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Emplacement of Carbonatite and Associate Rocks of Siriwasan Carbonatite Complex, Gujarat: Evident by Field Relationship and Petrology

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Abstract: **The Siriwasan carbonatite complex is situated in the western part of Deccan Basalt Province and belongs to Chhota Udepur carbonatite-alkaline sub-province. The area consist a variety of rock types including sedimentary rocks of Bagh Group (sandstone, limestone and shale), Deccan basalts, carbonatized sandstone, pyroclastic rocks, carbonatite breccia, carbonatites (Alvikite and Sovite), tinguaite, trachyte and dolerite. The detailed field studies and petrography of the carbonatites and associated rocks of the area concluded that there should be at least two episodes of carbonatitic magmatism of different ages. The older episode was extrusive coupled with intrusive dykes and the later event was intrusive only. The tinguaite is older than Deccan basalts while the trachyte and dolerite are younger rock units.**

Index Terms: **Carbonatite, Carbonatite breccia, Carbonatized sandstone, Pyroclastic breccia, Siriwasan complex.**

I. Introduction

Carbonatites are uncommon igneous rock units. They can occur as intrusive, extrusive, hydrothermal or replacements bodies (Streckeisen 1980; Jones et al., 2013). Carbonatites are defined as igneous rocks which contain more than 50% of carbonate minerals (Streckeisen, 1980).Thus by definition they should have more than 50 % modal carbonates (CO_3 bearing) and less than 10 % SiO_2 (Woolley and Kempe, 1989). Globally, there are around 527 carbonatite occurrences (Woolley and Church, 2005, Woolley and Kjarsgaard, 2008, Woolley, 2001). However, there is only one active volcano of carbonatite known as Oldoinyo Lengai volcano in Tanzania. In India about 20 major and 11 minor carbonatite occurrences have been reported by various workers.

The Siriwasan carbonatite complex is situated in the western part of Deccan Basalt Province in Chhota Udepur district of Gujarat (Toposheet No. 46 J/4 and 46 F/16). The study area covers an area of approximately 120 square km and belongs to Chhota Udepur carbonatite-alkaline sub-province. The famous Amba Donger alkaline complex is just 15 km from the Siriwasan. The area comprises hilly terrain with several ridges, plateaus and isolated relict hills. In the present area of study, very little work has been done on the petrological aspects by earlier workers. As such the primary objective of research work to study regional and local geological set up, prepare detail geological and lithological map of the area and study mineralogy and petrology of carbonatites and associated rocks of the area. In the present study the detailed geological mapping was conducted on a scale of 1:10000 (Fig. 1). During the mapping, contact between various litho-unit exposed was demarcated and the field relationship and field characteristics were studied carefully.

II. Lithology and Field Relationship

From the field study and geological mapping of the area it has been observed that the area consists of a variety of rock types including sedimentary rocks of Bagh Group (sandstone, limestone and shale), Deccan basalts, carbonatized sandstone, pyroclastic rocks, carbonatite breccia, carbonatites, tinguaite, trachyte and dolerite.

A. *Sedimentary Rocks of Bagh Group*

Sedimentary rocks of Bagh Group are exposed around the villages Kakanpur, Amalwat, Mohan Fort, Palaskuwa, Jambhan, Motichikhli, Rajawat. Among sedimentary rocks the sandstone is the main lithounit and at places the band of intercalated limestone (Fig. 2) and shale are also found. In most places, the limestone is unfossiliferous, however, in a few places (Rajawat, Motichikli) oyster bearing limestone beds are also exposed (Fig. 3). The sandstone of Bagh Group is almost horizontal however, at places gently dipping and has dip between 7^0 to 15^0 SSE (Sukheswala and Borges, 1975). At several places sedimentary structures like bedding, cross-bedding, ripple marks etc. have also been observed. In general the Bagh Group of the rocks is covered by the flood basalt lava (Deccan trap) however, in the study area, at the majority of the places, there is no capping of Deccan basalts on Bagh sediments. This may be due to the faulting and erosion (Viladkar and Gittins, 2016). However, near village Khatol (Ghantol) there is a clear cut contact between the older Bagh sediments and younger Deccan basalts. The Bagh Group of rocks is considered to be deposited over the Precambrian metamorphic (Aravalli Supergroup) however, in the present area Precambrian metamorphics are not exposed, the metamorphic occur only as xenoliths in carbonatite breccias and tinguaite.

