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Early Cretaceous alkaline/ultra-alkaline silicate and carbonatite magmatism in the Indian Shield – a review: implications for a possible remnant of the Greater Kerguelen Large Igneous Province

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ABSTRACT

The early Cretaceous (ca. 118-100 Ma) alkaline/ultra-alkaline silicate and carbonatite magmatism, exclusively recorded in the Chhotanagpur Gneissic Complex and the Shillong Plateau-Mikir Hills in the eastern/northeastern regions of the Indian Shield, have been reviewed to understand their genetic aspects. These are thought to be associated to the Kerguelen hot spot, active in this region during ca. 118-100 Ma. The existing geochemical, geochronological and isotopic data do not support any definite emplacement order for these diverse groups of magmatic suites. It is likely that they were derived from distinct magma batches with direct or indirect involvement of the Kerguelen plume. The available data suggest their possible derivation from the depleted asthenosphere/lithosphere with negligible contribution from the Kerguelen mantle plume. It is likely that mantle plume provided additional heat necessary to melt the asthenosphere/lithosphere. These data also suggest effects of low-pressure crustal contamination, crystal accumulation and fractional crystallization, rather than mantle-derived heterogeneity. These identified magmatic events together with other known magmatic events such as southeastern Tibet, Abor volcanics, SW Australia and eastern Antarctica during ca. 140-100 Ma could be related to the Kerguelen plume and integral part of the Greater Kerguelen Large Igneous Province, and have possible impact on the breakup of East Gondwanaland.

alkaline/ultra-alkaline silicate rocks is directly related to the nature and source of melts and their crystallization history. The origin of carbonated silicate melts through liquid-immiscibility or fractional crystallization suggest genetic connection between carbonate and silicate derivatives, whereas direct genetic connection between these two rocks is uncertain if derived directly from low-degree partial melts of carbonated mantle peridotite at deeper level (cf. Bell et al., 1998; Gittins and Harmer, 2003; Srivastava et al., 2005; Mitchell, 2005; Melluso et al., 2010; Beccaluva et al., 2017). Furthermore, the spatial and temporal connections between carbonatites and Large Igneous Provinces (LIPs), and ultimately to plume tectonics, are also well established (e.g. Simonetti et al., 1998; Bell and Tilton, 2001; Campbell, 2005; Ernst, 2014; Bryan and Ernst, 2008; Ernst and Bell, 2010). The Indian examples of such association include:

- (i) The Réunion plume induced ca. 65 Ma Deccan LIP and associated carbonatite-alkaline rock complexes (e.g. Simonetti et al., 1998; Ray and Pande, 1999) and kimberlites (e.g. Lehmann et al., 2010; Chalapathi Rao et al., 2011),
- (ii) The Kerguelen plume induced ca. 118-100 Ma Rajmahal-Sylhet Traps (e.g. Ray et al., 2005; Ghatak and Basu, 2011) and associated carbonatite-alkaline rock complexes (e.g. Srivastava et al., 2005; Srivastava and Sinha, 2007; Ghatak and Basu, 2013) and potassic-mafic intrusions (e.g. Kent et al., 1998; Mitchell, 2007; Mitchell and Fareeduddin, 2009; Chalapathi Rao et al., 2014; Srivastava et al., 2016). These are thought to be part of the Comie-Bunbury LIP (Zhu et al., 2009) (aka Greater Kerguelen LIP; Olierook et al., 2017), and
- (iii) A late Mesoproterozoic plume related ca. 1.12-1.05 Ga LIP (e.g. Ernst, 2014; Samal et al., 2019), which includes kimberlites (e.g. Chalapathi Rao et al., 2013a) and lamproites (e.g. Chalapathi Rao et al., 2016) intrusions.

In this communication, an attempt has been made to provide a comprehensive appraisal on petrological, geochemical, geochronological and isotopic characteristics of the early Cretaceous alkaline/ultra-alkaline-carbonatite magmatism recorded in the Indian Shield (exclusively in eastern and northeastern regions) to understand their genetic aspects. Their possible relation with the recently

Introduction

Genetic linkage between the spatially associated carbonatite and

identified Greater Kerguelen Large Igneous Province (LIP) and breakup of the East Gondwanaland are also discussed.

Geological Background

The Indian Shield is a composite ensemble of Archean cratonic blocks, tectonically girdled with Meso- to Neoproterozoic mobile belts (Fig. 1). The major cratonic blocks are Dharwar, Bastar, Singhbhum, Bundelkhand, Aravalli and Shillong Plateau-Mikir Hills (cf. Naqvi and Rogers, 1987; Sharma, 2009; Ramakrishnan and Vaidyanadhan, 2010). Amongst these, the Singhbhum craton (consisting of the Singhbhum Granite Complex, and the Chhotanagpur Gneissic Complex, and the Singhbhum Mobile Belt) and the Shillong Plateau-Mikir Hills in eastern and northeastern region of Indian Shield exclusively recorded the early Cretaceous alkaline/ultra-alkaline-carbonatite magmatic activities (Fig. 2a and 2b).

