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# Genesis of Graphite in Betul Belt, Madhya Pradesh, India: Inferences Based on Petrographic and Other Studies

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## Abstract

Betul belt is known for its volcanic massive sulphide type of mineralization in the geological circles of India. But here the betul belt has been presented with a different qualification, which is graphite mineralization. The graphite mineralization is popularly known within the proterozoic sediments of Aravalli Supegroup of rocks in South Rajasthan and in its extension in the Jhabua and Alirajpur districts of Madhaya Pradesh. The graphite mineralization in Betul belt is confined to the supracrustals enclosed within the granite gneisses and has been brought on the national map after the recently explored blocks by geological survey of India, which were auctioned for the commercial exploitation. This paper briefly discuses the possible mechanism of formation and the nature of mineralization of graphite here in this belt, essentially based on the inferences drawn from petrography supported by scanning electron microscopic and XRD data. It is concluded that major proportion of the graphite mineralization here is accumulated due to progressive metamorphism of the organic matter deposited along with various sediments, while a considerable component has been contributed by the precipitation from super critical graphite rich fluids.

## Keywords

Betul Belt, Graphite, Graphitization, Lensoid, Organic Matter

## 1. Introduction

The Betul belt is known for typical VMS type sulphide mineralization, which is possibly the result of the complex tectonic history and multiple magmatic episodes along the CITZ. Besides the bimodal magmatism and granite gneisses there is very miniscule proportion of supracustals, which incidentally form a considerable strike length in the Chiklar, Gauthana and surrounding areas in Sonaghati sector of Betul district of Madhya Pradesh. The litho package hosting the graphite mineralization occurs as thin lenticular bodies intercalated within the Betul gneisses. The graphite occurrences were initially brought to light by the locals , who excavated the black mineral presuming it to be coal, but when it did not burn they lost the interest. On the recommendations of the then collector Betul district, Geological Survey of India [1] carried out reconnoitery work and reported this black mineral as graphite. These occurrences remained hidden until in 2012, the current team of workers from the Geological Survey of India mapped these occurrences reported by Narayanmurthy, in detail and brought the exact disposition of these lenses. The exploration has revealed that the deposit has a potential of becoming possibly the largest deposit of Graphite in India if explored fully. The present paper describes the possible genesis of the graphite along with description of host lithopackage and an effort to conclude the genesis of graphite based on the petrographic observations, SEM and XRD studies of the host rock. It has been observed that there are two distinct modes of occurrences of graphite in this belt. One component is pre deformation and bears the evidences of deformation and has its origin in the organic matter which was deposited during the process of sedimentation, while the other component though small by volume, has an important bearing on genesis, is the post deformation precipitation of graphite from the supercritical fluids. The study area is located 4 km NW of Betul Town (**Figure 1**).

## 2. Geology of the Area

### 2.1. Regional Geology

The Betul belt forms a part of the Central Indian Tectonic Zone (CITZ) and represents a Proterozoic mobile belt [2]. The Betul belt is late Archean to Neoproterozoic in age, which is bounded by Two faults/ductile shear zones, The Son Narmada south fault (SNSF) in the North and Govilgarh Tan shear zone in South. This belt is disposed in the ENE-WSW direction and extends for a strike length of 135 km, lying between Mahakoshal belt in the North and Sausar supracrustal belt in the south. The average width of the Betul belt is 15 kms between Chindwada Town in the East and Chincholi village in Betul district in the west.

The belt comprises Volcano-sedimentary rocks intruded by mafic-ultra mafic and granitic suite of rocks [3]. Lithologically the belt is more similar to the Mahakoshal Group, in having large proportion of volcanic rocks than to the volcanics free Sausar belt. The Betul belt is surrounded by younger Gondwana sediments and Deccan traps from three directions through a narrow NW-SE trending corridor along Kanhan.

The litho-assemblage of this belt comprises three distinct suites of rocks. 1)

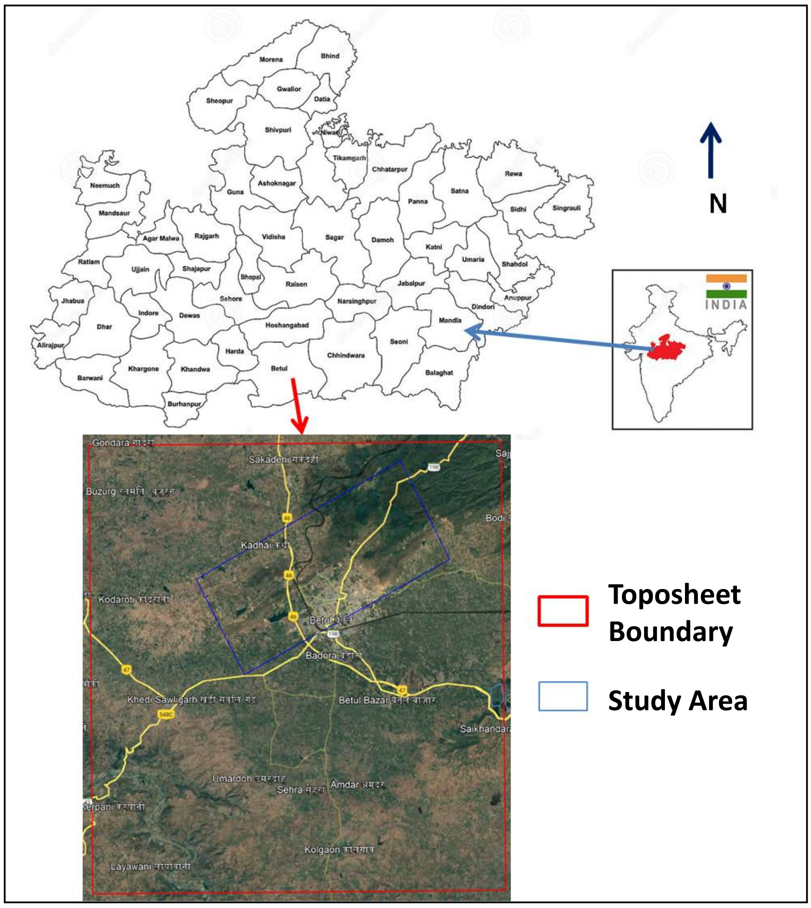


**Figure 1.** Location map of Betul Graphite.

Supracrustals rocks comprising quartzite, metapelites, bimodal volcanics (basalt and rhyolites), calc silicate and BIF which show evidence of shallow water sedimentation. 2) The mafic-ultramafic suite is represented by pyroxinite, hornblendite, rhyolite gabbro, dacite, quartzite-diorite association and 3) Syn to post tectonic granitic suite. The supracrustals are confined within the gneissic complex considered to be the basement. Due to shearing and copious granitic magmatism, the supracrustal are deposited as disturbed sequence. The Betul belt comprises a unique assemblage in CITZ of bimodal volcanics with abundance of felsic volcanics in particular. The belt is traversed by number of NE-SW trending ductile shear zones having sub vertical to steep dips due north which are developed due to deformation and show low to medium grade metamorphism.

The supracrustals in Betul belt are in abundance in the western and north western parts around Sonaghati, Bhopali, Golighat and Chincholi area, where as volcano sedimentary sequence dominates eastern and central part of the belt. The mafics and ultramafics are exposed in the western and northwestern part around Padhar, in the eastern part of the belt around Mordongari where, it occurs in association with bimodal volcanics. Apart from the mafic and ultramafic bodies, various units of Gabbro, pyroxinite, hornblendite occur in association with bimodal volcanics. Granites show both the intrusive and tectonised contacts with supracrustals, mafic and ultramafic rocks. The area also contains several ENE-WSW trending ductile shears, which often have served as the conducive zones for granitic emplacements.

The older palaeo stratigraphic meta sediments/Supracrustals comprising graphite schist, quartz mica schist, marble, calc silicate, tremolite-actinolite schist and quartzite are seen only around Sonaghati and Chincholi in the western and North western part of the belt. These supracrustals are intensely folded and occur as enclaves within the Betul gneisses. These enclaves are only sparsely exposed and comprise quartzite, calcareous quartzite, quartz mica schist with partings of graphite schist, carbon phyllite and marble. They occur as enclaves and form continuous exposure for a considerable strike length in Sonaghati area.

Large scale mapping [4] in an area of 75 sq.km on 1:12,500 scale, in and around Chiklar, Gauthana, Tikari, Betul Bazar and surrounding areas falling in parts of T. S No. 55G/13 (**Figure 2**) brought out in detail the disposition of the graphite bands besides new occurrences were traced.

Several stratigraphic successions have been proposed, the latest one [5] is presented for the reference in (**Table 1**). The basement of Betul belt comprises banded migmatitic gneisses termed as Amla gneiss extending from east of Betul through Kosmi and Bhadus towards further west, along Betul-Ranipur road and

