ORIGINAL ARTICLE

Decoding the nature of interaction between felsic clasts and mafic magma in a subvolcanic magma chamber from amphibole–titanite transformation and chemistry

Bibhuti Gogoi[1] (iD) · **Deepshikha Borah**[1]

Abstract The Ghansura Rhyolite Dome of Bathani volcano-sedimentary sequence, eastern India, represents a subvolcanic felsic magma chamber that was invaded by crystal-rich mafic magma during its cooling phase to form an assortment of hybrid rocks. A prominent solidified portion of the magma reservoir was embedded in the intruding mafic magma as fragments or clasts that produced mafic rocks with felsic clasts. Two distinct compositional zones could be identified in the mafic rocks containing felsic clasts- (a) medium-grained mafic zones that are dominated by amphiboles, and (b) fine-grained felsic zones consisting primarily of quartz and feldspar. Amphiboles occur in most of the felsic clasts suggesting the mechanical transfer of crystals from the mafic to the felsic zones. Compositions of amphiboles were determined from both the mafic and felsic zones that show linear compositional variation from actinolite to ferro-hornblende through magnesio-hornblende, suggesting the interplay of complex substitutions in individual amphibole sites. Cationic schemes have confirmed the role of pargasite (Pg)-type substitution, which is a combination of edenite (Ed)- and tschermakite (Ts)-type substitutions. Moreover, amphibole has been extensively replaced by titanite in the studied rock. Titanite produced in the mafic zones due to the destabilization of amphiboles was observed migrating from the mafic to the felsic zones through mineral-transporting veins. Compositions of titanite were determined from grains that occur in association with amphiboles and those which are present as individual entities in the felsic zones. Similar to amphiboles, titanite also displays cationic substitutions in the studied rock. From the results presented in this work, we infer that extensive replacement of amphibole by titanite and cationic substitutions in amphiboles, and also titanite, may be considered important petrogenetic indicators to decipher magma mixing events.

Keywords Magma mixing · Mineral-transporting veins · Crystal transfer mechanism · Cationic substitutions · Amphibole–titanite replacement

1 Introduction

One of the most intriguing yet rudimentary phenomena that is prevalent in igneous petrology is magma mixing and mingling. Mixing and mingling of magmas is considered one of the most important petrogenetic and volcanological processes and has been extensively observed in plutonic and subvolcanic environments (Gogoi et al. 2018a; Gogoi and Chauhan 2021; Hazarika et al. 2022). In the mixing process, two or more compositionally dissimilar magmas mix together such that the melts of each are blended into a compositionally uniform single magma (in addition to crystals and gasses; Anderson 1976). Physically, whether magmas will be mixed or mingled, will mainly be controlled by the viscosity contrast between the two magmas. Lower viscosity contrast results in progressively more efficient mixing, whereas an increase in viscosity disparity entails proficient mingling dynamics (Sparks and Marshall 1986; Grasset and Albarede 1994; Bateman 1995; Perugini and Poli 2005). When two or more magmas come in contact with each other, mechanical processes and chemical diffusion result in

✉ Bibhuti Gogoi
  bibhuti.gogoi.baruah@gmail.com

1 Department of Geology, Cotton University, Guwahati,
   Assam 781001, India

diversified chemically mixed or mechanically mingled final products (Donoghue et al. 1995; Cole et al. 2001).

Although there has been much advancement in knowing about the mechanisms persistent during magma mixing at a grander-scale, i.e., in magma chambers or conduits; very little knowledge is available regarding the dynamics of small-scale processes, particularly, about the interplay between chemical diffusion and dynamics of magmas at the microscopic scale (of the order mm to μm). However, these small-scale features are well-preserved and can be easily inferred from mineral transformations and textural interpretations. Rapakivi texture, quartz and titanite ocelli, complex zoning in minerals, resorbed crystals, acicular apatite, etc. are considered excellent petrographic benchmarks of magma mixing (Hibbard 1991; Kuşcu and Floyd 2001; Baxter and Feely 2002; Gogoi et al. 2017, 2021a), whereas structures like back-veining, crenulated margins of enclaves, reaction surfaces, and hybrid zones at mafic–felsic contacts are direct field evidence of magma mingling, and indicate thermal disequilibrium which causes the comingling phenomenon, especially in scenarios where relatively hotter mafic magma injects into a colder felsic magma chamber (Dorais et al. 1990; Waight et al. 2001; Tepper and Kuehner 2004; Gogoi et al. 2018a, 2020).

There is a consensus that textural features preserved in hybrid rocks play a pivotal role in interpreting the behavior and the nature of mixing between two compositionally dissimilar magmas (Hibbard 1981; Gogoi et al. 2017). Also, textural constraints can play an important role in understanding magma chamber dynamics (Agangi et al. 2011; Weidendorfer et al. 2014; Gogoi and Chauhan 2021). Interpreting the genesis of textural features preserved in hybrid rocks can significantly contribute toward a better understanding of magma mixed systems, as mixing is intrinsic for magma diversification and is considered one of the most dominant mechanisms that trigger volcanic eruptions. In this paper, we are trying to understand the dynamics of mixing between felsic clasts and mafic magma in the Ghansura Rhyolite Dome (GRD) of Bathani volcano-sedimentary sequence (BVSs), eastern India. The GRD is a fossilized subvolcanic magma chamber and hosts a variety of hybrid rocks, including mafic rocks with abundant felsic clasts (Gogoi et al. 2018b). Interaction between the felsic clasts and mafic magma caused the widespread transformation of amphibole to titanite. We are focussing on the amphibole–titanite transformation to decipher the nature of the interaction between felsic clasts and mafic magma in the subvolcanic magma chamber.

2 Geological setting

The crustal architecture of the Indian subcontinent is defined by the amalgamation of two large-scale cratonic blocks, namely the North Indian Block and the South Indian Block. These two crustal blocks are sutured by a prominent, approximately 1500 km long, ENE-WSW trending Proterozoic mobile belt, known as the Central Indian Tectonic Zone (CITZ), which runs through the heart of Peninsular India. The northern crustal block hosts two cratons, i.e., the Aravalli and the Bundelkhand cratons, which are believed to be Archean at the earliest; whereas the southern block is a composite assemblage of the Dharwar, Bastar, and Singhbhum cratons, which are Archean in age too. The CITZ can be broadly specified into three regions from west to east, viz., the main portion of the CITZ occupying the central region of Peninsular India, the Chotanagpur Granite Gneiss Complex (CGGC) lying to the east of the main CITZ, and the easternmost Assam–Meghalaya Gneissic Complex (Fig. 1). The research area of interest, the Ghansura Rhyolite Dome located in the Bathani volcano-sedimentary sequence, which lies in the northernmost periphery of CGGC, is a broad magmatic tectonic terrain and an idealized geological setting to understand the dynamics of a shallow-level magma chamber. The BVSs is considered the eastern extension of the Mahakoshal Mobile Belt of CITZ (Saikia et al. 2014, 2017; Gogoi 2022 and references therein).