The Chhotanagpur Gneissic Complex (CGC), considered as a cratonized mobile belt (e.g. Sharma, 2009; Srivastava et al., 2014; Chalapathi Rao et al., 2014), has recorded a continuum of polyphase tectono-magmatic activity from Archean to early Cretaceous manifested in the form of (i) Archean magmatic events spurred with spinifex textured volcanic activity (e.g. Bhattacharya et al., 2010), (ii) Mesoproterozoic magmatism emplaced in an extensional tectonic regime (e.g. Srivastava et al., 2012), (iii) within-plate setting early Cretaceous potassic/ultrapotassic and basic intrusions (cf. Kent et al., 2002; Srivastava et al., 2009, 2014; Chalapathi Rao et al., 2014), and (iv) early Cretaceous Rajmahal (-Sylhet) traps (cf. Kent et al., 1997; Ghatak and Basu, 2011).

The Shillong Plateau and the Mikir Hills (SPMH) share almost similar geological features in the form of Archean gneisses, Proterozoic mafic dykes, Shillong Group of rocks, 700–450 Ma granite plutons (intruding the gneissic basement as well as the Shillong Group cover), the early Cretaceous Sylhet Traps, a number of ultramafic-alkaline-carbonatite complexes, and potassic lamprophyre (e.g. Nambiar, 1988; Kumar et al., 1996; Das Gupta and Biswas, 2000; Srivastava and Sinha, 2004a,b; Ghatak and Basu, 2011; Srivastava et al., 2016, 2019 and references therein; see Fig. 2).

Petrological and Geochemical Characteristics

A number of radiometric ages on the early Cretaceous alkaline/ultra-alkaline-carbonatite (Table 1) and mafic (Table 2) magmatic rocks, emplaced within the CGC and/or the SPMH, suggests that the

Figure 1. Generalized geologic and tectonic map of the Indian shield (modified after French et al. 2008). C, Cuddapah basin; Ch, Chattisgarh Basin; CGC, Chhotanagpur Gneissic Complex; CISZ, Central Indian Shear Zone; GR, Godavari Rift; M, Madras Block; Mk, Malanjkhanda; MR, Mahanadi Rift; N, Nilgiri Block; NS, Narmada-Son Fault Zone; PC, Palghat-Cauvery Shear Zone; R, Rengali Province and Kerajang Shear Zone; SMB, Singhbhum Mobile Belt; SGC, Singhbhum Granite Complex; V, Vindhyan Basin. Box represents area of reference of this study.

Kerguelen hot spot was active in this region over a protracted period of ca. 18 Ma, i.e. between ca. 118 Ma and ca. 110 Ma, and experienced several magmatic activities in this parts of the Indian Shield. The three major components of these magmatic intrusions, viz. (i) ultrapotassic, (ii) silicate (ultramafic-alkaline)-carbonatite complexes, and (iii) mafic, are described in subsequent sections.

Ultrapotassic intrusive

The Early Cretaceous (ca. 115–114 Ma) ultrapotassic dykes are pervasively emplaced in the CGC, particularly within the Damodar Valley Gondwana sedimentary basins (Fig. 2; cf. Kent et al., 1998; Coffin et al., 2002; Srivastava et al. 2009; Chalapathi Rao et al., 2014). They show porphyritic texture and composed of pseudomorphosed olivine, phlogopite-biotite, diopside, amphibole, Cr-spinel, K-feldspar, calcite, apatite, rutile, Mg-ilmenite, chlorite, serpentine, and iron oxides/sulphides in varying proportions. K-rich titanate is also recorded in a couple of samples (Chalapathi Rao et al., 2013b). These intrusive rocks are variously referred to as mica-traps, mica-peridotites,

Figure 2. (a) Geological sketch map of the eastern and north-eastern region of the Indian Shield (simplified from Bhowmik et al., 2012). CGC, Chhotanagpur Gneissic Complex; CHB, Chhattisgarh basin; DV, Dalma volcanic; EGMB, Eastern Ghats Mobile Belt; MH, Mikir Hills; RTB, Rajmahal tholeiitic basalt; SGC, Singhbhum Granite Complex; SMB, Singhbhum Mobile Belt; SP, Shillong Plateau; STB, Sylhet tholeiitic basalt; V, Vindhyan Basin. (b) Enlarged geological sketch map of the eastern and north-eastern India showing the locations of early Cretaceous magmatic activity in the Damodar Valley, Rajmahal- Sylhet tholeiitic basalts, Shillong Plateau, and Mikir Hills (modified after Melluso et al., 2012; Srivastava et al., 2016, 2019).