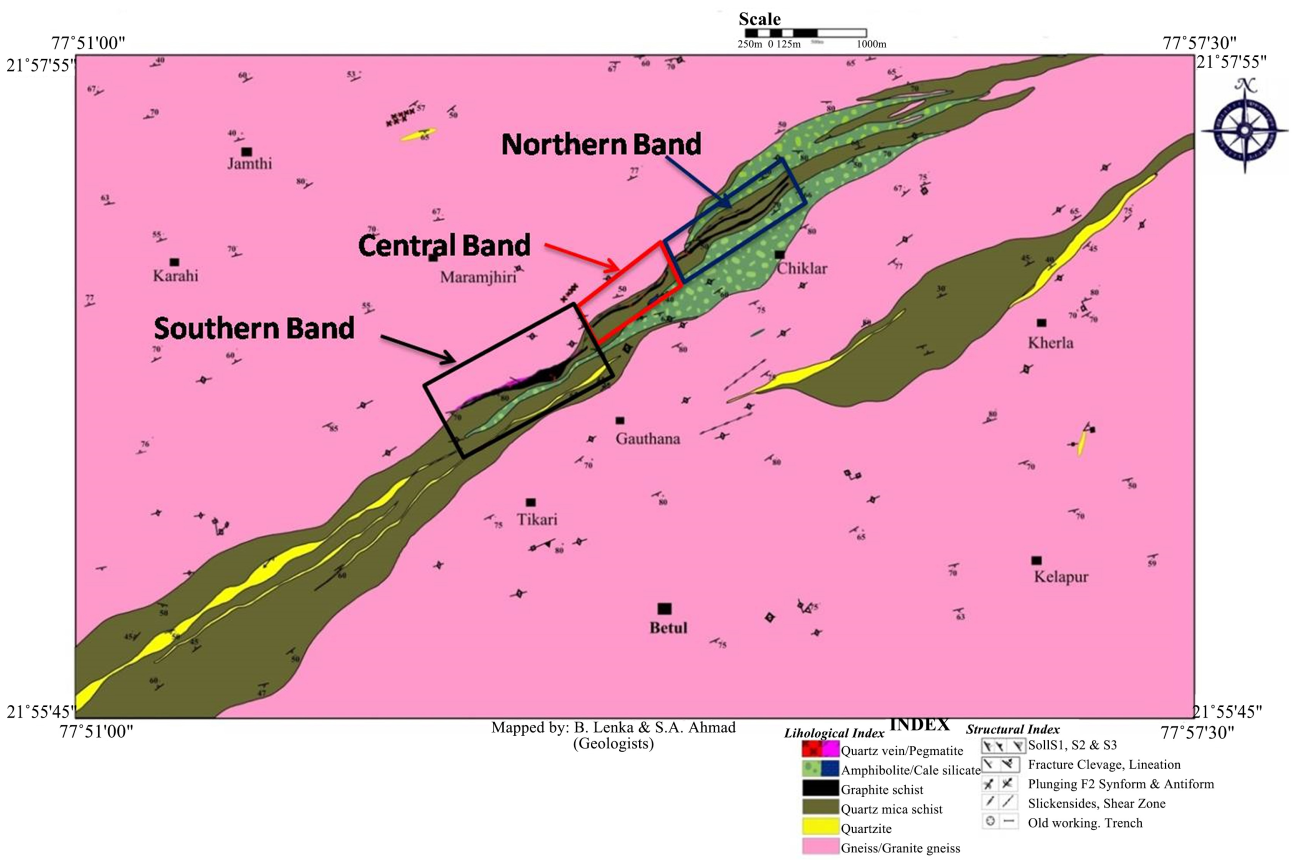


**Figure 2.** Large Scale Geological Map on 1:12,500 scale of Chiklar, Gauthana, Tikari and surrounding areas, Betul district, Madhya Pradesh.

Table 1. Modified tectono-stratigraphic succession of Betul belt, [5], 2009.

| | |
|---|---|
| **DECCAN TRAPS** Basaltic lava flows and dolerite dykes | |
| ***Intrusive contact/ Disconformity*** | |
| **GONDWANA SUPERGROUP** | Conglomerate, sandstones, and shales |
| ***Unconformable/ Tectonic Contact*** | |
| **BETUL GROUP** INTRUSIVES | Basic dykes, pegmatites, quartz veins, homophanous amphibole-mica-granite, porphyritic granite |
| ***Intrusive/ Tectonic contact*** | |
| PADHAR MAFIC - ULTRAMAFIC SUITE | Diorite, epidiorite, gabbro, norite, pyroxenite, hornblendite, websterite, harzburgite, anorthosite, diorite, talc - serpentinite rock, quartz - epidote rock |
| ***Intrusive/ Tectonic contact*** | |
| SONAGHATI FORMATION | Intercalated sequence of quartzite, quartz-mica schist and graphite schist |
| ***Conformable/ Tectonic contact*** | |
| BARGAON FORMATION | Meta-sediments (mica schists), meta-rhyolite and felsic metatuff, metabasalt and amphibole-chlorite schist |
| ***Conformable/ Tectonic contact*** | |
| RANIPUR FORMATION | Phyllite, banded hematite/magnetite quartzite, BIF, granulite, meta-basalt, amphibolites, carbonaceous phyllites, calcareous quartzite, calc-silicates, marble |
| ***Un-conformable/ Tectonic contact*** | |
| **AMLA GNEISS/**BASEMENT ROCK | |

south of Sonaghati ridge. Three fold litho-stratigraphic subdivisions of the Betul supracrustal rocks were proposed [5]. The basal sequence of calc-arenite, marble, B.I.F. phyllite, metabasalt and carbonaceous phyllite is termed as "Ranipur Formation" exposed continuously towards WSW in Sonaghati ridge area and forms the basal sequence. The southern margin of the basal supracrustal sequence (*i.e.* in the area south of Sonaghati ridge) is marked by the presence of calcareous, gritty, feldspathic quartzite which is highly tectonised and is in juxtaposition with the basement migmatitic gneiss, thereby indicating the tectonised unconformity. The migmatitic gneiss occurring as basement to the supracrustals of the Betul Group is termed as "Amla gneiss". The contact between Ranipur Formation and the basement gneiss is unconformable at places and faulted at other. The lithounits of the basal "Ranipur Formation" are co-folded with and conformably overlained by the inter banded sequence of micaceous ferruginous quartzite + magnetite and quartz-mica schist/phyllite and graphitic schist and is being termed as "Sonaghati Formation" and have undergone low grade of regional metamorphism with development of low green schist facies minerals. In rest of the area, Amla gneiss is having a tectonic contact with different litho units of supracrustal sequence. Due to intense tectonism and profuse granitic activity, it is difficult to work out the proper litho stratigraphic succession of the Betul belt.

The Sonaghati Formation extends as a linear ridge in NE-SW direction from SW of Pangra via Sonaghati towards Ranipur. Another major outcrop of the formation extends in a NNE direction from east of Padhar through south of Arjongondi. Isolated outcrops are also seen as patches resting over the basement Amla gneiss. The continuation of these has been disrupted at places by a major faults occurring in the area. Apart from these, several small detached exposures of granulites, B.I.F., calc-silicate marble and amphibolite (possibly belonging to the basal Ranipur Formation) occur as enclaves in the mafic-ultramafic complex and intrusive granites. Large intrusive bodies of pyroxenite, gabbro, diorite and foliated mafic-ultramafics exposed around Padhar, Gajpur and at several places within the Betul belt have been termed as Padhar mafic-ultramafic Complex. A number of amphibolites to granulite facies supracrustal enclaves are recorded within the complex. Besides these, small exposures of gabbro, pyroxenite and hornblendite are also seen within the bimodal assemblage of Bargaon Formation. Granitoid rocks in the area show both intrusive as well as tectonic contact relationship with the basement gneiss, supracrustal rocks and the mafic-ultramafic rocks. Syn-to post tectonic, prophyritic to homophanous granites were emplaced along several ENE-WSW trending ductile shear zones. Due to intense shearing and copious granitic magmatism, the supracrustal litho assemblage of Betul belt occurs as dismembered sequences within the granitic host. Apart from these granitoids, tourmaline mica pegmatite, quartz veins and dolerites of different generations intrude almost all the rock types of Betul belt.

## 2.2. Tectonic Setting

The timing and tectonic setting of deposition of the Betul supracrustal rocks is not yet certain. Previous workers with the available geochemical data indicate that the mafic volcanic rocks of the bimodal suite are low-K tholeiites and contain geochemical signatures of near arc magmatism. Copious granitic magmatism around the belt, which is common to many arc settings, also corroborates the above contention. Further, the syn-to post-tectonic mafic ultramafic rocks are interpreted to have been generated from an enriched mantle source, which is different from the source mantle for low-K tholeiites. Such a variable mantle source characters are also common to arc environment, where in subduction-related fluids enrich the source mantle. Based on the above, previous workers have inferred an arc setting for the Betul belt. This, coupled with the presence of clastic quartzite in the sequence which would require a sialic crust, indicates a continental margin arc setting. In addition to major prominent shear zones, there are several shear zones along the margins of Betul, Sausar and Bilaspur supracrustal belts, which have channeled volumes of syn-tectonic granitic magmatism. The timing of the basin initiation is not known. Since, this basin was situated in an arc environment, it may be considered as coeval with the Mahakoshal basin of the back-arc. The basin closed at ca. 1.5 Ga, as recorded by the syn-tectonic granitic rocks. This event was also accompanied by large scale mantle melting, which resulted in copious hydrous ultramafic-mafic magmatism. The lithology and metamorphism of the Betul belt is more akin to Mahakoshal-sand that the tectonic setting of the Betul belt may be near the arc environment, [2].

### 2.3. Geology of the Study Area

Geologically, the area forms the western part of the Betul inlier and comprises meta sedimentaries like quartz mica schist, graphitic schist, amphibolite and quartzite traversed by minor quartz and pegmatite veins of different generations within the gneisses. The mapping has revealed presence of rocks of Golighat Group comprising quartz mica schist, biotite schist, quartzite, amphibolite, calc-si1icate rock and Betul gneiss. This lithopackage has been intruded by diorite/dolerite dykes, quartz and pegmatite bodies of various dimensions spanning a long geological period. The general trend of the rocks is ENE-WSW with dip towards northwest in the northern part and south east in the southern part. Meta sedimentary rocks of the area have been grouped in Golighat Group, after the name of a locality Golighat (toposheet no. 55G/09), where they are best exposed.

#### 2.3.1. Granite Gneiss

Granite gneisses represent one of the common rock types in the area and occupy nearly 60% of the study area forming low lying undulatory topography equally in eastern as well as western part. The exposed granite gneisses are differing from each other in terms of composition, stratigraphic position and genetic history. Though the present work is not focused on the study of granite gneisses exposed in the area but broadly the area under study mainly exposes granite gneisses, both older and younger. Older gneiss are marked by migmatisation with ptygmatic folding, (**Figure 3(A)**), whereas the variants of younger gneiss are comparatively less affected by shearing, at places are hard compact, and form high hills. Granite gneisses are well exposed around Chiklar, Rathipur, Bori and areas surrounding the Betul town. The variants include pink porphyroblastic gneisses (**Figure 3(D)**), homophanous pink biotite gneisses and quartzo feldspathic gneisses. They are well foliated, where foliation is defined by parallel arrangement of feldspars and flakes of biotite and at places (**Figure 3(B)**) the gneissocity is highly obliterated due to shearing. The western contact of granite gneisses and quartz-sericite-muscovite-biotite schist is sharp, intermittently exposed and marked by the occurrence of intrusive small and large pegmatite bodies. The general trend of the rocks is NE-SW with dips of 50˚ to sub vertical due NW to SE. In the western side, a prominent shear zone, characterized by presence of quartz reef, parallel to the regional foliation due to which the area attained a topographic high compared to the surrounding areas.

