Early Cretaceous ultramafic-alkaline-carbonatite magmatism in the Shillong Plateau-Mikir Hills, northeastern India – a synthesis

Rajesh K. Srivastava1 · Vincenza Guarino2 · Leone Melluso2

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Abstract
A comprehensive mineralogical, geochemical and isotopic review of six ultramafic-alkaline-carbonatite magmatic intrusions of the Shillong Plateau (Sung Valley, Jasra, Swangkre-Rongjeng, and Mawpyut) and Mikir Hills (Samchampi-Samteran and Barpung) is presented here, using the published data. These intrusions emplaced ca. 115–102 Ma ago, thus are significantly younger than the tholeiitic flood basalts erupted in Rajmahal-Sylhet province (ca. 118–115 Ma). The intrusive lithologies vary from ultramafic (dunites, clinopyroxenites, melilitolites) to mafic (ijolites, gabbros sensu lato, shonkinites), to felsic (syenites, nepheline syenites) and carbonatites (mostly calcite-rich varieties). The volcanic-subvolcanic facies (lamprophyres, phonolites) are not abundant. The range of chemical compositions of the magmatic phases in the various assemblages is notable; the intrusive rocks are thus the result of crystallization of magmas from variably evolved, independent liquid-lines-of-descent, generally of alkaline/strongly alkaline lineages and sodic-to-potassic in affinity. The large variations of the Sr–Nd isotopic ratios of the silicate intrusive rocks (sensu lato) suggest a role of shallow-level crustal contamination during their formation. The carbonatites of the Sung Valley and Samchampi-Samteran have different isotope ratios than the associated silicate rocks, have some isotopic affinity with the Group I tholeiitic basalts of Rajmahal Traps and have an ultimate genesis in a carbonate-bearing lithospheric mantle.

Keywords Carbonatites · Alkaline rocks · Early Cretaceous · Shillong Plateau-Mikir Hills · India

Introduction

Large Igneous Provinces (LIPs) related to Gondwana dispersal are commonly associated with alkaline igneous intrusions (Bryan and Ernst 2008; Ernst 2014; Parisio et al. 2016; Natali et al. 2018; Cucciniello et al. 2022). These alkaline rocks are often very useful to constrain the mantle composition in the area, as they are less prone to the effects of crustal contamination during the ascent through the crust than generally evolved, hotter, and poor in incompatible element, tholeitic basalts. Nonetheless, alkaline magmas ponded in crustal reservoirs for significant periods of time and so can be subject to interaction with continental crust (e.g., De Paolo 1981). This effect, visible in the isotopic composition of evolved volcanic rocks, must be also recorded in complementary cumulates and slowly cooled intrusive rocks.

The link between alkaline igneous rocks and carbonatites is well documented and reported worldwide (cf. Woolley 1987, 1989, 2003, 2019; Bell 1989; Bell et al. 1998; Mitchell 2005; Woolley and Kjarsgaard 2008a, b and references therein). However, this link is not straightforward. Carbonatite magmas are thought to be generated after three major processes: 1) fractional crystallization of primary carbonate-rich nephelinitic magma; 2) immiscible liquid products of variably carbonated nephelinitic-to-phonolitic melts and 3) direct melting of a carbonated mantle (e.g., Bell et al. 1998; Harmer 1999; Woolley 2003; Gittins and Harmer 2003; Mitchell 2005; Srivastava et al. 2005, 2019; Melluso et al. 2010; Guarino et al. 2017; Beccaluva et al. 2017). A connection between carbonatites and Large Igneous Provinces (LIPs) and possible direct or indirect links with plumes has also been suggested (e.g., Simonetti et al. 1998; Bell 2002; Ernst and Bell 2010;
Ernst 2014; Srivastava, 2020, 2022; Guarino et al. 2017; Srivastava et al. 2019).

The Indian Shield comprises a number of ultramafic/mafic and alkaline igneous intrusions often associated with carbonatite intrusions (e.g., Srivastava and Hall 1995; Krishnamurthy 2019). Based on the position of silicate ultramafic-alkaline rocks and carbonatites in various tectonic settings, Srivastava and Hall (1995) identified six areas for their emplacement, which were later modified by Krishnamurthy (2019). These domains include (i) the Cambay graben/Aravalli rift zone, (ii) the Narmada-Son rift zone (Central Indian Tectonic Zone, CITZ), (iii) the Shillong Plateau-Mikir Hills (SPMH), (iv) the Eastern Ghat fault systems, (v) deep fault systems in the Granulite Terrain of the southern India, and (vi) the Western Ghat fault systems (Fig. 1b). Six Early Cretaceous intrusions are reported in the SPMH massif of the northeastern India (cf. Kumar et al. 1996; Srivastava et al. 2005, 2019; Srivastava 2020; see Fig. 1 and Table 1). The Sung Valley, Jasra, Swangkre-Rongjeng, and Mawpyut intrude the Shillong Plateau; Samchampi-Samteran and Barpung intrude the Mikir Hills (Fig. 1b).

Petrological, geochemical (including radiogenic and stable isotopes), and geochronological data are known on the ultramafic-alkaline-carbonatite complexes (hereafter UACC) emplaced within the SPMH (see Table 2 for references). However, there is still no conclusive agreement on a few points, particularly (i) the genetic link between carbonatites and associated silicate rocks, (ii) their connection with a mantle plume and (iii) search for economic deposits. Many have suggested their genetic link with the Kerguelen plume activity (e.g., Ray et al. 1999; Srivastava et al. 2005; Srivastava and Sinha 2007; Ghatak and Basu 2013); however, Srivastava et al. (2019) have suggested genesis of some of these complexes through low-pressure crustal contamination, crystal accumulation and fractional crystallization, rather than mantle heterogeneity or mantle plume involvement. The purpose of this review is to provide a comprehensive report

Fig. 1  (a) Sketch map of India with inset of Shillong Plateau location; (b) Regional geological and tectonic setup of the Shillong Plateau and Mikir Hills (modified from Srivastava and Sinha 2004c) with location of the compared intrusions: (a) Sung Valley, (b) Jasra, (c) Swangkre-Rongjeng, (d) Mawpyut, (e) Samchampi-Samteran, and (f) Barpung

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and hypotheses on the genesis of these six UACC intrusions emplaced in the Early Cretaceous of SPMH massif.

Geological framework

Shillong Plateau-Mikir Hills

The SPMH massif (also known as Assam-Meghalaya Plateau or Meghalaya craton; Sharma 2009; Jain et al. 2020) is an uplifted horst-like structure, which is bordered and cross-cut by fault systems (e.g., Desikachar 1974; Nandy 1980, 2001; Gupta and Sen 1988). The two major, approximately E-W trending, fault systems are the Dauki to the south, the Brahmaputra to the north (see Fig. 1). Several other faults/lineaments are also recorded around and within the SPMH; these include N-S trending Jamuna, Nongchram and Um Ngot, and NE-SW trending Badapani-Tyrsad (see Fig. 1; Gupta and Sen 1988; Nandy 2001). The major structural features are thought to be related to the Gondwana fragmentation during Jurassic-Cretaceous and Cenozoic, due to the northward migration of the Indian plate and its subsequent collision with the Asian continent, and “pop-up” of the Shillong Plateau (e.g., Desikachar 1974).

