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Himalayan Magmatism through space and time

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(Received : 25/10/2018; Revised accepted : 20/05/2019)

<https://doi.org/10.18814/epiiugs/2020/020022>

Available ages from Himalayan domain indicate that Himalaya has experienced different episodes of magmatism starting from Paleoproterozoic, Neoproterozoic, Cambro-Ordovician, Permian through Cenozoic. The Indian and Eurasian Plates together document the Cretaceous and Cenozoic events after collision. The identified age peaks can be correlated with amalgamation and breakup of supercontinent cycles starting from Columbia/Nuna (Paleoproterozoic), Rodinia (Neoproterozoic), Gondwanian (Cambro-Ordovician), Pangaea (Permian) and Himalayan (Cretaceous to Tertiary). The Himalayan orogenesis incorporates subduction related magmatism followed by collisional magmatism until present time at or near syntaxial bends within the Himalayan domains. It is also very evident that spatially all granitic rocks have southernmost limit at sensu stricto Main Central Thrust (MCT). Paleoproterozoic magmatic rocks are exposed within window zone as well as basal parts of the Higher Himalayan Crystallines (HHC) just above the MCT, however, the Neoproterozoic bodies are restricted very close to the MCT. Cambro-Ordovician bodies are most widespread, whereas, the Permian magmatism is restricted to either to NW or NE Himalaya. But the Himalayan magmatism is present both in Indian as well as Eurasian Plates.

Introduction

The Himalayas is defined as a 2500-km long arc bounded by two structural syntaxes: Nanga Parbat (8125 m) on the west and Namcha Barwa (7782 m) on the east (Fig. 1a), and has resulted from continent-continent collision no later than 57 Ma (Leech et al., 2005, 2007). Prior to collision, Indian Plate and Eurasian Plate converged upto 3600 ± 35 km (van Hinsbergen et al., 2012), which included the oceanic plate as well as continental crust (Greater India). Post-collisional tectonics accommodated crustal shortening ranging from 3000 km to 318 or 419 km (for summary see Singh et al., 2009), and recently this has been estimated to the order of 2675 ± 699 km (van

Hinsbergen et al., 2012) along various tectonic boundaries viz. the South Tibetan Detachment System (STDS), the Main Central Thrust (MCT), the Main Boundary Thrust (MBT), the Himalayan Frontal Fault (HFF) and their splays (Jain et al., 2002; Steck, 2003; Yin, 2006 and references therein).

Attempts have been made to reconstruct the position of Indian Plate with respect to various plate tectonic configurations. Pre-Himalayan configuration of the Himalaya (Greater India) in view of Paleoproterozoic Columbia/Nuna Supercontinent along with Mesozoic to Neoproterozoic Rodinia Supercontinent has not been taken into consideration for the position of Greater India in details (Dalziel, 1991, 1992; Powell et al., 1993; Li et al., 1996; Dalziel et al., 2000; Rogers and Santosh, 2002, 2009; Meert, 2014). There has been formation of a supercontinent which got episodically amalgamated and broken up in Earth's history causing the supercontinental cycles (Nance and Murphy, 2013 and references therein), peaks of U-Pb crystallization ages, magmatic rock formation match with amalgamation and breakup of these supercontinents (Voice et al., 2011).

Since the proposal of one supercontinent Pangaea during Late Paleozoic (Wegner, 1912), various supercratons have been stabilized during the Mesoproterozoic till Paleoproterozoic, which included Vaalbara (between 3,400–2,800 Ma), Superia (between 2,800–2,400 Ma) and Sclavia (between 2,600–2,200 Ma) (Bleeker, 2003). Each of these supercontinent cycles requires collision leading to amalgamation and rifting, which leads to breakup, and has been documented in geological past with episodic peaks of collisional orogenesis and rift-related mafic dyke swarms (Worsley et al., 1984). Based on the episodic peaks of U-Pb ages first true supercontinent accretion happened to be Columbia/Nuna (between 1.9 and 1.5 Ga with a 1.8 Ga orogeny), followed by Rodinia (ca. 1,000–750 Ma), Gondwana/Pannotia (ca. 550–180 Ma) and Pangaea (ca. 250–180 Ma) (Rogers, 1996; Rogers and Santosh, 2002, 2009; Zhao et al., 2002, 2004). The accretion of these supercontinents have also been correlated with increased geothermal gradient caused due to rising mantle plume leading to heat transfer in the continental lithosphere (Kuzmin et al., 2010; Taylor et al., 2010) and enhancement of production of continental crust (Taylor and McLennan, 1995; Condie, 1998, 2014; Wang et al., 2009) by fractional crystallization and extraction of felsic magma from mafic residues (Jaupart et al., 2016) and causing crustal preservation peaks as shown by igneous and detrital zircon populations (Condie, 2014).

