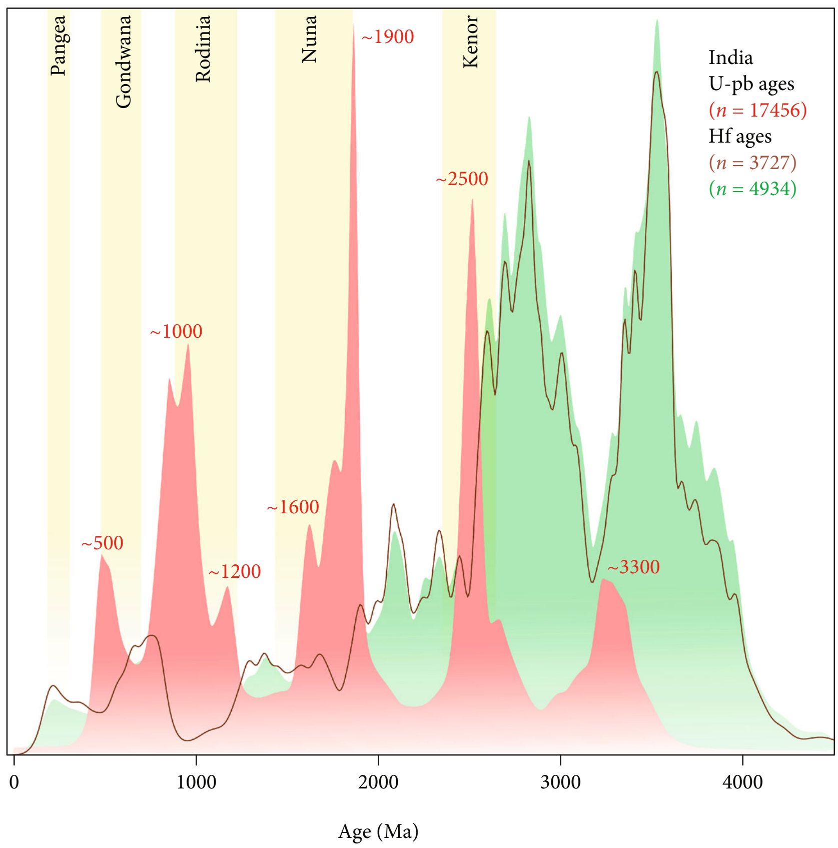

Figure 2: KDE plot for U-Pb ages (red: [12] and present study) and Hf DM (brown: [12]; green: [12] and present study) of detrital zircons from the Indian subcontinent. The yellow bands depict the ages of supercontinent assembly (see Figure 1 for reference).

$^{176}Hf/^{177}Hf$ ratios of the standards within 2σ of the recommended values, and the Yb and Lu isobaric interferences on ^{176}Hf were corrected. For contributions in which no information was provided on the correction of interferences, it was assumed that the appropriate correction was applied to the originally published data.

The kernel bandwidth is considered a key parameter for any distribution estimation wherein a narrow bandwidth will produce numerous insignificant peaks while a broader bandwidth will smoothen the curve [26, 54, 55]. On the basis of kernel density analysis of zircons from orogenic granitoids and detrital zircons, it was suggested that 25 Ma to 30 Ma is an optimal bin width for peak identification [26]. However, another recent study used a 20 Ma bandwidth for deciphering age peaks from ancient and modern sediments [14]. For the present study, we have used 20 Ma bandwidths (after [14]) to show the age distribution of detrital zircons from the global database as well as from the Indian subcontinent (Figures 2 and 3).

Binary scatter plots are generally used to depict U-Pb and Hf zircon data; however, a few studies have recently utilised bivariate KDEs to visualise U-Pb and Hf zircon data [56–58]. We plotted traditional binary scatter plots (Figure 4) and 3D density volume plots (Figure 5) from the Indian subcontinent as well as the global database to understand the data density distribution. Additionally, the unevenly spaced time series for εHf (t) on detrital zircon data from the Indian subcontinent and global Hf and $\delta^{18}O$ database [12, 59] were subjected to fast Fourier transform (FFT) followed by continuous wavelet transform (CWT) for improved understanding of engrossed nonlinearities and complexities in the heterogeneous geological records. The CWT plots were computed using a MATLAB-based algorithm wherein the data was processed in four steps. First, sorting was carried out on the raw data, which was standardised, and finally, the computation was carried out using a 101-point moving average (Figures 6(b), 6(d), and 6(f)). Further, in order to explore the consistency in the phase relationship within the regions in time-frequency space with large common power and to demonstrate significant coherence between CWTs, cross wavelet transform (XWT) and wavelet coherence (WC) were performed on detrital zircon populations from the Indian subcontinent as well as global data (Figure 7). More details on the wavelet transform can be found in Appendix 1.

