CHAPTER-3

GEOLOGICAL SETTING

3.1 Introduction

The Central Indian Tectonic Zone (CITZ) is hypothesised to function as a trans-continental suture [12-14]. This suture is believed to be the site where the main crustal blocks of peninsular India, specifically the Northern Block (consisting of the Bundelkhand and Aravalli cratons) and the Southern Block (comprising the Dharwar, Bastar, and Singhbhum cratons), merged together [4, 12]. The tectonic zone is comprised of several crustal blocks that underwent various occurrences of subduction, collision, and accretionary orogenesis throughout the Proterozoic epoch [15, 16]. These geological formations provide significant observations regarding the Proterozoic evolution of the Indian subcontinent.

The CITZ, which extends over 1500 kilometres in an east-west to east-northeast to west-southwest orientation, has a maximum width of around 400 kilometres [17]. The geographical extent of this region begins from the Chhota Udepur region in Gujarat, extending westward, and continues via the Chhotanagpur Gneissic Complex (CGC) till reaching the Shillong plateau in the east [18]. The lithotectonic units observed within the region comprise a diverse assemblage of metamorphosed supracrustal and granulite belts and mafic/ultramafic bodies, voluminous metacarbonates, BIFs, tonalite trondhjemite granodiorite (TTG) gneisses, charnockites, and related arc magmatic suites. Furthermore, it is worth noting the presence of exhumed belts that display characteristics of high-pressure and ultrahigh-temperature metamorphism. These belts also contain postcollisional granites enriched in potassium [21-25].

The CITZ displays a number of large-scale tectonic lineaments inside its crust that are aligned parallel to its strike length. The lineaments observed in the region, extending from the southern to the northern parts, consist of the Central Indian Shear (CIS), Gavilgarh-Tan Shear Zone, Son-Narmada South Fault (SNNF), and the Son-Narmada North Fault (SNSF) (Fig.1b). The Mahakoshal supracrustal belt is situated between the boundaries of the Sausar-Narmada North Fault (SNNF) and the Sausar-Narmada South Fault (SNSF). Meanwhile, the Gavilgarh-Tan Shear Zone acts as a demarcation line between the Sausar belt and the Betul belt.