The SPMH geology has been described in detail (e.g., Desikachar 1974; Das Gupta and Biswas 2000; Nandy 2001; Sharma 2009; Jain et al. 2020). The SPMH consists of an Archean Gneissic Complex, rocks of Proterozoic Shillong Group, mafic igneous rocks, late Neoproterozoic-Paleozoic porphyritic granitoids, Sylhet Traps, and ultramafic-alkaline-carbonatite complexes (Fig. 1). The Archean Gneissic Complex mainly consists of granite gneiss, augen gneiss, and upper amphibolite to granulite facies metamorphic rocks with an age between 2637 ± 55 and 2230 ± 13 Ma (Bidyananda and Deomurari 2007). The rocks of Proterozoic Shillong Group (mainly consists of mica schist, phyllite, quartzite and slate) unconformably overlie the Archean Gneissic Complex. The Proterozoic mafic intrusive igneous rocks (hornblende gabbros) and Late Neoproterozoic-Paleozoic porphyritic granites are emplaced within the Gneissic Complex as well as Shillong Group of rocks. Early Cretaceous (K–Ar age 110 ± 3 Ma; Sarkar et al. 1996) basaltic flows (Sylhet traps), are exposed along the southern edge of the Shillong Plateau. The UACCs (emplaced between 115 and 102 Ma; see Table 1) are intruded within the SPMH massif (cf. Kumar et al. 1996; Srivastava et al. 2005, 2019; Srivastava 2020). Cretaceous-Cenozoic sedimentary rocks of the southern margin mark the youngest geological feature of the SPMH.

Ultramafic-alkaline-carbonatite complexes of the SPMH

Sung Valley UACC

The Sung Valley is most studied UACC emplaced within the Shillong Plateau (e.g., Krishnamurthy 1985; Viladkar et al. 1994; Veena et al. 1998; Sen 1999; Srivastava and Sinha 2004a; Srivastava et al. 2005, 2019; Melluso et al. 2010;
| Name                  | Rock types associated                                                                 | Data available                                                                 | Magmatic affinity                  | $^{87}\text{Sr}/^{86}\text{Sr}_i$ | $\varepsilon_{\text{Nd}}$ | Key references                                      |
|----------------------|---------------------------------------------------------------------------------------|--------------------------------------------------------------------------------|------------------------------------|----------------------------------|-----------------------------|---------------------------------------------------|
| **Shillong Plateau:**|                                                                                       |                                                                                  |                                    |                                  |                             |                                                   |
| Sung Valley          | Ultramafic silicate rocks (serpentinitized dunites, wehrlites, and clinopyroxenites), | Whole-rock geochemistry, stable (C, O, N) and radiogenic (Nd, Sr, Hf) isotopes, | Sodic affinity                     | Silicate rocks (s.l.): 0.70479–0.71080; carbonatites: 0.70442–0.70487 | -13.12 and 0.81; 0.25 and 1.81 | Krishnamurthy (1985), Viladkar et al. (1994), Veena et al. (1998), Sen (1999), Ray et al. (1999, 2000), Ray and Pande (2001), Srivastava and Sinha (2004a), Srivastava et al. (2005, 2019), Basu and Murty (2006), Melluso et al. (2010), Ghatak and Basu (2013), Choudhary et al. (2020) |
|                     | uncompahgrites, alkaline rocks (ijolites, nepheline syenites) and carbonatites         | mineral chemistry, and mineral in-situ radiogenic isotopes (Sr, Nd, Hf)         |                                    |                                  |                             |                                                   |
| Jasa                 | Clinopyroxenites, gabbro and syenite/nepheline syenite. Small pockets (visible only by | Whole-rock geochemistry, stable (C, O, N) and radiogenic (Nd, Sr, Hf) isotopes, | Slight potassic affinity           | Silicate rocks (s.l.): 0.70652–0.70908 | -4.8 and -0.7              | Mamallan et al. (1994), Heaman et al. (2002), Srivastava and Sinha (2004b, 2007), Melluso et al. (2012), Srivastava et al. (2019) |
|                     | hand lenses) of ijolitic and carbonatitic rocks were also observed                     | mineral chemistry, and mineral in-situ radiogenic isotopes (Sr, Nd, Hf)         |                                    |                                  |                             |                                                   |
| Swangkre-Rongjeng    | Potassic lamprophyre, carbonatite, alkaline (ijolite, syenite) and mafic dykes         | Whole-rock geochemistry, and mineral chemistry                                 | Slight potassic affinity           | n.a                              |                             | Nambiar and Golani (1985), Nambiar (1988), Sarkar et al. (1996), Srivastava and Sinha (2004c), Srivastava et al. (2016) |
| Mawpyut              | Ultramafic–mafic rocks (mostly gabbroids) and dyke/vein of syenite/nepheline syenite  | Whole-rock geochemistry, mineral chemistry, and radiogenic isotopes (Sr, Nd)    | Sodic affinity                     | Silicate rocks (s.l.): 0.70595–0.71028 | -0.89 and -7.14            | Chaudhuri et al. (2009, 2014), Maitra et al. (2011) |
| **Mikir Hills:**     |                                                                                       |                                                                                  |                                    |                                  |                             |                                                   |
| Samchampi-Santeran   | Ultramafic–mafic rocks (alkali pyroxenite and gabbro), alkaline rocks (syenite/      | Whole-rock geochemistry, mineral chemistry, and radiogenic isotopes (Sr, Nd)    | Slightly potassic to highly potassic affinity | Silicate rocks (s.l.): 0.70138–0.72734; carbonatites: 0.70471–0.70477; one carbonatite: 0.70728 | -17.8 and 1.1; 0.3 and 1.2; one carbonatite: -3.1 | Kumar et al. (1996), Nag et al. (1999), Saha et al. (2010, 2017) |
|                     | nepheline syenite, ijolite-melteigite) and carbonatites                                |                                                                                  |                                    |                                  |                             |                                                   |
| Barpung              | Ultramafic rocks (pyroxenite), alkali syenite, magnetite-rich rocks and fenite        | Trace elements and radiogenic isotopes (Sr, Nd). No major elements and mineral data are available | Sodic affinity                     | Silicate rocks (s.l.): 0.70503–0.71516 | -12.3 and -0.1             | Kumar et al. (1996), Ghatak and Basu (2013)      |

Also see reviews by Srivastava and Hall (1995), Kumar et al. (1996), Krishnamurthy (2019), Srivastava (2020, 2022)

*n.a.* no data available
Ghatak and Basu 2013; Choudhary et al. 2020). It consists of ultramafic silicate rocks (serpenitized dunites, wehrlites, and clinopyroxenites), uncomphagrites, ijolites, nepheline syenites and calcicarbonateites (Fig. 2a; cf. Srivastava and Sinha 2004a; Srivastava et al. 2005, 2019; Melluso et al. 2010). Srivastava and Sinha (2004a) pointed out that the ultramafic silicate rocks form the central part of the intrusion and were emplaced first, later intruded by a ring dyke and plug of ijolite. Ijolite intrusions, formed by crystallization of a perovskite-to-titanite-bearing evolved nephelinitic melt, are followed by intrusions of melilitolite, nepheline syenite and carbonatite, respectively. All these rock types show sharp contacts between each other and do not support any apparent genetic relationships (cf. Srivastava and Sinha 2004a; Srivastava et al. 2005).