3.2. Results. The compiled detrital zircon age spectrum from previous studies ($n = 17456$) of the Indian subcontinent yielded six significant peaks, viz., ca. 3200–3400, ca. 2400–2700, ca. 1600–1900, ca. 850–1200, and ca. 450-550 Ma. The compiled U-Pb age data [4] show an additional peak at <100 Ma (Figures 2 and 3). Unlike the U-Pb age peaks, the detrital zircon Hf model ages from India exhibit broad peak ages at ca. 3300-3700, ca. 2500-3100, and ca. 1700-

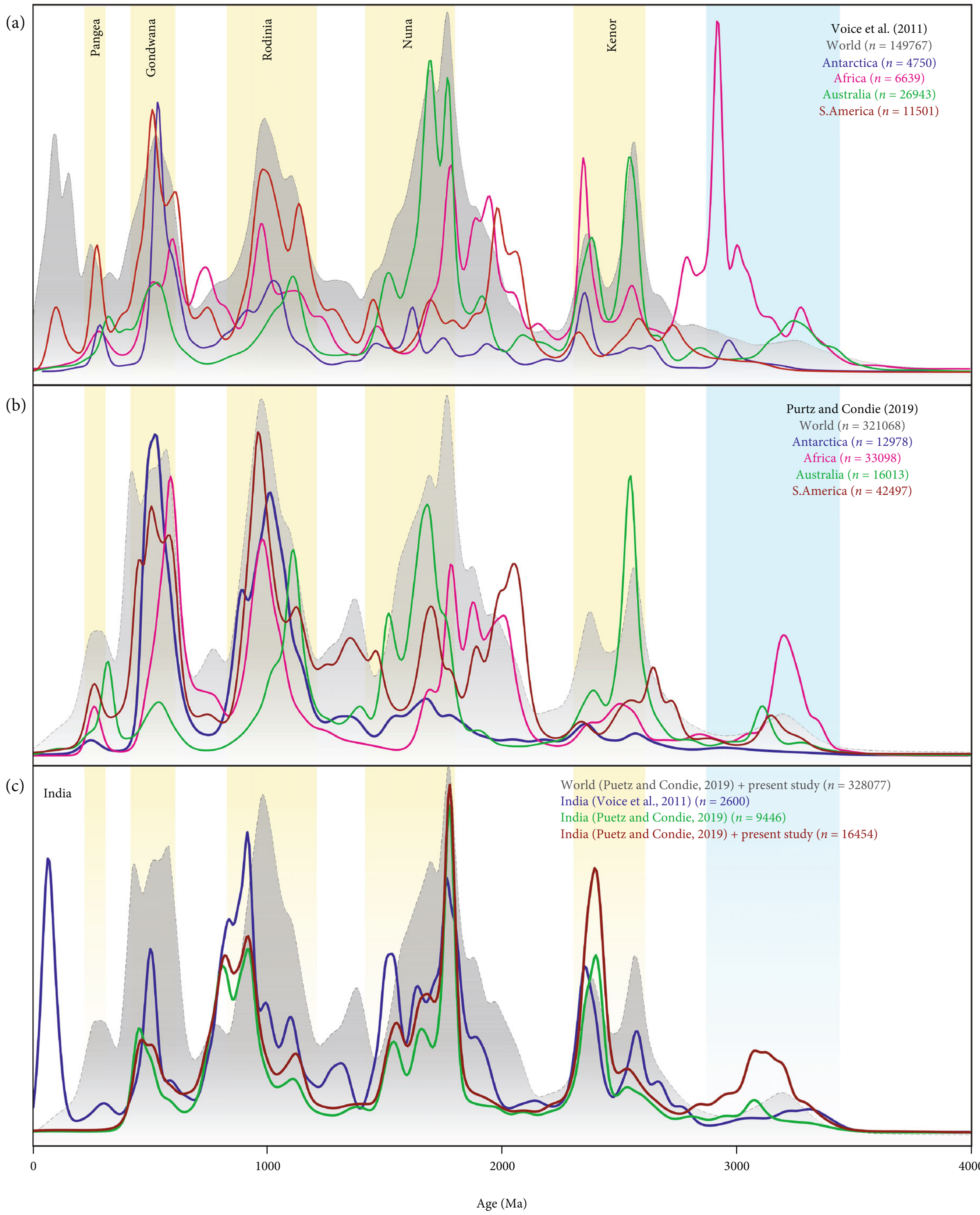

Figure 3: (a) KDE plots of U-Pb detrital zircons ages for World, Antarctica, Africa, Australia, and S. America compiled by Voice et al. [4]. (b) KDE plots of U-Pb detrital zircons ages for World (without India), Antarctica, Africa, Australia, and South America. (c) KDE plots of U-Pb detrital zircons ages from the Indian subcontinent: compiled in the present study and compared with Voice et al. [4] and Puetz and Condie [12]. The yellow bands depict the ages of supercontinent assembly (see Figure 1 for reference), while the blue band represents 3200-3400 Ma peaks possibly associated with uneven geographic sample density due to enhanced erosion and exhumation of Archean sources.