The BVSs is a bimodal volcanic and volcano-sedimentary sequence (Fig. 2a; Ahmad and Wanjari 2009; Ahmad et al. 2021), which encompasses an aerial distance of approximately 40 km, with type area being located at Bathani village (24°59.5′ N, 85°16′ E) of the Nalanda district in Bihar, India. The rock types visible in the volcano-sedimentary section of the BVSs are banded iron formation, chert bands, garnet-mica schist, rhyolite, carbonate rocks, and tuff, whereas the differentiated volcanic portion comprises massive basalts, pillow basalts, rhyolite, tuff, and mafic pyroclasts. Granites were later emplaced into the volcanic sequence and appeared as plutons/hillocks crosscutting the entire sequence. This granite magmatic event in the BVSs is hypothesized to be a remnant of the Columbia supercontinent assembly that occurred during 2000–1700 Ma (Saikia et al. 2017, 2019). The volcano-sedimentary sequence of the BVSs is overlain by the differentiated volcanic sequence. An appraisal of the primarily exposed sedimentary and volcanic structures refers that there is no remarkable unconformity between the two sequences. Moreover, the association of rock types like pillow basalts, rhyolites, volcanogenic and chemogenic sediments, and explosive rock types suggest a subaqueous environment for an eruption of mafic/felsic magmas and the ejection of pyroclasts. Such an emplacement signature is a singular expression of subduction zone volcanism, associated with island arc volcanism and obduction (Wilson 1989).
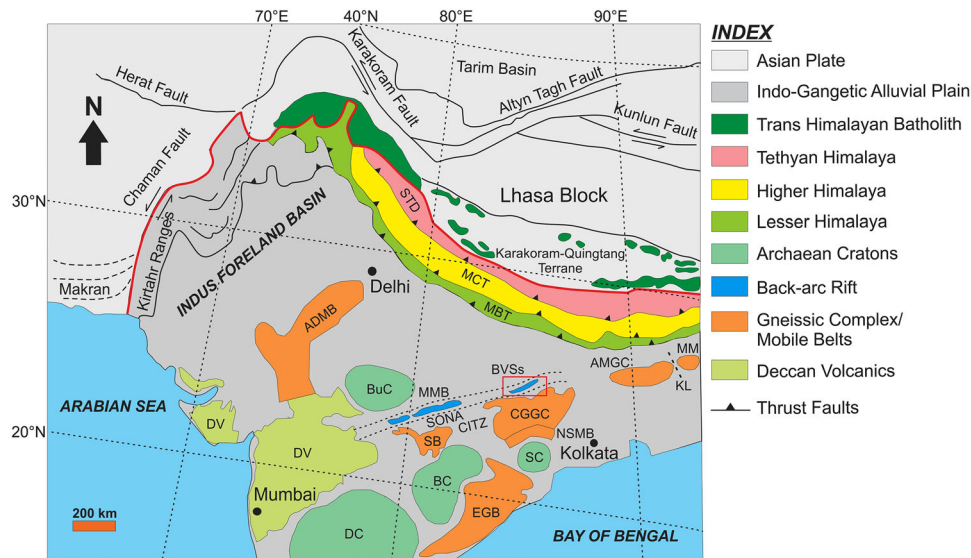
Fig. 1 A simplified geological and tectonics map of the Greater Indian Landmass and its surrounding region. The Bathani volcano-sedimentary sequence is shown in the red box. Abbreviations: BC = Bastar Craton, BuC = Bundelkhand Craton, DC = Dharwar Craton, SC = Singhbhum Craton, ADMB = Aravalli Delhi Mobile Belt, BVSs = Bathani volcano-sedimentary sequence, CITZ = Central India Tectonic Zone, CGGC = Chotanagpur Granite Gneiss Complex, EGB = Eastern Ghats Belt, KL = Kopili Lineament, MMB = Mahakoshal Mobile Belt, NSMB = North Singhbhum Mobile Belt, SB = Satpura Belt, SONA = Son-Narmada graben, MBT = Main Boundary Thrust, MCT = Main Central Thrust, STD = South Tibetan Detachment, DV = Deccan Volcanics
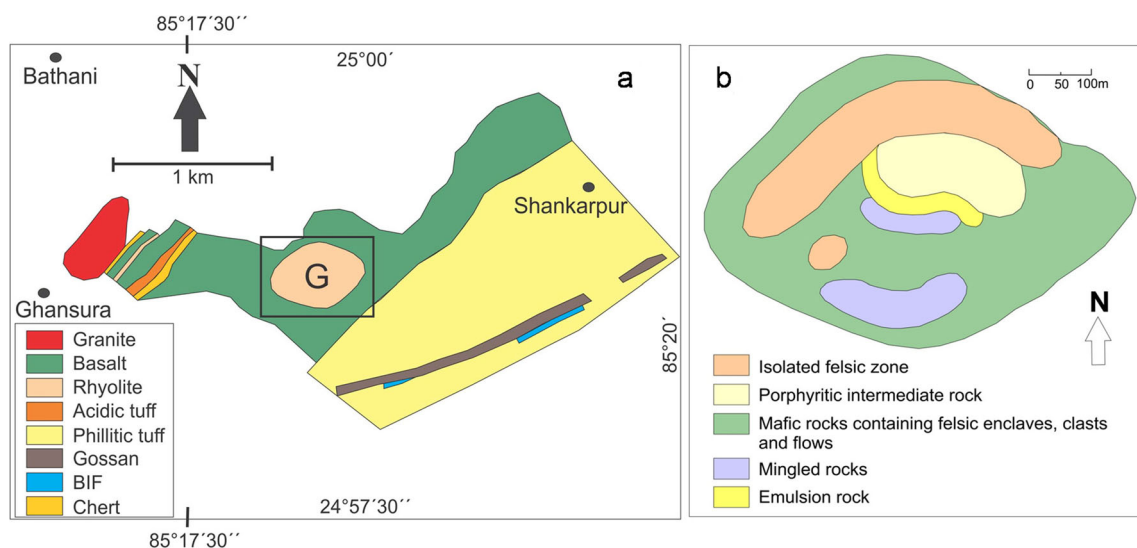

Fig. 2 **a** Simplified geologic map of the Bathani volcano-sedimentary sequence illustrating the disposition of different litho-units (modified after Ahmad and Paul 2013). The Ghansura Rhyolite Dome is demarcated as "G" **b** Simplified Geologic Map of the Ghansura Rhyolite Dome showing the disposition of different rock types

3 Field relationships and petrography

The GRD is a signature model for research on magma mixing and mingling. It represents a subvolcanic felsic magma chamber exposed in an outcrop area of ca. 0.25 km^2, that was intruded by crystal-rich basaltic magma during its evolution leading to the formation of an assortment of hybrid rocks (Gogoi and Saikia 2018, 2019; Gogoi et al. 2018b, 2021a). The GRD crosscuts the bimodal

volcanic sequence suggesting that the rhyolite dome or laccolith was emplaced at a later stage in the BVSs (Fig. 2b).

The GRD has recorded a wide range of rock types ranging from felsic to mafic (Fig. 3a–d), with four distinct hybridized varieties, which include basaltic rocks containing rhyolite clasts, comingled mafic–felsic rocks, and porphyritic and non-porphyritic intermediate rocks. The mafic rocks exposed in the GRD essentially consist of

clinopyroxene, plagioclase, and Ti–Fe oxide. Clinopyroxene occurs as a phenocryst phase in the mafic endmember and laths of plagioclase are engulfed within the phenocrysts depicting ophitic texture (Fig. 3b). Meanwhile, the rhyolites are fine-grained and consist of feldspar, quartz, biotite, and iron oxide (Fig. 3d). A detailed petrographic overview of the mafic and felsic rocks can be found in Gogoi and Chauhan (2021). The hybrid rocks have resulted from varied degrees of interaction between the felsic and mafic magmas. Because of their haphazard distribution over the entire rhyolite dome, the mapping of the different rock units at the outcrop scale is an arduous task. The hybrid rocks of GRD show a considerable number of textural and structural expressions associated with magma mixing, such as hybridized zones at felsic–mafic contacts, mantled rapakivi feldspars, crenulated margins of enclaves, mafic flows in the felsic host and felsic flows in mafic rocks, back-veining, and veins transporting mineral phases. Our study domain exhibits a complex scenario in which many individual zones have formed due to varying degrees of interaction of the mafic melt with the felsic host and each zone is characterized by a different type of hybridized rock. A brief description of each hybridized rock is given below:

(a) *Mafic rocks with felsic clasts* The outermost zone of the GRD is composed of mafic rocks with abundant angular or tapered felsic clasts (Fig. 4a, b). It is characterized by fine-grained felsic leucocratic fragments of variable size embedded in melanocratic mafic groundmass (Fig. 4c–f). The contacts between the felsic clasts and mafic rock are usually sharp, with certain entities displaying prominent reaction rims. The colour of the aphanitic, elongated felsic clasts ranges from white to light grey, with sizes ranging from 1 cm to about 5 cm, all embedded within the fine-grained mafic groundmass. The clasts do not show any radial internal structure or zoning. Occasionally, stretched-out thin streaks of felsic clasts are also observed. The felsic entities display various types of juxtaposition and coalescence. They merge, juxtapose, or sometimes, even multiple clasts coalesce into larger domains of over 20 cm. The groundmass of the mafic host is highly vesicular.