**Jasra UACC**

The Jasra intrusion emplaced within the Shillong Plateau and intrudes the Proterozoic Shillong Group and Neoproterozoic granitoids. The main rock units are pyroxenite (clinopyroxenite and olivine clinopyroxenite), shonkinite, gabbro (monzogabbro and olivine gabbro), mafic dykes and syenite/nepheline syenite (Fig. 2b; cf. Mamallan et al. 2004c; Chaudhuri et al. 2014) and of (e) Samchampi-Samteran and (f) Barpung intrusions emplaced in the Mikir Hills (modified after Kumar et al. 1996; Saha et al. 2017).
Small dykes/dykelets/veins of trachyte, alkali pegmatite, ijolite, carbonatite are also reported (Mamallan et al. 1994). Based on a detailed field work, Srivastava and Sinha (2004b) suggested that: 1) pyroxenite and gabbro exposures occur as distinct intrusive events; any direct field relationship between these two is difficult to identify; 2) mafic dykes are contemporaneous to the gabbro; they crosscut pyroxenites and granitic rocks, and 3) dyke/dykelets of nepheline syenite crosscut all the formations suggesting them to be the youngest unit of the complex. These observations clearly indicate derivation of these rock units from different magma batches. Calcite clusters are also noticed in a few thin sections.

**Swangkre-Rongjeng UACC**

The Swangkre-Rongjeng region is known for a number of Early Cretaceous dykes of different compositions, mostly trending N-S (parallel to the Nongchram fault); these include mafic dykes and potassic lamprophyres (Nambiar and Golani 1985; Nambiar 1988; Srivastava and Sinha 2004c; Srivastava et al. 2016), syenite, ijolite, and carbonatite (Nambiar and Golani 1985; Nambiar 1988) (Fig. 2c). Mafic and alkaline dykes are frequent (Srivastava et al. 2016). These dykes are intruded within the Archean Gneissic Complex of the Shillong Plateau. A N-S-trending highly porphyritic potassic lamprophyre dyke exposed at the Rongjeng has been studied in detail (Srivastava et al. 2016).

**Mawpyut alkaline-ultramafic–mafic complex**

The ultramafic–mafic Mawpyut complex is a dome-shaped arcuate body intruded within the Shillong Group (Fig. 2d; Chaudhuri et al. 2009, 2011) and shows intrusive relationships with Archean gneisses (Maitra et al. 2011). It is formed by a variety of mafic–ultramafic rocks; cumulate variants show several gabbroic facies (olivine gabbro-norite, melagabbro-norite, mela-gabbro, orthopyroxene gabbro and gabbro), whereas non-cumulate variants are gabbro and leucogabbro (cf. Chaudhuri et al. 2014). Syenite/nepheline syenite veins and dykelets are also reported to crosscut gabbroid bodies. No carbonatite are reported from this complex. Chaudhuri et al. (2009, 2014) and Maitra et al. (2011) infer that this complex is a differentiated product of ultramafic–mafic rocks, probably Sylhet Trap. Maitra et al. (2011) argued that the Mawpyut complex has different genetic history than the other UACCs of the SPMH.

**Samchampi-Samteran UACC**

The Samchampi-Samteran UACC is a plug-like intrusion intruded within the Archean Gneissic Complex (Kumar et al. 1996; Nag et al. 1999; Saha et al. 2010, 2017). Syenite is the most abundant rock type. As Sung Valley complex, an ijolite-melteigite intruded the syenitic body and formed a ring structure (Fig. 2e). Alkali pyroxenite, alkali gabbro, nepheline syenite and carbonatite are also found. Alkali pyroxenite and alkali gabbro are exposed as lenticular bodies within the ijolite-melteigite; field relationship suggests that they are older than the latter. Nepheline syenite and carbonatite intruded syenite rocks as a dyke/dykelet; therefore, they are likely to be youngest units. Magnetite-bearing ore bodies intruded the syenitic pluton.

**Barpung alkaline-ultramafic complex**

Barpung is a roughly circular body intruded within the Shillong Group; the E-W trending Kalyani lineament is likely to control its emplacement (Kumar et al. 1996). Little is known about this complex except that it is mainly formed by pyroxenite, magnetite-rich rocks, alkali syenite and fenites (Fig. 2f). No carbonatite occurrence is known to date.

**Geochronology**

All geochronological data available in the published literature are summarized in the Table 1. The age of the Sung Valley intrusion varies from 115.1 ± 5.1 Ma (perovskite of an ijolite) to 101.7 ± 3.6 Ma (perovskite of an uncompahgrite). The ages of Jasra vary from 106.8 ± 0.8 Ma (zircon from a syenite) to 101.6 ± 1.2 Ma (perovskite in a clinopyroxenite). The age of a lamprophyre of Swangkre-Rongjeng is 107 ± 3 Ma. The age of apatite separated from a carbonatite of Samchampi-Samteoran is ~105 Ma. No geochronological data are available in the literature for Mawpyut and Barpung. Mawpyut is thought to be part of the Early Cretaceous magmatism (Chaudhuri et al. 2009, 2014; Maitra et al. 2011). Magmatism emplaced in the SPMH (ca. 115–102 Ma) is significantly younger than the tholeiitic flood basalts of Rajmahal-Sylhet volcanic province, erupted ca. 118–115 Ma ago (e.g., Baksyi 1995; Kent et al. 2002).

**Mineral chemistry**

**Generalities**

Table 3 reports the list of mineral phases of each rock type identified in all UACC intrusions. No chemical mineral analyses are available for Barpung, where the main identified minerals are clinopyroxene, olivine, rutile, magnetite and apatite in pyroxenites, ilmenite, titanomagnetite, titanite, clinopyroxene and perovskite in magnetite-rich rock and alkali feldspar, clinopyroxene, and haematite in alkali
Table 3 Summary of paragenesis of rocks identified in the Early Cretaceous ultramafic-alkaline-carbonatite intrusions in the SPMH