The older gneisses in the area include the banded migmatitic gneisses and are occurring in the low lying areas. The rock is highly foliated with foliation trending in NE-SW to ENE-WSW direction with moderate to steep dips (40˚ to 75˚)

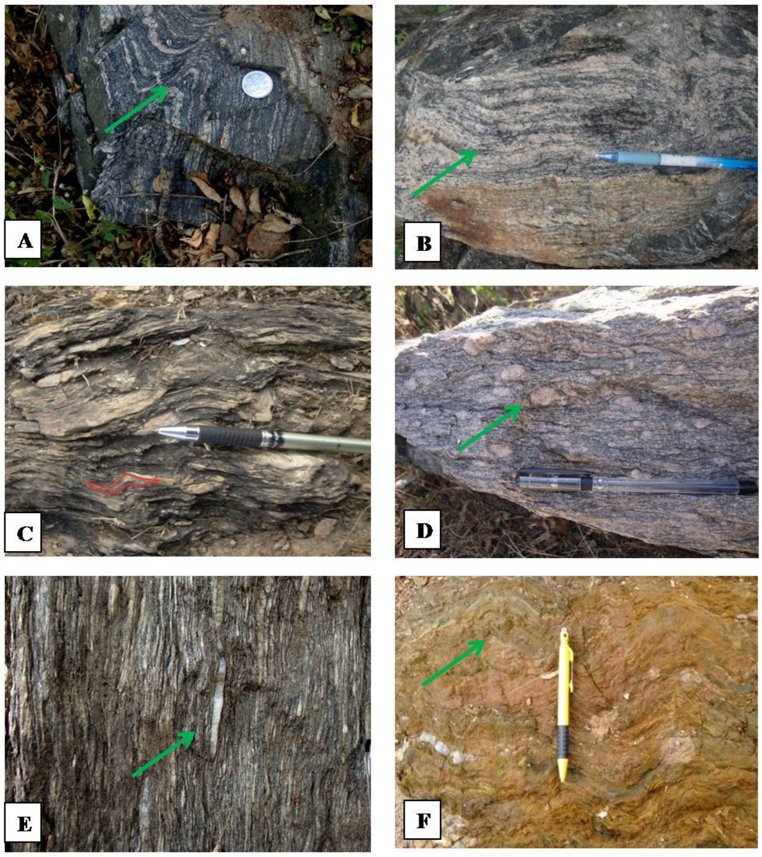


**Figure 3.** Typical field expression of the litho units exposed in study area. (A) Ptygmatic folding and small scale displacements in quartzo-feldspathic bands within the older gneiss, south east of Chiklar village (21˚56'11"N & 77˚54'43"E); (B) Foliation is defined by parallel arrangement of Quartz, feldspars and biotite flakes exposed near Chiklar Village;. (C) S-shaped folding in quartz-muscovite-biotite schist, north of Gauthana village, (21˚55'57" & 77˚53'13"); (D) Porphyroclasts of K-feldspar in the younger gneiss, near Soumuari village (21˚55'36"N & 77˚55'37"E); (E) Quartz ribbons within Graphite schist, north of Sonaghati ridge, (21˚55'57"N & 77˚53'13"E); (F) F3 fold developed in Quartz mica schist, road section, way to Maramjhiri, (21˚56'12"N & 77˚53'45"E) Betul dist., M.P.

mostly towards SE direction. Ptygmatic folds and small scale folding are observed at many places, which are the product of partial melting and lit par lit intrusions of quarto-feldspathic veins along the foliation planes as seen in the Chiklar-Ranipur road, north of Betul, and near Gauthana area. The Quartz, white feldspar, mica (muscovite) and biotite are common minerals. The younger gneisses (**Figure 3(D)**) are the most common variety of the gneisses, forming the country rock and are characteristically defined by coarse biotite, flattened and augen feldspar porphyroblasts with lesser amount of quartz and absence of prominent quartzo-feldspathic layers. In east of near Chiklar bands of porphyroblastic gneiss/augen gneiss are noticed within the Granite gneisses, such bands are also exposed along Betul-Ranipur road.

### 2.3.2. Quartz Mica Schist

It is a prominent litho-unit among the meta sediments and occurs on either side of the Sonaghati ridge. Which is aligned along the foliation of the host rock that trends ENE-WSW with dips varying both in amount and direction due to intense folding? Quartz mica schist occurs in a continuous linear narrow belt from Amdol in the southwest to Rathipur in the north eastern part of the study area. Another band occurs south of Chiklar and continues towards north eastern direction with NE trend. Quartz mica schist is of utmost importance as it hosts graphite schist. The main unit is exposed continuously in the entire strike length in the mapped area with width varying from few meters to hundreds of meters in the central part. In hand specimen these rocks are fine to medium grained in texture and is characterized by large porphyroblasts of muscovite, light grey to silver grey, greenish grey in colour, limonitised well foliated, and mainly composed of quartz, muscovite, biotite with some chlorite, epidote and garnet in decreasing order. Pyrite and pyrrhotite are common sulfide minerals as large disseminated grains. Parallel alignment of mica flakes defines the plane of schistocity along with flattened Quartz grains. This unit is highly folded, exhibiting pinch and swell structure with well developed folds and are intruded by several quartz and pegmatite veins of different generations. Swerving of mica layers around the quartz porphyroblasts are recorded from the area as a testimony to intense shearing (**Figure 3(C)**). The gradational nature of quartzite to micaceous quartzite to quartz-mica schist to mica schist depending upon the proportion of phyllosilicates indicates depositional facies variation. Mesoscopic folds of the third generation, defining crenulations are also recorded from the mica schist (**Figure 3(F)**).

#### 2.3.3. Graphite Schist

Graphite schist occurs as a parting within the quartz mica schist, where ever graphitic content dominates it is referred as graphite schist, very fine grained rock which soils the hand occurs in gradational relation with Quartz mica schist-Graphite schist and carbon phyllite, that is a transition from quartz mica schist to graphite schist through carbonaceous phyllite, could be well observed in various localities. This association indicates a depositional environment with facieses variation from carbonaceous clay grading into coarse grained silt and sand grade material with varying proportions of organic matter resulting in to the current association due to varying degree of metamorphism. Three distinct and separable lensoid bodies of graphite schist enclosed within the Quartz mica schist are exposed 2 km south east of Maramjhiri railway station to North West of Chiklar village. The bands have been divided into three lenses for the convenience of description; the Southern, Central and Northern graphite bands [4]. Graphite is widely associated with the meta-sedimentary rocks of the Betul Group, predominantly in the Kosmi Formation. The width of the graphite bearing zone varies from 2 m to 135 m as observed in north of Gauthana village. The graphite schist mainly comprises of small flakes of steel grey graphite mixed intimately with muscovite flakes and ash grey powdery material, which soils the hand and becomes greasy on smudging (**Figure 3(E)**). Both amorphous and flaky variety of graphite are seen, however the flakes are small and occur mainly along the foliation planes of rocks as disseminations, aggregates, thin stingers and veinlets in the quartz mica schist.

#### 2.3.4. Quartzite

Quartzite is an important litho-unit occurring as intercalations within the quartz mica schist as a facies variation. It helps in building the structural history of the meta-sedimentaries. The primary and secondary structures are well preserved within the quartzite. Primary structure like colour banding is preserved in the quartzite (**Figure 4(A)** and **Figure 4(B)**) the thickness of quartzite varies between 10 to 20 m. Interlayers of quartzite are present within meta basics and schists throughout the meta-sedimentary sequence as linear, discontinuous ridge, within the thick schistose envelope, but commonly are concentrated in well-defined bands along the prominent NE-SW striking Sonaghati ridge. These quartzite bands have considerable strike continuity, where as the width varies between 5 - 10 meters. The quartzite is disposed in NE-SW direction with sub-vertical to vertical dips due SSE. The gradational nature of quartzite to quartz-mica schist is clearly seen in the Sonaghati area as the composition varies from quartzite to micaceous quartzite to quartz mica schist on both the sides of the ridge depending upon the proportion of phyllosillicates. Mesoscopic folds and pucker axis lineation are observed in the quartzite besides the mino slip planes. The micaceous quartzite occupies low lying area displaying an undulatory outcrop pattern. Sharp contact between quartzite and quartz mica schist is also observed at places.

#### 2.3.5. Amphibolite

Thin linear bodies of Amphibolite occur almost throughout the area and are disposed parallel or sub parallel to regional foliation assuming both concordant to discordant relationship with the country rocks and are associated with most of the older rocks like gneisses and quartz muscovite schist. The amphibolites of both Para and Ortho nature are exposed in the area and have various dimensions. These amphibolites contain enclaves of schist. Graphite mineralization In the amphibolites is seen as thin veins of less than 1m width, occur at Chiklar village and in the road section on the way to Maramjhiri railway station, where mesoscopic folds are recorded with in the Graphite veins. At places near Chiklar and in the road section of Dharakoh, the amphibolite appears grading into calc silicate rock suggests this amphibolite to be an ortho amphibolite, which due to folding gave rise to boudin like structure and F2 folds (**Figure 4(C)** and **Figure 4(E)**), whereas the calc silicate body exposed near Nandkheda area shows well developed MW folds. Elephant skin weathering is displayed within this calc silicate body which is also associated with thin amphibole veins and calcite veins. The calc-silicate body in the Nandkheda area (Central Graphite band) is nearly 130 m in strike length with lensoid appearance with width ranging from 12 to 25 m.