The reporting of magmatic ages from the Himalayan region has been attempted by earlier workers mostly in the light of geographical or litho-tectonics of Himalaya. This paper is an attempt to review the magmatic ages with respect to supercontinental cycles within the Himalayan domain.

Magmatic ages

The Himalayan domain within the Indian and the Eurasian Plates exposes various magmatic events ranging from Proterozoic to Late Cenozoic, mainly based on field relationships, nature of xenoliths, degree of metamorphism, petrographic similarities, structural trends, etc. by earlier workers (McMahon, 1884; Greisbach, 1893; Auden, 1935; Wadia, 1928, 1957; and others), prior to the application of isotopic methods of age determination (Fig. 1b; Singh, 2001, 2005 and references therein). Initially, the ages reported were by Rb-Sr and Sm-Nd whole-rock dating techniques (Singh, 2001; Singh and Jain, 2003 and references therein). In the recent past, the use of U-Pb systematics has shown an increase due to its advantages over other techniques (Singh, 2005). There has also been advancement from conventional time-consuming ID-TIMS (isotopic dilution thermal ionization mass spectrometry) data acquisition technique to rapid *in situ* U-Pb analysis (by SIMS or LA-MC-ICP-MS). These rapid analytical techniques have generated large amounts of data set. This has also diverted the focus from age of crystallization to sediment finger printing by detrital zircon studies. In this paper emphasis is only on crystallization ages of magmatic bodies from the Himalaya.

The first data published from Himalaya was by K-Ar technique in Nepal Himalaya (Krummenacher, 1961). However, the first Rb-Sr age was reported by Jager et al. (1971) on Mandi granite of Himachal Pradesh (Singh, 2001 and references therein). The first high resolution U-Pb dating in Himalaya was reported on zircons from Ladakh Batholith by Honegger et al. (1982), followed by dating of zircon

and monazite from the Palung Granite of Nepal Himalaya (Schärer and Allegre, 1983). Furthermore, it was followed by Makalu Granite of Nepal Himalaya and Gangadese Pluton of Trans-Himalayan region in Tibet, respectively (Schärer, 1984; Schärer et al., 1984). These ages were obtained by the conventional Thermal Ionization Mass Spectrometry. However, the first date using Secondary Ion Mass Spectrometry (SIMS) was obtained by Zeitler et al. (1989) on Nanga-Parbat Harmosh Massif in Pakistan by SHRIMP (Sensitive High Resolution Ion Micro Probe) analysis. In Indian Himalaya, the first SHRIMP analysis was published by Singh et al. (2002) on Chor Granite followed by many others (Singh, 2005 and references therein).

Various studies within the Himalayan domain indicate mafic magmatism during Neoproterozoic (~2.5 Ga) within the inner Lesser Himalayan (iLH) Sequence as well as sporadic 2.0 Ga granitoids, widespread Paleoproterozoic (1.8 Ga) (Fig. 1c), Neoproterozoic (0.9 – 0.8 Ga; Fig. 2b) and Cambro-Ordovician (0.46 Ga; Fig. 2c) voluminous granitoid (Fig. 2; Singh, 2001, 2005; Singh and Jain 2003 and references therein). In addition, there was widespread Lower Permian mafic volcanism, which could be related to the opening of Neo-Tethyan Ocean across the Himalaya in Pangaea Supercontinent ~300-250 Ma (Figs. 3a, b; Wegner, 1912; Smith and Livermore, 1991; Murphy and Nance, 2008; Stampfli et al., 2013; Zhao et al., 2018). These volcanics are popularly known as Panjal Trap, Phe Volcanics etc. in NW Himalaya and Abor Volcanics in Eastern Himalaya (Singh et al., 2019). There are occurrences of a few granitoids of the same age, mostly in NW Himalaya (Figs. 3a, b; also Shellnutt, 2018), viz. Maklad granite (Zeitler, 1988), LoeSar

Figure 1. (a) Simplified regional geological map of Himalayas with components of Indian Plate and Eurasian Plate. MBT – Main Boundary Thrust; MCT – Main Central Thrust; STDS – South Tibetan Detachment System (Modified after Singh and Jain, 2003; Singh, 2019). (b) Histogram and relative probability curve of the published data set on Himalayan magmatic bodies (Singh, 2001, 2005; Singh et al., 2009; Dhiman and Singh, 2018, 2020; Shellnutt, 2018 and references therein). (c) Histogram and relative probability curve of the published data set on Paleoproterozoic magmatic bodies lying above MCT and below Vaikrita Thrust.