| Name                        | Rock types associated                                      | Main mineral phases          | Accessory mineral phases                          | Mineral notes                                     |
|-----------------------------|------------------------------------------------------------|-------------------------------|---------------------------------------------------|--------------------------------------------------|
| **Shillong Plateau:**       |                                                            |                               |                                                   |                                                  |
| Sung Valley                 | Ultramafic silicate rocks (serpentinitized dunites, wehrlites, and clinopyroxenites) | Clinopyroxene, olivine, plagioclase | Phlogopite, perovskite, garnet, apatite, magnetite, amphibole, titanite, alkali feldspar |                                                  |
| Uncomplexgrites             | Clinopyroxene, melilite                                    |                               | Perovskite, magnetite, phlogopite, sulfides        |                                                  |
| Ijolites                    | Nepheline, clinopyroxene                                   |                               | Apatite, titanite, perovskite, garnet, phlogopite, magnetite, nosean | Perovskite with a reaction rim of titanite and garnet, likely itself a reaction rim on titanite |
| Nepheline syenites          | Alkali feldspar, nepheline, clinopyroxene                  |                               | Titanite, phlogopite, Fe-Ti oxides, cancrinite    |                                                  |
| Carbonatites                | Calcite                                                    |                               | Olivine, dolomite, phlogopite, clinohumite, apatite, Fe-Ti oxides | Perovskite overgrown by titanite                  |
| **Jasra**                   |                                                            |                               |                                                   |                                                  |
| Pyroxenites (clinopyroxenite, olivine clinopyroxenite and aegirine clinopyroxenite) /Shonkinites | Clinopyroxene                 |                               | Phlogopite, n似eline, olivine, oxides, titanite, alkali feldspar, perovskite, apatite, carbonat |                                                  |
| Gabbro (monzogabbro and olivine gabbro) | Clinopyroxene, olivine, plagioclase                          |                               | Orthopyroxene, alkali feldspar, nepheline, oxides, apatite, phlogopite, zirconolite, baddeleyite | Olivine commonly has a rim of orthopyroxene       |
| Syenite/nepheline syenite   | Alkali feldspar, nepheline, clinopyroxene                  |                               | Phlogopite, amphibole, titanite, garnet, oxides, olivine, zirconolite, baddeleyite | Clinopyroxene rimmed by brown amphibole            |
| Ijolites                    | Nepheline, clinopyroxene                                   |                               | Phlogopite, garnet                                |                                                  |
| Carbonatites                | Carbonates                                                 |                               | Phlogopite, garnet                                |                                                  |
| **Swangkre-Rongjeng**       |                                                            |                               |                                                   |                                                  |
| Potassic lamprophyres       | Clinopyroxene, phlogopite                                  |                               | Olivine, amphibole, apatite, oxides, alkali feldspar, carbonate |                                                  |
| Mafic dykes                 | Plagioclase, clinopyroxene                                 |                               | Ilmenite, magnetite, apatite, zircon, palagonite, calcite, quartz |                                                  |
| Syenites                    | Alkali feldspar, clinopyroxene                             |                               | Titanite, magnetite                               |                                                  |
| Ijolites                    | Nepheline, clinopyroxene                                   |                               | Apatite, titanite                                 |                                                  |
| Carbonatites                | Calcite                                                     |                               | Apatite, fluorite                                 |                                                  |
| **Mawpyut**                 |                                                            |                               |                                                   |                                                  |
| Ultramafic–mafic rocks (mostly gabbroids) | Olivine, clinopyroxene                                     |                               | Plagioclase, olivine, oxides, orthopyroxene, phlogopite |                                                  |
| Syenite/Nepheline syenite   | Nepheline, alkali feldspar, clinopyroxene                  |                               | Garnet, titanite                                  |                                                  |

**Mikir Hills:**
Olivine

Olivine is found in the Sung Valley and Jasra mafic/ultramafic rocks, Sung Valley carbonatites, Jasra syenites and Swangkre-Rongjeng lamprophyres (Fig. 3a). Olivine is reported in some Mawpyut samples, but no chemical analyses are available (Chaudhuri et al. 2014).

The Sung Valley olivine grains in dunites and wehrlites are often altered, with a narrow range in forsterite (Fo$_{86-87}$; Fo = 100 × [Mg/(Mg + Fe)] mol%) with relatively high CaO (0.71–0.79 wt%). Olivine in the Sung Valley carbonatites have higher forsterite (Fo$_{94-96}$), but with much lower CaO (0–0.45 wt%), as typical of olivine crystallized from mafic carbonatites, and significantly more magnesian than olivine of mantle derivation. The Jasra olivine crystals are cumulus phases and often have inclusions of chromiferous spinel. They have variable forsterite (from Fo$_{99}$ of mafic/ultramafic rocks to Fo$_{47}$ in syenites). The rare Swangkre-Rongjeng olivine grains in the potassic lamprophyre are rich in forsterite (Fo$_{81-85}$) and CaO (0.20–0.57 wt%).

Pyroxene

Clinopyroxene is the main mafic mineral in all studied intrusions; orthopyroxene was detected in a gabbro of Jasra and dubitatively described at Mawpyut (Fig. 3a). Clinopyroxene of Sung Valley occurs as cumulus crystals or in interstitial position; they cover a complete range from diopside to aegirine [Wo$_{35-63}$En$_{29-30}$Fs$_{36-7}$; Na$_2$O = 0–13 wt%; TiO$_2$ = 0–2 wt%; Mg# = 4–89; Melluso et al. 2010]. The Jasra clinopyroxene, found as reaction rim of olivine in a gabbro, is enstatite (Wo$_2$En$_{61-65}$Fs$_{36-33}$). Clinopyroxene of the Swangkre-Rongjeng lamprophyre is diopside-augite (Wo$_{38-53}$En$_{50-35}$Fs$_{12-44}$; Na$_2$O = 0–5 wt%; TiO$_2$ = 0–5 wt%; Mg# = 18–85). The Mawpyut clinopyroxenes vary in composition from diopside to augite (Wo$_{42-53}$En$_{40-39}$Fs$_{17-31}$; Na$_2$O = 0–4 wt%; TiO$_2$ = 0–4 wt%; Mg# = 10–71). The Jasra clinopyroxene is observed as discrete crystals, often zoned, or as intercumulus phases. They vary in composition from diopside to augite (Wo$_{42-53}$En$_{40-39}$Fs$_{17-31}$; Na$_2$O = 0–4 wt%; TiO$_2$ = 0–4 wt%; Mg# = 10–71). The Jasra orthopyroxene, found as reaction rim of olivine in a gabbro, is enstatite (Wo$_2$En$_{61-65}$Fs$_{36-33}$). Clinopyroxene of the Swangkre-Rongjeng lamprophyre is diopside-augite (Wo$_{38-53}$En$_{50-35}$Fs$_{12-44}$; Na$_2$O = 0–5 wt%; TiO$_2$ = 0–5 wt%; Mg# = 18–85). The Mawpyut clinopyroxenes vary in composition from diopside to augite (Wo$_{38-53}$En$_{40-39}$Fs$_{17-31}$; Na$_2$O = 0–4 wt%; TiO$_2$ = 0–4 wt%; Mg# = 10–71). The clinopyroxene phenocrysts in the Samchampi-Samteran rocks are mainly diopside with subordinate augite (Wo$_{38-48}$En$_{41-39}$Fs$_{15-25}$; Na$_2$O < 5 wt%; TiO$_2$ < 0.68 wt%; Mg# = 30–84). The trace element geochemistry of the cumulus clinopyroxine in a Sung Valley ijolite is characterized by low concentration of rare earth elements (REE) (La$_N$/Yb$_N$ = 1.1–2.1) and other incompatible...
elements, and by relatively high Zr (335–651 ppm) and Hf (9.7–19.4 ppm) (Fig. 3b; Melluso et al. 2010). These concentrations are broadly similar to other clinopyroxenes found in highly alkaline rocks elsewhere (e.g., Guarino et al. 2021 and references therein).

