Submarine volcanic facies and its implication as possible tracker of sulphide mineralization – a study from Jilharidev area, Betul belt, central India

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Felsic volcanioclastic rock forms part of host rock sequences in many of the base metal prospects in the Betul belt. However, the volcanic facies, fragmentation processes and depositional environments in mineralized areas are poorly understood because of the effects of synvolcanic hydrothermal alteration and subsequent regional metamorphism. A section in the Kanhan river valley, which exposes volcanics with relatively well preserved primary textures was mapped in detail to understand the disposition of the felsic volcanics namely rhyolite and to identify the various volcanic facies present within them (viz. massive, flow-handed, autobreccia and hyaloclastite). Four different facies types were distinguished based on phenocryst type, size and abundance. Presence of hyaloclastite autioclastic rocks and pillow lava and absence of pyroclastic deposits suggest a deep, submarine, passive, effusive-type volcanic setting. Autobreccia and hyaloclastite in the felsic volcanic sequence of the present study area lying within Betul Belt has similarities with well-known volcanic-hosted massive sulphide (VHMS) bearing areas in other parts of the world. Proper identification of the volcanic facies within highly altered host rocks near the deposits can help in building up facies models that would establish the genetic relationship between sulphide mineralization and the host-rock facies which in turn will have important implications for base metal exploration in the area.

Keywords: Autobreccia, base metal exploration, Betul belt, hyaloclastite, massive rhyolite, submarine volcanic facies.

The felsic volcanic rocks belonging to the bimodal volcanic sequence of the Mesoproterozoic Betul belt contain a number of small base metal occurrences. It is being recognized that mineralization is of volcanic-hosted massive sulphide (VHMS) type and based on metal ratios, they range in spectrum from Zn–Cu to Zn–Pb–Cu type¹. Felsic volcanioclastics occur along with the massive rhyolites and form part of the host rock successions for sulphide mineralization¹⁻³. However, the fragmentation processes and depositional environments of these volcanioclastics are poorly understood. Recognition of primary volcanic facies near the prospects is difficult because of the effects of synvolcanic mineralizing hydrothermal alteration and subsequent regional metamorphism.

It is well known that volcanic setting and facies have significant influences on the style of mineralization, alteration patterns and metal content of VHMS deposits⁴⁻⁵. This study is an attempt at distinguishing the different phases of rhyolites and their associated facies based on primary volcanic textures that can be readily identified in the field. Their possible mode of origin is also discussed. For this purpose, a section in the Kanhan river valley near Jilharidev temple, 5 km north of Bhuyari Zn–Pb–Cu prospect was selected as the study area and mapped in detail to delineate the different rhyolite flows. Since primary volcanic textures are well preserved in the area, individual volcanic facies could be distinguished and studied in detail. This study indicates that fragmented felsic rocks present in the area are formed by autoclastic processes like flow-fragmentation (autobrecciation) and quench fragmentation and may have formed in a deep-water environment.

Regional geology

The study area is in Betul belt, an approximately 135 × 15 km, east–west trending, Mesoproterozoic inlier surrounded by sedimentary rocks of the Gondwana Supergroup towards the north and west and the Deccan basalts in the south and east. The Sausar belt is exposed to the southeast of Betul belt (Figure 1). The Betul belt which constitutes the central part of the E–W to ENE–WSW Central Indian Tectonic Zone (CITZ)⁷ contains three distinct suites of rocks, viz. supracrustal rocks, ultramafic suite, and syn- to post-kinematic granite suite. The belt is traversed by a number of ENE–WSW ductile shear zones with sub-vertical to steep northerly dips and show

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low to medium grade metamorphism. The tectonic setting may be nearer to the arc environment.

The central and eastern part of the Betul belt contains the bimodal volcanic sequence belonging to the Baragaon Group. Available whole rock geochemical data indicate the dominantly bimodal nature of the volcanics and their tholeiitic affinity. This part of the Betul belt contains several small base metal prospects namely those located at Banskhupa–Pipariya, Bhanwra–Tekra, Baragaon–Tarora, Ghisi, Mualiya, Koparpani, Dehalwara and Bhuyari.