Granite, Lower Swat (Anczkiewicz et al., 1998) Parkachic and Sanko in Zaskar (Nobel et al., 2001), Biotite granite below Shishma-Pangma Leucogranite (Searle et al., 1997), and Yunam Granite in Upper Lahaul (Spring et al., 1993) within NW Himalaya (also see Singh, 2005 and references therein). This magmatism is correlated with extensional tectonic setting (Spring et al., 1993; Nobel et al., 2001; Chauvet et al., 2008). The Permian magmatic bodies are occurring as dykes or small plutons within the THS or close to it (Fig. 3; also see Singh, 2005 and references therein and Singh et al., 2019). This magmatic phase is followed by the Himalayan subduction-related island arc magmatism due to separation of Indian Plate from Gondwanaland and its movement towards north at different rates (Klootwijk et al., 1985). In Dras and surrounding areas, an island arc during Cretaceous time was followed by widespread calc-alkaline I-type magmatism, which developed the Karakoram Axial and Trans-Himalayan Batholiths; this activity continued into Tertiary Leucogranite across the Greater Indian domain as well as Eurasian

Plate (Figs. 4a, b). The Trans-Himalayan Batholith represents Cretaceous to Early Tertiary Andean-type magmatic arc with calc-alkaline characters (Kumar, 2005). The age constraints on these bodies range from 113 to 46 Ma (Schärer et al., 1984; Singh, 2001, 2005; Singh et al., 2007, and references therein), whereas, the collision-related magmatism is mainly tourmaline-bearing leucogranite (TBL), a S-Type granite.

These various ages can be correlated with amalgamation and breakup of the supercontinental cycles like Columbia (Paleoproterozoic), Rodinia (Neoproterozoic), Gondwanian (Cambro-Ordovician), Pangaea (Permian) and lastly can be put in the bracket of Himalayan orogenesis (Cretaceous and Tertiary). The following section reviews plausible tectonic scenario within Himalayan domain in view of various age peaks (Fig. 1b).

Paleoproterozoic Scenario

Globally three basic models have been proposed for positioning India (not Greater India) in Columbia Supercontinent configuration with very limited paleomagnetic data (Kohn et al., 2010). Rogers and Santosh (2002) and Zhao et al. (2004) tried to position India away from North America with India having passive margin, whereas Hou

et al. (2008) placed India directly adjacent to North America with subduction zone in the north. The Paleoproterozoic magmatism within Greater India domain are either rift-related (Bhat, 1984, 1987; Bhat and Ahmad, 1985) or possess within plate characters (Singh, et al., 2009; Larson et al., 2017; Martin, 2017); these strongly support passive margin of India, as stated by Rogers and Santosh (2002) and Zhao et al. (2004).

Numerous ages, determined from volcanics and granites in various parts of Lesser Himalayan para-autochthon exposed in many windows and metamorphic allochthon in the NW-Himalaya, distinctly cluster around 2.5 Ga and 1.8-2.0 Ga (Fig. 1b), and reveal their extensive involvement in the Cenozoic Himalayan Collision zone. Extensive orthoquartzite-volcanic association in the Lesser Himalayan para-autochthon window zone of Kistwar, Kulu-Rampur and iLH sedimentary belt of Garhwal-Kumaon Himalaya plays an important role in tracing the Proterozoic evolutionary trend within the Himalayan domain (Fuchs, 1975; Sharma, 1977; Valdiya, 1980; Bhat and Le Fort, 1992). The Proterozoic interstratified mafic-volcanic bodies with orthoquartzite-limestone indicate a typical platform setup. Geochemically, these interstratified volcanic are typically characterized by transitional tholeiitic-to-alkalic composition with relatively enriched incompatible trace elements, similar to basalt erupted in a so-called “plume” setting (Bhat, 1984, 1987; Bhat and