Feldspars

Alkali feldspar is the main feldspar, with subordinate plagioclase at Sung Valley, Jasra, Swangkre-Rongjeng, Mawpyut and Samchampi-Samteran (Fig. 3c). Alkali feldspar in the Sung Valley intrusion is the main cumulus crystal of nepheline syenites; it also occurs as an interstitial phase in clinopyroxenites and has potassic composition (An$_{0.1}$Ab$_{18.4}$Or$_{82.4-93}$ in nepheline syenites and An$_{0.0}$Ab$_{29.4}$Or$_{71.96}$ in clinopyroxenites). Secondary albite is also identified (An$_{0}$Ab$_{99}$Or$_{1}$). The concentration of Ba and Sr is generally low (BaO < 0.67 wt%, SrO < 0.75 wt%). In the Jasra intrusion, alkali feldspar is interstitial in the clinopyroxenites and a cumulus phase in the syenites and nepheline syenites and varies from anorthoclase to alkali feldspar (An$_{16.1}$Ab$_{68.3}$Or$_{16.96}$). Ba and Sr are higher than alkali feldspar of Sung Valley (BaO < 1.3 wt% and SrO < 1.1 wt%). Plagioclase of the Jasra gabbroic rocks varies in composition from oligoclase to andesine (An$_{48.27}$Ab$_{50.66}$Or$_{2.13}$, BaO < 0.46 wt%; SrO < 1.42 wt%). Rare alkali feldspar is found in Swangkre-Rongjeng lamprophyre with a homogeneous composition (An$_{1.0}$Ab$_{12.11}$Or$_{87.89}$, BaO < 0.42 wt%; SrO < 0.91 wt%). Alkali feldspar occurs as groundmass phase in the Mawpyut rocks, with composition An$_{0}$Ab$_{17}$Or$_{83}$. Alkali feldspar in the Samchampi-Samteran is quite variable (An$_{2.0}$Ab$_{28.2}$Or$_{70.98}$). Plagioclase, with oligoclase composition (An$_{18.10}$Ab$_{81.80}$Or$_{1}$), occurs in syenite as exsolution blebs within perthite.
Feldspathoids and melilite

Nepheline is the main feldspathoid in these UACC intrusions. It occurs as micro- and macro-crystals. The Na$_2$O and K$_2$O concentrations of Sung Valley (Na$_2$O = 14.8–17.7 wt% and K$_2$O = 4.8–6.4 wt%) and Jasra (Na$_2$O = 14.2–17.1 wt% and K$_2$O = 3.3–7.2 wt%) nephelines are more variable compared to those of Mawpyut (Na$_2$O = 15.5–16.3 wt% and K$_2$O = 6.3–6.7 wt%) and Samchampi-Samteran (Na$_2$O = 15.4–16.0 wt% and K$_2$O = 6.7–7.6 wt%). Nocean is found in the Sung Valley ijolites and secondary cancrinite is found in the nepheline syenites of Sung Valley (Melluso et al. 2010).

Melilite is identified in the uncompahgrite of the Sung Valley intrusion. It is a solid solution of åkermanite (Ca$_2$MgSi$_2$O$_7$, 48–64 mol%), “Fe-åkermanite” (Ca$_2$FeSi$_2$O$_7$, 7–12 mol%) and “soda melilite” (CaNaAlSi$_2$O$_7$, 25–39 mol%). Their compositions fall within the compositional range of magmatic melilites worldwide, indicating that a batch of Ca-rich, highly silica undersaturated melt composition intruded in the Sung Valley complex. This is probably the most important magmatic occurrence of this phase in India (cf. Melluso et al. 2021).

Mica and amphibole

Mica is ubiquitous accessory mineral in the UACC intrusions, as cumulus or poikilitic crystals. All the analyzed micas are mainly phlogopite and plot along the phlogopite-annite join in Mg–Al-Fe diagram (Fig. 3d). They have variable Mg# (Mg# = 31–96 at Sung Valley; Mg# = 43–91 at Jasra; Mg# = 33–83 at Swangkre-Rongjeng; and Mg# = 62–73 at Samchampi-Samteran). Peculiar feature is the different TiO$_2$ concentration, generally low at Sung Valley (TiO$_2$ = 0.17–4.37 wt%) and Samchampi-Samteran (TiO$_2$ = 1.35–2.93 wt%), and slightly higher at Swangkre-Rongjeng (TiO$_2$ = 3.3–5.4 wt%) and Jasra (TiO$_2$ = 0.54–8.50 wt%). The presence of Fe$^{3+}$ in the tetrahedral site (i.e., Si$^{4+}$ + IVAl$^{3+}$ < 8) is observed in a few phlogopites (0.053–0.176 apfu at Sung Valley; 0.033–0.452 apfu at Swangkre-Rongjeng; 0.123 apfu at Samchampi-Samteran). This substitution is an indication of changes in the oxygen fugacity of the environment in which they crystallized.

Amphibole is present in interstitial position at Sung Valley, as rare rims surrounding clinopyroxene and as large idiomorphic crystals at Jasra, and quite rare as phenocrysts at Swangkre-Rongjeng and Samchampi-Samteran intrusions (Fig. 3e). The composition is pargasite at Sung Valley (Mg# = 79–82) and Swangkre-Rongjeng (Mg# = 64–71) and kaersutite at Jasra (Mg# = 44–71).

Titanite and perovskite

Titanite (CaTiSiO$_3$) and perovskite (CaTiO$_3$) are two main typical Ca-Ti–rich minerals in some UACCs. Titanite is ubiquitous in the UACC intrusions. Titanites have TiO$_2$ = 33.9–38.9 wt% and CaO = 26.7–29.1 wt% at Sung Valley, TiO$_2$ = 28.9–38.9 wt% and CaO = 26.3–28.5 wt% at Jasra, and TiO$_2$ = 33.5–37.3 wt% and CaO = 26.2–27.8 wt% at Samchampi-Samteran, throughout the various rock-types in the different intrusions. Titanite occurs in some Mawpyut samples, but no data are available (Chaudhuri et al. 2014; Maitra et al. 2011). In Sung Valley ijolite and Jasra clinopyroxenite, titanite is observed as a reaction rim of perovskite (Fig. 4a, b). The trace element concentrations of titanites in Sung Valley ijolite have high Nb (6758–7908 ppm) and Ta (158–236 ppm) and are moderately enriched in Sr (324–401 ppm), Zr (3088–3349 ppm), Hf (64–69 ppm) and LREE ($\Sigma$LREE = 4318–5046 ppm), and low in Pb (~ 3 ppm). The La$_N$ of titanites is up to 3700 times chondrite and the chondrite-normalized REE patterns have strong REE fractionation (La$_N$/Yb$_N$ = 38–57) (Fig. 3b).