2300 Ma (Figure 2). A plot of compiled Indian and global zircon εHf (t) against crystallization age is shown in Figure 4. The plot shows that most zircons have conspicuously lower εHf (t) than that of the depleted mantle (DM) or arc mantle (AM) at the time of crystallization. Six broad age clusters around ~<200, ~400-600, ~700-1200, ~1600-

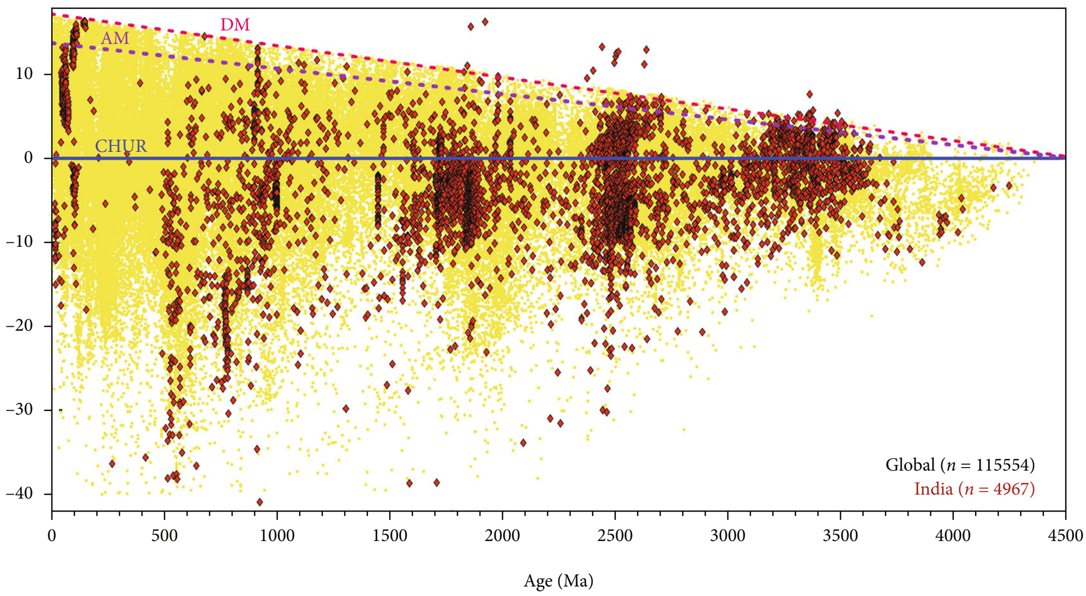

Figure 4: Compilation of the epsilon Hf (t) versus age plot for global (without India; [12]) and the Indian subcontinent (red; present study and [12]). DM: depleted mantle [116]; AM: arc mantle [69]; CHUR: chondrite uniform reservoir [66].

1900, ~2400-2600, and ~3150-3600 Ma are noted within the detrital zircon ages from the Indian subcontinent (Figure 4). The εHf (t) values from detrital zircons are variable even at similar U-Pb ages suggesting heterogeneity of the crust. The characteristic features revealed by the majority of the detrital zircon populations from India (Figure 4) are (a) the ca. >3600 Ma population has negative εHf (t) values and a sudden shift to positive εHf (t) is noted at ca. 3600 Ma; (b) nearly 44% of the detrital zircons with ages between ca. 3200 and 3600 Ma have positive εHf (t) values (~54% of this population has εHf (t) values ≥ 2); (c) ~27% of detrital zircons with ages between 2500 and 3200 Ma have positive εHf (t) values; (d) detrital zircons with ages between 500 and 2500 Ma have ~22% positive εHf (t) values with a significant negative variation in εHf (t); and (e) detrital zircons with ages <500 Ma revealed significant (~72%) positive εHf (t) values. Some samples from each of these age ranges lie above DM and AM.

4. Discussion

4.1. Uranium-Lead Isotopes from Detrital Zircons. The detrital zircon U-Pb age data from the Indian subcontinent shows peaks (at 2400–2700, 1600–1900, 850–1200, and 450–550 Ma) that correlate with the formation of the major known supercontinents: Kenorland, Nuna, Rodinia, and Gondwana (Figure 3). In addition, there are two peaks at 3200–3400 Ma and <100 Ma that lie outside the periods of supercontinent formation. The former peak is in agreement with the ancient sediments [14] and may represent uneven geographic sample density due to enhanced erosion and exhumation of Archean sources. The distinctly younger (<100 Ma) detrital zircon age peak may represent zircon preservation due to Himalayan orogeny.

When compared with the detrital populations from Australia, South America, Antarctica, and Africa (Figure 3), it is noted that all these continents have age peaks of ca. 3000-3400 Ma. Recently, the ca. 3200 Ma peak was also distinguished in the stream sediments from the North Atlantic Craton of Greenland [60]. Another recent study based on the geographic distribution of the detrital population revealed that the age spectra reflect tectono-magmatic production and preservation through time [61]. Further, it was proposed that the age peaks at <250 Ma in the global detrital population are related to North and Central America's detrital population [61].