Figure 2. (a) Simplified regional geological map of Himalayas with Higher Himalayan Granite Belt, which also host Himalayan Leucogranites and North Himalayan Granite Belt (modified after Singh and Jain, 2003). Tethyan sedimentary sequences are shown as white unfilled zone to show distribution of various magmatic bodies. (b) Histogram and relative probability curve of the published data set on Neoproterozoic magmatic bodies (Singh et al., 2002; DiPietro and Pogue, 2004; Richards et al., 2006; Yin et al., 2010; Web et al., 2011; Mottram et al., 2014; Clarke et al., 2016; Dhiman and Singh, 2018, 2020). (c) Histogram and relative probability curve of the published data set on Cambro-Ordovician magmatic bodies along with other Pan-African magmatism.

Ahmad, 1985). Bhat and Le Fort (1992) have obtained a Sm-Nd whole-rock isochron from these volcanic of the Kulu-Rampur Window representing intense rift-related volcanism of 2509 ± 94 Ma, thus constraining the rift basin around Archean-Proterozoic boundary. Some of these orthoquartzite-volcanic platform sequences are intruded by 1.8 Ga granitoids of which the Kishtwar and Bandal bodies reveal Rb-Sr whole rock isochron of 1861 ± 32 and 1840 ± 70 Ma, respectively (Frank et al., 1977; Miller and Frank, 1992), whereas U-Pb zircon SHRIMP age of Bandal is 1866 ± 4 Ma (Singh et al., 2009).

In addition, geochronological data are now available from many metamorphic allochthonous of the HHC and the Lesser Himalaya and reveal almost coeval ages of this extremely important phase of plutonism (Fig. 1b). Of these, two U-Pb zircon primary crystallization ages of granitoids from the HHC in immediate vicinity of the Kulu-Rampur Window are most significant and indicate 1.8-2.0 Ga (Singh et al., 2006, 2009) anorogenic within plate granitoids (WPG) like the Kaghan valley granitoids in Pakistan (Spencer, 1992) or younger Champawat granitoids in Uttarakhand Himalaya (Singh, et al., 1993). Looking at the data, three major magmatic phases can be demarcated; (i) the 2.5 Ga Rampur Volcanics (Sm-Nd WR age; Bhat and Le Fort, 1992), (ii) the 2.0 Ga grey granitoids from basal part of the HHC (U-Pb isotopic dilution zircon age; Singh, 1993; Singh et al., 2006) and (iii) the 1.8 Ga Wangtu granitoids and Kulu-Bajura nappe rock (Nirath-Baragaon mylonite gneiss or Garh Formation of Sharma, 1977) also from HHC (U-Pb isotopic dilution zircon ages and SHRIMP ages; Singh, 1993; Singh et al., 2009).

The oldest magmatic phase appears to be basic volcanics, interstratified with orthoquartzite-limestone association of Kulu-Rampur and Kishtwar Window zone, and are affected by the 1.8 Ga Bandal-Kishtwar granitoids (Singh, 1993; Miller et al., 2001; Singh et al., 2009). However, in the HHC the 1.8 to 2.0 Ga granitoids represent the earliest magmatic phase intruding the still older fine-grained pelitic and banded biotite gneiss. As no deformation episodes are associated with this anorogenic magmatic event, it appears that the biotite gneiss and thinly banded pelitic sequence of the HHC represent original geoclinal facies of shale and thin sandstone intercalations, probably coeval with the 2.5 Ga orthoquartzite-volcanic platform association of foreland, deposited on an older unknown basement. This setting appears to be similar to the basinal setting of the

Aravalli, Dharwar and other Proterozoic basins of Peninsular India (Ahmad et al., 2008; Manikyamba and Kerrich, 2012; Kale, 2016; references therein). Therefore, one can visualize an Early Proterozoic extensive ensialic basin in the Himalayan region with its shoulder, located southward in the Lesser Himalaya, represented by 2.5 Ga sedimentation of volcanic-orthoquartzite platform association and geoclinal pelites of the Higher Himalaya. Mafic volcanism was more likely to be associated with adiabatic rise of mantle plume in an extremely attenuated lithosphere rather than ocean floor spreading due to horizontal movement of continental plate by convection roll (Bhat, 1987). Geochemical signatures of the 1.8-2.0 Ga granitoids from the Kulu-Rampur and Kishtwar Window and the HHC reveal anorogenic WPG emplacement and possibly represent rise of the Early Proterozoic mantle plume diapirs within extended crust, both in the Lesser and Higher Himalayan domains. Heat source from such plumes has possibly partially melted lower and middle continental crust to generate granitoids, which is also evident from the high $^{87}\text{Sr}/^{86}\text{Sr}$ initial

Figure 3.(a) Simplified regional geological map of Himalayas with Permian magmatism. Tethyan sedimentary sequences are shown as white unfilled zone to show distribution of various magmatic bodies. (b) Histogram and relative probability curve of the published data set on Permian magmatism (table 1 of Shellnutt, 2018 and references therein).