Perovskites are found at Sung Valley as accessory phase of ultramafic silicate rocks, uncompahgrites and ijolites, at Jasra as interstitial minerals and overgrown by titanite in clinopyroxenites (Fig. 4a, b) and at Barpung in magnetite-rich rocks. The perovskites in a Sung Valley ijolite are mainly close to CaTiO$_3$ component (88 to 99 mol%), with significant Sr (1693–1926 ppm), Zr (63–66 ppm), and Nb (11582–12009 ppm), and relatively low Zr (192–371 ppm) and Hf (6–11 ppm) (Melluso et al. 2010). They have...
extremely high La (La_N ~ 20000 times chondrite), and high REE fractionated patterns (La_N/Yb_N = 292–391) (Fig. 3b). The Jasra perovskites, found in a clinopyroxenite and as resorbed cores of titanite (Fig. 4b), have high CaTiO_3 component (90–96 mol%), with lower Nb (Nb_2O_5 = 0.1–0.9 wt%) and Sr (SrO = 0.2–1.9 wt%) concentrations and variable light REE (ΣLREE_2O_3 = 0.8–5.8 wt%).

Garnet

A calcic garnet is found in the Sung Valley ijolites and clinopyroxenites. It is rich in FeOt (16.6–20.8 wt% in clinopyroxenites and 19.9–23.6 wt% in ijolites) and has variable TiO_2 (1.5–8 wt% in clinopyroxenites and 6.8–15.1 wt% in ijolites), suggesting the predominance of andradite [Ca_3Fe_3^3+Si_3O_12; 53–68 mol% in clinopyroxenites and 30–66 mol% in ijolites] with significant schorlomite in ijolites [Ca_4Ti_2(Si,Fe_3^+,Al,Fe_2^+)_3O_12, 6–24 mol%; Locock (2008)]. The trace element concentration of garnet in Sung Valley ijolite (Melluso et al. 2010; Fig. 3b, 4a) is extremely high for Zr (3739–6488 ppm), Hf (65–136 ppm) and Y (404–1058 ppm), and generally low in LREE (ΣLREE = 662–1626 ppm) and La_N/Yb_N (0.3–1.1). The Jasra, Mawpyut and Samchampi-Samteran garnets have high concentration in FeOt (24.0–25.7 wt% in Jasra; 25.1–26.1 wt% in Mawpyut) or Fe_2O_3t (20.4–26.2 wt% in Samchampi-Samteran) and relatively low in TiO_2 (5.5–6.6 wt% at Jasra; 5.2–7.5 wt% at Mawpyut; 4.1–12.9 wt% at Samchampi-Samteran). The main end-member is andradite (67–76 mol% in Jasra; 63–74 mol% in Mawpyut; 47–82 mol% in Samchampi-Samteran) followed by morimotoite at Jasra, Mawpyut, and Samchampi-Samteran (10–14 mol% in Jasra; 11–18 mol% in Mawpyut; 5–13 mol% in Samchampi-Samteran), schorlomite-Al at Jasra (8–9 mol% in Jasra), and schorlomite at Mawpyut and Samchampi-Samteran (5–8 mol% and 9–17 mol% respectively). The schorlomite-rich composition of the garnet of the ijolites matches the compositions found in the nephelinitic rocks of the northern Deccan Traps (cf. Gwalani et al. 2000).

Fig. 5  a, b, c, d Representative variation diagrams using MgO as abscissa elaborated from Sung Valley, Jasra, Swangkre-Rongjeng, Mawpyut, Samchampi-Samteran and Barpung silicate rocks and Sung Valley and Samchampi-Samteran carbonatites. See Table 2 for references.
Geochemistry

Bulk-rock geochemistry

The magmatism in the SPMH massif has a slight potassic affinity at Jasra and Swangkre-Rongjeng, a sodic affinity at Sung Valley and Mawpyut intrusions, and variable from slightly potassic to highly potassic at Samchampi-Samteran (see Table 2 for references).

The variations of MgO, SiO2 and Al2O3 highlight the distribution of the different lithologies of the SPMH intrusions, which are mainly the result of accumulus of mafic silicates and feldspars or feldspathoids (Fig. 5). A general decrease of MgO of silicate rocks (s.l.) corresponds to Sr increase, more pronounced in the Jasra rocks (Fig. 6). The concentrations of Rb, Ba, Nb, and Zr increase with Sr, where in the silicate rocks (s.l.) these elements increase in all the intrusions (Fig. 6).

The SPMH silicate rocks (s.l.) have variable concentration of high-field strength elements (HFSE) and large-ion lithophile elements (LILE), with variable peaks in these elements, as seen in the multi-elemental patterns (Fig. 7). All these patterns are influenced by the mineral assemblages of the rocks and cannot be taken as evidence of magmatic liquids. The pronounced peaks at Ba and Sr are related to accumulus of alkali feldspar, whereas the peaks are much less marked where alkali feldspar crystallized and accumulated from evolved magmatic liquids, such as trachytes of phonolites; similarly, the different enrichment pattern observed in the Zr-Hf and Th-U pairs are associated to the accumulation or removal of phases such as perovskite, zircon, zirconolite and so on.

The REE concentrations in the silicate rocks (s.l.) are generally high, with the LREE more enriched compared to heavy-REE (HREE), absence of Eu troughs or peaks and a relatively slight decrease in the HREE (from Gd to

Fig. 6  a, b, c, d Representative variation diagrams using Sr as abscissa elaborated from Sung Valley, Jasra, Swangkre-Rongjeng, Mawpyut, Samchampi-Samteran and Barpung silicate rocks and Sung Valley and Samchampi-Samteran carbonatites. See Table 2 for references
Lu). The chondrite-normalized REE patterns of silicate rocks (s.l.) of the main SPMH intrusions have a variably fractionated pattern [Swangkre-Rongjeng: \(\text{La}_{\text{N}}/\text{Yb}_{\text{N}}\) is 4–5 in silicate rocks (s.l.) and 21 in the ultramafic lamprophyre; Mawpyut: \(\text{La}_{\text{N}}/\text{Yb}_{\text{N}}\) is 2–9 in silicate rocks (s.l.); Barpung: \(\text{La}_{\text{N}}/\text{Yb}_{\text{N}}\) is 4–58 in silicate rocks (s.l.); Samchampi-Samteran: \(\text{La}_{\text{N}}/\text{Yb}_{\text{N}}\) is 3–89 in silicate rocks (s.l.); Sung Valley: \(\text{La}_{\text{N}}/\text{Yb}_{\text{N}}\) is 2–64 in silicate rocks (s.l.) and 90–186 in dunites; Jasra: \(\text{La}_{\text{N}}/\text{Yb}_{\text{N}}\) is 13–41 for silicate rocks (s.l.)] (Fig. 8).

The Sr concentration is high in the Sung Valley and Samchampi-Samteran carbonatites but Rb, Ba, and Nb are not very enriched. The Zr concentration in the Sung Valley and Samchampi-Samteran carbonatites is widely variable (Zr > 400 ppm at Sung Valley and Zr < 90 ppm at Samchampi-Samteran) (Fig. 6). The multi-elemental patterns of Sung Valley and Samchampi-Samteran carbonatites have a trough at Zr and Hf relative to the neighboring REE (Fig. 9), as commonplace of igneous carbonatites worldwide. This feature is mainly related to poor solubility of Zr and Hf in carbonatitic magmas and/or strong partitioning of these elements in immiscible silicate rather than conjugate carbonated magmas rather than to effects of fractional crystallization of a specific phase (Andrade et al. 2002; Chakhmouradian 2006; Guarino et al. 2017). The chondrite-normalized REE patterns of carbonatites are more fractionated at Samchampi-Samteran (\(\text{La}_{\text{N}}/\text{Yb}_{\text{N}}\) = 49–101) than at Sung Valley (\(\text{La}_{\text{N}}/\text{Yb}_{\text{N}}\) = 33–57) (Fig. 9).