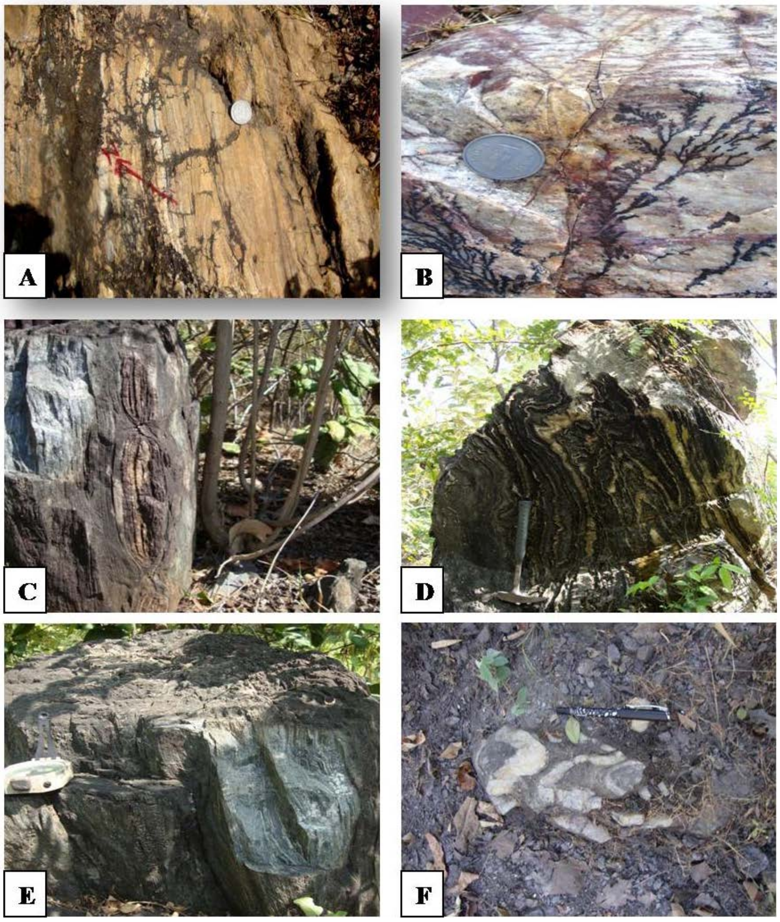


Figure 4. Various salient features of litho units from the studied area. (A) Silicification of quartzite along the foliation planes, north of Gauthama. (21˚56'02"N & 77˚53' 53"E); (B) Iron Dendrites within quartzite indicates shearing, Sonaghati area (21˚55'35"N 77˚53'09"E); (C) Boudins produced at the expense of stretching of QV within amphibolite, north of Chiklar village (21˚57'02"N 77˚54'43"E); (D) M-W folding in Calc silicate body, Nandkheda village, Gauthana area; (E) Amphibolite body exposed in Chiklar village on the way to Darahkoh. (21˚58'35"N 77˚54'47"E); (F) Folded quartz vein within graphite schist, south of Maramjhiri area (21˚56'12"N & 77˚53'45"E).

### 2.3.6. Intrusives

Quartz and pegmatite veins occur abundantly within the gneisses and meta-sediments. The pegmatite veins are intruded sub-parallel or parallel to the gneissosity and schistosity in gneisses and meta-sediments. The pegmatite bodies also mark the contact between the schist and gneisses at places. Thick quartz veins confined to a particular zone are ferruginised, preserve quartz sigmoid, representing the occurrence of a prominent shear zone. whereas the minor quartz veins are found in the entire area, emplaced parallel to $S_1$ as well as $S_2$ foliations The quartz veins comprise of milky, opalescent, large crystals of quartz fissured by thin vein-lets and stringers of graphite often associated with pyrite. Most of these veins are devoid of mineralization, but the quartz veins emplaced within graphite schist or within the shear zone contain sulphides and are ferruginised.

## 3. Nature of Occurrence and Control of Mineralization

The Betul belt is a known geological milieu for its volcanic hosted massive sulphides mineralization, to the geological community since long. Due to its complex tectono litho-stratigraphy, structure and potentiality for mineralization related to acid magmatism in the western part, tungsten mineralization, molybdenum, anomalous incidences of niobium and tantalum have been reported where as in the northern part (Padhar mafic-ultramfic) and in the eastern part Mordongri ultramafic complex higher values of PGE, Ni, Co, Cr and Cu mineralization are reported from this suite of rocks. Though there are many important prospects of base metal in Betul belt but are not being discussed as the paper deals with Graphite mineralization and its possible genesis. The report of occurrence of graphite is dated back to 1958, the presence of graphite in the supracrustals of Betul belt in Golighat and Junewani are [1] [6] was reported but no subsequent prospecting/exploration was ever planned. During the year 2012 prospecting for graphite in Chiklar-Gauthana-Tikari areas, Betul district, of Madhya Pradesh was carried out carried out [4]. The prospecting work has revealed the presence of significant mineralization of graphite contained in the supracrustal rocks of proterozoic age. Based on the reported occurrence, reconnoitory work in Golighat and Junewani area suggests presence of graphite for a strike length of nearly 700 m. discontinuously [7].

The surface manifestations of graphite mineralization in the area are record in terms of few old pits and mine dumps, ant and termite/ant hills and insect borrowings composed of the graphitic black coloured clayey soils indicate presence of graphite below the surface (**Figure 5(A)** & **Figure 5(B)**). Apart from these two surface manifestations, it has also been observed that graphite being hosted within the quartz mica schist has a contrast in the appearance of soil colour than the surrounding areas. In Golighat area, the surface manifestation occurs only in the form of few insect burrowings with limited surface exposures and blackening of the surface soil. The old workings were reported in Tikari-Gauthana, and Chiklar (north of Betul town) falling in Survey of India toposheet no. 55G/13, [1], are test pits rather than old workings and are confined within the muscovite-quartz schist where its graphitic and turned in to graphite mica schist. The graphite schist which is a host lithology extends from Tikari (1.5 km south east of Maramjhiri railway station) in the southwest to Chiklar in the NE over a strike length of more than 3.5 km. The graphite bodies exhibit a discontinuous lensoid disposition, more or less in strike continuity with a slight dextral shift at Chiklar village. Graphite has been noticed in a compact soft schistose litho-unit, composed of varying proportions of quartz, feldspar and mica. (**Figure 5(C)**) The foliation planes are well defined by compactly packed flakes of mica and graphite (**Figure 5(D)**). Prominent concordant veinlets of quartzo-felspathic material and siliceous partings are well recorded in graphite-schist. The graphitic schist shows well developed schistocity. All the constituent minerals displaying elongation in parallelism and graphite occupies the foliation planes. Quartz,

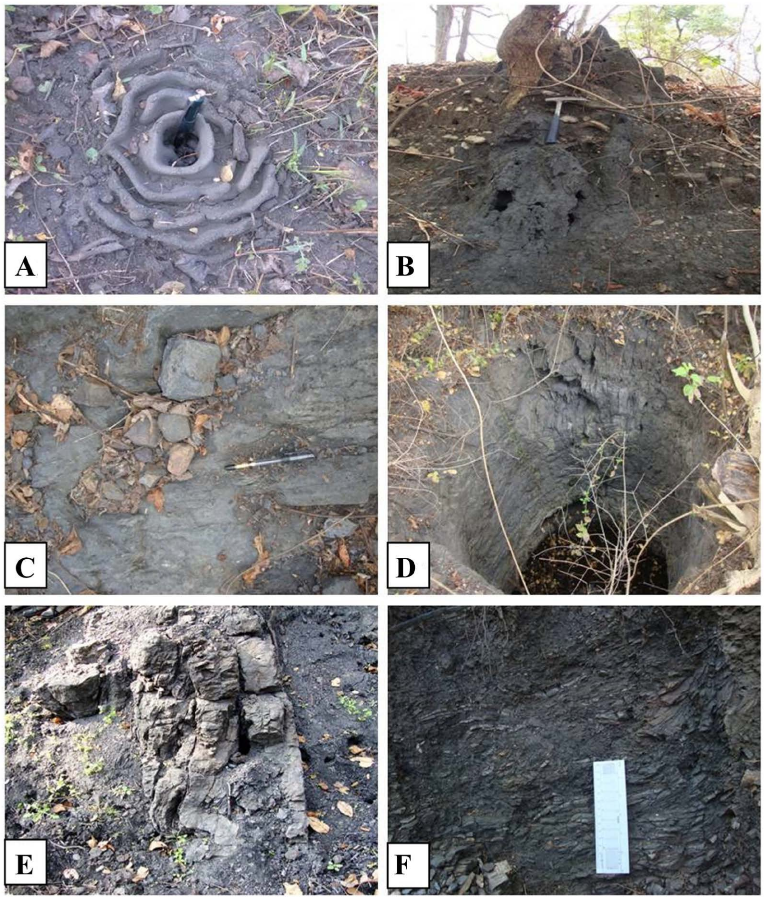


**Figure 5.** Surface manifestations of graphite, from the study area. (A) Exposure of graphitic schist in a nullah section in forest area, Gauthana (21˚55'45"N 77˚54'19"E); (B) Well preserved anthill composed of graphite Gauthana area; (C) banded graphitic body exposed in the forest area Central band (D) The entire wall of the well is composed of graphitic schist suggests, vertical dips, southern band, Gauthana area; E: Silicified, ferruginised graphitic schist exposed in the Nala section, Gauthana area.F: Thinly laminated graphite band exhibits crude schistosity.

feldspar and micas are frequently impregnated with the dusty particles of graphite and are cloudy in appearance. The graphite bodies are mostly sub vertical to vertical, thin, linear and disposed sinuously, restricted to the shear zones, often criss crossed by calcite veins (Figure 5(D) and Figure 5(F)), dips of these graphite mineralized bodies however keep changing due to intense folding.

The contact between this graphitic schist and the biotite-gneiss is gradational at places, while it is sharp at other. The graphite content decreases with increasing distance from the biotite gneiss as seen from the geochemical contour map where the high Fixed carbon, occurs towards the proximity to the contact of granite gneiss. Graphite occurs as concordant bands, veins, clots and pockets in the area of investigation. The graphite bodies of lensoid nature vary in width from 1 m to as large as 135 m, and in strike length from 300 m to more than 1400 m on surface. These lenses exhibit pinching and swelling both laterally as well as vertically as established from subsurface multi level exploration. In general, the graphitic bands occur as singular lensoid bodies. However, branching and braided nature of the graphite bands have also been observed particularly in the swelled portion of the band. The borehole data confirms the branching observed on the surface to continue with the depth. The bulk of the graphitic schist acquiring lensoid geometry is confined to the quartz muscovite schist, but some pencil thick veins are also recorded from the amphibolite occurring in contact with the mica schist. The vein type of mineralization occurs along the foliation and joints with individual veins being 0.50 cm to 10 cm in thickness. The pegmatite bodies exposed and disposed along the contact of quartz mica schist do contain occasional clots, patchy mass and disseminations of Graphite. The host rock of graphite (quartz-mica ± graphite schist and quartz-graphite-muscovite schist) is generally highly sheared and intruded by pegmatite/quartz veins. These veins intruding into the graphite bodies have concentrated graphite along the margins. The second phase of folding has influenced the graphite localization as could be observed from the thickening of the graphitic bodies along the hinge of the folds, as could be seen on the way to Maramjhiri railway station. Besides these a linear discontinuous silicified, ferruginised and brecciated zone traversing the southernmost graphitic schist band has been traced for a strike length of 1000 m with exposed width varying from 05 m to 10m and is found to be radioactive as tested with scintillometer. The radioactivity is of the order of twice to four times higher than the background for graphitic rock which is (*i.e.* 02 mr/hr).