Table 1: Available radiometric ages on the Kerguelen plume induced early Cretaceous alkaline/ultra-alkaline-carbonatite magmatic rocks in the eastern and north-eastern Indian shield.

Area/Region	Dated rock/mineral	Age in Ma	Method	Reference
1. Damodar Valley, CGC	Whole rock Orangeites	113.5±0.5	Ar-Ar laser probe	Kent et al. (1998)
2. Damodar Valley, CGC	Whole rock Lamprophyre	114.9±0.3	Ar-Ar*	Coffin et al. (2002)
3. Sung Valley, SP	Whole rock pyroxenite and phlogopite from carbonatite	107.2±0.8	Ar-Ar*	Ray et al. (1999)
4. Sung Valley, SP	Whole rock carbonatite and pyroxenite, and phlogopite from carbonatite	106±11	Rb-Sr	Ray et al. (2000)
5. Sung Valley, SP	Perovskite from ijolite	115.1±5.1	U-Pb	Srivastava et al. (2005)
6. Sung Valley, SP	Perovskite from ijolite	104.0±1.3	In situ U-Pb SIMS	Srivastava et al. (2019)
7. Sung Valley, SP	Perovskite from dunit	109.1±1.6	In situ U-Pb SIMS	Srivastava et al. (2019)
8. Sung Valley, SP	Perovskite from uncompahgrite	101.7±3.6	In situ U-Pb SIMS	Srivastava et al. (2019)
9. Sung Valley, SP	Zircon from nepheline syenite	106.8±1.5	In situ U-Pb SIMS	Srivastava et al. (2019)
10. Jasra, SP	Zircon and baddeleyite from gabbro	105.2±0.5	U-Pb TIMS	Heaman et al. (2002)
11. Jasra, SP	Zircon from syenite	106.8±0.8	In situ U-Pb SIMS	Srivastava et al. (2019)
12. Jasra, SP	Perovskite from clinopyroxenite	101.6±1.2	In situ U-Pb SIMS	Srivastava et al. (2019)
13. Swangkren, SP	Whole rock lamprophyre	107±4	K-Ar	Sarkar et al. (1996)

* Plateau ages; CGC: Chhotanagpur Gneissic Complex; SP: Shillong plateau

Table 2: Available radiometric ages on the Kerguelen plume induced early Cretaceous mafic magmatic rocks in the eastern and north-eastern Indian shield.

	Area/Region	Dated rock/mineral	Age in Ma	Method	Reference
1.	RB, CGC	Whole rock (basaltic flow)	116.2±0.6	Ar-Ar*	Pringle et al. (1994)
2.	RB, CGC	Whole rock (basaltic flow)	117.5±0.5	Ar-Ar*	Baksi (1995)
3.	Galsi, Bengal basin borehole basalt	Whole rock (basaltic flow)	117.1±0.4	Ar-Ar*	Baksi (1995)
4.	Jalangi, Bengal basin borehole basalt	Whole rock (basaltic flow)	116.9±2.3	Ar-Ar*	Baksi (1995)
5.	Raniganj basin, CGC	Whole rock (dolerite dyke)	112.5±0.5	Ar-Ar*	Kent et al. (2002)
6.	Koderma, CGC	Whole rock (dolerite dyke)	115.3±0.4	Ar-Ar*	Kent et al. (2002)
7.	Dhanbad, RB, CGC	Whole rock (basaltic flow)	117.9±0.4	Ar-Ar*	Kent et al. (2002)
8.	Mirza Cauki, RB, CGC	Whole rock (basaltic flow)	117.4±0.5	Ar-Ar*	Kent et al. (2002)
9.	Mirza Cauki, RB, CGC	Whole rock (basaltic flow)	112.2±0.5	Ar-Ar*	Kent et al. (2002)
10.	Lalmatia, RB, CGC	Whole rock (basaltic flow)	105±0.5	Ar-Ar*	Kent et al. (2002)
11.	Mahadeogan, RB, CGC	Whole rock (basaltic flow)	115.3±0.6	Ar-Ar*	Kent et al. (2002)
12.	Gogra Hill, RB, CGC	Whole rock (basaltic flow)	102.8±1.8	Ar-Ar*	Kent et al. (2002)
13.	Sitalpur, RB, CGC	Whole rock (basaltic flow)	109.6±0.8	Ar-Ar*	Kent et al. (2002)
14.	Kunda Pahar, RB, CGC	Whole rock (basaltic flow)	118.2±0.3	Ar-Ar*	Coffin et al. (2002)
15.	Sylhet trap	Whole rock (basaltic flow)	110±3	K-Ar	Sarkar et al. (1996)