Radiogenic-isotope geochemistry

A significant variation is noted in Sr–Nd isotopic compositions in all ultramafic-alkaline-silicate rocks belonging to the different intrusions of the SPMH (Fig. 10).
The initial $^{87}\text{Sr}/^{86}\text{Sr}$ of the Jasra intrusion ranges from 0.70652 and 0.70908 and $\varepsilon_{\text{Ndi}}$ from -4.8 to -0.7 (Srivastava and Sinha 2007; Srivastava et al. 2019). The initial $^{87}\text{Sr}/^{86}\text{Sr}$ of Sung Valley silicate rocks (s.l.) is 0.70479–0.71080 and $\varepsilon_{\text{Ndi}}$ varies from -13.12 to +0.81 (Srivastava et al. 2005, 2019; Veena et al. 1998; Ghatak and Basu 2013); the initial $^{87}\text{Sr}/^{86}\text{Sr}$ of Samchampi-Samteran silicate rocks (s.l.) is 0.70138–0.72734 and $\varepsilon_{\text{Ndi}}$ is from -17.8 to 1.1 (Saha et al. 2017; Ghatak and Basu 2013). The initial $^{87}\text{Sr}/^{86}\text{Sr}$ and $\varepsilon_{\text{Ndi}}$ for the Mawpyut intrusion have two different ranges of values for cumulate rocks (0.70595–0.70606 and -0.89 and -1.53) and for non-cumulate rocks (0.71002–0.71028 and -7.05 and -7.14) (Chaudhuri et al. 2014). The Barpung rocks have initial $^{87}\text{Sr}/^{86}\text{Sr}$ is 0.70503–0.71516 and $\varepsilon_{\text{Ndi}}$ variable from -12.3 and -0.1 (Ghatak and Basu 2013). No isotopic data are available for the Swangkre-Rongjeng dyke.

The Sung Valley carbonatites have initial $^{87}\text{Sr}/^{86}\text{Sr}$ of 0.70442–0.70487 and $\varepsilon_{\text{Ndi}}$ of 0.25–1.81, similar to those of the Samchampi-Samteran carbonatites (initial $^{87}\text{Sr}/^{86}\text{Sr}$ = 0.70471–0.70477; $\varepsilon_{\text{Ndi}}$ = 0.3–1.2; Ghatak and Basu 2013). Saha et al. (2017) reports one carbonatite sample from Samchampi-Samteran with a highly anomalous Sr–Nd isotopic value (initial $^{87}\text{Sr}/^{86}\text{Sr}$ = 0.70728 and $\varepsilon_{\text{Ndi}}$ = -3.1).

**Discussion**

**Evolution processes within the various intrusions in SPMH areas**

The Sung Valley is a plagioclase-free ultramafic alkaline intrusion. The data resulting from field-setting, bulk-rock geochemical, mineral chemistry, and Sr–Nd isotopes highlighted the absence of a genetic correlation between silicate rocks (s.l.) and carbonatites (Melluso et al. 2010; Srivastava et al. 2005, 2019; Srivastava and Sinha 2004a). The silicate rocks (s.l.) were generated by different pulses of magmas, each with its own composition formed the cumulitic intrusive rocks. The silicate rocks (s.l.) are ultramafic perovskite-bearing and olivine-bearing rocks,
uncompahgrites, ijolites, clinopyroxenites and nepheline syenites, which formed after the accumulation of different mineral assemblages from variably evolved magmas, with incompatible-element nature, ranging from melilititic and nephelinitic to phonolitic types.

The Sung Valley carbonatites are not likely to be formed after immiscibility of carbonated “nepheline syenitic” or carbonated “ijolitic” melts or their equivalents, due also to markedly different isotopic compositions (cf. Srivastava et al. 2019). Their mineral assemblages, characterized by highly magnesian olivine, phlogopite and ilmenite (plus clinohumite and dolomite), and some high concentration of Cr in spinel, indicate a different genesis from the surrounding silicate rocks (cf. Srivastava et al. 2005, 2019).

The shallow intrusion of Jasra comprises ultramafic to felsic lithotypes. The genesis of ultramafic rocks is likely due to mineral accumulation from magmas of different compositions, likely ranging from basalt/basanite. The gabbroic rocks and nepheline syenites were originated by mineral setting of clinopyroxene, kaersutite, sodic plagioclase, relatively Fe-rich olivine, phlogopite and nepheline, from slightly evolved alkaline magmas (tephrites, trachybasalts), and syenites formed after accumulus of alkali feldspar and Fe-rich phases from trachytic magmas (s.l.). Some of the gabbroic rocks have a subalkaline affinity, related to the presence of olivine with orthopyroxene rims and augite clinopyroxene. An interesting mineralogical feature observed at Sung Valley and Jasra is the peritectic replacement of perovskite by titanite (see Fig. 4a, b; Table 3; cf. Melluso et al. 2010, 2012). At Sung Valley, the presence of perovskite with garnet and titanite rims in an ijolitic rock (sample SV58) are indicative of increase of silica activity in the equilibrium melt of larnite-normative affinity, stabilizing titanite. More interestingly, perovskite was found as corroded grains within euhedral titanite in a Jasra clinopyroxenite, hence never in contact with alkali feldspar, testifying the same peritectic reaction in a more evolved rock type (cf. Melluso et al. 2012).
The Swangkre-Rongjeng potassic lamprophyres were likely generated during partial melting of hydrous mantle source (Srivastava et al. 2016), whereas, the Mawpyut intrusion is characterized by the presence of two different ranges in the Sr–Nd isotopes for mafic ultramafic cumulate and non-cumulate rock types (Fig. 10) that suggest a different role of upper crustal contamination as evident in the higher initial $^{87}\text{Sr/}^{86}\text{Sr}$ ratio of non-cumulate rocks.

The Samchampi-Samteran UACC has markedly different isotopic composition between alkaline silicate rocks and carbonatites, like at Sung Valley; hence these rocks cannot be derived by simple fractional crystallization and accumulation of phases of a single parental melt composition. Fractional crystallization and upper crustal contamination have played a marked role in the high variability of Sr–Nd isotopes. In the Samchampi-Samteran intrusion, the isotopic similarity between one carbonatite and the associate silicate rocks (s.l.) are indicative of a similar petrogenetic process (Fig. 10). View the strong isotopic affinity between Samchampi-Samteran and Sung Valley carbonatites, it is possible to consider that the Samchampi-Samteran carbonatites may be derived by melt originated at greater depths in the mantle.

The Barpung intrusion is formed by pyroxenites, alkali syenites and fenites; despite the low amount of data available, the silicate rocks may have formed through fractional crystallization/accumulation from mantle-derived magmas, mainly associated with upper crustal contamination as highlighted by their higher $^{87}\text{Sr/}^{86}\text{Sr}$ ratios (Fig. 10).