Zn–Pb–Cu and Zn–Cu ore bodies are associated with metamorphosed hydrothermal alteration zones which contain various assemblages of metamorphic minerals which include chlorite, biotite, garnet, staurolite, sillimanite, gehlenite, anthophyllite, actinolite and tremolite. Ghosh and Praveen proposed that most of these minerals formed in a single metamorphic regime of continually decreasing growth kinetics generally linked to progressive cooling. Mahakud et al. reported that the rocks were metamorphosed to staurolite–almandine subfacies of
Figure 2. Field photographs of a. pillow lava; b. mafic autobreccia with clasts showing crude lineation (arrows); c. Apophyses of porphyritic granite in mafic volcanics showing chilled margins; d. massive facies of type-1 rhyolite showing large, abundant quartz (dark grains) and feldspar (white) phenocrysts; e. photomicrograph of type-1 rhyolite showing quartz phenocryst in a fine grained quartz-rich groundmass; f. field photographs of flow-banded facies of type-1 rhyolite with contorted flow banding.

almandine-amphibolite facies, and subsequently subjected to retrograde metamorphism.

The eastern part of the bimodal volcanic region is dominated by felsic volcanics (Figure 1). Felsic volcanics are composed of massive rhyolite, flow-banded rhyolite, felsic volcanioclastics and thin horizons of felsic chert. Felsic volcanics are intensely altered near mineralized areas like Bhuyari. A sequence of mafic volcanics (basalt) occurring to the north of the felsic volcanics is composed dominantly of pillow lavas (Figure 2 a). Massive and volcanioclastic facies are also present. The mafic volcanioclastics are composed of angular rafts like clasts which display a crude lineation and many clasts are flattened and stretched (Figure 2 b), indicating that these are products of autobrecciation. The mafic volcanics are intruded by younger porphyritic granites (Figure 2 c). These granites form the northern contact of the Betul belt in this area with the Gondwana Supergroup. The granites show minimum deformation and are related to the younger Navegaon granite as described by Mahakud et al.12. A regional ENE–WSW to EW trending schistosity with moderate southerly dips is developed in the rocks. The general E–W trend of the volcanics is deduced from the contact between the felsic and mafic volcanics, which is also sub-parallel to the regional schistosity.

The Bhuyari base metal prospect towards the south of the study area has many features similar to typical VHMS deposits and contains disseminated, vein and minor massive Zn–Pb–Cu sulphides.8,13 The prospect area is dominated by massive, quartz-porphyritic rhyolite which is intensely altered close to the ore bodies. Chemical analyses of felsic volcanic rocks at Bhuyari prospect show that they are rhyolitic in composition.9 Primary textures like relict flow banding are only occasionally preserved in the rhyolites. Ore bodies are hosted by hydrothermally altered and metamorphosed massive rhyolite which has given rise to
various assemblages of metamorphic minerals like quartz–muscovite schist, quartz–biotite–muscovite–garnet ± plagioclase ± staurolite ± garnet schist and tremolite–carbonate rock. The tremolite–carbonate rocks are very localized in nature and based on their close spatial association with massive sulphide mineralization and preservation of relict soft-sediment, deformation structures are interpreted as meta-exhalites related to a mineralizing hydrothermal vent. Metamorphosed hydrothermally altered felsic volcanics occur as lensoid bodies comparable to the volcanic sequence near Pipariya, Belkheri and Jiyadehi villages (Figure 1). At these places, the altered rocks consist of quartz–sericite ± garnet schist, quartz–chlorite–garnet schist and quartz–biotite–chlorite ± garnet schist and their alteration pattern is similar to those in other prospects of Betul belt. Outcrops of altered rocks at Belkheri contain specks of sphalerite, galena and chalcopyrite along with disseminated pyrite and pyrrhotite. Bed rock values of altered rock from Pipariya and Belkheri show anomalous values for zinc and lead. Such garnet bearing quartzo-feldspathic schist rocks showing bed rock base metal anomalies have been observed to occur between Kohat and Lawagohri, a few kilometres to the south of Bhuvari and it was proposed that these rocks may represent an exhalative component of the felsic volcanics.