The occurrence of graphite as wide spread dissemination in quartz veins, braided disposition of graphitic vein lets within the mica schist, clots and sporadic patches in Pegmatites and veins of graphite with in Amphibolite adds credence to the hydrothermal mode of occurrence, besides being of the syn-depositional in nature.

Graphite occurs as amorphous mass- to flaky-type, reflecting thermal effects of low- to high grade metamorphism on organic-rich carbonaceous sedimentary and carbonate rocks. The graphite schist mainly comprises of small flakes of steel grey graphite mixed intimately with muscovite flakes and ash grey powdery material (**Figure 5(C)**). In hand specimen it appears black to steel grey in colour and usually soils hand due to its extreme softness and greasiness. The amorphous variety has a comparatively dull luster looking more or less like carbon phyllite, whereas the flaky variety has a shiny luster with flakes of muscovite, biotite and graphite. It is further observed that the flaky variety is softer with visible flakes of graphite and mostly muscovite whereas the amorphous variety is extremely fine grained and is intimately associated with mostly quartz and mica. At places minute calcite and silica veins are also associated with the graphite bands as observed in the drill cores. The graphite bands are invariably associated with thicker quartz veins, which show extreme brecciation and ferruginization and are found to contain some oxidized sulphides. Prominent concordant vein-lets of quartzo-felspathic material and siliceous partings are well recorded in graphite-schist.

Sulfide disseminations including pyrite and minor chalcopyrite is seen associated with the thicker parts of the graphite band. The Fixed carbon value of graphite varies from 3.23% to 12.03% with an average of 7.7% [4].

## 4. Petrography of Host Rock

The graphite schist under microscope, is fine to medium grained rock with euhedral to subhedral meso-crystalline, hypidiomorphic having variable proportion of major mineral phases quartz, biotite, muscovite, and amorphous (**Figure 6(A)** and **Figure 6(B)**) to flaky graphite. Graphite is one of the several opaque minerals which appear silvery and metallic, occasionally brownish gray in reflected light and black in transmitted light. Minor mineral phases are hornblende and sphene. The schistosity is defined by the parallel alignment of flaky graphite,

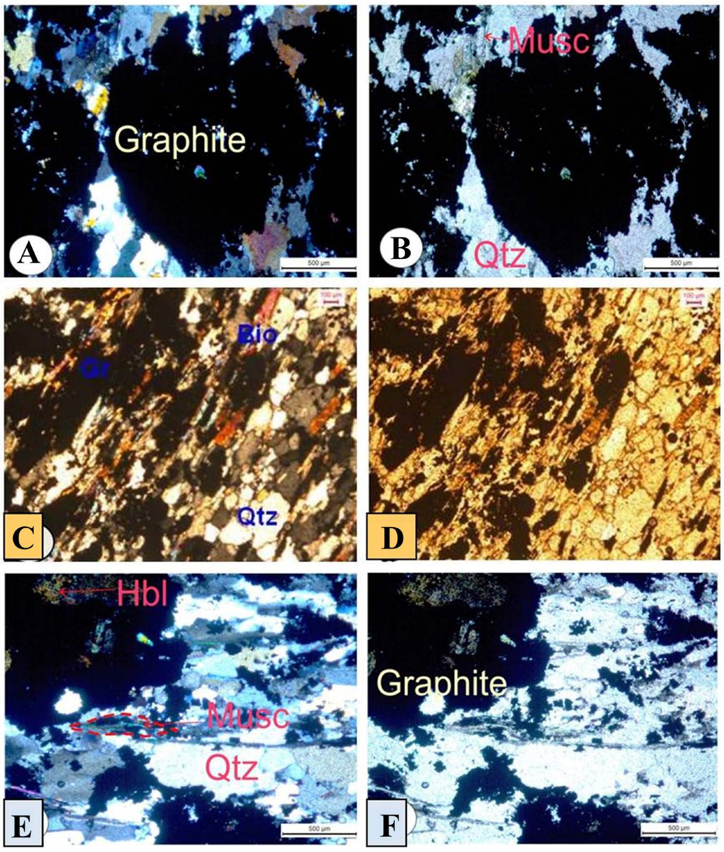


**Figure 6.** Photomicrographs depicting composition and textural characteristics of host lithology in Betul belt. (A & B) Photomicrograph of graphitic schist with major mineral as quartz, graphite, hornblende, biotite and muscovite; the overall texture is granoblastic. The large spherulitic aggregates of Graphite suggest precipitation from fluids rather than graphitization from organic matter during metamorphism. (C & D) Photomicrograph of typical graphitic schist where graphite and mica are defining the plane of schistocity. (PPL and cross nicol view (right and left half respectively). (E & F) Photomicrograph of graphitic schist with quartz, biotite and muscovite defining the schistosity and presence of graphite globular/spherulitic grains lying across schistosity and retrogration of hornblende is seen. Undeformed globules and spherulites suggest crystallization from carbon rich supercritical fluid, post deformation.

biotite and muscovite, whereas anhedral and equigranular grains give rise to interlocking granoblastic texture (**Figure 6(C)** and **Figure 6(D)**). Mica (muscovite and biotite) occur as fine to medium sized flaky grains. Most of the mica grains are free but a few grains are interlocked with graphite and quartz, with mica grains carry minute disseminated inclusions of graphite. The undulose extinction and flattening of quartz indicates shearing. Most of the quartz grains carry very fine grained disseminated inclusions of graphite. Medium sized quartz grains carry more number of inclusions of graphite than mica.

Graphite displays two distinctive textural habits here in Betul meta-sedimentary rocks and these are similar to graphite textures observed in members of the New Hampshire Plutonic Series [8]. The first type is flake graphite [8] the familiar form of graphite in meta sedimentary rocks, particularly schists [9]. Flake graphite consists of thin, micaceous foliation (0001), which has hexagonal or rounded outlines. Graphite flakes may occupy grain boundaries or be partially enclosed in quartz or feldspar in the igneous rocks. Flakes are generally foliated parallel to biotite; Despite its low hardness flake graphite is stable under conditions of differential stress, as it is the common form of graphite in high-grade schists and gneisses in dynamically metamorphosed terrains [10] [11]. The second type of graphite consists of fine-grained (0.01 - 0.1 ram) polycrystalline aggregates composed of tiny (<0.01 ram) graphite crystallites, this grades from irregular aggregates of randomly oriented crystallites to graphite spherulites (up to 0.225 ram) with a well-developed radial arrangement [8] commonly occurs inter grown with fine-grained alteration minerals (sericite, chlorite, zoisite, carbonate) or coarser, decussate micas formed as a result of post kinematic retrograde breakdown of garnet, cordierite, and other minerals. Petrographic observations of graphite indicate that flake graphite crystallized early in both igneous and meta-sedimentary rocks, but that spherulites or irregular graphite aggregates are late stage, secondary phases. Spherulitic graphite is commonly inter-grown with products of hydration or carbonation reactions that have affected primary silicates, whereas flake graphite displays no obvious reaction textures. A distinct correlation between graphite and hydrous silicates was similarly noted in the Bushveld Complex [12]. Co-precipitation of spherulitic graphite and hydrous silicates constitutes evidence that the formation of secondary graphite spherulites proceeds only in the presence of a supercritical carbon-saturated aqueous fluid. This fluid was the main agent of retrograde hydration and carbonation reactions, and graphite was produced as a by-product of these silicate-fluid reactions. The occurrence of abundant spherulitic graphite along with retrograde silicates in shear zones that served as fluid pathways through the plutonic rocks further supports the role of C-O-H fluids in forming the secondary graphite. Moreover, the similarity of spherulitic graphite to certain textures in graphite veins, which are clearly of hydrothermal origin, is additional evidence for the presence of a fluid phase during formation of spherulite graphite. Under equilibrium conditions, the carbon speciation and isotopic composition of this fluid would be buffered by coexisting flake graphite, if present. Fluid super saturation is also indicated by examples of heterogeneous nucleation of secondary graphite. Graphite is commonly inter-layered in secondary muscovite or chlorite [8] as flakes parallel (0001) or as spherulites embedded in the micas. Pyrrhotite also provides a catalyst in nucleation of radially oriented spherulites on flakes Graphite textures. Graphite occurs as fine grained opaque anhedral to cryptocrystalline globular or spherulitic aggregates of crystals. Such globular and/or spherulitic aggregates indicate crystallization from the super critical carbon rich fluid post metamorphism or deformation as they have no evidences of penetrative deformation. Spherulites are invariably fine grained than coexisting flake graphite and crystallites cross cut foliation. These observations indicate the graphite spherulites or aggregates grew after crystallization and deformation. Furthermore, the delicate textures of spherulites are unlikely to have sustained penetrative deformation [11]. Spherulitic graphite has been observed In addition, several cases of radially arranged graphite occurring as flower have also been observed [11]. The catalytic effects of micas and sulfides in industrial graphitization processes have been noted by others [10] [13]. The graphite porphyroblasts have inclusions of quartz and muscovite. These inclusions have orientation perpendicular to the dominant schistosity. Graphite occurs along the foliation planes as crystalline flakes as isolated, flat, Figure-like particles with broken, irregular or angular edges. (**Figures 7(C)-(F)**) The graphite flakes together with mica flakes occur parallel to the foliation (**Figure 6(C)** and **Figure 6(D)**). Graphite occurs as flaky opaques and intimately associated with the biotite. Biotite grains are spotted with small grains of graphite. Spherulitic graphite is fine in nature and occurs as clot within the schist. At places the graphite has been seen pseudo-morphing hornblende porphyroblasts (**Figure 6(E)** & **Figure 6(F)**) and irregularly digested amphiboles. It also occurs as euhedral prophyroblasts and also in inter-granular spaces between quartz and biotite grains (**Figure 6(C)** & **Figure 6(D)**). At places graphite also forms corona over the quartz grains and also occurs as glomero-porphyroblasts.