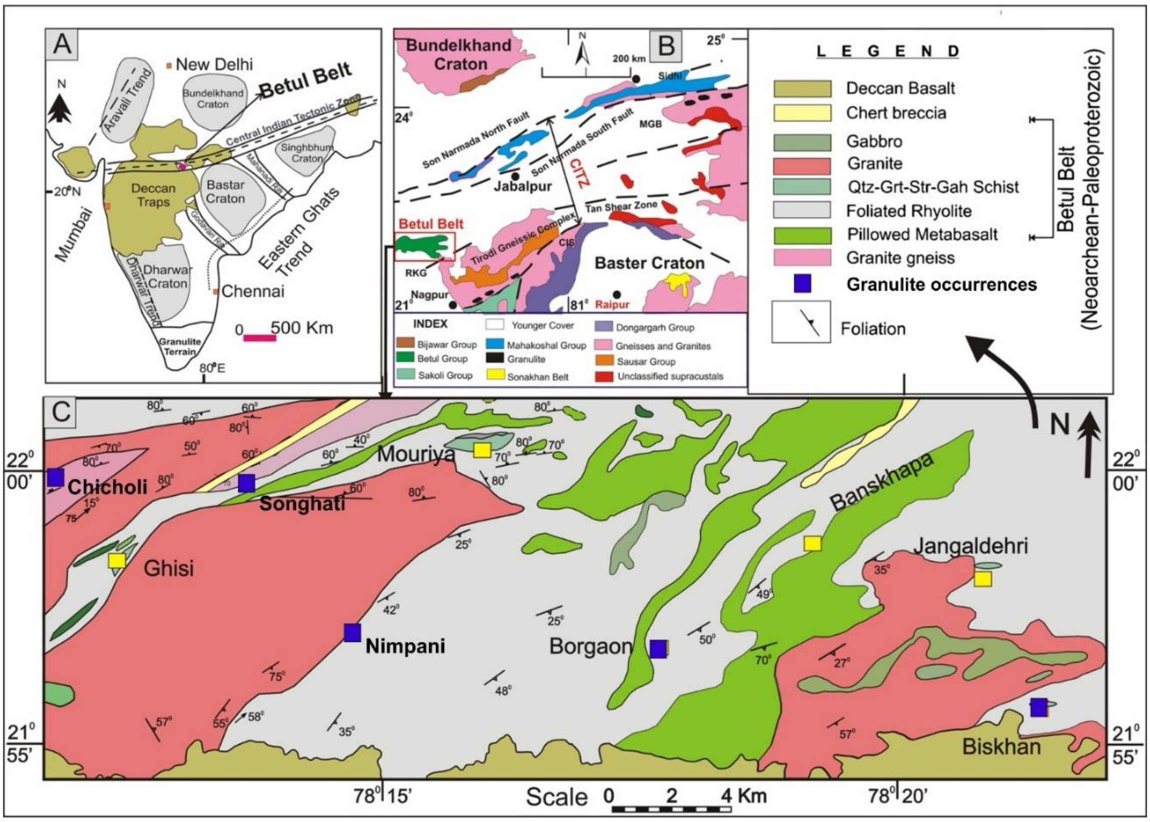

Fig. 3. (a) Regional Geological map of India, showing Cratonic blocks modified after [68]; Inset shows. (b). Geological map of Central Indian Tectonic Zone (CITZ) after [69], (c). Geological map showing granulite occurrences of the Betul Belt.

The CIS demarcates the southern boundary of the CITZ. The Cental Indian Tectonic Zone (CITZ) encompasses several significant geological formations, including the Mahakoshal, Betul, and Sausar supracrustal belts. Additionally, it is home to prominent granulite terranes such as the Balaghat-Bhandara belt situated in the southern region, the Ramakona-Katangi band located in the centre area, and the Makrohar belt in the northern section. The tectonic evolution of the CITZ has been the subject of scholarly discourse and deliberation for the past thirty years [20-22]. The CGGC (Chotangapur Gneissic Complex) situated at the east of the central region and the eastern fringe is known as Shillong Meghalaya Gneissic Complex (SMGC) [211, 212]. The CITZ has extensive suture zone which was formed around 1600 Ma due to the collision of the South Indian Block (SIB) and North Indian Block (NIB), where SIB subducted beneath NIB to form the Great Indian Peninsular shield [15, 16].

3.2 Geology of Betul Belt (BB)

The Betul belt is comprised of a distinctive collection of Precambrian gneiss and supracrustal rocks located within the Central Indian Tectonic Zone (CITZ). The Belt under consideration is located in the south-western region of CITZ (as shown in Figure 1C). CITZ is a composite zone spanning approximately 150 km in length, with an ENE-WSW orientation, extending from Chicholi in the west to Chhindwara in the east. This Belt traverses the Peninsular Shield [26]. The Belt belt is characterized by an inlier that is covered by a Phanerozoic succession of the Gondwana Supergroup and Deccan Traps. The Betul Belt comprises a diverse assemblage of lithological units, including metabasalts, rhyolites, mafic-ultramafic rocks, volcano sediments, and banded iron formation (BIF). The Sm-Nd model dates of Group I rhyolites range from 2284 to 2464 Ma, while the ages of Group II rhyolites range from 2174 to 2863 Ma [28]. The region including the centre and eastern portions of the Betul Belt is characterised by the presence of a volcano-sedimentary Belt. This Belt is known to contain numerous volcanogenic base metal deposits, which have been identified and classified as the Kherli Group by [28], as well as [29]. The subsequent workers incorporated volcano-sedimentary rocks located in the southern region of the Belt into the Banskhapa Formation [30]. Granitoids have both intrusive and tectonic contact associations with the supracrustal and mafic-ultramafic rocks. The Betul Belt exhibits the occurrence of syntectonic to post-tectonic granite, which takes the form of plutons aligned in an ENE-WSW direction and emplaced along ductile shear zones. The syntectonic granite with deformities located in the western region of the Betul Belt has been assigned a Rb-Sr date of 1550 ± 50 Ma [31]. The granite located in the vicinity of Navegaon has been dated using the Rb-Sr method, yielding an age of 850 million years [31]. The Betul Belt is characterized by the presence of ductile shear zones that exhibit signs of oblique-slip motion. These shear zones have caused the displacement of supracrustal rocks with different levels of metamorphic alteration, as well as the emplacement of syn-tectonic granites. These geological features are found in a continental margin arc tectonic setting within the Betul Belt. [29]