Thin section study has revealed that the mafic rocks with felsic clasts consist of two distinct compositional zones- (a) medium-grained mafic zones that are dominated by amphiboles; (b) fine-grained felsic zones consisting primarily of quartz and feldspar. The felsic zones/clasts appear to be embedded in the mafic zones (Fig. 5a). Most
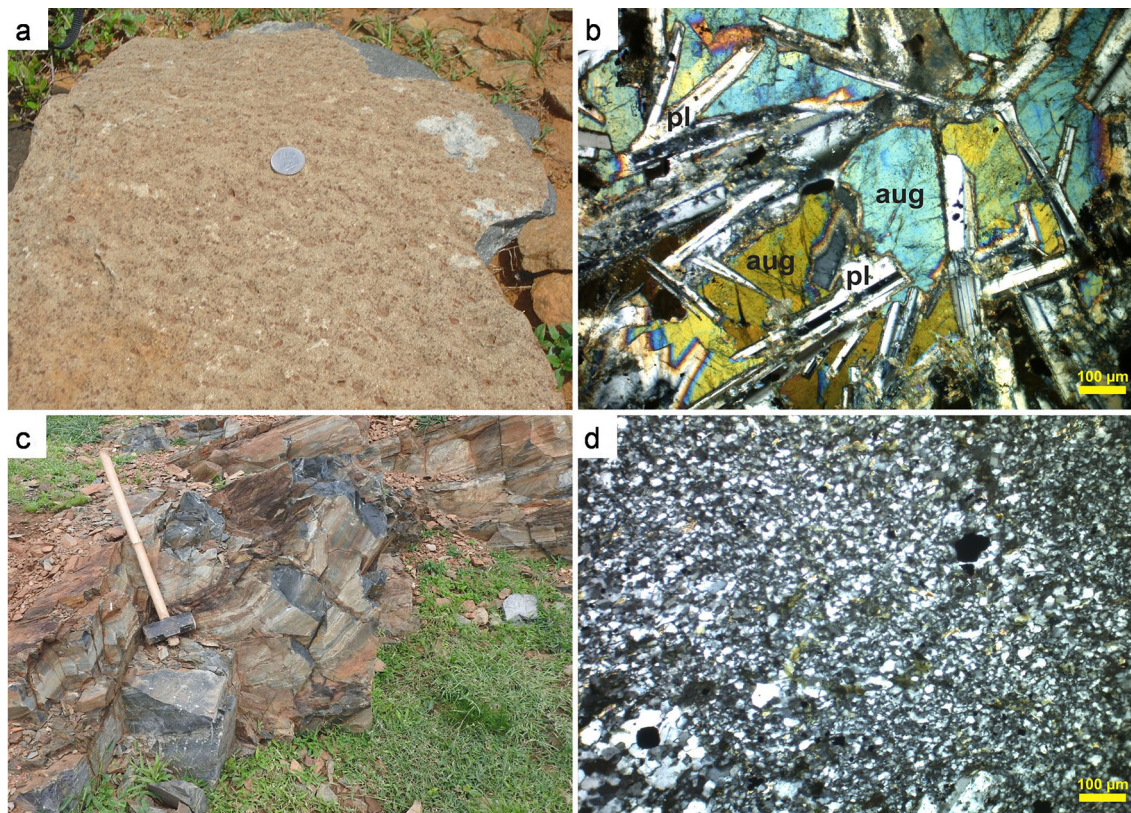

Fig. 3 a Field photograph showing the mafic endmember with vesicles. The vesicles are filled with secondary minerals like chlorite and calcite b photomicrograph showing the dominant mineral assemblage of the mafic endmember c field photograph of the felsic endmember d photomicrograph of the felsic endmember. Mineral abbreviation: aug = augite, pl = plagioclase

Fig. 4 **a–f** Field photographs displaying mafic rocks containing abundant angular or tapered felsic clasts. The elongated nature of the felsic clasts and their alignment along a particular direction was probably achieved as a result of magmatic flow and may indicate mingling within a conduit

of the felsic clasts are elongated in nature with tapered ends and aspect ratios up to 1:10. The elongated nature of the felsic clasts was probably achieved as a result of magmatic flow and may indicate mingling within a conduit (Vernon et al. 1988).

Amphiboles in the mafic zones display prismatic or acicular habit. Other than amphiboles, titanite is a ubiquitous mineral phase in the mafic zones. Titanite occurs as small anhedral grains or specks, mostly within amphibole crystals, which suggests that they are replacement products of amphiboles. Barring a few, most of the felsic zones are occupied by amphibole and titanite. Extensive replacement

of amphibole by titanite is evident in the felsic zones (Fig. 5b–d).

A salient feature observed in this rock is the presence of mineral-transporting veins (Fig. 5e, f). These veins appear to transport titanite from the mafic to the felsic zones. This distribution of titanite through the mineral-transporting veins has led to the enrichment of titanite in the felsic zones. The movement of titanite from mafic to felsic domains through veins in mingled rocks has earlier been reported by (Gogoi et al. 2018b). Such movements of mineral phases occur in mingled rocks to attain equilibrium in the disequilibrated mingled system.
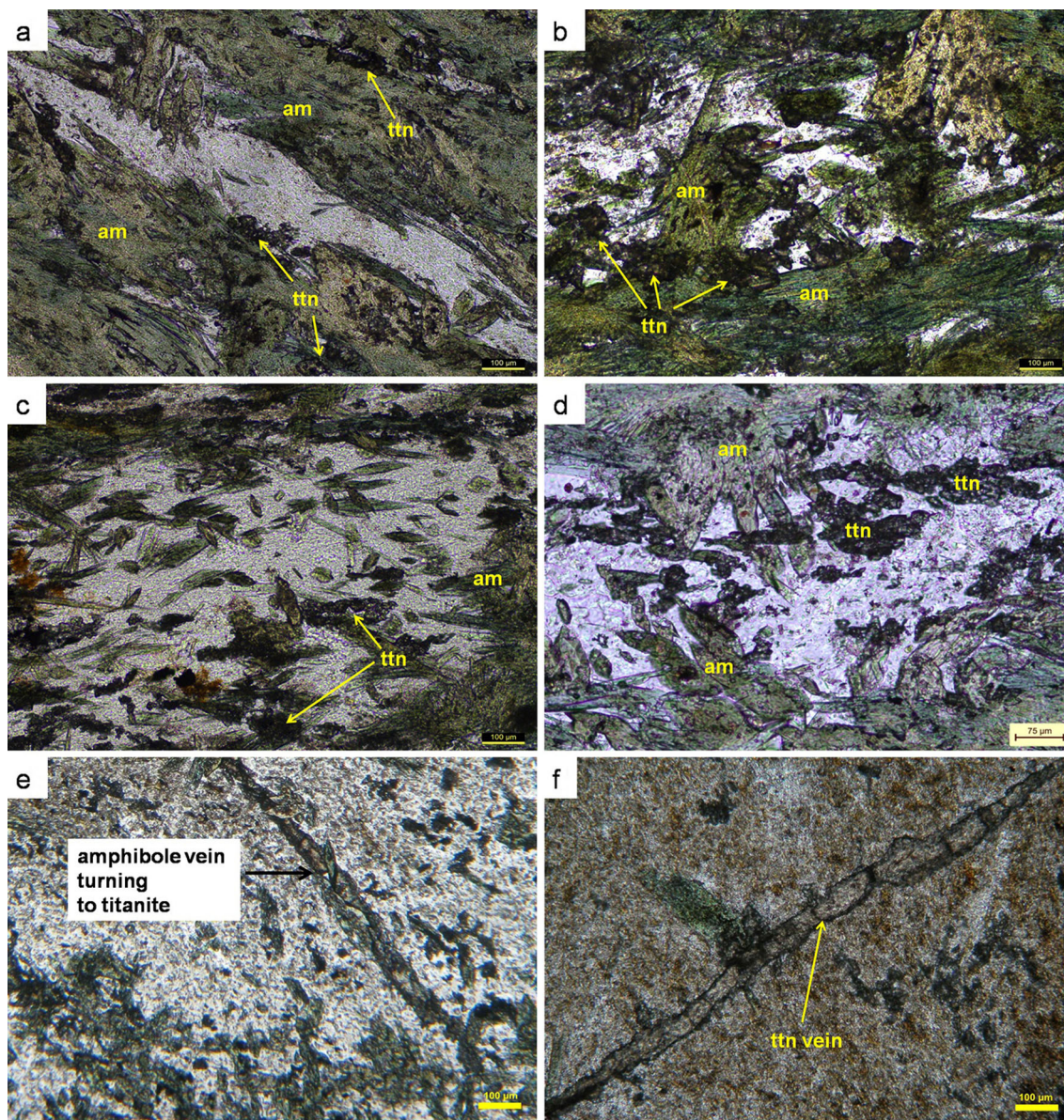
Fig. 5 Photomicrographs displaying **a** an elongated felsic clast embedded in amphibole-rich mafic groundmass. Amphibole-titanite replacement can be seen in the mafic zone **b, c, d** extensive replacement of amphibole by titanite in the felsic zones **e** a mineral-transporting vein migrating from mafic to felsic zone. Note that amphibole is replaced by titanite as the vein treads into the felsic zone **f** a titanite vein preserved in felsic zone. Mineral abbreviations: am = amphibole, ttn = titanite

This particular rock shares a boundary with the mingled rocks, which constitute the next category of hybrid rock. (b) *Mingled rocks* The coexistence of mafic and felsic entities is a signature of mingled rocks. Mingled rocks are a result of intermingling between two distinct magmas and are identified by comingled mafic–felsic zones, where the individual mafic and felsic components are distinguishable (Fig. 6a). Presence of sharp cuspate-lobate contacts between felsic and mafic entities at the outcrop scale is the effect of magma mingling of synchronous mafic and felsic magmas that have been observed in the mingled rocks of our study domain (Barbarin and Didier 1992).