4.2. Hafnium Isotopes in Detrital Zircons. Hafnium model ages indicating the time when the magma separated from the mantle provide chronological constraints on the generation of juvenile continental crust [40, 62]. The oldest zircon model age for the Indian subcontinent suggests that crust formation started in the Hadean. The generation of crust subsequently peaked at ca. 3300 Ma and was later reworked into a younger crust (Figure 2). Model ages can represent crust generation only in the absence of mixed inputs. Such influence of mixed inputs has been established from many granitoids that contain components of both crusts as well as juvenile mantle sources [2, 48]. Studies advocate that the Hf model ages, which are typically older than the observed U-Pb ages, are considered evidence of the growth and reworking of the continental crust [63, 64]. However, the model ages being derivative parameters should be evaluated carefully especially from older rocks, as the old and variable model ages from zircon can also be caused by unknown lead loss events, which may lead to inaccurate age estimates [62]. Figure 2 shows that limited peaks are found <1700 Ma from the model age plot. On the contrary, prominent peaks are observed in the U-Pb spectra (Figure 2). This suggests that

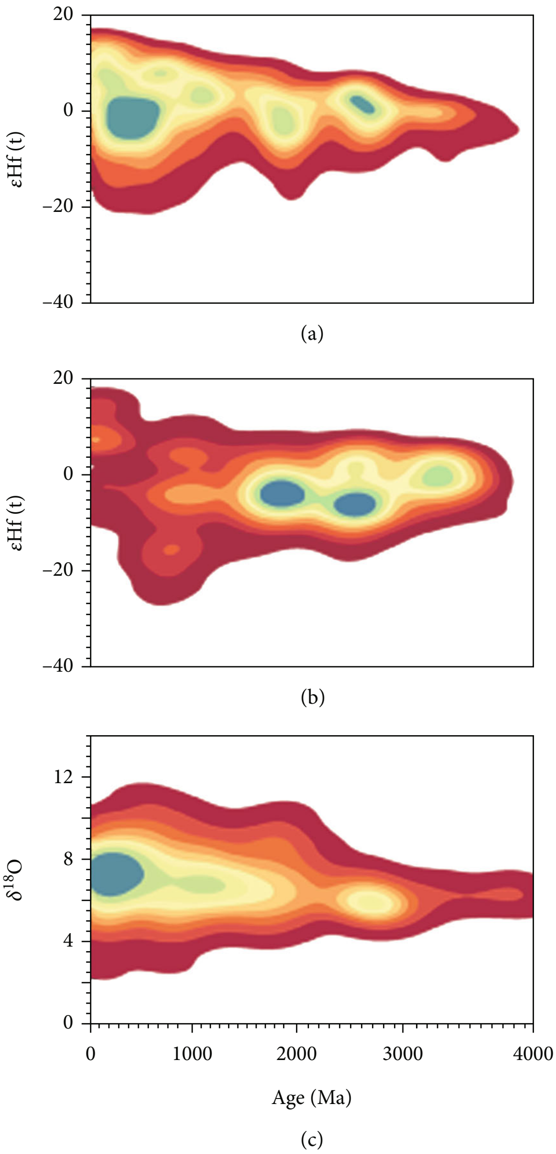

FIGURE 5: 3D bivariate KDE plots for (a and b) U-Pb vs. Hf (t) from the global and the Indian detrital zircons. (c) U-Pb vs. oxygen isotopes of the global detrital zircon population.

the Precambrian crust was the major source for the continental crust at young ages.

The CHUR-normalized Hf isotope ratios denoted as epsilon (ε) Hf [65–67] of zircons are also used to trace the source of the melt from which the zircon crystallized. Many workers suggested that only a limited amount of new crust formed between the U-Pb zircon age peaks as only a few zircons have compositions close to the depleted mantle (DM) [41, 68]. However, the magmas that formed the new crust may have been derived from the subduction wedge, i.e., arc mantle (AM) with slightly lower εHf (t) values as compared to DM [69]. Generally, highly negative εHf (t) values are associated with the parent magmas, which are produced primarily from recycled crustal materials and the contribution of juvenile mantle-derived melts are limited in such cases. On the other hand, the involvement of significant portions of mantle-derived juvenile material and limited crustal reworking leads to positive εHf (t) for the detrital grains [70]. The detrital zircon data from the Indian subcontinent suggest that the most significant contribution of juvenile (εHf (t) > 2) continental crust is associated with the ca. 3200-3600 Ma and <500 Ma clusters (Figures 4 and 5).

When compared with the global εHf (t) values, it is noted that most (~70%) of the global populations with ages older than ca. 3200 Ma fall below CHUR (Figures 4 and 5). This is contrary to what is observed in the Indian subcontinent wherein positive εHf (t) values (~44%) are noted for ca. 3200 to 3600 Ma age clusters (Figures 4 and 5). The shift from nonradiogenic to radiogenic Hf isotopes in the εHf (t) values at ca. 3600 Ma in the Indian subcontinent has been mainly noted in the Singhbhum Craton [71–73]. A few studies related this shift to processes similar to subduction wherein the older continental crust is destroyed and new crust is added or it may be due to the formation of the mafic plateau due to mantle overturn [73–77]. Recently, on the basis of geochemical (Nb/Th and Nb/U ratios) and Hf isotopic signatures from detrital zircons of the Singhbhum craton, it was suggested that the shift at ~3600 Ma to positive εHf (t) values can be due to deeper crustal melting in arc-like environments probably denoting the shift from a stagnant lid to an intermittent plate tectonic regime [72]. Mukhopadhyay and Matin [78] suggested that such shifts in isotopic compositions occurred due to the mixing of depleted mantle-derived juvenile magma with an enriched reservoir. The mafic-ultramafic rocks (~3400 Ma komatiites or high Mg-mafic rocks) of the Iron Ore Group and the chromitites (Sukinda and Nuasahi) are considered the most plausible representatives of the depleted lower mantle below the Singhbhum Craton [79, 80].