Figure 4. (a) Simplified regional geological map of Himalayas with Trans-Himalayan Batholith and Karakoram Batholithic Complex (modified after Singh and Jain, 2003). Tethyan sedimentary sequences are shown as white unfilled zone. (b) Histogram and relative probability curve of the published data set on Cretaceous and Tertiary magmatic bodies.

ratio between 0.70 and 0.74 from these bodies. This find support from the rise of small granitoids plutons like Bandal, Kishtwar and Wangtu, which incorporated numerous deformed metamorphosed restites and xenoliths, as well.

Neoproterozoic Scenario

Peaks of U-Pb crystallization ages of indicate magmatic events between 1000 Ma and 720 Ma that mark the assembly and breakup of Rodinia supercontinents, and characterized by intracontinental mobile belt formation along with widespread shearing, and post-tectonic magmatism (Unrug, 1997). The name Rodinia Supercontinent was proposed by McMenamin and McMenamin (1990). Recent work revealed that this supercontinent had amalgamated during Meso-Neoproterozoic time, whereas classical geodynamic scenario indicates 800-700 Ma span is related to the Rodinia breakup (Merdith et al., 2017; Oriolo et al., 2017; references therein). After assembly, the Rodinia underwent rifting at ca 800-700 Ma during the Late Mesoproterozoic, and lead to opening of a major rift between Laurentia and Eastern Gondwana cratons. The amalgamation of Gondwanaland

has been recorded after 550 Ma (Merdith et al., 2017; Oriolo et al., 2017), causing a supercontinent cycle which has started at 630 Ma and continued upto 550-530 Ma (Dalziel, 1997; Meert and Torsvik, 2003; Collins and Pisarsersky, 2005; Cawood and Buchan, 2007). Bleeker (2003) and Ernst and Bleeker (2010) compiled timing of supercontinent formation and have shown reasonable synchronicity with U-Pb zircon peaks. However, Bradley (2011) and Condie (2011) correlated the data with assembly of Rodinia, between 1200 and 900 Ma, and assembly of Gondwana around 600 Ma.

During breakup of Rodinia or amalgamation of Gondwanaland magmatic rocks have played an important role in Greater India (Himalayan) domain. There are very limited Neoproterozoic magmatic ages reported from Himalayan Domains (Fig. 2b). Geochemical characteristics of these magmatic activities within plate granite field suggest a continuation of a passive northern margin of India even during Neoproterozoic time (Singh et al., 2002). The Chor, Chaupal, Audi, all in Himachal (Singh et al., 2002; Webb et al., 2011), orthogneiss in Sikkim (Mottram et al., 2014), Tashi Yangtse augen gneiss and Kuru Chu augen gneiss in Bhutan (Thimm et al., 1999; Richards et al., 2006), Zimithang augen gneiss in Kameng and Subansiri augen gneiss in Arunachal (Yin et al., 2010; Clarke et al., 2016) along with other bodies and recently-recognized Dalhousie and Dhauladhar granite (Dhiman and Singh, 2018, 2020) represent Neoproterozoic magmatic events within the Himalayan domain. These granites are representing a major site of juvenile crustal addition by

thermal perturbation during fragmentation/breakup of Rodinia.

Cambro-Ordovician Scenario

The Cambro-Ordovician magmatism is marked by emplacement of series of granite plutons within the HHC south of Main Central Thrust (MCT) as the Lesser Himalayan Granitic Belt or close to South Tibetan Detachment System (STDS) as two-mica granites. These bodies are also exposed within a series of domes as a discontinuous culminations within the Tethyan Sedimentary sequence north of the STDS as independent plutons like the Kaghan, Lhago-Kangri, Kangmar, Nyimaling, Tso-Morari, Rupsu, Jispa, Kade, Kokhsar, Kaghan to name a few (Gansser, 1977; Frank et al., 1977; Wang et al., 1981; Spencer, 1993; Girard and Bushy, 1999). These bodies are mostly occurring as gneissic bodies.