* Plateau ages; CGC: Chotanagpur Gneissic Complex; SP: Shillong plateau; RB: Rajmahal basaltic flow

lamprophyres, glimmerites, orangeites, lamproites and ultramafic lamprophyre (aillikite) (e.g. Middlemost et al., 1988; Rock and Paul, 1989; Rock et al., 1992; Kent et al., 1998; Jia et al., 2003; Mitchell and Fareeduddin, 2009; Srivastava et al., 2009; Chalapathi Rao et al., 2014). However, mineral chemistry of these ultrapotassic intrusive rocks suggests their lamproitic nature; not orangeitic and kimberlitic characteristics (see Fig. 4; Chalapathi Rao et al., 2014). These studies suggest that both plume component and ancient subduction event have affected diverse nature of ultrapotassic rocks. Small degree-partial melting of a metasomatically veined and thinned lithosphere, probably depleted garnet bearing harzburgitic source modified through metasomatism by carbonate- and rutile-rich fluids/melts via Kerguelen plume, have produced diverse nature of ultrapotassic rocks (e.g. Srivastava et al., 2009; Mitchell and Fareeduddin, 2009; Chalapathi Rao et al., 2014).

A lamprophyre dyke, reported from the East Garo Hills, Shillong Plateau (Nambiar, 1988; Srivastava et al., 2016) is composed of large phenocrysts of clinopyroxene and phlogopite with lower amounts of amphibole, olivine and Fe-Ti oxides in a groundmass of clinopyroxene, phlogopite, apatite, and alkali feldspar. Carbonates, analcime, other zeolites and rutile are secondary minerals. This dyke has yielded a slightly younger age (107±4 Ma; Sarkar et al., 1996). Earlier it was believed that this might be contemporaneous to the ultrapotassic dykes of the CGC (Nambiar, 1988). However detailed studies by Srivastava et al. (2016) suggest that it is distinctly different from that of the Damodar Valley lamproites (see Fig. 5) and derived from a heterogenous lithospheric mantle sources rather than input of plume-related magmatism.

Silicate (ultramafic-alkaline)-carbonatite complexes

Four early Cretaceous (ca. 115-101 Ma) silicate-carbonatite magmatic intrusions are emplaced within the Shillong Plateau-Mikir

Hills (Fig. 2; e.g. Srivastava et al., 2019), which include (i) Sung Valley, (ii) Jasra, (iii) Swangkren-Rongjeng, and (iv) Mawpyut. The Sung Valley and Jasra complexes have been studied in detail for their petrological, geochemical, and geochronological accounts and discussed origin of different units of these two complexes. Although many earlier workers favored co-genetic nature of the Sung Valley complex formed through the late-stage liquid immiscibility (e.g. Veena et al., 1998; Ray et al., 2000), however, later studies advocated that different rock units were crystallized from batches of independent magmas with distinct magmatic affinity (Srivastava and Sinha, 2004a; Srivastava et al., 2005, 2019; Melluso et al., 2010). The latter theory is well supported by field-setting (Srivastava and Sinha, 2004a), mineral chemistry (Melluso et al., 2010; Ghatak and Basu, 2013; see Fig. 5), geochemistry (Srivastava and Sinha, 2004a; Srivastava et al., 2005; see Fig. 6 for distinct rare-earth patterns for different rocks) and geochronology (Ray et al., 1999, 2000; Srivastava et al., 2005, 2019; see Table 1 – distinct intrusions have different emplacement ages).

Different petrogenetic models for the genesis of the Sung Valley and Jasra complexes have been comprehensively reviewed by Srivastava et al. (2005) and Srivastava and Sinha, (2007). However, a model based on experimental results, which is well supported by field setting, geochemistry and isotopic data, is thought to be best explanation for the genesis of such alkaline-carbonatite complexes (cf. Wallace and Green, 1988; Lee and Wyllie, 1997; Wyllie and Lee, 1998; Harmer, 1999; Srivastava et al., 2005; Srivastava and Sinha, 2007), has been proposed (Fig. 7). This model explains that carbonate melts may be generated by direct melting of a carbonated peridotite mantle source at depths equivalent to ~20–35 kbar, which could be in equilibrium with phlogopite lherzolite and rich in magnesium and significant amount of alkalis (5–7%) (cf. Wallace and Green, 1988). This model also demonstrate that how metasomatic clinopyroxene, olivine, and free CO₂ fluid could be formed by consuming orthopyroxene (lherzolite) by the melt under equilibrium conditions