**Brief overview on submarine felsic volcanics**

Submarine silicic lavas can be divided into three main types: lava domes, laterally extensive lava flows and largely intrusive high-level domes (cryptodomes) that intrude the sediment pile and rarely breach the sediment surface. De Rosen-Spence et al. found that the rhyolitic to dacitic Archean flows of the Rouyn-Noranda area vary from above-vent domes to more extensive tabular masses, however they commonly formed stacked sequences of lavas with their boundaries being marked by variations in the abundance and size of quartz and plagioclase phenocrysts. For rocks related to intrusions and lavas, individual facies correspond to various different textural components of the body, based on which Allen identified massive coherent lava, flow banded coherent lava, autobreccia and hyaloablacite as the main original facies within the silicic volcanic units hosting volcanic associated mineralization at Benamba, southeastern Australia. Submarine volcanioclastics could form by autobrecciation (flow-fragmentation), quench fragmentation, pyroclastic fragmentation and resedimentation. Submarine lavas consist of at least 30% by volume of autoclastic rocks (hyaloablacite and autobreccia). Autobreccias result from the fracturing of solidifying magma under the influence of shear stresses induced by the flow of nearby magma. They can form in intrusive magma masses but are more common in the margins of lava flows and may also occur within lavas. Autobreccias are usually coarse aggregates with minimal finely granular debris and they may form substantial proportions of lavas. Autobreccias have been identified in all submarine lava types from basaltic to rhyolitic.

Hyaloablacites are products of quench fragmentation, which may occur when hot magma and cold water come in contact, producing thermal stresses which lead to cooling contraction granulation. Originally applied the term ‘hyaloablacite’ to the broken, spalled glassy shells of basaltic pillows but its definition has evolved to include all quench-fragmented aggregates, irrespective of composition. Hyaloablacite may form when subaerial lavas flow into water, when lavas are erupted subaqueously, or when magma intrudes water-saturated sediments. Hyaloablacite can consist of large glassy blocks through to finely granulated sand and silt-size glassy fragments. Fragments generally have curvilinear surfaces and may be equant and blocky or blade-like and splintery in shape.

**Volcanic facies of the Jilharidev area**

Primary volcanic features and textural characteristics of the rhyolites in the eastern part of Betul belt are best exposed in the N–S trending Kanhan river section occurring to the north of the Bhuvari base metal prospect (Figure 1). The present study is restricted to the identification of rhyolite types and facies in a single section in the Kanhan river across the strike of the volcanics, lateral tracing of the rhyolite type and facies was not attempted due to thick forest cover and scanty outcrops. Depending on the nature and size of the phenocrysts and their relative proportions, four different types of rhyolites (Types 1–4) and based on structures and textures present in them, four different facies (massive coherent lava, flow banded lava, autobreccia and hyaloablacite) were recognized. Besides rhyolites, the mapped area also contains (1) 10–20 m wide conformable metabasic sill; (2) 10 m wide mafic extrusive (basalt) with ill-preserved pillows and (3) few 50–100 m wide mafic intrusive rocks represented by dolerite and hornblende gabbro. Structurally, most rocks in the area are massive in nature and display minimum deformation. Only a crude foliation could be identified at places with strike parallel to the E–W trend of the volcanics and moderate dips to the south. Although no pronounced hydrothermal alteration is present in the rocks, the rhyolites at many places show extensive development of 1–3 cm long hornblende along with discrete crystals of magnetite and rare garnets; such hornblende-bearing rhyolites are common in Betul belt and may represent low intensity hydrothermal alteration. Pyrites is ubiquitous in the rhyolites of the area and occur as disseminations and rarely as 1 cm clots, the presence of pyrite also indicates hydrothermal activity. The weathering of pyrite gives the rhyolites a deep red surface
Table 1. Different types of volcanic facies of the Jilharidev area