During the Gondwana amalgamation, southern tip of India collided with Congo and northwest margin with Azania and northern Madagascar during early Pan African event. On the other hand, Australia-East Antarctica collided with India during late Pan-African event (Le Fort et al., 1983, 1986); also known as Kuunga orogeny

(Merdith et al., 2017). A low-pressure contact metamorphism along with pre-Himalayan fabric (around Mandi area) has also been associated with these Cambro Ordovician granites (Baud et al., 1982; Guntli, 1993; Purkayastha et al., 1999; Girard and Bussy, 1999; Singh and Jain, 2008). Along with this pronounced thermal event coeval garnet ages are also been reported from the various localities (Chor mountain: 485 ± 19 Ma, 473 ± 14 Ma – Bhargava et al., 2016; Alaknanda valley: 534 ± 24 Ma – Argles et al., 1999; NW Himalaya: 467 ± 3 Ma – Foster, 2000; Central Nepal: 445 ± 16 Ma – Catlos et al., 2000; Namche migmatites: 548 ± 17 Ma – Catlos et al., 2002; Barun Gneiss: 436 ± 8 Ma – Catlos et al., 2002), recording Pan-African – Caledonian – Hercynian orogenic cycles within the Himalayan domain, making this an important event. In the Nepal Himalaya, Gehrels et al (2003) observed that the Cambro-Ordovician granites are cutting across the regional ductile folds and foliation (Stocklin and Bhattarai, 1977) and post-date regional garnet-grade metamorphism (Stocklin, 1980). Based on these observations they proposed a Late Cambrian – Middle Ordovician period of thin-skinned thrusting in the Himalaya. Looking at intrusion of rocks along the earliest Himalayan fabric, contact metamorphism and garnet ages the Pan-African period indicates a major tectonic event within the Himalayan domain, corresponding to the Kurgakh Orogeny by Srikantia (1977) and Kuunga Orogeny by Merdith et al., (2017).

Himalayan Orogenic Scenario

The Himalayan orogenesis involved about 1200 ± 200 km northward movement since the Indian Plate separated from Antarctica. Initially there was subduction of the Neo-Tethyan oceanic plate during Cretaceous followed by Cenozoic collision (Jain et al., 2002 and references therein). As a result of the northward subduction, Dras volcanic arc has formed with ages ranging from 105 to 65 Ma (Sharma et al., 1978; Honegger et al., 1982; Schärer et al., 1984; Reuber, 1989; Reuber et al., 1989). At the same time, the Kohistan arc also developed with calc-alkaline batholith emplacement between 120–85 Ma (for review see Singh, 2001, 2005 and references therein) and development of Trans-Himalayan Batholith representing Andean-Type magmatism due to melting of north dipping Tethyan oceanic crust (Schärer et al., 1984). Both the batholiths have developed below an island arc situated along the southern margin of Eurasia (Raz and Honegger, 1989). The age of Trans-Himalayan bodies predate collision and represent subduction-related magmatism ranging from 102–54 Ma (for details see Singh, 2001, 2005, Singh and Jain, 2003 and references there in)

The subduction-related phase was followed by collision-related magmatism of smaller volumes forming discontinuous small pluton known as the Higher Himalayan Leucogranites (HHL). These intrude closer to the STDS. These syn- to post-Himalayan leucogranites have attained large attention due to its collision-related characters (Le Fort, 1986; Le Fort et al., 1987; Zeitler et al., 1993; Searle, 1996; Harrison et al., 1997; Searle et al., 1999; Schneider et al., 1999, 2001, Singh, 2001, 2005, 2019 and references therein), and are interpreted to have resulted from either (i) crustal anatexis melting due to fluid migration during intracontinental thrusting along the MCT (Le Fort et al., 1987; France-Lanord and Le Fort, 1988), (ii) decompression-controlled dehydration melting due to slip along the STDS, which controls the emplacement of leucogranite plutons (Searle et al., 1992; Guillot and Le Fort, 1995), or (iii) vapor-absent muscovite dehydration melting of metamorphic rocks due to shear heating along continuous active decollement (Harrison et al., 1997, 1999). However, irrespective of