Petrographic study of graphite from Betul belt reveals that the schistosity is defined by the parallel alignment of flaky graphite, biotite and muscovite and both Q-domain & M-domain can be identified. Alternate domains of quartz rich layer and graphite rich layers are seen (**Figure 8(E)** & **Figure 8(F)**). M domain is dominantly composed of tabular micaceous grains and the graphite along the schistosity plane with occasional presence of quartz. But some muscovite grains are oriented at an angle with the major schistosity plane. Kinked muscovite crystals are also seen whereas Q domain is defined by quartz as the major phase with small amount of mica in the inter-granular spaces. At places typical granoblastic texture is seen with the development of porphyroblasts of hornblende and graphite. The triple point junction is also seen. Although in most of the places the cryptocrystalline graphitic mass defines the schistosity but at places it occurs at an angle with the major schistosity plane. The folded and cleaved graphite crystals

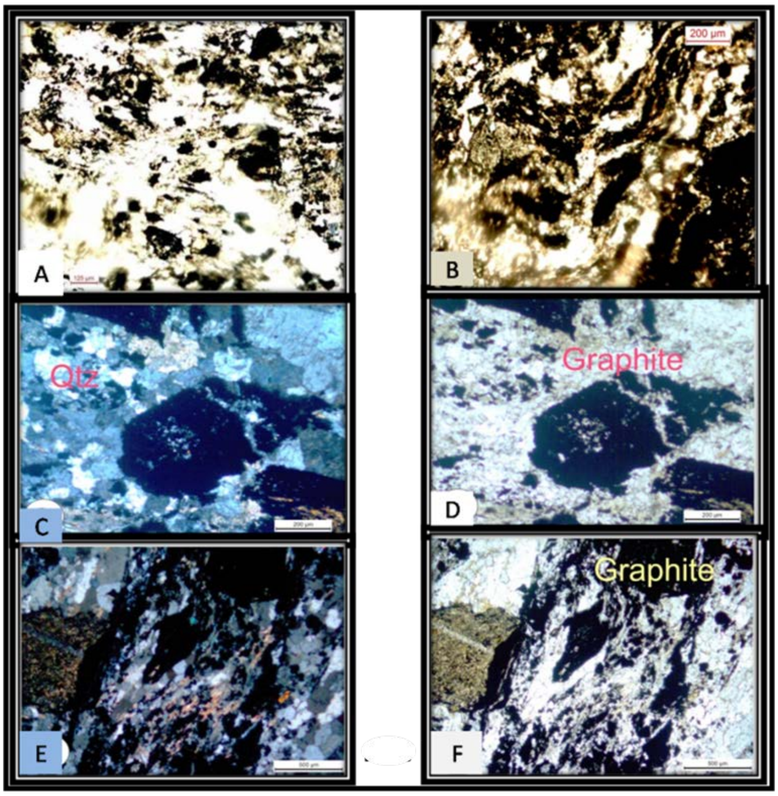


Figure 7. Photomicrographs of host lithology, exhibiting various modes of occurrences and textures of graphite: (A) Photomicrograph of tiny crystals of graphite occupying the margins of silicate minerals, suggesting their graphitization during metamorphism; (B) Photomicrograph of folded flakes of graphite indicating its Organic origin and graphitization during metamorphism and deformation; (C & D) Photomicrograph of porphyroblast of graphite suggests post deformation growth and retrogration of Hornblende; (E & F) Photomicrograph of graphitic schist with alternate domains of quartz rich layer and graphite rich layers are seen. PPL and cross nicol view (right and left half respectively).

in the graphite schist suggest its formation prior to F2 deformation (**Figure 7(B)**). Evidence of shearing is depicted by pinch & swell structure and presence of mica fish (**Figures 8(A)-(F)**). Sericitization is also observed. A later intrusive quartz vein is also present. These veins also have subhedral to sub rounded opaques (graphite globules). Besides all this graphitic veins are also present. These veins are cross cutting the existing schistosity plane (**Figure 8(A)** & **Figure 8(B)**).

## 4.1. Scanning Electron Microscope (SEM) Studies

Scanning electron microscopy (SEM) attached with energy dispersive spectroscopy (EDS) is widely used for the qualitative and semi-quantitative analysis of mineral identification. Though SEM technique is generally used for the morphological analysis and interpretation of submicroscopic particles (organic and inorganic), this technique has been used to interpret the minerals with the help of EDS spectra. The size, shape, morphology of minerals and their texture pattern can be deduced by using a SEM and it gives in depth understanding about intergrowth, inclusion, solid solution and composition of different phase by using

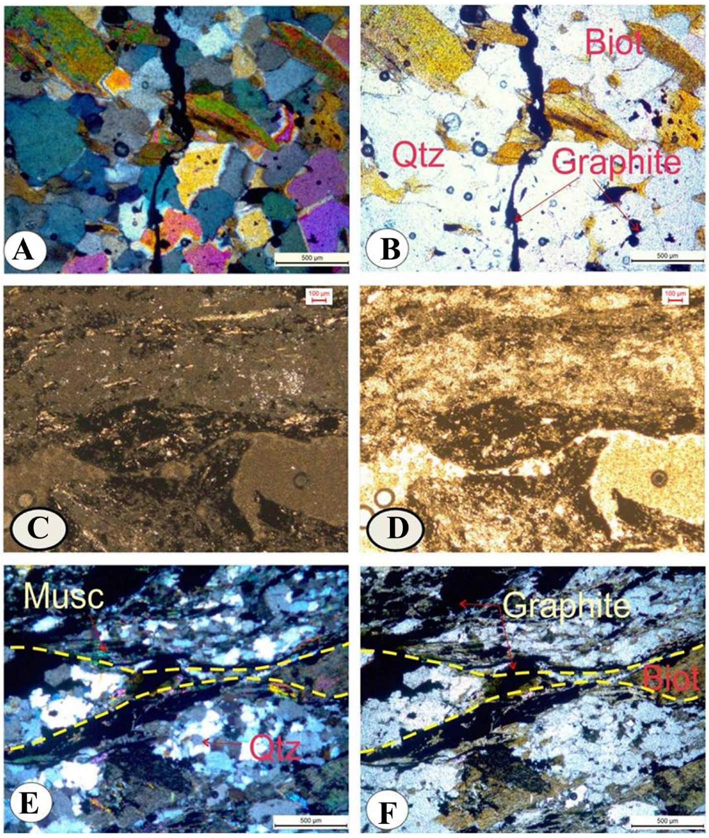


**Figure 8.** Graphite schist, exhibiting various modes of occurrences of Graphite. (A & B) Photomicrograph of graphitic schist with quartz, graphite, biotite and few muscovite grains as major mineral phases. The graphitic vein displaying discordant relation, points towards post deformation fluid precipitated graphite, originated from critical fluids. Also inclusions of graphite within quartz; (C & D) Photomicrograph of graphitic-schist showing pinch and swell structure depicting the evidence of shearing. Cross nicol and PPL and view (left and right half respectively); (E & F) Photomicrograph of graphitic schist with alternate Q and M domains and pinching and swelling suggesting origin from organic matter.

Energy Dispersive Spectrometer (EDS). In order to understand the crystalline behaviour, stacking pattern, size and shape of the graphite flakes, SEM analysis on a few graphite and graphitized rocks was attempted Carl-Zeiss Supra-55 SEM at Central Research Facility (CRF), Indian Institute of Technology (Indian School of Mines) Dhanbad, India. SEM-EDS analysis has been done to analyze the graphite samples with an accelerating voltage of 20 kV, a working distance of 15 mm, a beam current of 1.5 nA and a detector process time of 4 second.

Various types of graphite and graphitize rocks suggest different degree of crystallinity, stacking behavior, grain sizes and regularity/randomness of the developed graphite flakes. The SEM study suggests that the low specific gravity graphite, steel grey to black coloured graphite samples with less siliceous gangues are structurally ordered possibly due to the intense metamorphism and a pure carbonaceous precursor. The same is clearly depicted from (**Figure 9(A)** & **Figure 9(B)**) where, the transformation stage of carbonaceous material trapped

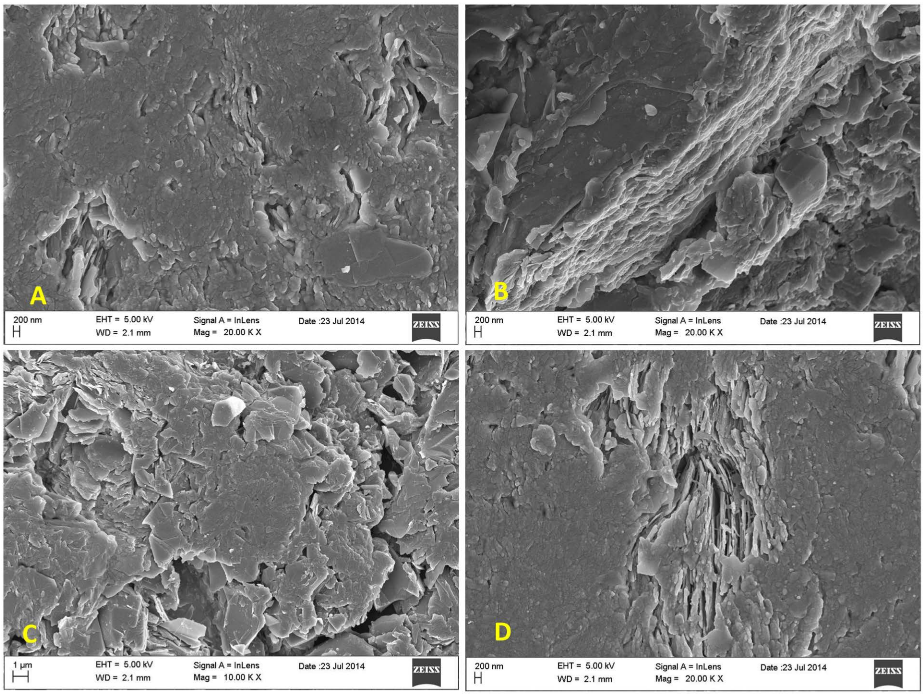


**Figure 9.** BSE images of various graphite samples from the study area, exhibiting surficial morphology of the graphite crystals. (A to D): (A) SEM BSE image showing partially crystalline graphite with smaller flakes of graphite associated with the micaceous schist; (B) SEM BSE image of a crystalline elongated graphite with intrinsic structurally ordered flaky morphology with low siliceous matrix suggesting maturity of the graphite from the precursor material under metamorphic evolution; (C) SEM BSE image of the surficial feature of a graphite sample showing micro granular tabular flakes of graphite crystals in random structural ordering, depicting graphitization during the process of metamorphism; (D) SEM BSE Image showing transformation stage of carbonaceous material trapped within the mica schist in to graphite flakes with remnants of micro pores on to the surficial part of the carbonaceous rich mica schist.