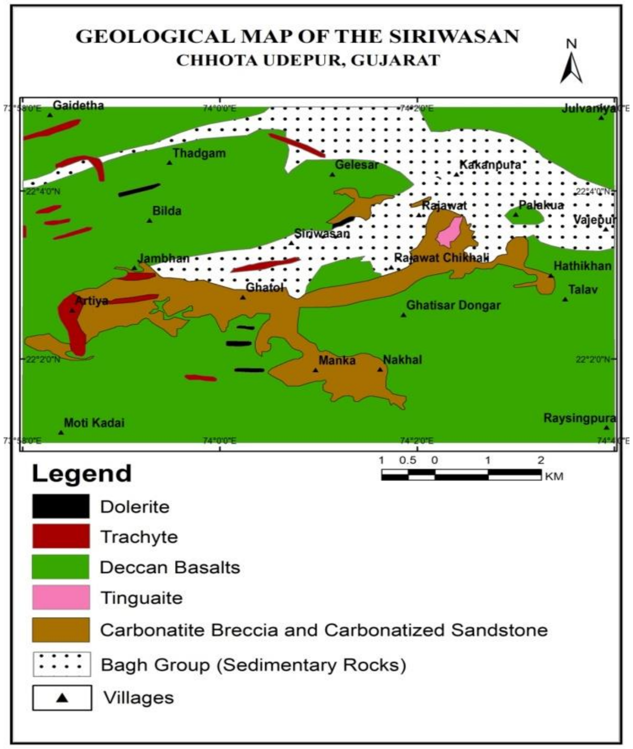

Fig. 1 Geological Map of Siriwasan and adjacent area, Chhota Udepur Gujarat

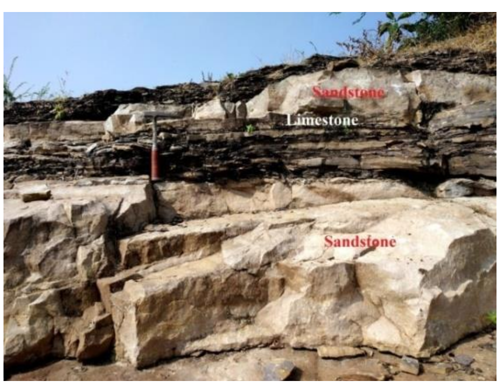

Fig. 2: Field photograph showing the intercalated beds of sandstone and limestone

B. Deccan Basalt

Major part of the area is covered by the Deccan Trap basalts, which belong to the central part of Deccan Trap Province of Gujarat. Most flows are of porphyritic basalt and are vesicular to amygdaloidal (Fig. 4). The Deccan Traps are directly overlying the Bagh Group (Fig. 5) and carbonatite breccias rocks and belong to Lower Traps as per the classification of Wadia (1966). At village Manka and Nakhal it appears that carbonatite seems to be younger than basalt but, it may be due to the step faulting. The age of Deccan basalt is considered between 60 to 68 Ma (Viadyanathan and Ramakrishnan, 2008).

Fig.3: Sample of Oyster bearing limestone

Fig. 4: Sample of Basalt showing the vesicular nature

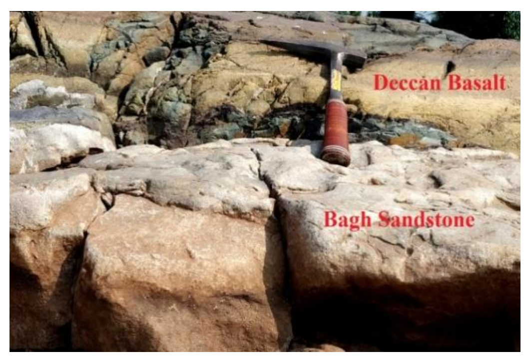

Fig. 5. Field Photograph showing the contact between Bagh Sandstone and Deccan Basalt.

C. Carbonatite Breccia

This lithounit horizon is mainly distributed in the central and southwestern part of the area as an irregular shape outcrop. It is extended up to 11 km from village Hathikhan to the west of village Artiya and village Manka in the south (Fig. 1). The outcrop varies in width from 50 m to 1.2 km. The carboantite breccia has complex texture, structure and variable mineral composition. The lithounits is subdivided into four units vertically. The uppermost part is undoubtedly an igneous breccia (**pyroclastic rocks**). They are well exposed near villages Manka and Nakhal. Below them the sandstone showing a brecciated appearance is exposed which has been influenced by the carbonatitic fluid and fragments of older rocks termed as **carbonatite breccia**. Just below it is the non-brecciated sandstone horizon which shows a soaking effect of carbonatitic fluid. This unit is termed **carbonatized sandstone**. The fourth and lowermost unit is of **unaffected sandstones** of Bagh Group.