A similar shift from nonradiogenic to radiogenic Hf isotopes has also been observed at different times (between ~3600 and 3800 Ma) from the Acasta Gneiss Complex and the Jack Hills, Pilbara, Slave, Zimbabwe, and Wyoming cratons suggesting a shift from a stagnant lid to a mobile lid tectonic environment, i.e., from reworking of the older crust by shallow level melting of a mafic lid (which can provide long residence time as indicated by negative Hf isotopes) to input from the juvenile crust by melting surface-derived juvenile mantle [74, 81–83]. Similar pulses of juvenile inputs from ca. 3000 to 3200 Ma in Canada, Australia, Southern Africa, South America, and Greenland have been noted [60]. These overlap with peaks of MgO, Ni, and Cr in basalts, crust formation ages, Osmium model ages, mantle depletion curves, maximum mantle potential temperature, and Urey ratio (mantle heat production divided by heat loss) [34, 60, 84–88]. Kirkland et al. [60] suggested that the shift towards more juvenile values was probably related to a greater degree of mantle melting and emplacement of mafic-ultramafic magma into the preexisting crust. Unlike the oldest rocks from the Singhbhum and Slave cratons, the oldest rocks in Brazil have negative to near-zero εHf at ~3600 Ma; however, positive epsilon values are noted at ~3300 Ma and ~3500 Ma [89, 90] suggesting that felsic crust production in this terrane started at ~3600 Ma with signatures of crustal rejuvenation