Figure 3. Location of distinct magmatic activities of the Kerguelen plateau, Broken Ridge, Naturaliste plateau, Bunbury, Rajmahal-Sylhet, and associated alkaline/ultra-alkaline silicate and carbonatite magmatism of the Shillong Plateau-Mikir Hills, supposed to be connected to the Kerguelen hot spot during early Cretaceous (modified from Kent et al., 2002). The box denotes the area of the present study where early Cretaceous (ca. 118-101 Ma) alkaline/ultra-alkaline silicate and carbonatite activities are recorded in the Indian Shield.

at ~20 kbar that metasomatizes the lherzolite to an alkaline wherlite, which is thought to be possible source to form an ultrabasic alkaline silicate magma of melilitic to nephelinitic compositions (see Fig. 7). In conclusion, it is believed that melts originated from alkaline wehrlite are probably responsible for the crystallization of different rocks of these complexes.

In addition, Ghatak and Basu (2013) have suggested that the different rocks of the Sung Valley are result of low-degree partial melting of carbonated garnet peridotite, located in the Kerguelen plume. The similar genetic mechanism, i.e. different rock units were formed by batches of independent magmas with distinct magmatic affinity, is also suggested for the Jasra complex (Srivastava and Sinha, 2004b, 2007; Melluso et al., 2012). In a recent study, based on *in-situ* U–Pb ages on zircon and perovskite, and Sr–Nd–Hf isotope

data on zircon, perovskite, baddeleyite, apatite, titanite and calcite and *in-situ* Sr–Nd–Hf isotope data on different minerals of the Sung Valley and Jasra complexes, it is suggested that different rock units of these two complexes are not co-genetic and indicate the effects of low-pressure crustal contamination, crystal accumulation and fractional crystallization, rather than mantle-derived heterogeneity (Srivastava et al., 2019).

Not much is known about other alkaline complexes emplaced within the Shillong Plateau. Nambiar and Golani (1985) have reported a carbonatite and alkaline dykes from the Swangkre area of the Shillong Plateau but no detail information is available except on a potassic lamprophyre dyke, mentioned above. The Mawpyut complex is consisting of cumulate (broadly derivatives of clinopyroxenite, gabbro, monzonite, and quartzsyenite) units of ultramafic/mafic rocks and minor younger syenitic veins (Chaudhuri et al., 2014). A melanite garnet-bearing nepheline syenite intrusion is also reported from this complex (Maitra et al., 2011). Based on whole rock geochemistry and isotope systematic, Chaudhuri et al. (2014) have suggested that melts generated through partial melting of an enriched mantle source, which later modified due to assimilation and fractional crystallization, have produced the variety of cumulate-noncumulate lithologies of the Mawpyut complex, however more detailed work is required to confirm this assumption.

The Mikir Hills experienced emplacement of two alkaline-(carbonatite) complexes in Samchampi (-Samteran) and the Barpung regions (Kumar et al., 1996; Saha et al., 2010, 2017). The Samchampi complex is intruded within the Precambrian basement gneisses and consists of syenite, alkali pyroxenite, ijolite, melteigite, shonkinite, malignite and arbonatite (e.g. Kumar et al., 1989; Saha et al., 2010, 2017). Saha et al. (2017) suggested that a plume-related enriched mantle (~EM II) source was responsible for the genesis of different rocks of the Samchampi complex. Their isotopic signatures are similar to the earlier studied early Cretaceous magmatic rocks such as the Sung Valley, Jasra, Rajmahal-Sylhet and Kerguelen plateau basalts. It is further suggested that different melts generated from melting of an isotopically heterogeneous, metasomatized mantle source produced variety of magmatic silicate and carbonate rocks of the Samchampi alkaline complex. Not much is known for the Barpung complex except that it consists of magnetite-rich pyroxenite, alkali syenite, aegirine-augite bearing fenites, and potassic fenites (Kumar et al., 1996).

Mafic (basic) magmatic rocks

A number of early Cretaceous mafic magmatism, in the form of the Rajmahal and Sylhet tholeiitic basalts and mafic dykes are also reported from this region. It is believed that all these rocks and alkaline/ultra-alkaline–carbonatite complexes are part of a protracted LIP event and the Kerguelen plume has played an important role in their genesis (e.g. Baksi, 1995; Kent et al., 1997, 2002; Ghatak and Basu, 2011, 2013; Srivastava et al., 2005, 2014; Chalapathi Rao et al., 2014).