The pyroclastic rocks (pyroclastic breccia) are grey and have pyroclasts of variable size and having juvenile pyroclasts derived from chilled carbonatite magma (Fig. 6). It has mainly the calcareous matrix.

Fig. 6. Field Photograph showing the exposure of Pyroclastic breccia exposed near the village Manka

The Carbonatite breccia which is major lithounit is the upper part of the sandstone of the Bagh Group. The Bagh Sandstone has been modified to a brecciated appearance due to intrusion and sub-aerial carbonatitic explosive eruption. The sandstone appears as a chocolate brown in colour and consists clasts of carbonatites, Bagh sandstones and older Precambrian basement rocks (quartzite, phyllite, mica schist, older basalt), and metavolcanics and fenitized rocks (Fig. 7). The size of the fragment varies from a few mm to 24 inches. At places the carbonatite breccias also show bedding (Fig. 8) represented by, alternating layers of coarse and fine material and ripple marks. These features indicate that this lithounit was the part of uppermost portion of the Bagh sandstone. Near the base of the carbonatite breccias, clear cut stratification and current bedding have been observed. However, at places this sandstone is having uncommon composition due to the presence (soaking) of carbonatitic material. The lower portion of such sandstone is unaffected by carbonatite fluid.

Fig. 7. Field Photograph showing the exposure of carbonatite breccia having fragment (xenolith) of phyllite (older metamorphic)

D. *Carbonatite*

The carbonatites are found as a boulders, pocket, veins and intrusive form of variable size and shape, ranging from a few cm to many meters. Two types of carbonatites have been found. One is fine-grained (alvikite) and another is coarse-grained (sovite). In the carbonatite breccia horizon, the juvenile clasts (Fig. 9) of carbonatitic magma are also found along with the intrusive dyke (Fig. 10) of fine-grained carbonatite (alvikite). At some places well formed visible cubic crystals of magnetite are present within sovite boulder (Fig. 11). In the *nalla* section near Manka village the deposit of travertine is found which is supposed to be the weathering product of carbonatite. Here a clear cut contact between the travertine and Deccan basalt is observed. The deposition of travertine is fairly thick and extends much about the present flood level of the *nalla*.

Fig. 8. Field Photograph showing the exposure of carbonatite breccia having bedding.

E. *Tiguaite*

Near Rajawat village, large-sized outcrop of tinguaite is exposed (Fig. 12) which is found within the carbonatite breccia. The tinguaite rock is pinkish-brown in colour and at places, it is also brecciated and contain fragments of older metamorphic and also carbonatite which can be termed as tinguaite breccia.

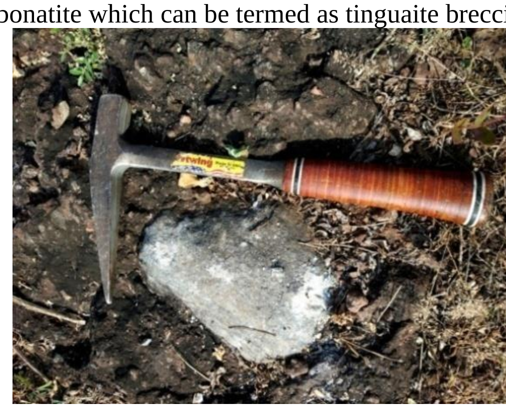

Fig. 9 Field Photograph of Carbonatite Breccia showing the juvenile clast of carbonatite

F. *Trachyte*

In the western part of the area, a number of dykes of trachyte of variable size and dimension have been observed. One such dyke is also present in the central part of the area north of the Siriwasan. The trachyte dyke has intruded the Bagh sandstone, carbonatite breccia, as well as in Deccan trap.

G. *Dolerite*

Exposures of dolerite dyke are found in south of Siriwasan and near village Thadgaon. These dykes are small in size and intruded the Deccan trap. However one dyke near the village Nani Chikhli has found intruded Bagh sandstone as well as in Deccan Trap. The dolerite dykes at places show spheroidal weathering.

Fig. 10. Field Photograph showing intrusive dyke of fine grained carbonatite (alvikite) within the Carbonatite Breccia, exposed near village Rajawat.