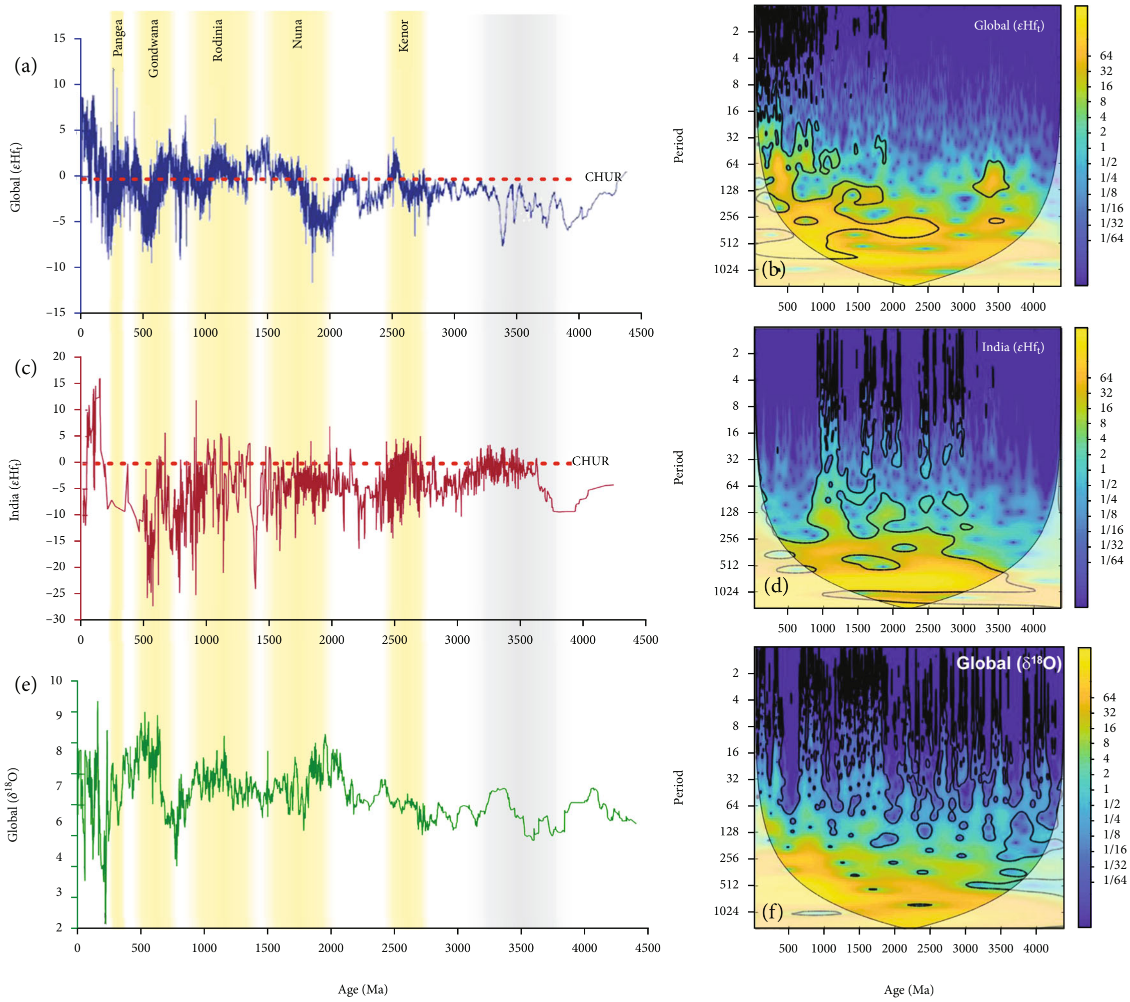

Figure 6: εHf (t) from detrital zircons vs. crystallization age of (a) global dataset [12] and (c) Indian subcontinent (present study and [12]) and (e) global δ^{18}O [59]. The yellow bands depict the ages of supercontinent assembly (see Figure 1 for reference), while the grey band highlights the difference between epsilon Hf (t) values from India and the global population. (b), (d), and (f) represent the continuous wavelet transform for epsilon Hf (t) for global, India, and global δ^{18}O values. The thick black contour designates the 95% significance level against red noise and the cone of influence (COI) where edge effects might distort the picture is shown as a lighter shade.

in the late Paleoarchean, which coincides with higher ambient mantle temperatures [60].

The strongly negative εHf (t) values since ~3200 Ma from the Indian subcontinent (Figures 4 and 5) are in agreement with the global εHf (t) cluster thereby signifying a greater degree of recycling and reworking of the older continental crust. This is also supported by a rapid change in mantle chemistry (recorded on trace elemental ratios which are widely accepted to track the recycling of terrestrial materials and Nd isotopes) at ca. 3200 Ma recorded in basalts and komatiites and is suggested to be due to subduction [85]. Low εHf (t) values were also recognised in detrital zircons from the Mississippi, Congo, Yangtze, and Amazon Rivers [40]. However, few studies propose that the tectonic processes, like plate tectonics, started to become global at around 3000 Ma. The reduction in the rate of global continental growth since ~3000 Ma has been related to plate tectonic processes that increased the rate of crustal recycling into the mantle and reduced the continental growth rate [91]. It has been suggested that the continental crust prior to ca. 3000 Ma was thin and mafic and had lower Rb/Sr ratios as compared to the crust generated post 3000 Ma [92]. The global onset of plate tectonics at ~3000 Ma is also supported by the change in inclusions from peridotitic at ~3200 Ma to eclogitic (at ~3000 Ma) from diamonds [93] and the occurrence of sanukitoids [94, 95]. The reworking of the preexisting crust is also supported by δ^{18}O values from post-Archean zircons, which show an increase in δ^{18}O suggesting crustal thickening and reworking [23, 59]. In addition, studies based on Xenon isotopes in glass vesicles from mid-Oceanic Ridge Basalt (MORB) also suggest considerable recycling of volatiles into the mantle via subduction post 3000 Ma thereby pointing toward the operation of plate tectonic processes [96]. It can be suggested from the previous discussion that the recycling of continental crust into the mantle started sometime between ca. 3200 and 3000 Ma. More recently, Windley et al. [97] suggested that the period between ca. 3200 and 3000 Ma marked a