<table>
<thead>
<tr>
<th>Type</th>
<th>Mode of occurrence</th>
<th>Phenocryst</th>
<th>Groundmass</th>
<th>Dominant structural/texture pattern</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>Type-1</td>
<td>Massive coherent facies, locally flow banded</td>
<td>Quartz and feldspar-phyric (together 20%), equal proportion of quartz and plagioclase phenocrysts evenly distributed, quartz phenocrysts are generally 3 mm and feldspar phenocrysts are &lt;5 mm in size. The quartz phenocrysts are rounded to euhedral in shape and show varying degrees of resorption of grain margins whereas feldspars are generally euhedral plagioclase laths</td>
<td>Finer grained mosaic of mainly quartz, minor feldspar and sericite</td>
<td>Flow banding, porphyritic</td>
<td>Features in this rhyolite (viz. the large and abundant phenocrysts, mostly massive nature and absence of hyaloclastite) are similar in character to sub-volcanic rhyolite domes and sills, which are common in rhyolite lava complexes(^5,26)</td>
</tr>
<tr>
<td>Type-2</td>
<td>Massive (60%) autocrastics (30%) flow banded (10%)</td>
<td>Aphyric to sparsely feldspar-phyric</td>
<td>Fine grained feldspar and quartz</td>
<td>Brecciated/fragmented (flow fragmentation), microbreccia (quench fragmentation), flow banding, porphyritic, Nodular devitrification texture (1-3 cm diameter)</td>
<td>Autobreccia with hyaloclastite matrix indicates that auto-brecciation and quench fragmentation occurred simultaneously. These features together with presence of widespread planar flow banding in this rhyolite gives evidence for extrusion of lava on to the sea floor</td>
</tr>
<tr>
<td>Type-3</td>
<td>Hyaloclastite (80%) with small lobes of massive facies</td>
<td>Dominantly feldspar-phyric (15-20%) with (&lt;3%) quartz</td>
<td>Fine grained feldspar and quartz</td>
<td>Microbreccia, porphyritic, ill-developed flow banding</td>
<td>Appears to have been emplaced as an extensive flow, which has had extensive interaction with seawater</td>
</tr>
<tr>
<td>Type-4</td>
<td>Mainly massive with intermittent thin flow banding</td>
<td>Aphyric to sparsely feldspar-phyric</td>
<td>Cryptocrystalline quartz-feldspathic material</td>
<td>Planar flow banding, porphyritic, nodular devitrification texture (&lt;1 cm diameter)</td>
<td>Presence of planar flow banding and extensive nodular devitrification textures indicate that this rhyolite was originally glass-rich extrusive lava</td>
</tr>
</tbody>
</table>

colour. Characteristics of different types of volcanic facies are given in Table 1.

**Type-1 rhyolite**

Type-1 rhyolites occur mainly as massive coherent facies and are only locally flow banded. Type-1 rhyolites are strongly quartz and feldspar-phyric, with about 20% quartz + feldspar phenocrysts and quartz phenocrysts are generally less than 3 mm and feldspar phenocrysts are less than 5 mm in size. This rhyolite has an equal proportion of both quartz and plagioclase phenocrysts evenly distributed in a quartz-feldspathic groundmass (Figure 2d). The quartz phenocrysts are rounded to euhedral in shape and show varying degrees of resorption of grain margins (Figure 2e), whereas feldspars are generally euhedral plagioclase laths. The groundmass consists of a finer grained mosaic of mainly quartz and minor feldspar and sericite. Flow banding is present as mm to cm thick alternating layers of light siliceous and dark phyllosilicate rich layers. Evidence for viscous flow is provided by contorted flow banding (Figure 2f). Disseminated pyrite is commonly present in the rock and at places the pyrite forms centimetre sized aggregates. At places 1–3 cm long hornblende along with discrete grains of magnetite and rare garnets are present (Figure 3a).

Many of the features in this rhyolite (viz. the large and abundant phenocrysts, mostly massive nature and absence of hyaloclastite) are similar in character to sub-volcanic rhyolite dome and sills. Such domes and sills are common in rhyolite lava complexes\(^5,26\).