The Betul Belt is characterized by a distinctive litho-package consisting of bimodal volcanics composed of both basic and acid compositions, as well as meta-exhalites, quartzites, metapelites, calc-silicates, and granite gneiss. The rocks in question were subjected to intrusions by felsic-mafic-ultramafic compositions [26-28, 31]. Bimodal volcanic rocks are composed of both metabasalt and meta-rhyolite. The mafic volcanic rock comprises both pillowed and non-pillowed meta-basalts, accompanied by mafic volcaniclastics and cherts (refer to Figure 1C). Felsic volcanic materials are exemplified by the presence of rhyolites, rhyolitic volcaniclastics, and cherts [32]. The fundamental volcanic textures in the majority of the rocks have been eradicated due to hydrothermal alteration and subsequent metamorphism. Nevertheless, there are some comparatively unmodified rocks that exhibit preserved textural features, allowing for the identification of distinct volcanic facies. Rhyolite bands are found in the eastern region, within a broader context of fine-grained quartzo-feldspathic rock that contains biotite and amphibole, commonly referred to as sub-volcanic rocks. The litho units under consideration are distinguished by the presence of biotite and hornblende grains that have a needle-like morphology, typically lacking any discernible preferred alignment. The two most prevalent felsic volcanic facies are characterized by the presence of large rhyolite and felsic volcaniclastics. The rhyolite in question has a significant size, characterized by the presence of quartz phenocrysts with a rounded shape and a diameter of around 2 mm. Additionally, certain areas of the rhyolite have flow banding, which is characterized by alternating bands of light siliceous material and darker phyllosilicate-rich material. This information is sourced from reference [32]. Volcaniclastic deposits typically consist of siliceous clasts that range in shape from angular to rounded, embedded within a groundmass characterized by a finer-grained, recrystallized siliceous matrix.

The structural properties indicates that the supracrustal rocks have undergone deformation as a result of three distinct periods. The initial set of structures, referred to as the first generation (D1), are characterized by folds that range from isoclinal to reclined. The subsequent set of folds, known as the second generation (D2), exhibit a tight to isoclinal configuration and are oriented in an upright to inclined manner. These folds collectively form the regional tectonic trend of the belt, which runs in an ENE–WSW direction. The D2 structures have seen the influence of superposed folding (D3), resulting in the development of broad open folds that tend in a north-south direction. The D1 and D2 deformations are associated with greenschist to lower amphibolite facies metamorphism [16].

The southern boundary of the Betul Belt exposes the highly deformed gneisses and granitoids of the Sausar Mobile Belt. The shear zone encompasses a mylonitic foliation oriented in an east-west direction, exhibiting parallelism with the GTSZ situated to the southern region. The rocks within the Betul Belt have seen three distinct episodes of deformation. The initial stage resulted in the formation of isoclinal to reclining folds characterized by axial planes oriented in an ENE-WSW direction. The subsequent deformation exhibited coaxial refolding of the preceding folds, but the subsequent phase is characterized by the occurrence of cross folds [32]. The rocks have a widespread foliation that trends in the ENE-WSW to EW direction. The Betul Belt is known for its documentation of metamorphism ranging from the lower to middle amphibolite facies, as indicated by previous studies [16, 27-28].