within the mice schist into graphite flakes with remnants of micrpores on the surfacial part of the carbonaceous rich mica schist is observed. Even if, an organic precursor is suggested for the graphitization on the basis of carbon isotope analysis, no organic evidences/signatures were traced during the SEM studies. This could be due to the intense metamorphism and maturity of the carbonaceous material into the flaky graphite. From (**Figure 9(D)**) it is clearly observed that the crystalline elongated graphite with intrinsic flaky morphology (structurally ordered) with low siliceous matrix suggesting maturity of the graphite from the precursor material under metamorphic evolution. On the other hand, the graphite flakes are very small, irregular, non-continuous without any solid stacking behavior which is associated with the micaceous schist and quartzite which is very well depicted by partially developed crystalline graphite with smaller flakes of graphite associated with the mica.(**Figure 9(C)**) At places, micro-granular tabular flakes of graphite crystals arranged in random structural ordering depicting the process of graphitization under the process of metamorphism (**Figure 9(C)**)

### 4.2. XRD-Analysis of the Graphite Schist

In order to know the mineralogical composition of the graphite bearing zones and its host rock, 10 samples collected from surface and boreholes were analysed using XRD at PPOD laboratory, GSI, Bangalore. Analysis was carried out by P analytical X'pert PRO XRD system. Carbonaceous materials in meta-sedimentary rocks recrystallize to form graphite structure with increasing diagenesis and metamorphism, it transforms to fully ordered graphite. This recrystalization is called graphitization and can be examined by the X-ray powder diffractometer. The mineralogical constituents of the graphite schist are quartz as a major mineral phase and graphite, muscovite, albite are occurring in small amounts whereas clinochore, pyrite & orpiment are occurring in traces. Since, the host rock for graphite in the studied area is schist or graphitic schist, micaceous minerals along with quartz and feldspar were detected by XRD. In the diffractograms less numbers of graphite peaks suggest low abundance and omnipresence of the graphite crystals/flakes in the analysed samples (**Figure 10**, **Figure 11**). The interfering peak positions of graphite and quartz suggest that graphite in the study area is intimately associated with the quartz while some isolated peaks of graphite suggest that the graphite is free from quartz. The very sharp peaks, obtained at about 26.5˚C, 2 theta positions in some samples, indicate better ordering of the atoms in Graphite. The $A^0$ value varies between 1.2 to 3.541$A^0$. The peaks having $A^0$ value of 3.54 corresponds to crystals with near perfect ordering. The similar peaks in most of the diffrectograms indicate either preferred orientation during growth or subsequently. The width and intensity of the peaks is controlled by the degree of graphitization. The width of the peaks is relatively narrow with the intensity of counts varying from 350 to 3300 counts per second. Hence the degree of graphitization achieved was fully ordered graphite crystals in the graphitic schist, but in isolated cases. The similar peaks in most of the samples with isolated sharp peaks suggest the ordering of graphite between d2 and d3 with isolated d1 category of graphite of Landis, 1971 [14]. Here it could be indirectly deduced that the d1 class may belong to the fluid crystallized graphite while the d3 and d2 graphite [15] may belong to the graphitization from organic matter due to metamorphism. As the area defines mostly green schist facies of metamorphism, the bulk of the graphite produced is of the d3 and d2 category while the d1 is of fluid origin, as the perfect ordering of the metamorphic graphite is achieved only at amphibolite facies of metamorphism [15] while fluid precipitated graphite is independent of grade of metamorphism.

## 5. Possible Genesis of Graphite in Betul Belt

Graphitization of naturally occurring organic carbon may occur at temperatures as low as 300˚C to 500˚C or as high as 800˚C to 1200˚C, when an igneous intrusion gets in contact with a carbonaceous body [16]. Since the graphitization process is irreversible it's an important indicator of grade of metamorphism. Carbonaceous matter is ubiquitous in sedimentary and metamorphic rocks; hence

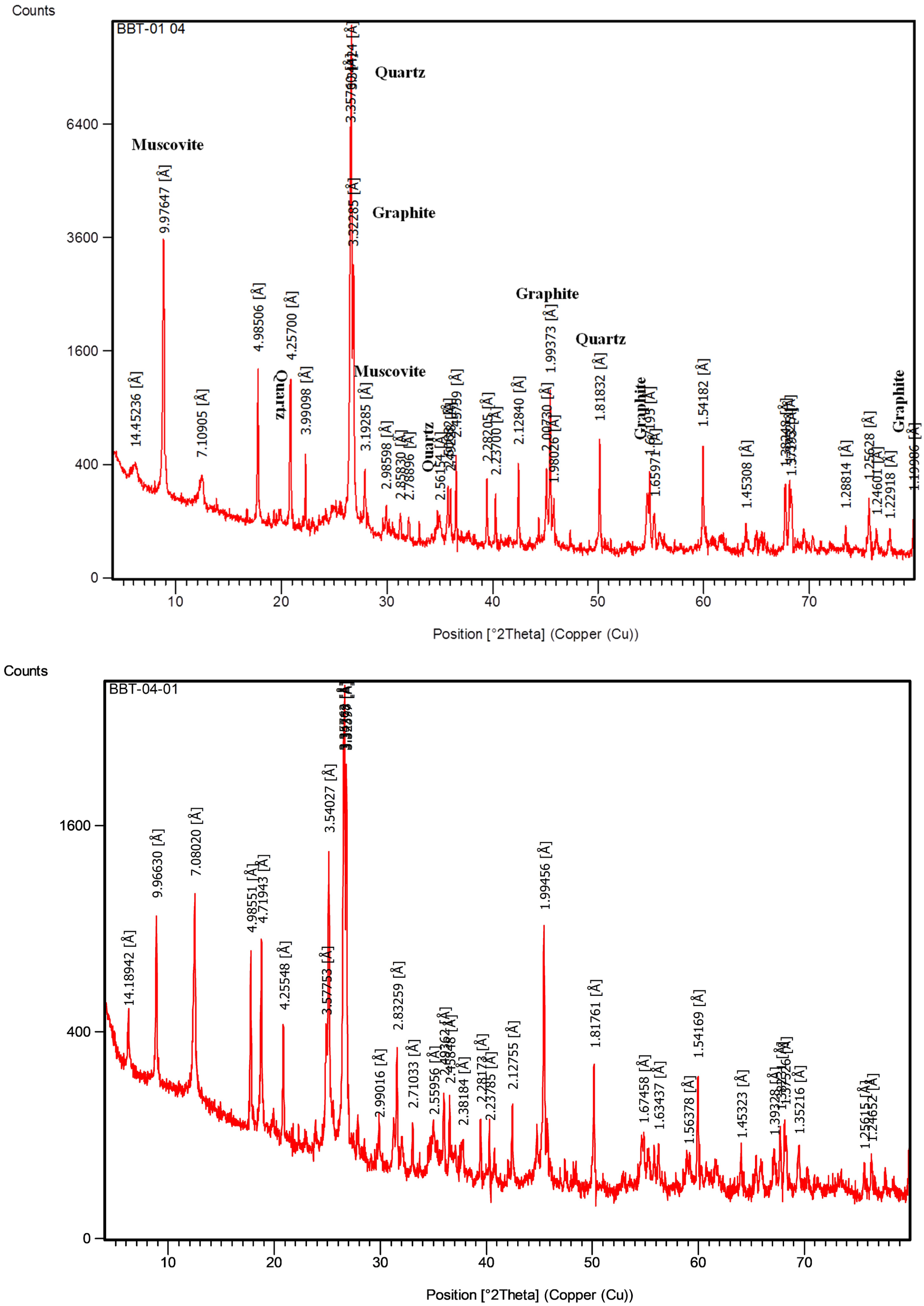


**Figure 10.** X-ray diffrectograms of various graphite samples depicting different associations and different intensity peaks of graphite depending on degree of maturity.