**Type-2 rhyolite**

Type-2 rhyolite is sparsely feldspar-phyric with up to 5% (<1 mm) feldspar phenocrysts and quartz phenocryst are
absent. Volumetrically this rhyolite contains approximately 60% massive facies, 30% autoclastics (autobreccia and hyaloclastites) and about 10% flow-banded facies. The massive facies is aphyric to sparsely feldspar-phryic rhyolite and quartz phenocrysts are absent or rare. At places the massive facies rock show 1–3 cm, rounded, white coloured quartzo-feldspathic aggregates. They form discrete and interconnected masses with bulbous, cauliflower-like margins (Figure 3 b). These textures are similar to nodular devitrification textures as described by Allen\textsuperscript{14}, where they are similar to other devitrification structures like large spherulites and lithophyseae. When devitrification spreads radially outwards from a smaller number of nuclei or spreads further out from flow bands, more irregular, nodular to cauliflower shaped devitrification was formed; they commonly exhibit sharp, finely bulbous margins, which are devitrification fronts. They can form interconnected structures. Growth of such textures requires a coherent glassy host and they are therefore to be expected only in lavas, shallow intrusions, or strongly welded glassy pyroclastic rocks\textsuperscript{14}.

Type-2 rhyolite displays spectacular development of flow-banded facies, which occur in a number of parallel zones ranging from few centimetres to several metres wide within the massive and autoclastic facies, the layering in the flow bands is mostly planar with strike generally parallel to those of the volcanic sequence (Figure 3 c). Flow banding is considered to be a record of the movement of the lava mass\textsuperscript{37}. Flow bands consist of alternating mm to cm thick light and dark coloured layers.
The pale siliceous layers are considered to represent devitrified glass and the dark phyllosilicate layers are nondevitrified altered glass and such layering is formed when devitrification commences from numerous nuclei along a primary flow foliation and progresses a short distance from the flow fabric as relatively planar devitrification fronts\(^\text{13}\). At places wispy, flame-like textures are found extending from the flow bands (Figure 3d); these may have developed due to compaction and shearing of flow-bands in a semi-molten state.

A 10–40 m wide horizon of in situ and clast rotated autoclasis rocks which consist of both autobreccia and hyaloclastite occur intercalated with flow banded facies within the type-2 rhyolite near the contact with the type-1 massive rhyolite (Figure 1). Although autobreccia and hyaloclastite occur together in this rhyolite, they have formed by different processes and can be differentiated based on certain textural features.

Autobreccia consists of large, blocky to medium sized clasts, which routinely preserve flow-bandling and commonly occur adjacent to flow-banded rhyolite (Figure 3e), indicating that they formed by breaking up of flow-banded rhyolite. Autobreccias can be distinguished from hyaloclastite by the flow-banded character of the clasts and by the paucity of granule sized clasts\(^\text{15,16}\). Locally, in situ autobreccia is preserved in which flow-bands continue into adjacent clasts (Figure 3f), in situ breccias occur as pockets within more widespread disorganized aggregates. Unequivocal evidence for brecciation to have occurred during flow of the lava is provided by lineated flow-banded clasts which preserve a flow fabric (Figure 4a), these clasts are tightly packed, flattened and stretched to elongate shapes giving evidence for plastic moulding or accommodation of shapes, such features are formed when the breaking magma is plastic\(^\text{5}\).

Hyaloclastite can be distinguished from autobreccia by their lack of flow banding and plastic deformation textures. Hyaloclastite can also be differentiated because they can also occur as small granule sized clasts and frequently they occur as fine-grained microbreccia between the intergranular spaces of larger flow-banded clasts of autobreccia (Figure 3f). De Rosen-Spence et al.\(^\text{15}\) suggested that autobrecciation and quench fragmentation can occur simultaneously, where initial autobrecciation, particularly of viscous magma which breaks by brittle fracture, would give water access to the interior of the flow, so triggering quench fragmentation. Kokelaar\(^\text{20}\) also suggested that hyaloclastite may result from the dynamic stressing of chilled lava surfaces as lava continues to flow.

At places, the autoclastic facies is mainly composed of hyaloclastite, these consist of clasts which show a size range from sand sized microbreccia to block sized clasts, and more commonly contain pebble sized clasts. They form closely spaced, polygonal fragments with curvilinear and serrated margins that are common (Figure 4b).Certain groups of clasts display jigsaw-fit textures (Figure 4c), these occur as isolated in a more disorganized hyaloclastic matrix. Occurrence of such jigsaw-fit textures between groups of clasts is considered a diagnostic feature of in situ hyaloclastite\(^\text{25}\). Also, these breccias do not show flow banding and are not intimately associated with flow bands or show flow fabric, these evidences indicate that parts of the autobreccias in flow-2 rhyolite have formed exclusively by quench-fragmentation.