It is remarked that none of these intrusions can be considered as feeders of the tholeiitic lavas of the Rajmahal-Sylhet traps, for the highly alkaline affinity of the outcropping lithotypes and the ages, making any link with the tholeiitic magmatism of the area fully unjustified. At the same time, there is no evidence of crystallization in the mantle of any lithotype and its phases found in the various intrusions, from the silicate rocks to the carbonatites.

**Isotopic signature and mantle source characteristics beneath the Shillong Plateau-Mikir Hills**

The marked similarity in the initial $^{87}\text{Sr/}^{86}\text{Sr}$ and $\varepsilon\text{Nd}_i$ of Sung Valley and Samchampi-Samteran carbonatites is remarkable. Their similarity suggests an origin from a mantle source with an isotopic composition similar to that of the mantle source of Rajmahal Group I basalts, and different from source of present-day Indian MORB (Fig. 10). The melt that have crystallized the Sung Valley carbonatites is originated through low degree of partial melting of a metasomatized carbonated mantle; by analogy, a similar process may be assumed for the formation of Samchampi-Samteran carbonatites. This assumption suggests the role played by a metasomatized carbonated mantle throughout the whole province (Fig. 1). The presence of a carbonate-bearing mantle, which produce melts of olivine melilititic, olivine nephelinitic and basanitic composition, was responsible for the crystallization of various

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**Fig. 10** $\varepsilon\text{Nd}$, and initial $^{87}\text{Sr/}^{86}\text{Sr}$ diagram for the isotopic data from ultramafic-alkaline-carbonatite intrusions of the Shillong Plateau-Mikir Hills massif, NE India. The Sung Valley data are from Veena et al. (1998), Srivastava et al. (2005), Ghatak and Basu (2013) and Srivastava et al. (2019); Jasra data from Srivastava and Sinha (2007) and Srivastava et al. (2019); Samchampi-Samteran data from Ghatak and Basu (2013) and Saha et al. (2017); Barpung data from Ghatak and Basu (2013); Mawpyut data from Chaudhuri et al. (2014). Isotopic variations in Kerguelen basalts are from Storey et al. (1992), Mahoney et al. (1992, 1995, 2002), Kumar et al. (2003); compiled in Srivastava et al. (2005), Srivastava and Sinha (2007), Ghatak and Basu (2013), and Mattielli et al. (2002), Ingle et al. (2002), Doucet et al. (2005); Rajmahal basalts Group I and II are from Storey et al. (1992), Baksi (1995) and Kent et al. (1997); Sylhet tholeiitic basalts from Ghatak and Basu (2011); Jharia lamproites from Kumar et al. (2003). The continental clasts from IODP site 1137 are from Ingle et al. (2002). The Indian MORB is from Mahoney et al. (2002). Springer
types of intrusive alkaline rocks, often in the same intrusive complex. The range of initial Sr and Nd isotopes of the silicate rocks (s.l.) belonging to these six UACC intrusions suggests the presence of an open magmatic system in throughout the whole SPMH province (Fig. 10). The increase in the initial \(^{87}\text{Sr}/^{86}\text{Sr}\) and decrease in the \(\varepsilon_{\text{Nd}}\) in the silicate rocks (s.l.) define a trend towards the underlying SPMH crust suggesting that during their ponding and emplacement in the SPMH area there is the involvement of an upper continental crust component, rather than isotopic heterogeneity within the mantle, during the crystallization processes related to the formation of these silicate rocks (s.l.), as happen for Rajmahal Group II (Kent et al. 1997) and some Sylhet basalts (Ghatak and Basu 2013; Srivastava et al. 2005; Srivastava and Sinha 2007; Veena et al. 1998).

**Economic aspects of the SPMH UACCs**

An important aspect in the six UACCs is their marked enrichment in some elements as P, Ti, Ba, Th, U, Nb, Ta, and LREE. These elements are hosted in some typical mineral observed and analyzed in these complexes, and looking the chemical analysis of bulk-rocks, they reveal a high potential of substantial resources of these elements (Table 3). The main minerals of economic significance are pyrochlore, apatite, magnetite and vermiculite at Sung Valley (Kumar et al. 1996); magnetite, ilmenite, perovskite, Nb-Th-phases, and the occurrence of sulfides (pyrite, chalcopyrite, covellite) in association with pyroxenites and high amounts in REE (up to 9500 ppm) in the soils above titanomagnetite-rich rocks at Jasra (Kumar et al. 1996). The Sung Valley carbonatites have high economic potential view their enrichment in REE carbonates and phosphates associated with REE-Nb bearing pyrochlore (Sadiq et al. 2014). The residual soil related to alteration processes over the Sung Valley carbonatite are extremely enriched too; it contains about 1300 tons of Nb\(_2\)O\(_5\) in 6.75 million tons ore, mainly due to pyrochlore (8.50% ThO\(_2\) and 2.2% U\(_3\)O\(_8\)) (Singh 2020 and references therein). The soils above Barpung complex contain high concentrations of LREE and Y (Kumar et al. 1996).

High absolute concentrations in P (41.68%), REE (62.60%) and Nb (60.19%) have been noted in the Samchampi-Samteran intrusion (Hoda and Krishnamurthy 2016a). These authors estimated a reserve of 15 million metrics tons of phosphatic ore, and the possibility of associate uranium and rare-earth elements as possible by-products, all economically viable. Instead the residual soil contains 10,970 tons Nb and 3740 tons of Ta in an area of 10.94 km\(^2\) (Hoda et al. 1997) and 3644 tons Y resource in 41.88 million tons ore (Hoda and Krishnamurthy 2016b).

**Final considerations**

By combining mineral chemistry, bulk-rock geochemical and Sr–Nd isotopic composition of the UACC intrusions in the SPMH area, several different processes acted in the petrogenesis of the alkaline province above SPMH, such as upper crust contamination and fractional crystallization. They are synthesized as follows: (i) a carbonate-bearing lithospheric mantle is proposed to produce different melts for the genesis of these six SPMH intrusions, (ii) the marked similarity in the initial \(^{87}\text{Sr}/^{86}\text{Sr}\) and \(\varepsilon_{\text{Nd}}\) of Sung Valley and Samchampi-Samteran carbonatites, and the high variability in the initial Sr–Nd isotopes of silicate rocks (s.l.), are indicative of different processes of formation, (iii) the geochemical features of silicate rocks (s.l.), related to their ponding and emplacement, are indicative of different parental magmas (alkali basalts, basanites, nephelinites, melilitites), associated with crustal contamination during their ascent, (iv) the melts that crystallize carbonatite in Sung Valley and Samchampi-Samteran could have been at the base of lithospheric mantle in areas far from the influence of mantle plumes and high geothermal gradients. (v) the absolute REE abundance observed in the Sung Valley and Samchampi-Samteran carbonatites are related to the melts from which they crystallized, melts ultimately generated in the lithospheric mantle, and (vi) the presence of economic minerals and soils in the UACC intrusions bearing REE, P, Ti, Ba, Th, U, Nb, Ta will be useful for their expanding applications in various strategic and high technological fields.

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