3.3 Lithostratigraphy of Betul Belt (BB)

3.3.1 Granite gneisses

The gneisses of Betul exhibit their most prominent outcrops along the road from Betul to Ranipur, situated to the south of the Sonaghati ridge in close proximity to Chiklar. The rocks exhibit banding and migmatitic characteristics, displaying a prominent foliation oriented in a NE-SW to ENE-WSW direction. The foliation is inclined at moderate to steep angles, ranging from 40° to 75°, with a general dip towards the southeast. The Machna River portion located northwest of Bhadus provides the most favorable exposure of unconformable basement-cover interactions.

3.3.2 Supracrustals

The supracrustal rocks found within the Betul Group are classified as the Ranipur and Sonaghati Formations, which are prominently uncovered in the central and western zones of the geological belt. The base Ranipur Formation is characterized by its co-folding and conformable overlay by a succession of micaceous ferruginous quartzite and quartz-mica schist/phyllite with interbanding, known as the Sonaghati Formation. This geological formation extends as a linear belt in a northeast-southwest orientation, spanning from the southwest of Pangra via Sonaghati to Ranipur.

The middle and eastern regions of the belt exhibit volcano-sedimentary associations consisting of bimodal meta-volcanics, which are integral components of the Bargaon Formation. The basalts exhibit a pillow-like morphology, with dimensions typically ranging from 20 to 50 cm. These basalts are found in the form of elongated bodies, often intercalated with felsic volcanic materials and metasediments. These metasediments serve as the host rocks for volcanogenic massive sulphide deposits. The pillows exhibit deformations characterized by elongated axes that are parallel to the direction of the prevailing foliation. In the Mordongri region, located south of Laminia, and in the Kanhan River section at Jilharighat, there is an uninterrupted series of metabasalt formations that are either pillowed or non-pillowed in nature. This trend extends in an east-west direction, as depicted in Figure 3b-c. Shearing is observed in the Kanhan River area north of the Jilharighat, where there is contact between the southern region and the felsic volcanic series. No lithological contact is seen between the lithounits of the Bargaon Formation and the Ranipur and Sonaghati Formations. The syn- to post-kinematic granites are intruded within well-defined ductile shear zones, leading to their subsequent separation. The geological formations in question consist of felsic volcanic rocks, including rhyolites and volcaniclastics, which are prominently exposed in the regions of Ghisi, Mouriya, Bhawatekra, Kherlibazar, and Bhuyari. The rhyolites have primary flow banding [28] and, in certain locations, feature randomly-oriented needle-shaped biotite and hornblende. The metamorphic sequence consists of schists including garnetiferous anthophyllite, sillimanite, staurolite, biotite, chlorite, and gahnite, as well as tremolite-actinolite schists. The aforementioned package has been previously characterized as metamorphosed alteration zones that are linked to volcanogenic massive sulphide (VMS) deposits [23-32].

3.3.3 Mafic granulites

These rocks occur as enclaves within granitic gneiss and are dark grey to black, coarse to medium grained with granulitic texture. The observed phenomenon manifests as fragmented, dispersed, and lens-shaped areas across the region. The prevailing strike orientation of the mafic granulite within the studied region is in the northeast-southwest direction. In the investigated area, mafic granulites occur as large lensoide patches within granite gneiss. The main constituents are orthopyroxene, clinopyroxene, garnet, hornblende, plagioclase, cummingtonite and quartz, whereas magnetite, ilmenite, apatite etc. are present in minor amount.

3.3.4 Pelitic granulites

The rocks exhibit significant size and possess a medium to coarse grain structure. Their colour ranges from grey to pink, which can be attributed to the high concentration of garnet. Additionally, these rocks display a greasy sheen and exhibit a granulitic texture. The large size of garnet grains has appeared on the rock surface. The pelitic rock mainly consists of garnet, cordierite, sillimanite, biotite, plagioclase, Kfeldspar, quartz, and opaque minerals (ilmenite and magnetite).