Minimum deformation in the rocks together with the unequivocal evidences as given above for the presence of autobreccia and hyaloclastite clearly indicates that fragmentation was caused by primary autoclastic processes. Autobreccia with hyaloclastite matrix in type-2 rhyolite indicates that autobrecciation and quench fragmentation occurred simultaneously. These features together with the presence of widespread planar flow-bandning in this rhyolite give evidence for extrusion of lava on to the sea floor. A thin 10 m wide outcrop of pillows metasalt separates type-2 rhyolite from type-3 rhyolite, pillows are not well-developed and outcrops of this metasalt are scanty. The rock is fine grained and composed of chloritized amphibole and plagioclase.

**Type-3 rhyolite**

This rhyolite mainly consists of hyaloclastite facies which encloses small lobes of massive facies. Volumetrically, it contains almost 80% of hyaloclastite. Massive coherent rhyolite is represented by a moderately to strongly porphyritic rhyolite characterized by 15–20%, less than 2 mm phenocrysts of plagioclase feldspar (Figure 4d). Quartz phenocrysts are up to 3% and not readily apparent to the naked eye, however small (<1 mm) rounded phenocrysts can be seen with a hand lens. Massive coherent lava exists as small lobes within more extensive hyaloclastite of the same rhyolite. Flow banding, although present, is not well developed. Hyaloclastic consists of mm to cm sized angular fragments that show polygonal to splintery shapes with curvilinear margins (Figure 4e). Clasts are monomictic and preserve the same phenocryst size and abundance of the massive coherent facies. Rarely, do they contain coarse block sized clasts. Absence of flow banded clasts and the predominance of small clasts ranging from sand sized to less than 2 cm distinguish this breccia as hyaloclastites.

Type-3 rhyolite appears to have been emplaced as an extrusive flow, which has had extensive interaction with seawater. It is distinguished from type-2 rhyolite on the basis of its moderately to strongly porphyritic nature, absence of autobreccia and by the predominance of hyaloclastite microbreccia. A 20 m wide concordant amphibolite (meta-dolerite) sill is present within this rhyolite. The rock is medium grained and composed mainly of green coloured amphibole, chlorite and plagioclase.
**Type-4 rhyolite**

Type-4 rhyolite is an aphyric to sparsely feldspar-phyric rhyolite with up to 3%, less than 1 mm feldspar phenocrysts. This rhyolite has a smooth surface appearance on account of the lack of phenocrysts and clasts. Most of the rhyolite is composed of massive coherent facies with intermittent thin zones of flow-banded facies. Massive coherent lava consists of extremely fine grained cryptocrystalline quartzo-feldspathic material and ranges from being aphyric to sparsely feldspar porphyritic with up to 3% less than 1 mm euhedral feldspar phenocrysts. Nodular devitrification textures are common in this rhyolite, they are similar but smaller in size to those in type-2 rhyolite, generally less than 1 cm in diameter and has a distinct cauliflower-like shape, they occur as discrete and coalesced aggregates (Figure 4f). Flow banding is extremely planar and thinly layered with layering parallel to the E–W strike of the volcanics with vertical dips. Flow banding is not associated with autobreccia. This rhyolite could at places be confused for thinly laminated chert, because of the straight, apparently sedimentary laminations and fine grain size of the rock. However, presence of feldspar phenocrysts and nodular devitrifying textures provide unequivocal evidence for a volcanic parentage. Presence of planar flow banding and extensive nodular devitrification textures indicate that this rhyolite was originally glass-rich extrusive lava.
Discussion

In the study area in Kanhan river section near Jilhariedev, four different types of rhyolite emplacement can be distinguished mainly based on their phenocryst-mineralogy, phenocryst size and abundance. This indicates that multiple phases of extrusive and some related intrusive phases were associated with this lava complex. These might be similar to the submarine dome and lava complex as described by Cas5 which are nonexplosive siliceous volcanic centres dominated by coherent lavas, cross cutting dykes and feeders, hyaloelastics and autobrecia. Also, the presence of multiple types of rhyolite and associated facies in the study area indicate that they comprise a proximal (volcanic centre or vent area) to medial facies association. De Rosen-Spence et al.15 have identified systematic proximal to distal variations in Archean lavas, where the proximal facies consists mainly of massive lavas and medial facies consists of lava lobes in hya landsite breccia. Proximal facies association as described by Allen et al.29 consists of multiple generations of lavas and in situ hyaloelastics breccia.