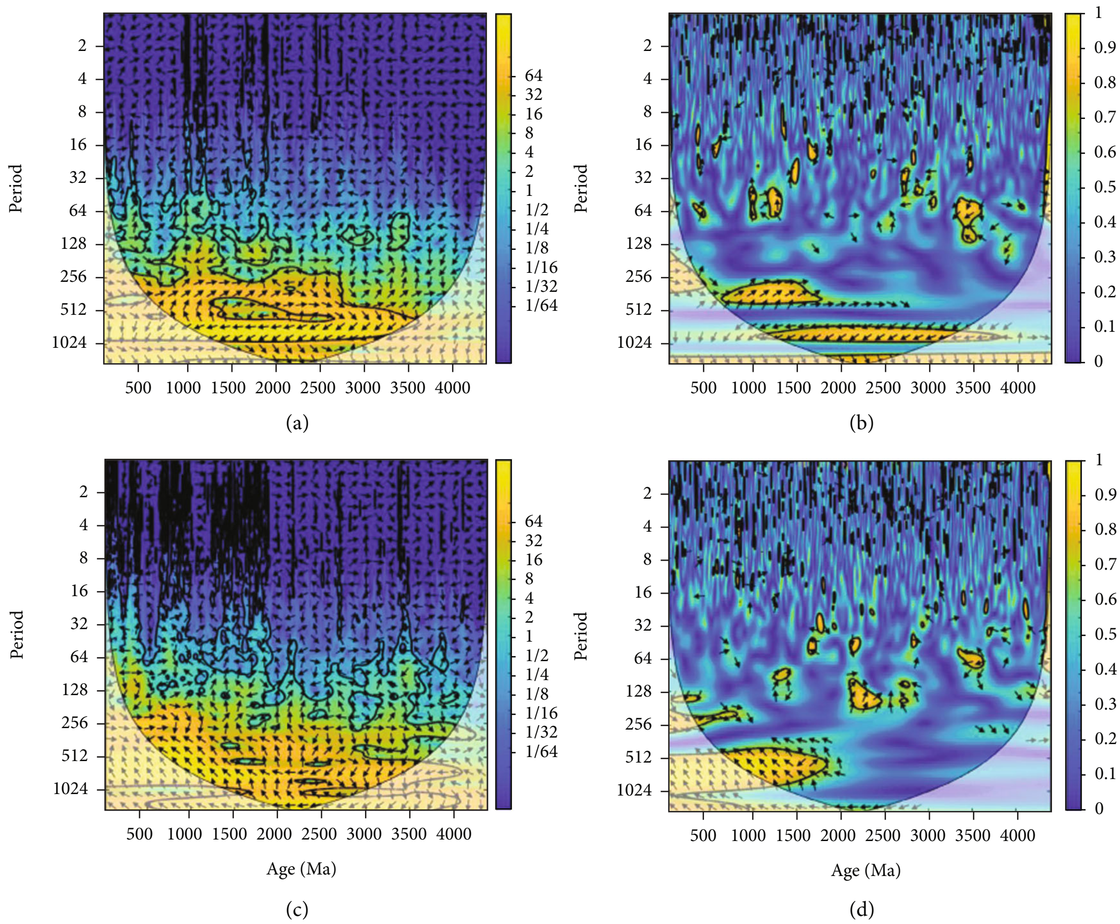

Figure 7: (a and b) Cross wavelet transform (XWT) of the standardised global Hf and India Hf time series and their wavelet coherence (WC). The 95% significance level against red noise is shown as a thick contour. The relative phase relationship is shown as arrows (with in-phase pointing right, antiphase pointing left, and global Hf leading India Hf by 90° pointing straight down). (c and d) Cross wavelet transform (XWT) of the standardised global Hf and global $\delta^{18}O$ time series and their wavelet coherence (WC). The 95% significance level against red noise is shown as a thick contour. The relative phase relationship is shown as arrows (with in-phase pointing right, antiphase pointing left, and global Hf leading India Hf by 90° pointing straight down).

shift from the development of the lithosphere from juvenile ocean crust to a continental-influenced crust in convergent settings.

As discussed in the preceding section, the contribution from juvenile versus reworked crust can be addressed with oxygen isotopes. As a limited number of studies have addressed crustal reworking using oxygen isotopes in the Indian subcontinent, we limit our discussion regarding the contribution of juvenile versus reworked continental crust.

4.3. Continuous Wavelet Transform (CWT) on the Detrital Zircon Dataset. The identification of geological events and their periodicity in a natural system provides clues on either future prediction or delineating the past cyclic events [98]. The CWT analysis for εHf (t) on detrital zircons data from the Indian subcontinent (compiled and discussed in the previous section) and global Hf and $\delta^{18}O$ database [12, 59] is shown in Figure 6. The CWT analysis reveals a prominent cyclicity of ~800 Myr and ~350 Myr in the global and Indian datasets representing the supercontinent cycle and its half cycle (Figures 6(b), 6(d), and 6(f)). The isolated peaks at ~128 and ~64 Myr are the harmonics of the principal cycles. During Paleo-Mesoarchean, the CWT for global εHf (t) indicates high power from ~64 to 800 Myr, while comparatively low power is observed in the Indian εHf (t) and global oxygen isotope record. This incongruence in power is possibly associated with the geological processes operating locally in the Indian subcontinent. At 3000 Ma, the global Hf signal indicates low power periodicity from ~128 to 250 Myr; however, a marginal increase in the power is revealed by the global oxygen isotope data, which is possibly associated with processes similar to plate tectonics. Unlike global Hf, a high-power periodicity from 128 to 256 Myr at 3000 Ma observed from the Indian subcontinent may signify variable timing of tectonic processes.

Generally, harmonic and cyclic patterns in million-year timescales have been deciphered for a number of studies [99–102]. Rohde and Muller [102] noted harmonic and periodic patterns in marine organisms and atmospheric carbon dioxide over the past 500 Ma. Prokoph and Puetz [101] noted period-tripling patterns in geological and paleobiological events on a timescale of ~30 to 1600 Myr, while periodtripled multiples of ~91 Myr cycle were found in the ultramafic and mafic rock record [99].

The Earth's continental crust has archived its evolutionary cycles and associated supercontinent formation [23]. The events of continental growth during 3600, 2700, and 1800 Ma prevailed at an interval of ~900 Ma [103], while based on modelling and the reconstruction of supercontinents, an ~800 Ma supercontinent cycle was deciphered [104]. Similarly, a prominent cyclicity of ~700-800 Ma was revealed based on the formation of the supercontinents, viz., Kenorland (~2600 Ma), Nuna (~1800 Ma), Rodinia (~1100 Ma), and Pangea (~400 Ma) [105]. Recently, the CWT of the global U-Pb zircon ages [12, 26] underscored several continental growth cycles (~1600, 800, 280, 60 Ma, etc.) using a period-tripling [101], while ~760 Myr was linked to supercontinent formation [98]. Prokoph et al. [106] exploited the large igneous provinces (LIPs) database and observed ~170, ~330, and ~650 Myr cycles. They related the 170 Myr cycle to the LIP events, and the supercontinent or core nutation cycle was associated with the ~650 Myr cycle. They further inferred the likelihood of the ~170 Myr cycle as being the main and the ~330 and ~650 Myr cycles as its multiples. The possibility of ~650 Myr cycle as fundamental and 330 and 170 Myr cycles representing harmonics was also proposed in their study.