Stable and Radiogenic Isotopic Geochemistry

Stable isotope geochemistry

Although no C–O stable isotope data is known for any alkaline

Figure 4. Compositional variations in phlogopites, plotted between (a) $\text{FeO}^{\text{Total}}$ (wt.%) versus Al_2O_3 (wt.%) and (b) TiO_2 (wt.%) versus Al_2O_3 (wt.%), of the ultra-potassic intrusives from the Damodar valley province, CGC (data taken from Mitchell and Fareeduddin, 2009; Chalapathi Rao et al., 2014). Compositional fields and trends for micas from kimberlite, lamproite, orangeite and minette are taken from Mitchell (1995).

Figure 5. Compositional variations in (a) pyroxene and (b) mica compositions in the Damodar Valley lamproites (Mitchell and Fareeduddin, 2009), Rongjeng potassic lamprophyre (Srivastava et al., 2016), silicate rocks of the alkaline-carbonatite complexes of the Shillong Plateau (Melluso et al., 2010, 2012), plotted on the standard Ca-Mg-Fe (after Morimoto et al., 1988) and Al-Mg-Fe (after Bailey, 1984) ternary diagrams (in wt%), respectively.

Figure 6. Chondrite normalized rare-earth element patterns for the distinct alkaline silicate rocks and carbonatites of the Sung Valley complex, Shillong Plateau (Srivastava et al., 2005). Chondrite values are after Evensen et al. (1978).

silicate rocks of the region, however, Jia et al. (2003) presented ^{15}N -isotope data for Gondwana lamproites and suggested that their genesis from partial melting of enriched harzburgitic mantle lithosphere during the rifting event. It is also suggested that all lamproites (and other ultrapotassic rocks) have a recycled crustal nitrogen component within their mantle sources during some ancient (Archean) subduction events at the northern margin of the Singhbhum craton (e.g. Jia et al., 2003; Srivastava et al., 2009; Chalapathi Rao et al., 2014).

On the other hand, detailed C-O isotope data are available for the carbonatites of the Shillong plateau (Fig. 8) that show mantle values and clearly discard any role of either crustal assimilation or loss of

Figure 7. Melting relationship in carbonated peridotitic mantle (after Wallace and Green, 1988; Lee and Wyllie, 1997; Harmer, 1999). Arrows symbolize carbonatitic near-solidus melts ascending through the mantle. At ~20 kbar, the melts react concerting mantle lherzolite to wehrlite. Black solid dots represent positions of experimental P–T conditions under which carbonate melt exists in equilibrium with peridotite (see Harmer, 1999 for more details). Solid squares represent invariant points marked by the intersection of the relevant solidus curve with the carbonation–decarbonation reaction $\text{Mg Carb} + \text{Opx} = \text{Cpx} + \text{Ol} + \text{CO}_2$.

Figure 8. $\delta^{18}\text{O}\text{‰}$ and $\delta^{13}\text{C}\text{‰}$ plot. Taylor's PIC box after Taylor *et al.* (1967), modified PIC box after Deines (1989) and Keller and Hoefs (1995), and normal mantle values after Kyser (1990) and Keller and Hoefs (1995). Data source: fields 1, 3 and 4 from Ray *et al.* (1999) and field 2 from Srivastava *et al.* (2005).

fluids during emplacement (e.g. Srivastava *et al.*, 2005). Ray *et al.* (1999) and Ray and Ramesh (2006) have examined all the available C–O isotopic data on the carbonatites from the Sung Valley, Samchampi and Swangkri alkaline complexes and suggested that these early Cretaceous carbonatites are derived from ^{13}C enriched mantle sources. The enrichment probably took place sometime in the

Archean, as also noticed for the lamproites and other ultrapotassic rocks from the CGC (cf. Chalapat Rao *et al.*, 2014). Almost similar inference has also been suggested on the basis of ^{15}N -isotopic compositions of carbonates, apatites, and magnetites in the Sung Valley carbonatites. It indicates co-existence of at least two nitrogen components in the mantle, i.e. primary and recycled sediments, which suggest that carbonatite magmatism originated from small-scale heterogeneous subcontinental mantle (Basu and Murthy, 2015).