3.3.5 Older Intrusive Granite-I

The Morkha/Nagdev granite, also known as Granite-I, is prominently exposed over various regions within the Betul belt. The aforementioned geological formations, namely the basement granite gneiss and the accompanying volcano-sedimentary rocks, are subject to intrusive processes. The Morkha granite outcrop is prominently observed in the vicinity of Nagdev temple, Morkha, situated to the south of Biskhan, Jangeldehri, Bargaon-Tarora, Mauriya, and Kherli Bazar regions. The rock in question exhibits foliation and shearing characteristics, and it is in tectonic contact with the metasediments, specifically the quartz mica schist, found within the Sonaghati Formation. The sheared contact is observed between the felsic and mafic volcanic units. The rock under examination has distinct mylonitic foliation, which is distinguished by the deformation and elongation of quartz and feldspar grains. Additionally, sigmoid-shaped feldspar clasts have formed inside the rock.

3.3.6 Mafic and Ultramafic intrusives

The mafic-ultramafic rocks consist of metagabbro and pyroxenite with a medium grain size. These rocks are found in both the western and eastern regions of the belt. The mafic-ultramafic intrusions in the eastern region span a distance of more than 8 km, stretching from Jamtara in the east to the western area of Piparia. These intrusions exhibit widths ranging from 750 metres to 1000 metres. The Padhar mafic ultramafic intrusion, located at coordinates 22º02’51” N and 77º51’36” E, is a distinct geological formation in the western region. This complex has a clear differentiation, with ultramafic rocks occupying the middle area and mafic rocks found in the outer regions. In certain locations, they exhibit intrusion into pillow-shaped metabasalts and rhyolites (see Figure 3b). The Padhar region exhibits a complex assemblage of extensive intrusive formations, including pyroxenite, gabbro, and diorite. These formations are prominently exhibited inside and in the vicinity of Padhar.

The Jakhli region exhibits a mafic-ultramafic sequence characterised by a central core composed of olivine websterite, which is surrounded by hornblende gabbro and gabbro units. The outer boundary of these intrusions is composed of diorite. The zoned plutons under study exhibit an elliptical outcrop pattern and display a zonal arrangement of components, characterised by a prevalence of hydrous mafic mineralogy. These plutons have been likened to Alaskan complexes that originated in an arc context. The formation of these rocks has been regarded as occurring within a continental arc setting.

3.3.7 Younger Navegaon Granite (Granite–II)

The Navegaon Granite (Granite-II) is a type of intrusive rock found in the Betul belt. It is characterized by its pink color and can range from younger, porphyritic to homophonous, non-foliated textures. This granite is observed to intrude into all the older litho-units in the region, and its outcrops are well-exposed in the area between Navegaon and Chhindwara. The composition of these rocks primarily comprises quartz, alkali feldspar, with tiny amounts of biotite and hornblende. The presence of enclaves composed of metarhyolite, metasediments, and gabbro in the immediate area provides evidence for their comparatively recent formation, a conclusion that is further reinforced by the forthcoming discussion of our newly acquired age data.

3.4. Deformation and metamorphism

The rocks of the Betul belt have experienced three distinct stages of deformation, as shown in previous studies [22-32]. The first deformation event resulted in the production of isoclinal to reclining folds on axial planes striking in an ENE–WSW direction (F1) [18, 21]. At a mesoscopic scale, the F2 folds can be observed on the limbs of the macroscopic fold within the quartz-mica-schist. Bedding (S0) is observed in limited locations, whereas the prevailing planar arrangement is characterized by a schistosity (S1) that exhibits axial planarity with respect to an isoclinal F1 fold, which is particularly evident in quartz-mica schist. The F2 folds have a moderate degree of openness and an upright orientation, characterized by the presence of chevron hinges. The third phase of deformation resulted in the development of F3 cross folds, which exhibited wide, open warps and slight kinks. These folds were characterized by steeply inclined to upright asymmetric geometries, with trends ranging from NNE-SSW to NNW-SSE. Concurrently with the preceding folding process, a series of ductile shear zones with an ENE–WSW orientation and strong northerly dip, ranging from sub-vertical to vertical, have formed. The mylonitic foliation exhibits a shallow to moderately plunging stretching lineation, suggesting the occurrence of oblique-slip displacement in certain locations.