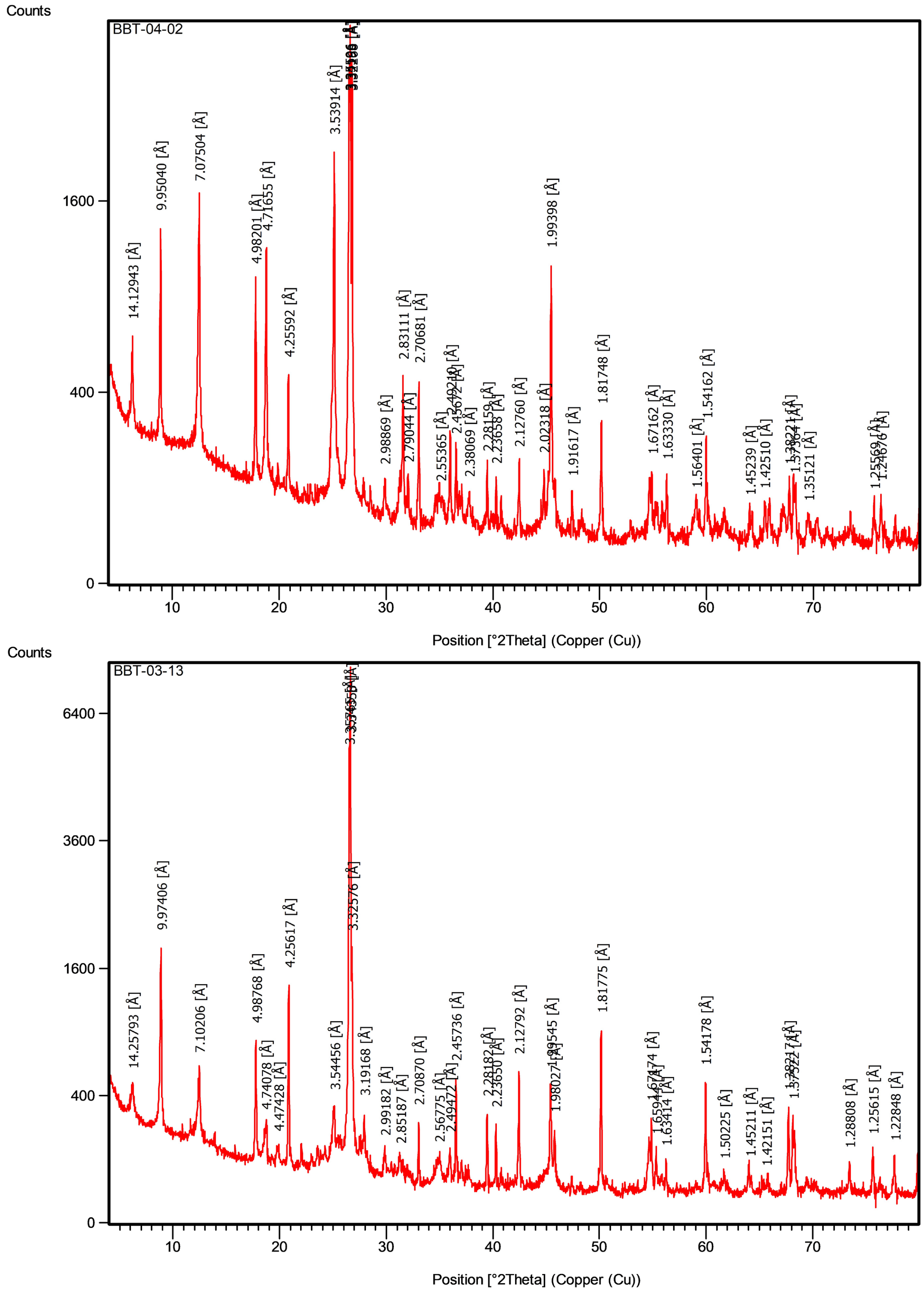


**Figure 11.** X-ray diffractograms of various graphite samples depicting different associations and different intensity peaks of graphite depending on degree of maturity.

the carbonaceous matter changes its crystal structure and its composition systematically with increase in grade of metamorphism irrespective of its origin. At a low grade of metamorphism up to green schist phases, the composition of the precursor material will control the process of graphitization [17] [18] [19] whereas, in the high grade metamorphism, all the carbonaceous matter is converted to graphite [19]. In low grade rocks many authors [20] [21] have noted mixture of carbonaceous matter and graphite (detrital graphite) can be identified by Xray diffraction [17] [22]. Graphitization process is accelerated in the presence of calcite in pelitic rocks in comparison to psamatic rocks. It was reported further, [21] [22] that to a great extent, graphitization in a regional terrain of metamorphism compared to a contact metamorphic terrain is attained in the temperature range of 410˚C to 440˚C with little pressure dependence. Thus the degree and process of graphitization of carbonaceous matter is considered to be controlled mainly by the metamorphic temperature, the duration of metamorphism and metamorphic fluid with some influence from the lithology and original texture of the organic matter. With burial, heating and deformation, organic matter deposited in sedimentary rocks matures and becomes increasingly well-structured and carbon rich through the release of hydrogen, nitrogen and oxygen, eventually becoming crystalline graphite [23]. The mobilization of carbon from carbonate and organic carbonaceous crustal reservoirs releases carbon and volatile species into metamorphic fluids, which can progress to higher crustal levels to react with overlying lower grade rocks [24] or be released into the atmosphere via hot springs [25] providing an important link between the atmospheric and crustal carbon cycles [26]. Graphite formation in metamorphic terrenes is traditionally considered to be a progressive temperature-dependent transition from amorphous kerogen to crystalline graphite, with crystallinity of the carbonaceous material an indicator of the metamorphic grade [10] [15] [18]. However, other studies indicate that graphitization is a discontinuous process controlled by temperature, pressure, the original composition of the organic matter, shear stress, duration of metamorphism and metamorphic fluid composition [14] [27]. In contrast to the progressive maturation of carbonaceous material, graphite can precipitate directly from C-saturated fluids, forming discrete graphite vein deposits [28]. Recent work has highlighted that disseminated carbonaceous material and graphite can be formed by fluid mixing under conditions typical of many metamorphic belts, which may be a significant and hitherto unaccounted for, sink in the global C budget. These contrasting processes can profoundly influence the composition of metamorphic fluids and hence there is a need for the clear distinction between graphitized carbonaceous material and fluid-deposited graphite, as this will affect our understanding of geological processes.

The progressive transformation of carbonaceous matter through prograde metamorphism (graphitization) and the deposition from C-O-H fluids are the two major processes responsible for the formation of graphite in rocks. Transformations induced by metamorphism of carbonaceous matter include both structural and chemical modifications that eventually lead to the formation of graphite. Thus, metamorphic graphite distinctively shows a wide range of structural ordering that can be correlated with metamorphic grade, mainly with temperature [15] [29] [30] [31] [32]. That is, crystallinity, described as the degree of crystalline perfection (*i.e.*, the similarity of a given arrangement of carbon atoms to the ideal graphite structure, both along the stacking direction of the carbon layers and along the a-b plane), increases with metamorphic grade. Compared with metamorphic graphite, fluid-deposited graphite in volumetrically large occurrences is known to be restricted to high-temperature environments and universally displays high crystallinity [28] [33] [34] Small-volume, poorly crystalline fluid-deposited graphite has been described associated with hydrothermal gold quartz veins [35] or along shear zones [36]. Precipitation of graphite has also been observed within fluid inclusions, both by natural and experimental mechanisms involving re equilibration of meta-stable C-O-H fluids [37] [38]. Such mechanisms systematically resulted in the formation of poorly crystalline graphite. The evidence of crystalline graphite precipitated from moderate temperatures fluids comes from the mineral assemblages and textural relationships between graphite and other mineral phases, along with fluid inclusion micro-thermometric data from the historic Borrowdale graphite deposit in northwestern England. The findings of this study clearly contrast with previous work that argued against volumetrically large highly crystalline graphite deposits being precipitated from carbon-bearing fluids at low pressures and low to moderate temperatures [34]. In addition, this study sheds new light on the constraints controlling highly crystalline graphite precipitation from low- to moderate-temperature fluids, which could be of interest for laboratory, and even industrial, synthesis.

Poorly ordered, low-crystalline graphite has been observed in a wide variety of metamorphic terrenes. Graphitization involves the progressive solid state transformation of carbonaceous matter with increasing crystallinity as metamorphism proceeds. The array of carbon atoms in the graphitizable aromatic molecules of the carbonaceous matter influences the six fold arrangement of carbon atoms within the layers of the graphite structure. That is, the original array of carbon atoms in the carbonaceous matter acts as a team during the graphitization process. Thus, graphite with low crystallinity formed under low-grade metamorphism reflects the original disordered pattern of carbon compounds within the organic matter (short continuity of the aromatic skeleton along both the in-plane directions and the stacking direction).

Fluid-deposited graphite results from the nucleation and growth from a carbon-bearing fluid, and kinetics might therefore affect the precipitation conditions and the physical properties of fluid-deposited graphite [28]. Since both nucleation and growth require high activation energy [39] this could be one of the reasons why highly crystalline fluid deposited graphite is restricted mostly to high temperature environments [33] [34]. In addition, precipitation of graphite from low- to moderate-temperature fluids is hindered by the high solubility of carbon in such C-O-H fluids [34]. Thus compared with high-temperature, high-pressure C-O-H fluids, low-pressure, lower-temperature fluids demand a very high initial concentration of carbon for graphite to be precipitated.

The spherulitic morphologies in graphite suggest high carbon super saturation in the fluids. These morphologies are consistent with high nucleation rates and rapid crystal growth from a large number of crystalline nuclei [40]. Moreover, the formation of cryptocrystalline and spherulitic graphite implies a mechanism of heterogeneous nucleation; that is, graphite nucleation occurs over a pre-existing substrate (mainly silicate grains). It is well known [41] that such a mechanism reduces considerably the energy barrier for nucleation with respect to the direct crystallization from an initially homogeneous fluid (homogeneous nucleation). The results demonstrate that under appropriate pressure-temperature-composition, highly crystalline graphite can precipitate at moderate temperature (~500˚C) from fluids containing $CO_2$ and $CH_4$.

## 6. Discussion

The graphite formation is associated with the process of metamorphism, which has been established through petrography of the host rock and graphite in Betul belt as described in the preceding pages without any doubt. The occurrences of globular/spherulitic aggregates of the graphite, having no effect of penetrative deformation on them are strong evidence of the fact that a sizeable proportion of the graphite has been crystallized from the fluid which was rich in Graphite post metamorphism. Such super critical fluids can generate at any stage of graphitization. Here in the present case such possibility is expressed due to intrusion of Betul porphyritic gneisses which are syn to post $D_2$ deformation, and has been responsible for generation of fluid rich in carbon and leading to precipitation of graphite. Such graphite has short crystallites as depicted in SEM studies. The other population exhibited in SEM of graphite is the highly ordered graphite having large optical continuity pointing towards the organic precursor matured through metamorphism between green schist and Amphibolite facies of metamorphism. The organic source of carbon graphite for betul graphite is also evidenced by the good amount of organic and miniscule percentage of inorganic carbon obtained in the analysis of 24 numbers of samples. Hence based on the all evidence derived from petrography, SEM studies association of silicate minerals with the graphite nature of distribution and mode of occurrence in field, it could be comprehensively concluded that Betul graphite is the result of metamorphism of the organic material deposited with in the pelitic rocks in an environment which was hot humid and reducing in nature was metamorphosed. The metamorphism allowed gradual structural ordering of the graphite which reached its near complete structural ordering during the Amphibolite grade of metamorphism. The Amphibolite facies of metamorphism is represented by the amphibole and its retrogression recorded in petrography. The another mechanism responsible for the presence of crypto crystalline to amorphous components of graphite being associated to the crystalline flakey graphite also points towards the separate process of graphite precipitation, fuelled and facilitated by the granitic intrusion syn to post $D_2$ deformation. This granitic intrusion provided local high temperature environment near the contact of the litho package and helped generate the super carbon rich hydrous fluid responsible for precipitation of globular and spherulitic component of graphite occurring as amorphous and short prismatic in nature. Hence the Betul Graphite derived its carbon component from the organic matter as a major source leading to the graphitization with progressive metamorphism, has partly been aided by the heat derived from the granitic intrusion, which helped generate the fluid rich in carbon (a C-O-H) system which was post process of metamorphism hence a fluid generated and precipitated component is also associated to it.

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## Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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