At Jilhariedev area, the common association of hyaloelastics in the felsic volcanic succession together with the presence of pillow basalt lavas indicates that the volcanics were extruded in a submarine setting. Volcanic facies association of lavas and autoelastic rocks at Jilhariedev area indicate passive submarine volcanism rather than explosive pyroclastic eruption. The facies association within the felsic volcanics comprising massive, flow-banded and autoelastic (autobreccia and hyaloelastics) facies are considered to be products of effusive hyaloclastite eruptions that are formed at submarine volcanic centres6,29 and represent ambient submarine volcanism7.

Explosive eruptions are generated by volatiles of varying origins. The most common volatiles are exsolved magmatic volatiles, such as water and carbon dioxide (magmatic explosions30) or superheated external water in contact with the magma (phreatic explosions) or a combination of magmatic volatiles and superheated external water which are known as phreato-magmatic explosions31,32. In case of submarine lava-forming eruptions, the non-explosive nature of the eruption could be due to the ambient hydrostatic pressure of the seawater column being high enough to suppress the explosive expansion of magmatic volatiles and the explosive expansion of superheated seawater in contact with the erupting magma2. McBirney33 estimated that practical maximum water depths for explosive eruption of acid magmas with known volatile contents are probably in the range of 500–1000 m.

Explosive silicic eruptions are characterized by vesicular, pumiceous clasts, whereas dense non-vesicular clasts are related to lava flows79. No evidence of pyroclastic deposits is found in the study area. Since all other primary volcanic textures are relatively well preserved, any original vesicular clasts could have been easily recognized. However, in the present case, the clasts in the volcanioclastics are dense and completely lacking in vesicles or amygdules. The non-vesicular nature of the rhyolites at Jilhariedev together with the conspicuous absence of pumiceous clasts suggest that rhyolite extrusions were not associated with pyroclastic eruptions. It would be therefore reasonable to infer that they were emplaced at sufficient water depths so that vesication of volatiles could not take place due to high hydrostatic pressures. Additional evidence for deep water setting for the emplacement of these volcanics is the presence of massive sulphide at the nearby Bhuyari prospect. On the basis of studies in several VHMS deposits, it is generally agreed upon that a water depth of more than 500 m is required for the formation of massive sulphides5. Massive sulphide occurrences within the felsic volcanics in many other places of Betul belt may indicate prevalence of a regional deep marine setting for the emplacement of the volcanics.

It is interesting to note that the presence of autobrecia and hyaloelastics in the felsic volcanic sequence of Betul belt has similarities with the well-known VHMS bearing areas in other parts of the world. Autobreccia and hyaloelastics form host-rock successions for the Kuroko massive sulphide deposits, Japan14,15, the Silurian Currawong and Wilga deposits, Australia14,35, Que River and Hellyer deposits in Tasmania27 and the Archean Golden Groove VHMS succession in Western Australia36. It is probable that the autobreccia and hyaloelastics (similar to that recorded in the presently studied Jilhariedev area) may be found at many base metal prospects of the Betul belt. Proper identification of the volcanic facies within highly altered host rocks near the deposits can help in building up facies models that would establish the genetic relationship between sulphide mineralization and the host-rock facies and in turn, this will have important implications for base metal exploration in the area.

6. Large, R. R., McPhie, J., Bruce, G. J., Herrmann, W. and Davidson, G. J., The spectrum of ore deposit types, volcanic environments, alteration halos, and related exploration vectors in submarine vol-

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CURRENT SCIENCE, VOL. 97, NO. 5, 10 SEPTEMBER 2009
RESEARCH ARTICLES


ACKNOWLEDGMENTS. We thank Mr H. S. Shrivasatava, GSI, Bhopal for stimulating discussion; Mr M. L. Dora, GSI, Nagpur for support, and Mr A. Majumdar, GSI, Jabalpur for technical assistance.

Received 28 February 2008; revised accepted 24 July 2009