Petrographic observations have revealed that amphiboles in the mafic zones show compositional variation from light green to dark green amphiboles (Fig. 6b). The light green amphiboles are actinolite, while the dark green amphiboles are hornblende. Biotite, ilmenite, and calcite were observed in the regions occupied by dark green amphiboles. Veins of biotite and ilmenite appear to be transporting components or mineral phases from the mafic to the felsic zones and enriching these mineral phases in the latter (Fig. 6b, c).

(c) *Non-porphyritic intermediate rocks with emulsions* The third genre of hybrid rocks occurring in the GRD is the
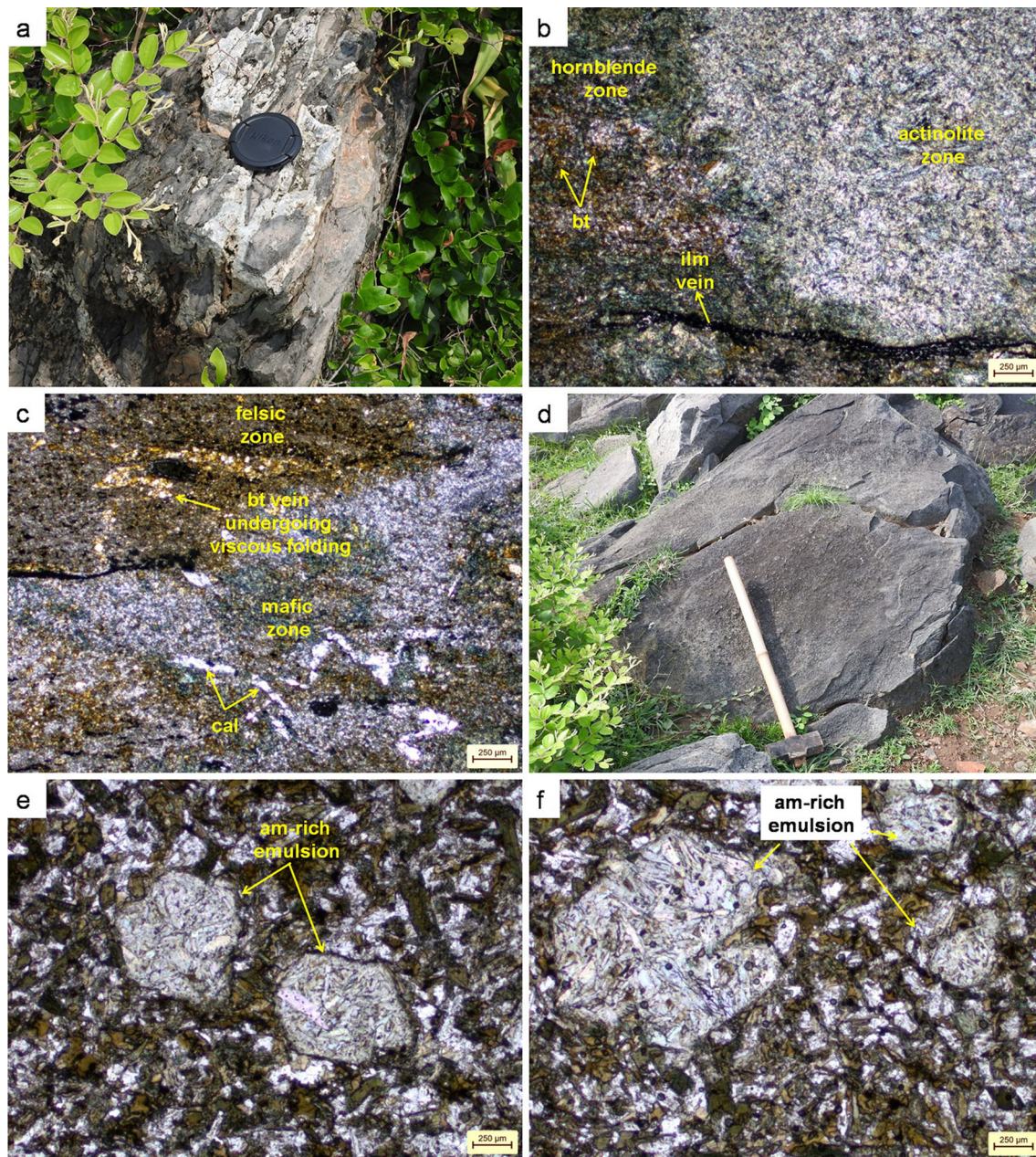
Fig. 6 a Field photograph of the mingled rock **b** photomicrograph showing actinolite- and hornblende-rich zones within a mafic zone. Note the occurrence of biotite and ilmenite vein in the hornblende zone **c** photomicrograph showing the contact between mafic and felsic zones. Note a biotite vein undergoing viscous folding in the felsic zone and occurrence of calcite in the mafic zone **d** field photograph showing the non-porphyritic intermediate rock with emulsions **e, f** photomicrograph showing amphibole-rich emulsions within biotite dominated matrix in the non-porphyritic intermediate rock. Mineral abbreviations: am = amphibole, bt = biotite, cal = calcite, ilm = ilmenite

non-porphyritic intermediate rock with emulsions (Fig. 6d; Gogoi and Saikia 2019). Similar to the mingled rocks, the non-porphyritic rock is heterogeneous and displays very distinct felsic and mafic zones. This particular rock is characterized by a fine comingled texture where darker amphibole-rich emulsions are embedded in a biotite-dominated groundmass, causing heterogeneities of minuscule sizes (Fig. 6e, f). The amphibole-rich emulsions are present as an assortment of bubble-like heterogeneities ranging

from spherical to subspherical in shape. This non-porphyritic emulsion rock occupies a small portion of the study domain, sandwiched between the mingled rocks and the porphyritic intermediate rock.

(d) *Porphyritic intermediate rock* The porphyritic hybrid rock is a homogenized product of magma mixing. It is a grey-coloured homogeneous mixed rock in which individual components of the mafic and felsic magmas could not be identified. It is the last category of hybrid rock

which is in contact with the emulsion rock and it occupies a significant portion of the GRD (Gogoi et al. 2021b). Plagioclase phenocrysts are distinctively visible in the hand sample. The phenocrysts are set in a fine- to medium-grained grey groundmass giving the rock its characteristic porphyritic nature (Fig. 7a). Also, abundant rapakivi feldspars are seen in these rocks (Fig. 7b). The presence of rapakivi feldspars is an important textural feature which characterizes hybrid rocks that have formed as a result of mixing between compositionally dissimilar magmas (Hibbard 1991; Baxter and Feely 2002).

The various rock types discussed above are haphazardly distributed within the felsic dome. However, based on field observations, we were able to establish field relationships between the different rock units to some extent. The mafic rocks consisting of felsic clasts mostly occupy the outer portion of the felsic dome. These rocks are seen at the junction of the intermingled mafic–felsic rocks. At the other end, the mingled rocks share their contacts with the porphyritic hybrid rock and the non-porphyritic rock displaying an emulsion texture. At a few places, contacts between the emulsion rock and the porphyritic rock are well exposed. On the other hand, unaltered felsic rocks are present as randomly distributed isolated pockets throughout the GRD.

4 Analytical methods

Mineral composition was determined with the Electron Probe Micro Analyzer (EPMA) CAMECA SXFive instrument at the Geological Survey of India, Kolkata, India. The CAMECA SXFive instrument was operated by SXFive Software at a voltage of 15 kV and 12 nA current with a LaB_6 source in the electron gun for generation of electron beam. The natural silicate mineral andradite was used as

internal standard to verify the positions of crystals (SP1-TAP, SP2-LiF, SP3-LPET, SP4-LTAP, and SP5-PET) for corresponding wavelength dispersive (WD) spectrometers (SP). The following X-ray lines were used in the analyses: F-Kα, Na-Kα, Mg-Kα, Al-Kα, Si-Kα, P-Kα, Cl-Kα, K-Kα, Ca-Kα, Ti-Kα, Cr-Kα, Mn-Kα and Fe-Kα. Natural mineral standards fluorite, halite, apatite, periclase, corundum, wollastonite, orthoclase, rutile, chromite, rhodonite, and hematite standard supplied by CAMECA-AMETEK were used for routine calibration, X-ray elemental mapping, and quantification. Routine calibration, quantification, acquisition, and data processing were carried out using SxSAB version 6.1 and SX-Results software of CAMECA. The precision of the analysis is better than 1% for major element oxides and the error on trace elements concentrations varied between 3% and 5% based on repeated analysis of standards.

5 Mineral chemistry

Mineral chemical analyses were carried out on two important mineral phases (i.e., amphibole and titanite) occurring in the mafic rock with felsic clasts to understand the small-scale processes of magma mixing that operated in this particular rock.