The rocks within the Betul belt have seen regional metamorphism characterized by upper amphibolite facies, followed by a subsequent greenschist facies [28-32]. The rocks in the Bhuyari area have been analyzed to determine the peak metamorphic pressure-temperature (P-T) conditions. The estimated values range from 5.8 to 7 kilobars (kbar) for pressure and 580 to 650 degrees Celsius (°C) for temperature. These conditions indicate that the rocks have undergone metamorphism in the amphibolite facies.

3.5 Metallogeny in Betul Belt (BB)

There are more than 800 existing volcanic massive sulphide (VMS) deposits globally, exhibiting a wide variation in size, from 200,000 tonnes of ore to exceptionally large deposits over 150 million tonnes. The typical size of a Volcanogenic Massive Sulphide (VHMS) deposit ranges from 1 to 3 million metric tonnes (Mt). The Betul Belt, located within the Central Indian Tectonic Zone, has garnered considerable attention as a valuable area for mineral exploration. This is primarily due to the identification of numerous substantial VHMS Zn-Cu ± Pb deposits within the region.

Notable deposits include Mouriya and Ghisi in the western section, Dehalwara, Banskhapa-Pipariya, Koparpani, Bhawaratekra, and Tarora in the central portion, as well as Biskhan, Jangaldehri, Borkhap, and Bhuyari in the eastern area [22-28]. Within these geological formations, the presence of Zn-Pb-Cu mineralization is primarily observed in the form of dissemination, stringers, and occasionally in significant quantities (> 50% of the volume consisting of sulphides), as well as in semi-massive occurrences (with sulphides comprising 25-50% of the volume). Mineralization is observed in the presence of quartz-biotite garnet-plagioclase assemblages, as well as in quartz-sericite containing assemblages, within altered rhyolite [26]. The mineralization mostly comprises sphalerite, pyrite, galena, chalcopyrite, and pyrrhotite. Previous research conducted in the Betul Belt has predominantly concentrated on the characterization of gahnite, the geochemistry of rhyolites and mafic ultramafics, exploration strategies, and resource estimation within the VHMS deposits.

Ore petrography, sulfur isotope and sulfide chemistry studies of the three VHMS deposits of the Betul Belt in central India have revealed the following conclusions:

The presence of chalcopyrite disease in Fe^{2+} rich sphalerite at Biskhan and Jangaldehri in the eastern part of Betul Belt is confirmed by ore petrography and mineral chemistry. On the other hand, the absence of chalcopyrite disease in Fe2+ poor sphalerite at Ghisi in the western part can be attributed to the variable conditions of the reduced hydrothermal fluid, metamorphism, and varying depths of mineralization.

The variation in sulphur isotope (δ34S) values across the Betul Belt, extending from Ghisi in the west to Biskhan in the east, exhibits distinct isotopic characteristics. This can be attributed to the presence of hydrogen sulphide (H2S) originating from diverse sources through multiple processes. These sources include thermochemically reduced sulphate from seawater and magmatic sulphur, which can be derived either directly from a vapor-rich magmatic fluid or through leaching of the volcanic host rocks.

The present study encompasses a comprehensive examination of three volcanogenic massive sulphide (VHMS) deposits through a combination of field observations and laboratory analyses. The findings reveal distinct variations in the composition and concentration of ore minerals across these deposits. These discrepancies are likely attributed to the precipitation of metals from diverse hydrothermal fluid conditions, as well as the involvement of multiple sources of sulphur and varying reduction process (Zn–Cu–Pb to Zn–Cu).