the mechanism of its generation, leucogranite belt was emplaced ~24 Ma after collision (Davidson et al., 1997; Searle et al., 1997, 1999; Guillot et al., 1999; Montomoli et al., 2017). U-Th-Pb ages of these HHL range between ~24 Ma to 12 Ma (Searle and Godin, 2003; Carosi et al., 2013 and references therein) and frequently occupy peaks of higher Himalaya. Crystallization ages from the HHL indicate younger ages as compared to peak metamorphic ages, e.g. 44–26 Ma of Garhwal Himalaya (Prince et al., 2000, 2001; Foster et al., 2000), 41–22 Ma of Himachal Himalaya (Stübner et al., 2014), 37 – 28 Ma in Zaskar Himalaya (Vance and Harris, 1999; Walker et al., 1999), 36 Ma (Hodges et al., 1996) and 36–28 Ma (Laccarino et al., 2015) of Annapurna in Nepal, and 36–34 Ma in Bhutan (Edward and Harrison, 1997). The ϵ_{Nd} values of some of the plutons range between –11 to –18 indicating that there are no mantle components (Vigneresse and Burg, 2003 and references therein) rather they match well with the ϵ_{Nd} values (–13 to –19) of the Vaikrita Group of rocks (Ahmad et al., 2000).

Apart from these, a few coeval *in situ* melts have also been reported from the migmatite zone (e.g., Harris et al., 2004; Rubatto et al., 2013, Singh, 2019). In the NW Himalaya, the migmatite zone is present in the center of HHC with highest grade of metamorphism, and show flowage and *in situ* melt generation of tourmaline bearing leucogranite (Singh, 2019). These tourmalines are the result of high boron content (Hu et al., 2018 and references therein). The zircon growth within the *in situ* melt from migmatites along Bhagirathi Valley reveals episodic influx between 46 Ma and 20 Ma (Singh, 2019) indicating a coeval event related with peak metamorphism and HHL emplacement.

Conclusions

The magmatic ages reported from Himalayan domain are biased towards preservation of part of any supercontinental cycle as they reflect only addition of continental crust, whereas, any supercontinental cycle involve both breakup and amalgamation. The magmatic ages from Himalayan domain represent apparent episodic distribution of ages involving various tectonic processes such as plume, rifting, subduction, slab break-off, collision etc. This can also be correlated with supercontinent cycles and continental growth and has also been reflected in the global-data of peaks of U-Pb ages and their relations with continental growth. The first true supercontinent is that of Columbia/Nuna with the next to be Rodinia supercontinent followed by Gondwana and Pangea. These supercontinent cycles involve complete separation prior to re-amalgamation into single supercontinents.

The Paleoproterozoic ages from Himalayan domain are overlapping well with Columbia/Nuna Supercontinent cycle and are occurring within the Inner Lesser Himalayan Sequence as well as the basal part of the Higher Himalayan Crystallines (HHC), close to *sensu stricto* Main Central Thrust (MCT), as described by Heim and Gansser (1939). However, limited Neoproterozoic data from granitoids are available from NW Himalaya as well as Eastern Himalaya and can be correlated with Rodinia Supercontinent cycle. The Cambro-Ordovician magmatism is not restricted to a zone rather they are distributed within HHC (bearing basal part), Tethyan Sedimentary Sequences (TSS) and northern domal structures (e.g. Tso-Moriri, Kangmar etc.) due to its widespread nature indicating a wider zone. This event of Cambro-Ordovician magmatism can be correlated with Gondwana Supercontinent cycle. Permian ages are also reported

mainly from NW Himalaya as well as Eastern Himalaya and related with formation of Pangaea. The Indian Plate and the Eurasian Plate collision involve subduction-related magmatism followed by collision-related magmatism. The continental collisional event also indicates recycling of pre-existing crust as well as formation of juvenile crust.

Acknowledgements

Author thanks Department of Science and Technology, New Delhi and Ministry of Earth Sciences for funding at various stages of the study which helped in understanding the Himalayas. During the course my *guru* A K Jain, along with David G Gee, Stefan Claesson, Rm Manickavasagam, PG Andreasson, Ake Johnsson, Rasoul Sorkhabhi, Mary Leech, Neal McNaughton helped in understanding the intricacies. There has always been constant encouragement from late K.R. Gupta which is thankfully acknowledged. I also thank all my students of PhD and postgraduate dissertation who made me think beyond the realm of actual work, to name a few are Rajeev Kumar, Th Nikunja Bihari Singha, Rimpi Dhiman.

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