5.1 Amphibole

Amphibole compositions were determined from the mafic as well as the felsic zones to check for compositional variations in this particular mineral. Amphiboles from the mafic zones show a linear variation in composition, plotting in the fields of actinolite, magnesio-hornblende, and ferro-hornblende (Fig. 8a), whereas amphiboles from the felsic clasts show linear compositional variation from
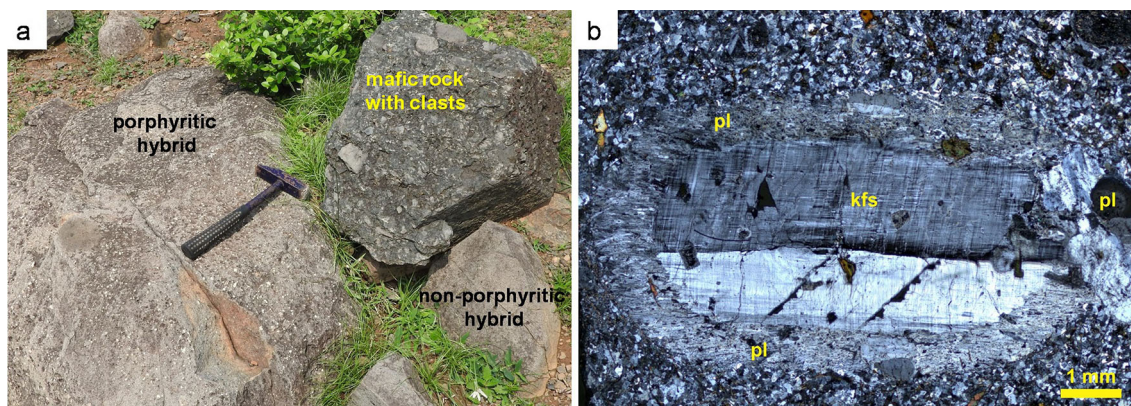

Fig. 7 a Field photograph showing the porphyritic intermediate rock along with non-porphyritic intermediate rock and mafic rock with felsic clasts **b** photomicrograph showing rapakivi feldspar preserved in the porphyritic intermediate rock. Note the cellular morphology of plagioclase surrounding the K-feldspar phenocryst. Mineral abbreviations: kfs = Kfeldspar, pl = plagioclase

magnesio-hornblende to ferro-hornblende (Fig. 8b). Representative compositions of amphiboles from the mafic zones are presented in Supplementary Table 1 and those from the felsic zones are reported in Supplementary Table 2.

The linear compositional variations observed in amphibole chemistry from the mafic and felsic zones suggest the interplay of complex substitutions in individual amphibole sites. Such substitutions can be recognized using simple cationic schemes that relate a number of endmember amphibole compositions to the tremolite (Tr) endmember (Czamanske and Wones 1973; Blundy and Holland 1990; Castro and Stephens 1992). One such substitution is the edenite (Ed)-type substitution in which the addition of alkalis in the A site is compensated by the incorporation of Al in the tetrahedral site. This common substitution may be formulated as:

$$Si + \square_A = Al^{iv} + Na_A \tag{1}$$

Another important substitution in amphiboles is the tschermakite (Ts)-type substitution in which divalent cations are replaced by octahedrally coordinated Al in the M1-M3 sites. The Ts-type substitution may be formulated as:

$$Si + R^{2+}_{(M1-M3)} = Al^{iv} + Al^{vi} \tag{2}$$

The aforementioned substitutions can be recognized using simple cationic plots (Fig. 9). The Ed-type substitution can be recognized using alkalis in the A site versus Al^{iv} plot (Fig. 9a), whereas octahedral sites versus Al^{iv} plot (Fig. 9b) can be used to recognize Ts-type substitution.

Amphibole compositions from the studied rock display good linear correlation in both plots suggesting the role of both Ed- and Ts-type substitutions. However, the correlation in the octahedral sites versus Al^{iv} plot is better than in the alkalis versus Al^{iv} plot. This suggests that Ts-type substitution has played a more prominent role in the amphibole chemistry of the studied rock.

Cationic substitutions in amphiboles can also be recognized using the vector plot of Blundy and Holland (1990). The vector plot is an efficient tool to recognize simple cationic schemes that relate a number of endmember amphibole compositions to the tremolite (Tr) endmember. The compositional vector of amphiboles from the studied rock point towards the pargasite (Pg) endmember (Fig. 10). Thus, amphiboles occurring in the mafic rocks with felsic clasts have undergone pargasite substitution, which is an amalgamation of Ed- and Ts-type substitutions.

5.2 Titanite

Titanite compositions were determined from grains that occur in association with amphiboles and those which are present as individual entities in the felsic zones. Backscattered electron (BSE) images clearly illustrate the extensive replacement of amphibole by titanite in the studied rock (Supplementary Fig. 1). Representative EPMA analyses of titanite are presented in Supplementary Table 3. Mineral chemical analyses have revealed that titanite exhibits similar compositions throughout the studied rock, which suggests a common origin for the mineral in this rock (i.e., replacement product of amphiboles). An
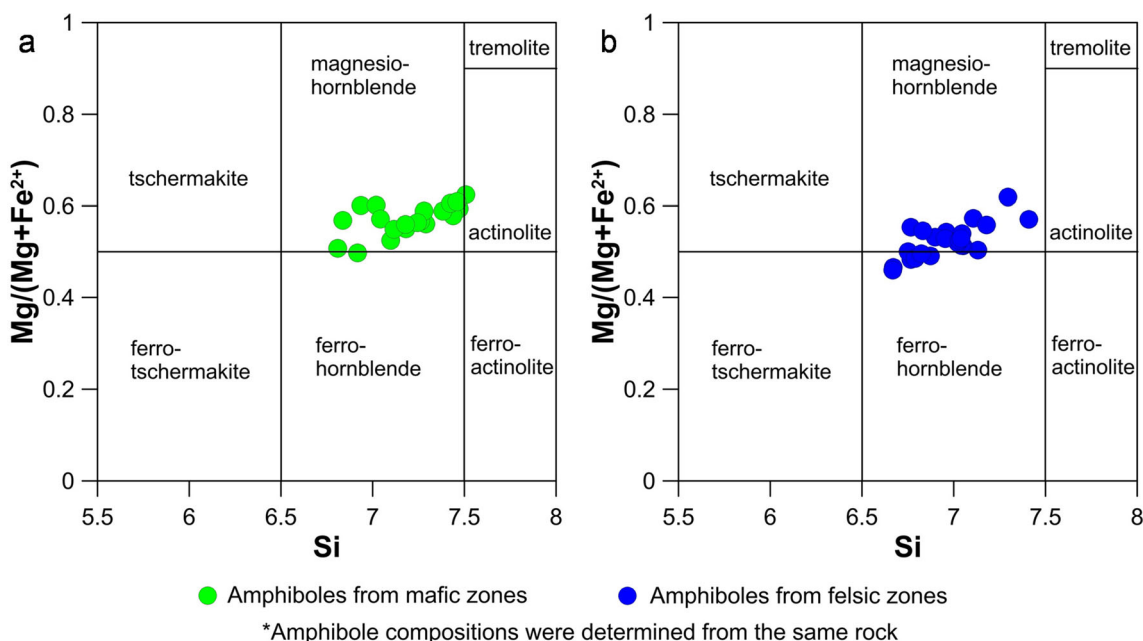