Radiogenic isotope geochemistry

A fair amount of the bulk-rock Sr and Nd isotopic data for lamproitic intrusions (ultrapotassic rocks), carbonatites and associated silicate rocks of the CGC and the SPMH is available (e.g. Middlemost *et al.*, 1988; Rock *et al.*, 1992; Veena *et al.*, 1998; Kumar *et al.*, 2003; Srivastava *et al.*, 2005, 2019; Srivastava and Sinha, 2007; Ghatak and Basu, 2013; Chaudhuri *et al.*, 2014; Saha *et al.*, 2017). Chalapati Rao *et al.* (2014) have evaluated the available Sr and Nd isotopic data on lamproites and suggested (i) their derivation from source regions with long term incompatible element enrichment relative to that of Bulk Earth, and (ii) $^{87}\text{Sr}/^{86}\text{Sr}_i$ and ϵNd_i values of these ultrapotassic rocks are different from the primitive Kerguelen plume component but similar to those of the pristine Kerguelen mantle plume derived basalts. Recently, Srivastava *et al.* (2019) have presented a detailed discussion based on the bulk-rock Sr and Nd isotopic data together with recently acquired *in-situ* Sr–Nd isotope data on zircon, perovskite, baddeleyite, apatite, titanite and calcite and also Hf isotopic data on Sung Valley and Jasra complexes (Fig. 9). They suggested that the effects of low-pressure crustal contamination, crystal accumulation and fractional crystallization, rather than mantle-derived heterogeneity as processes responsible for genesis of these two complexes.

Genesis

Notwithstanding the suggestion by the earlier workers regarding direct or indirect involvement of the Kerguelen plume in their genesis, the age data is not straightforward to establish any definite emplacement order and probably suggest distinct magma batches were responsible for crystallization of different intrusive/extrusive units. It is also difficult to explain petrogenesis of the wide range of alkaline/ultra-alkaline silicate and carbonatite rocks and tholeiitic mafic rocks of this region emplaced in the large time span (ca. 17–14 Ma) by any simple process. Srivastava *et al.* (2019), based on *in-situ* U–Pb ages and Sr–Nd–Hf isotope data on different minerals from the distinct litho-units of the Sung Valley and Jasra complexes, concluded that plume melting of a heterogeneous mantle to explain the genesis of these rocks is unlikely. This is because the alkaline melts should be generated at lower temperatures than the tholeiitic melts and, obviously, alkaline melts should be generated before or close to the massive tholeiitic event. Furthermore, it is also difficult to explain how a mantle plume could generate a variety of alkaline melts (lamproites, carbonatites + ultra-alkaline and slightly alkaline rocks) at the same time; it also contradicts the petrological/geochemical observations on these rocks. Therefore, it is difficult to establish any causal relationship with the generation of tholeiitic and alkaline magmatism. A wide range of isotopic compositions of alkaline/ultra-alkaline silicate and carbonatite rocks from the Shillong Plateau

Figure 9. Diagram showing initial ϵNd and $^{87}Sr/^{86}Sr$ ratios of whole-rock and minerals for the different early Cretaceous rocks from the eastern and northeastern parts of the Indian Shield (for different fields and data source, refer to Srivastava et al., 2019 and references therein).

suggest effects of low-pressure crustal contamination, crystal accumulation and fractional crystallization, rather than mantle-derived heterogeneity and therefore is different from the Rajmahal-Sylhet tholeiitic basalts (Fig. 9).

Different petrogenetic models are presented to explain the genesis of diverse group of early Cretaceous magmatic rocks. Ghatak and Basu (2013) suggest that primitive garnet lherzolite mantle was metasomatised by deep mantle CO_2 , which also enriched incompatible elements of the garnet peridotite source. Melting of this metasomatised mantle source produced distinct alkalic-mafic-ultramafic-carbonatitic rocks of this region. Srivastava et al. (2019) explains that melts of carbonatite, melilitite and nephelinite compositions can be formed by direct melting of a metasomatized carbonated mantle source, which is also responsible for the crystallization of different silicate rocks after their emplacement in the crust. It is suggested that eruption of the Sylhet-Rajmahal tholeiitic basalts, mafic dykes and lamproites at ca. 118-112 Ma have their possible genetic connection with a mantle plume, however, relatively younger (ca. 109-101 Ma) alkaline carbonatite complexes and lamprophyre of the Shillong Plateau have their derivation from the lowermost parts of the Indian lithosphere and connection with the mantle plume is unlikely.

Possible Connection to the Kerguelen Plume and Large Igneous Province

The precise radiometric ages (Table 1) for ultrapotassic/carbonatite-alkaline complexes of this region suggest a prolonged intrusion time (ca. 115-101 Ma). It is observed that Damodar Valley ultrapotassic dykes (mostly lamproites) of the CGC are emplaced slightly earlier (ca. 115-114 Ma) than the most of the litho-units associated to the alkaline-carbonatite complexes and lamprophyre of the Shillong Plateau (ca. 109-101 Ma). An ijolite intrusion of the

Sung Valley, emplaced at 115 ± 5.1 Ma, is similar to the Damodar Valley lamproites. These ages are also very close to the ages of the early Cretaceous extrusive and intrusive tholeiitic mafic rocks emplaced within the CGC (ca. 118-112 Ma; see Table 2).