4.3.1. Cross Wavelet Transform (XWT) and Wavelet Coherence (WC). In order to explore the consistency in the phase relationship within the regions in time-frequency space with large common power generally, a cross wavelet transform (XWT) is performed. The XWT aids in revealing their common power and relative phase in time-frequency space. The statistically significant common features in the XWT of global and Indian εHf (t) time series (Figure 7(a)) stand out at a 5% error. In general, a simple causal and effect relationship between phenomena recorded in the CWT should be in-phase. However, a significant similarity with mostly antiphase behavior in the ~600–900 Myr period band throughout the time series (Figure 7(a)) is observed suggesting variable phenomena operative on global and local (Indian subcontinent) scale with significant similar power. However, a significant common power with in-phase is observed in both time series at ~300-500 Myr during ca. 500-2800 Ma. Since both the global and Indian εHf time series are mostly in antiphase, it can be suggested that possibly the Indian εHf to a large extent mirrors the global Hf (t).

Further, significant coherence in spite of low common power between two CWTs can be demonstrated through the wavelet coherence (WC). The squared WC of global and Indian εHf (t) series is shown in Figure 7(b). When compared with the XWT (Figure 7(a)), a small section stands out as being significantly coherent and in-phase (~300–500 Myr; ca. 500-2700 Ma); however, a section at 800 Myr is coherent and antiphase at 900 to 3200 Ma (Figure 7(b)). Furthermore, we also utilise the XWT and WC (Figures 7(c) and 7(d)), to investigate the correlation between the identified cycles of the two global time series of εHf (t) and δ^{18}O sequences. The results demonstrate a prominent antiphase relationship for ~> 500 Myr cycle between the two series throughout the time scale (Figure 7(c)). An in-phase relation is more widespread from 3000 Ma at ~200 Myr (Figure 7(c)). However, highly coherent and antiphase behavior is observed from ~500 to 1000 Myr from present to ca. 2000 Ma (Figure 7(d)) which possibly is suggestive of synchronization between geodynamic processes associated with magmatism, supercontinent assembly, and/or crustal reworking [98].

Limited δ^{18}O data availability from the Indian subcontinent restricts its comparison with global observations. Therefore, the δ^{18}O values of detrital zircons from the Indian subcontinent should be explored in the future to address global comparisons and crustal evolution.

5. Future Scope of Detrital Zircons in the Indian Subcontinent

In the Indian subcontinent, substantial U-Pb zircon ages exist for detrital zircons from ancient sediments, but inadequate detrital zircon studies have been conducted in modern river sediments. Recently, the combined bulk rock chemistry, Sr-Nd isotopes, and detrital monazites/rutile with the detrital zircons from clastic rocks have been attempted to reevaluate the provenance [107–109]. Nonetheless, there still exists a knowledge gap in crustal evolution studies from modern sediments.

The comparison of detrital zircons from modern sediments with the ancient sediments will provide crucial information on crustal evolution. Wherein the age population derived via detrital zircons from modern and ancient sediments will be representative of the continental crust age distribution and this will aid in using the complementary data for a better understanding of the crustal evolution. Emphases should be given on stable (δ^{18}O) and radiogenic (Hf) isotopes from the detrital zircons for a better understanding of juvenile versus reworked crust generation and long-term evolution of the subcontinent. Limited δ^{18}O data availability from the Indian subcontinent restricts its comparison with global observations. Therefore, the δ^{18}O values of detrital zircons from the Indian subcontinent should be explored in the future to address global comparisons and crustal evolutionary history. Furthermore, an exclusive focus on Archean cratons and associated mobile belts, especially Singhbhum Craton where the oldest detrital grains have been reported, should be given so that the nature of the first formed crust in the Indian landmass and its associated processes can be substantiated.

6. Conclusions

(1) The age spectrum of the detrital zircon population of the Indian subcontinent yielded four significant peaks (2400–2700, 1600–1900, 850–1200, and 450–550 Ma) that correlate with the major supercontinent cycles

(2) Two additional peaks at <100 Ma and 3200–3400 Ma may represent zircon preservation due to Himalayan

orogeny or enhanced erosion and exhumation of Archean sources, respectively

(3) The zircon Hf model ages from the Indian subcontinent suggest that the Precambrian crust was the major source of continental crust with younger ages. The positive zircon εHf (t) values from ca. 3600 to 3200 Ma age groups suggest a greater degree of mantle melting or a shift from stagnant lid to mobile/intermittent lid tectonic environment. The highly negative zircon εHf (t) values after 3200 Ma signify a greater degree of recycling and reworking of the older continental crust probably implying the onset of plate tectonic processes

(4) The CWT wavelet analysis on detrital zircons from the Indian and global databases reveals a prominent cyclicity of ~800 Myr and ~350 Myr plausibly representing the supercontinent cycle and its half cycle. However, an incongruence in power between the global and Indian εHf (t) could be due to the local subcontinental geologic processes during the Paleo-to Mesoarchean

Data Availability

The data used in the present study is compiled from the previously published papers. The corresponding author can make used datasets available upon request.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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Supplementary Materials

Basic details on the wavelet transform. *(Supplementary Materials)*

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