Fig. 8 Classification of amphiboles from **a** mafic zones **b** felsic zones
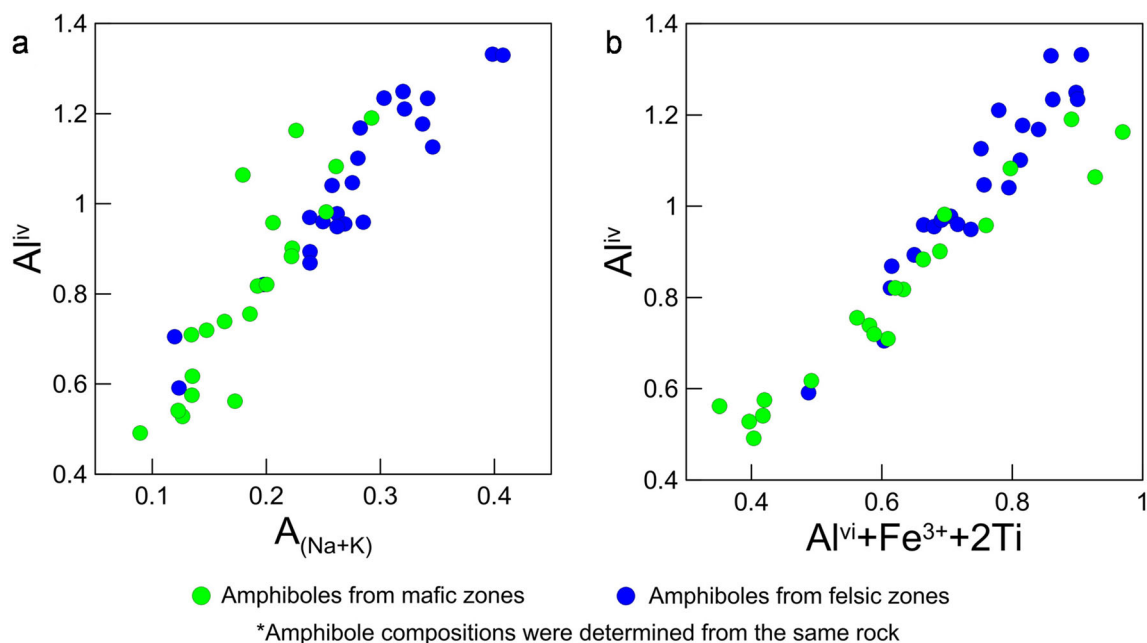
Fig. 9 Cationic substitution plots **a** alkalis in the A site versus Al^{iv} **b** octahedral sites versus Al^{iv}. Colors represent: green = amphiboles from mafic zones, blue = amphiboles from felsic zones
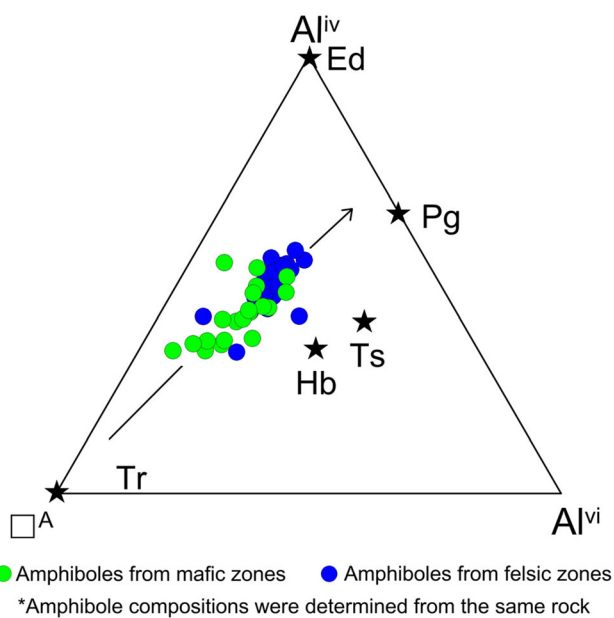

Fig. 10 Vector plot of Blundy and Holland (1990). Abbreviations: Ed = edenite, Tr = tremolite, Ts = tschermakite, Hb = hornblende, Pg = pargasite. Colors represent: green = amphiboles from mafic zones, blue = amphiboles from felsic zones

effort was made to look for possible substitutions in our titanite. The most common substitution observed in titanite is the replacement of Ti in octahedral coordination by Fe and Al (Kiss and Zaccarini 2020; Kowallis et al. 2022). The strong negative correlation observed in the Fe + Al versus Ti plot (Fig. 11) suggests the role of Fe and Al

substitutions in the Ti octahedral sites. Furthermore, it has been observed that titanite occurring in association with amphiboles displays higher Fe/Al ratios in comparison to titanite that occurs as individual entities in the felsic zones (Fig. 12). Thus, titanite associated with amphiboles is relatively more Fe-rich than those that occur as individual grains.

6 Discussion

6.1 Physical processes facilitating magma mixing in the studied rock

The Ghansura Rhyolite Dome was a subvolcanic felsic magma chamber that was invaded by mafic magma during its evolution to form a wide variety of hybrid rocks (Gogoi and Chauhan 2021). A substantial solidified portion of the felsic reservoir was embedded in the incoming mafic magma to form mafic rocks with felsic clasts (Fig. 4). Two distinct compositional zones could be identified in this rock- (a) medium-grained mafic zones that are dominated by amphiboles; (b) fine-grained felsic zones consisting primarily of quartz and feldspar. Petrographical observations have revealed that most of the felsic clasts consist of amphibole crystals, largely acicular in habit (Fig. 5a–d). These crystals undoubtedly appear to have been transferred to the felsic domains from the amphibole-rich mafic zones. Thus, the crystal transfer mechanism has played an important role in facilitating the mixing process in the
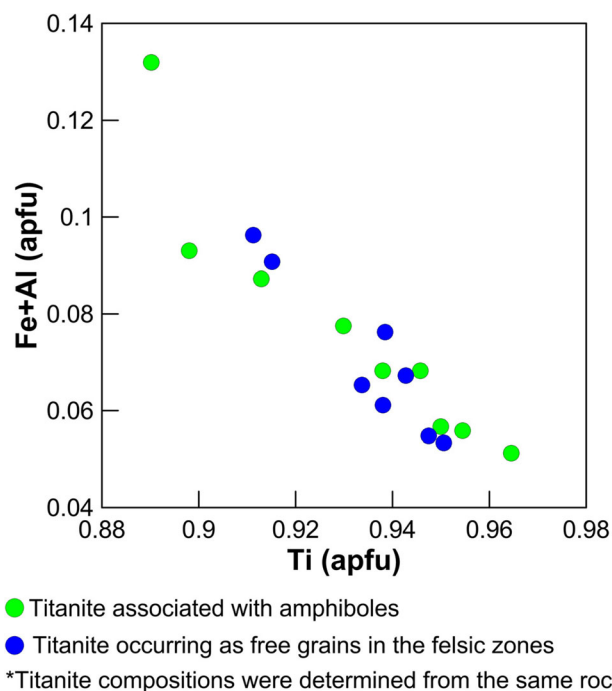
Fig. 11 Fe + Al versus Ti content of titanite. Colors represent green = titanite associated with amphiboles, blue = titanite occurring as free grains in the felsic zones
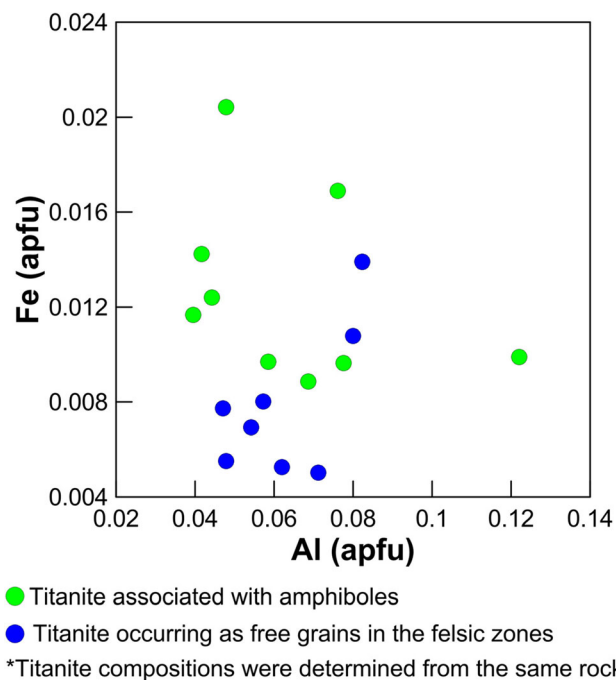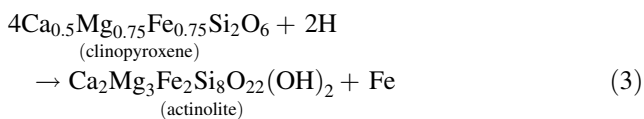

Fig. 12 Al versus Fe content of titanite. Colors represent green = titanite associated with amphiboles, blue = titanite occurring as free grains in the felsic zones

studied rock. It has been observed that amphibole crystals display different degrees of transfer from the mafic to the felsic zones such that some of the felsic zones contain less

amphibole while others are abundant in it (Supplementary Figs. 2, 3). It has to be noted here that the differential transfer of crystals to the felsic zones from the mafic zones is possible only in a viscous or ductile state. Thus, the high-temperature mafic magma must have significantly increased the temperature of the system, thereby modifying the physical properties of the felsic clasts from exhibiting solid-like behaviour at a lower temperature to liquid-like behaviour at a higher temperature. The liquid-like response of the felsic clasts allowed amphibole crystals to migrate from the amphibole-rich mafic zones to the felsic zones. Other than amphiboles, anhedral grains of titanite were also observed migrating from the mafic to the felsic zones. Titanite in the studied rock seems to have been transported through the veining mechanism (Fig. 5e, f). Such mineral-transporting veins carrying titanite from mafic to felsic zones in mingled rocks have been reported by Gogoi et al. (2018b) (Supplementary Fig. 4). These mineral-transporting veins can act as a powerful tool to enhance mixing between crystal-rich magmas. Thus, crystal transfer and veining mechanism were the dominant small-scale mechanical processes that facilitated mixing between the mafic and felsic phases in our studied rock. The degree of physical mixing in a hybridized rock can be estimated from the degree of homogenization attained by the participating discrete magmas or phases. In our scenario, discrete mafic and felsic zones could be easily identified in the mafic rocks with felsic clasts, suggesting that the overall degree of physical mixing was poor in the studied rock.
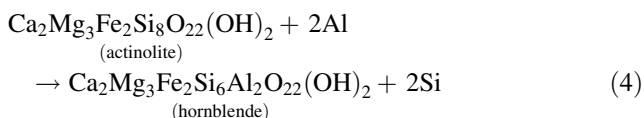
6.2 Chemical processes facilitating magma mixing in the studied rock