Although this part of the Indian Shield is known for the magmatic emplacements related to the Kerguelen plume during the early Cretaceous, slightly older remnants of the contemporaneous igneous activities in the Southeastern Tibet, Eastern Himalayan syntaxis (Abor volcanic) and Southwest Australia during ca. 138-130 are thought to be connected to the Kerguelen mantle plume and the breakup of the eastern Gondwana as well (Zhu et al., 2009; Olierook et al., 2016, 2017; Singh et al., 2019). Zhu et al. (2009) have categorically emphasized that at the time of emplacement of the Comei LIP, it has occupied a huge area

covering $>40,000$ km²; this area will be even larger if considered all the contemporaneous magmatism shown in Figure 10 and, therefore, very rightly qualified for a LIP (cf. Bryan and Ernst, 2008; Ernst, 2014). However, duration of a LIP emplacement is also an important factor. It is recommended that a LIP should be either of short duration (<5 Ma) or consist of multiple short pulses over a maximum lifespan of 50 Ma (Bryan and Ernst, 2008; Ernst, 2014). Therefore, identification of all these short duration magmatic pulses during ca. 140-100 Ma could be a part of the Comei-Bunbury LIP (Zhu et al., 2009), recently identified as the Greater Kerguelen LIP (Olierook et al., 2017), which are directly or indirectly associated to the Kerguelen mega plume (cf. Zhu et al., 2009; Olierook et al., 2016, 2017; Singh et al., 2019).

The Greater Kerguelen LIP include the Comei Province (Zhu et al., 2009), Bunbury Basalt (Olierook et al., 2016), Naturaliste Plateau (Pyle et al., 1995), Wallaby Plateau (Olierook et al., 2015), Rajmahal-Sylhet-Bengal Traps (Kent et al., 2002; Ghatak and Basu, 2011), Abor volcanic (Singh et al., 2019), Beaver Lake-Antarctica (Foley et al., 2002), Elan Bank (Ingle et al., 2002), Broken Ridge (Duncan, 2002), etc. Further, the Sr-Nd-Pb isotopic data on these magmatic events (compiled in Olierook et al., 2017) belonging to the Greater Kerguelen LIP perhaps suggest their derivation from the depleted asthenosphere and lithosphere with negligible contribution from the Kerguelen mantle plume (cf. Olierook et al., 2017); probably mantle plume provided additional heat necessary to melt the asthenosphere and lithosphere. Similar inferences are drawn for the Early Cretaceous alkaline/ultra-alkaline silicate and carbonatite magmatism in this part of the Indian Shield (cf. Srivastava et al., 2019).

Conclusions

- The early Cretaceous (ca. 118-100 Ma) alkaline/ultra-alkaline silicate and carbonatite magmatism together with

contemporaneous tholeiitic mafic magmatic events, exclusively recorded from the Damodar Valley and the Shillong Plateau of the eastern/northeastern regions of the Indian Shield, are thought to be associated directly or indirectly with the Kerguelen hot spot that was active in this region during ca. 118–100 Ma.

- Available petrological, geochemical and isotopic data do not suggest any definite emplacement order. They are likely to have derived from distinct magma batches generated through the depleted asthenosphere and lithosphere with negligible contribution from the Kerguelen mantle plume. The latter, however, have possibly provided additional heat necessary to melt the source regions.
- A wide range of isotopic compositions of alkaline/ultra-alkaline silicate and carbonatite rocks from the Shillong Plateau-Mikir Hills suggest effects of low-pressure crustal contamination, crystal accumulation and fractional crystallization, rather than mantle derived heterogeneity. In this regard they are different from the Rajmahal-Sylhet tholeiitic basalts.
- All these magmatic events together with magmatic events recorded from southeastern Tibet, Eastern Himalayan Syntaxis (Abor volcanic), southwest Australia and eastern Antarctica during the period of ca. 140–100 Ma, have their direct or indirect connection to the Kerguelen mega plume referred to as Greater Kerguelen LIP. This could be connected to the breakup of East Gondwanaland.

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Figure 10. Simplified plate tectonic reconstruction (modified from Zhu et al., 2009) of East Gondwanaland, showing major magmatic events during ca. 140–100 Ma which are supposed to be part of the Greater Kerguelen LIP. Location/events: AV, Abor volcanic; BB, Bunbury basalt; BL, Beaver Lake lamprophyres; CM, Comei magmatic province; DVAP, Damodar Valley alkaline province; NP, Naturaliste Plateau basalt; RB, Rajmahal basalts; SB, Sylhet basalts; SPAP, Shillong Plateau alkaline province. See text for data source.

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