The mafic rocks exposed in the GRD dominantly consist of clinopyroxene (augite) and plagioclase (Gogoi and Chauhan 2021). However, the mafic zones in our studied rock essentially consist of amphiboles. This implies that amphiboles were produced from earlier pyroxene crystals from the mafic magma. The replacement of clinopyroxene by amphiboles was facilitated owing to the interaction of the mafic magma with felsic clasts. Replacement of former pyroxene initially crystallized in the mafic magma by amphibole is a common phenomenon during mafic–felsic magma interaction (Vernon 1990; Castro and Stephens 1992; Choe and Jwa 2004; Gogoi and Saikia 2018). The first step during the interaction between clinopyroxene-bearing mafic magma and felsic magma is the replacement of clinopyroxene by actinolite. Replacement of clinopyroxene by actinolite is facilitated owing to the diffusion of volatiles and H ions from the felsic to the mafic domain. This conversion can be written as

$$4Ca_{0.5}Mg_{0.75}Fe_{0.75}Si_2O_6 + 2H$$
$$\text{(clinopyroxene)}$$
$$\rightarrow Ca_2Mg_3Fe_2Si_8O_{22}(OH)_2 + Fe \qquad (3)$$
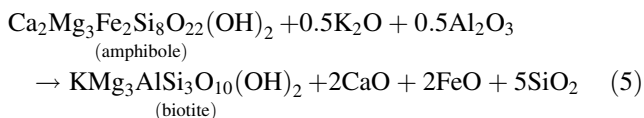$$\text{(actinolite)}$$

The occurrence of actinolite in the studied rock suggests that this mineral has formed by the solid-state reaction from augite, as actinolitic amphibole cannot crystallize from melt (Gogoi and Saikia 2019). Moreover, clinopyroxene-amphibole replacement is comparatively much easier than orthopyroxene–amphibole replacement. This is because orthopyroxene–amphibole replacement demands higher temperatures and larger mass transfers. The occurrence of clinopyroxene in the mafic rocks of GRD suggests that actinolite in the studied rock has formed by the replacement of primary clinopyroxene.

With further hybridization, the newly formed actinolite reacts with diffusing Al cations from the felsic domain to produce hornblende. This reaction can be written as

$$Ca_2Mg_3Fe_2Si_8O_{22}(OH)_2 + 2Al$$
$$\text{(actinolite)}$$
$$\rightarrow Ca_2Mg_3Fe_2Si_6Al_2O_{22}(OH)_2 + 2Si \qquad (4)$$
$$\text{(hornblende)}$$

The next step involves reaction of amphibole with diffusing K cations from the felsic magma to produce biotite. This reaction can be expressed as

$$Ca_2Mg_3Fe_2Si_8O_{22}(OH)_2 + 0.5K_2O + 0.5Al_2O_3$$
$$\text{(amphibole)}$$
$$\rightarrow KMg_3AlSi_3O_{10}(OH)_2 + 2CaO + 2FeO + 5SiO_2 \qquad (5)$$
$$\text{(biotite)}$$

Thus, with increasing hybridization clinopyroxene will produce actinolite followed by hornblende and biotite. During these transitions, a number of accessory phases like Fe–Ti oxides (titanite, ilmenite, etc.), calcite, and quartz are produced. These accessory phases are preserved in the hybrid rocks of our study area. It has to be noted here that the formation of a particular accessory phase will be governed by the degree of hybridization between the mafic and felsic components. The degree of chemical mixing between mafic and felsic magmas can be estimated by the appearance or abundance of biotite and the disappearance of ferromagnesian mineral phases like pyroxene and amphibole in the hybrid rocks. In our scenario, amphibole is the dominant ferromagnesian mineral, and biotite is not observed in the mafic rocks with felsic clasts, suggesting that the overall degree of chemical mixing was limited in the studied rock.

Amphibole compositions were determined from the mafic as well as the felsic zones in our studied rock. The mineral shows linear compositional variations (Fig. 8) suggesting the interplay of complex substitutions in individual amphibole sites. With the help of cationic plots

(Fig. 9), it has been observed that both Ed- and Ts-type substitutions have played an important role in the amphibole chemistry of the studied rock, with the Ts-type substitution playing a more prominent role. The vector plot of Blundy and Holland (1990) distinctly points towards Pg-type substitution (Fig. 10), which is an amalgamation of Ed- and Ts-type substitutions. Such substitutions in amphiboles during magma mingling events have been reported by earlier workers (Castro and Stephens 1992; Campos et al. 2005; Kocak et al. 2011; Ubide et al. 2014; Lisboa et al. 2020; Gogoi and Saikia 2018; 2019). A comparison of amphibole compositions reported in these works is illustrated in Supplementary Fig. 5. Most of these works have highlighted the role of pargasite substitution in their mingled rocks. From the above discussion, it may be inferred that cationic substitutions in amphiboles may be considered an important petrogenetic indicator to decipher magma mixing events. These substitutions occur in response to the mineral trying to attain an equilibrium within different zones (i.e., mafic, felsic, or hybrid) in a disequilibrated mingled system.

Amphiboles in our studied rock have been extensively replaced by titanite (Fig. 5). Extensive replacement of amphibole by titanite owing to magma mixing has earlier been documented by Gogoi et al. (2017). Titanite produced in the mafic zones due to the destabilization of amphiboles was observed migrating from the mafic to the felsic zones. Titanite is a Ca–Ti silicate mineral. The felsic zones in our studied rock were in all probability depleted in Ca and Ti. The movement of titanite from the mafic to the felsic domains was enriching the felsic zones in these two elements, thereby facilitating the process of chemical diffusion to attain equilibrium in the mingled system. Thus, movements of mineral phases as chemical species during magma mixing events can significantly enhance the process of chemical diffusion. Moreover, titanite from our studied rock also displays cationic substitutions (Fig. 11) suggesting the interaction between mafic and felsic domains at the small scale.

7 Conclusions

Magma mixing is a ubiquitous geological phenomenon and is considered one of the most important petrological processes. Although there has been much advancement in knowing about the mechanisms persistent during magma mixing at a grander-scale, i.e., in magma chambers or conduits; very little knowledge is available regarding the dynamics of small-scale processes. This work has implications for understanding magma mixing processes operating at the grain scale. Here, we would like to infer that.

(1) Crystal transfer mechanism has played an important role in promoting mixing between felsic clasts and mafic magma in our studied rock.

(2) Mineral-transporting veins have significantly improved the crystal transfer mechanism by transporting titanite from the mafic to the felsic zones.

(3) Extensive replacement of amphibole by titanite may be considered an important petrogenetic indicator of magma mixing.

(4) Cationic substitutions in amphiboles may be regarded as another important petrogenetic indicator to decipher magma mixing events. This also holds true for cationic substitutions in titanite.

Declarations

Conflict of interest The authors declare that in this present work there is no conflict of interests.

References

Agangi A, Mcphie J, Kamenetsky VS (2011) Magma chamber dynamics in a silicic LIP revealed by quartz: the Mesoproterozoic Gawler Range Volcanics. Lithos 126(1–2):68–83

Ahmad M, Wanjari N (2009) Volcano-sedimentary sequence in the Munger-Rajgir metasedimentary belt, Gaya district, Bihar. Indian J Geosci 63:351–360

Ahmad M, Paul AQ (2013) Investigation of volcano-sedimentary sequence and associated rocks to identify gold and base metal mineralization at Gere-Kewti Area of Gaya District, Bihar (G4). Unpubl Rep Geol Soc India, Bangalore

Ahmad M, Paul AQ, Negi P, Akhtar S, Gogoi B, Saikia A (2021) Mafic rocks with back-arc E-MORB affinity from the Chotanagpur Granite Gneiss Complex of India: relicts of a Proterozoic Ophiolite suite. Geol Mag 158:1527–1542

Anderson AT (1976) Magma mixing: petrological process and volcanological tool. J Volcanol Geotherm Res 1:3–33

Barbarin B, Didier J (1992) Genesis and evolution of mafic microgranular enclaves through various types of interaction between coexisting felsic and mafic magmas. Trans R Soc Edinburgh: Earth Sci 83:145–153

Bateman R (1995) The interplay between crystallization, replenishment and hybridization in large felsic magma chambers. Earth Sci Rev 39:91

Baxter S, Feely M (2002) Magma mixing and mingling textures in granitoids: examples from the Galway Granite, Connemara. Ireland Mineral Petrol 76(1):63–74

Blundy JD, Holland TJB (1990) Calcic amphibole equilibria and a new amphibole-plagioclase geothermometer. Contrib Mineral Petrol 104:208–224

Campos TFC, Neiva AMR, Naredi LVS, Pereira LS, Bonzanini LF, Petta RA, Meyer FM (2005) Magmatic epidote and amphibole from the Rio Espinharas hybrid complex, northeastern Brazil. Pesquiem Geocienc 32:41–55

Castro A, Stephens WE (1992) Amphibole-rich polycrystalline clots in calc-alkaline granitic rocks and their enclaves. Can Mineral 30:093–1112

Choe WH, Jwa YJ (2004) Petrological and geochemical evidences for magma mixing in the Palgongsan Pluton. Geosci J 8(4):343–354

Cole JW, Gamble JA, Burt RM, Carroll LD, Shelley D (2001) Mixing and mingling in the evolution of andesite-dacite magmas; evidence from co-magmatic plutonic enclaves, Taupo Volcanic Zone, New Zealand. Lithos 59:25–46

Czamanske GK, Wones DR (1973) Oxidation during magmatic differentiation, Finnmarka complex, Oslo area, Norway. 2. The Mafics Silicates J Petrol 14:349–380

Donoghue SL, Gamble JG, Palmer AS, Stewart RB (1995) Magma mingling in an andesite pyroclastic flow of the Pourahu Member, Ruapehu volcano, New Zealand. J Volcanol Geotherm Res 68:177–191

Dorais MJ, Whitney JA, Roden MF (1990) Origin of mafic enclaves in the Dinkey Creek Pluton, Central Sierra Nevada batholith, California. J Petrol 31:853–881

Gogoi B (2022) Late Paleoproterozoic bimodal magmatic rocks in the Nimchak Granite Pluton of the Bathani volcano-sedimentary sequence, Eastern India: implications for the Columbia supercontinent formation with respect to the Indian landmass. Period Mineral 91:1–20

Gogoi B, Chauhan H (2021) Dynamics of a subvolcanic magma chamber inferred from viscous instabilities owing to mafic–felsic magma interactions. Arabian J Geosci 14:1626

Gogoi B, Saikia A (2018) Role of viscous folding in magma mixing. Chem Geol 501:26–34

Gogoi B, Saikia A (2019) The genesis of emulsion texture owing to magma mixing in Ghansura Felsic Dome of Chotanagpur Granite Gneiss Complex of Eastern India. Can Mineral 57:311–338

Gogoi B, Saikia A, Ahmad M (2017) Titanite-centered ocellar texture: a petrological tool to unravel the mechanism enhancing magma mixing. Period Mineral 86:245–273

Gogoi B, Saikia A, Ahmad M (2018a) Field evidence, mineral chemical and geochemical constraints on mafic–felsic magma interactions in a vertically zoned magma chamber from the Chotanagpur Granite Gneiss Complex of Eastern India. Chem Erde 78:78–102

Gogoi B, Saikia A, Ahmad M, Ahmad T (2018b) Evaluation of magma mixing in the subvolcanic rocks of Ghansura Felsic Dome of Chotanagpur Granite Gneiss Complex, eastern India. Mineral Petrol 112:393–413

Gogoi B, Saikia A, Ahmad M (2020) Mafic-felsic magma interactions in the Bathani volcanic-plutonic complex of Chotanagpur Granite Gneiss Complex, eastern India: implications for assembly of the Greater Indian Landmass during the Proterozoic. Episodes 43(2):785–810

Gogoi B, Chauhan H, Saikia A (2021a) Understanding mafic-felsic magma interactions in a subvolcanic magma chamber using rapakivi feldspar: a case study from the Bathani volcano-sedimentary sequence, eastern India. Chem Erde 81(2):125730

Gogoi B, Hazarika G, Chauhan H (2021b) Origin of porphyritic texture by magma mixing in the andesitic rocks of Ghansura

Rhyolite Dome from the Bathani volcano-sedimentary sequence, Eastern India. Geochem J55:11–25

Grasset O, Albarede F (1994) Hybridisation of mingling magmas with different densities. Earth Planet Sci Lett 121:327–332

Hazarika G, Basumatary P, Prakash T, Chauhan H, Gogoi B (2022) Magma mixing dynamics in a vertically zoned granitic magma chamber inferred from feldspar disequilibrium assemblage and biotite composition: a case study from the Mikir Massif, eastern India. Acta Geochim 41(3):453–469

Hibbard MJ (1981) The magma mixing origin of mantled feldspars. Contrib Mineral Petrol 76:158–170

Hibbard MJ (1991) Textural anatomy of twelve magma-mixed granitoid systems. In: Didier J, Barbarin B (eds) Enclaves and granite petrology. Developments in petrology. Elsevier, Amsterdam, pp 431–444

Kiss GB, Zaccarini F (2020) Compositional variations of titanite: a possible new tool for cyprus-type volcanogenic massive sulfide deposit prospecting. Geosciences 10:290

Kocak K, Zedef V, Kansun G (2011) Magma mixing/mingling in the Eocene Horoz (Nigde) granitoids, Central Southern Turkey: evidence from mafic microgranular enclaves. Mineral Petrol 103:149–167

Kowallis BJ, Christiansen EH, Dorais MJ, Winkel A, Henze P, Franzen L, Mosher H (2022) Variation of Fe, Al, and F substitution in titanite (Sphene). Geosciences 12:229

Kuşcu GG, Floyd PA (2001) Mineral compositional and textural evidence for magma mingling in the Saraykent Volcanics. Lithos 56:207–230

Lisboa VAC, Conceição H, Rosa MLS, Marques GT, Lamarão CN, Lima ALR (2020) Amphibole crystallization conditions as record of interaction between ultrapotassic enclaves and monzonitic magmas in the Glória Norte Stock, South of Borborema Province. BrazJ Geol 50:1–10

Perugini D, Poli G (2005) Viscous fingering during replenishment of felsic magma chambers by continuous inputs of mafic magmas: field evidence and fluid-mechanics experiments. Geology 33(1):5–8

Saikia A, Gogoi B, Ahmad M, Ahmad T (2014) Geochemical constraints on the evolution of mafic and felsic rocks in the Bathani volcanic and Volcanosedimentary sequence of Chotangpur Granite Gneiss Complex. J Earth Syst Sci 123:959–987

Saikia A, Gogoi B, Kaulina T, Lialina L, Bayanova T, Ahmad M (2017) Geochemical and U-Pb zircon age characterization of granites of the Bathani Volcano Sedimentary sequence, Chotanagpur Granite Gneiss Complex, eastern India: vestiges of the Nuna supercontinent in the Central Indian Tectonic Zone. In: Pant NC, Dasgupta S (eds) Crustal evolution of India and Antarctica: the supercontinent connection, vol 457. The Geological Society of London, London, pp 233–252

Saikia A, Gogoi B, Ahmad M, Kumar R, Kaulina T, Bayanova T (2019) Mineral chemistry, Sr-Nd isotope geochemistry and petrogenesis of the granites of Bathani volcano-sedimentary sequence from the Northern Fringe of Chotanagpur GraniteGneiss Complex of Eastern India. In: Mondal M (ed) Geological evolution of the Precambrian Indian shield, society of earth scientists series. Springer, Cham, pp 79–120

Sparks RSJ, Marshall L (1986) Thermal and mechanical constraints on mixing between mafic and silicic magmas. J Volcanol Geotherm Res 29:99–124

Tepper JH, Kuehner SM (2004) Geochemistry of mafic enclaves and host granitoids from the Chilliwack Batholith, Washington: chemical exchange processes between coexisting mafic and felsic magmas and implications for the interpretation of enclave chemical traits. J Geol 112:349–367

Ubide T, Gale C, Larrea P, Arranz E, Lago M, Tierz P (2014) The relevance of crystal transfer to magma mixing: a case study in composite dykes from the central Pyrenees. J Petrol 55(8):1535–1559

Vernon RH (1990) Crystallization and hybridism in microgranitoid enclave magmas: microstructural evidence. J Geophys Res 95(B11):17849–17859

Vernon RH, Etheridge MA, Wall VJ (1988) Shape and microstructure of microgranitoid enclaves: indicators of magma mingling and flow. Lithos 22:1–11

Waight TE, Mass R, Nicholls IA (2001) Geochemical investigations of microgranitoid enclaves in the S-type Cowra granodiorite, Lachlan Fold Belt, SE Australia. Lithos 56:165–186

Weidendorfer D, Mattsson HB, Ulmer P (2014) Dynamics of magma mixing in partially crystallized magma chambers: textural and petrological constraints from the basal complex of the Austurhorn Intrusion (SE Iceland). J Petrol 55(9):1865–1903

Wilson M (1989) Igneous petrogenesis. Chapman and Hall, London