Fig. 11. Field Photograph showing the boulder of course grained carbonatite (sovite) rich in magnetite crystals.

Fig. 12. Field Photograph showing the intrusive dyke of Tinguaite exposed near the village Rajawat.

III. Petrographical Studies

Petrographical studies mainly focus on detailed descriptions of rocks with respect to the mineral content and the textural relationships. Based on the field observations, 45 samples were selected for petrographic studied. The samples were selected from different localities based on difference in field relationship and megascopic observations. The selected samples were of sandstone (2 samples), shale (1 sample), limestone (1 sample), basalt (2 samples), dolerite (2 samples), trachyte (3 samples), tinguaite (4 samples), carbonatized sandstone (4 sandstone), carbonatite breccia (14 samples), coarse carbonatite (6 samples), fine carbonatites (3 samples) and fenitized rock (3 samples).The brief description of rock types is as under:

A. Bagh Sediments

Sandstone of Bagh Group is fine to medium-grained, hard, compact and light grey to white. The rock mainly consists of detrital quartz grain (more than 97%). The quartz grains are variable size and are well sorted, having sub-angular to sub-rounded grains with low sphericity (Fig. 13). Both type of quartz grains i.e. monocrystalline and polycrystalline are present. However, monocrystalline quartz is the dominant one. The quartz grains are closely spaced and cementing material is mainly siliceous. Rock fragments are rarely present in the rock. Scattered grains of muscovite and chert are also present as accessory minerals. The Shale is light brown in colour, soft, showing fine-grained clastic texture. Microscopically rock is very fine-grained having thin compositional lamellae. Alternating bands contain fine grained angular to sub-rounded quartz with few grains of biotite, muscovite and felspar. The other band is very fine-grained and made up of clay minerals. Disseminated grains of iron oxides are widely present in the rock. The limestone is light grey to light blue, hard, compact and fine-grained rock showing thin beddings. Microscopically the rock is fine grained, having microcrystalline mosaic of calcite and interlocking silica particles with a small proportion of iron impurity.

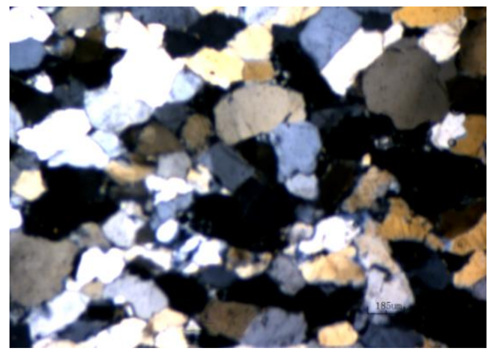

Fig. 13. Photomicrograph of sandstone of Bagh Group showing sub-angular to sub-rounded grains of quartz with low sphericity

B. Deccan Basalt

The rocks are hard, compact, and blackish to dark green in colour. Microscopically rock is inequigranular showing porphyritic texture with amygdaloidal structure. Rock is essentially composed of plagioclase showing carlsbad and pericline twinning. At places, the rocks show glomeroporphyritic texture where plagioclase is present as phenocrystic aggregates (Fig. 14). Augite pyroxene is another essential mineral in the rock and is interstitial to the plagioclase laths. Hornblende is the third important mineral and is having variable in shape and size. Scattered grains of olivine are also found in minor amounts. Disseminated grains of magnetite are the other accessory mineral.

C. Dolerite

The rock is black in, hard, compact and fine to medium-grained. Microscopically the rock is showing sub-ophitic to ophitic texture wherein grains of augite enclose partly or completely the laths of plagioclase of variable size (Fig. 15). At places the plagioclase phenocrysts segregate as glomeroporphyritic cluster. Plagioclase is showing Carlsbad and pericline twinning. Augite crystals are variable in shape and size. Opaque iron oxide minerals and apatite is the main accessory mineral.

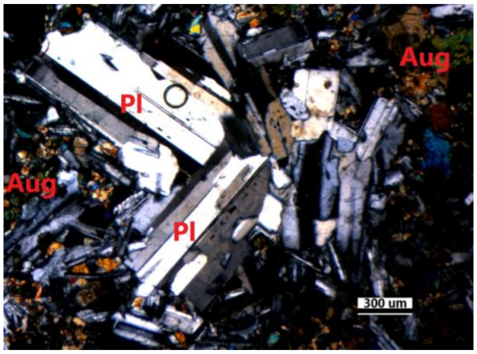

Fig. 24. Photomicrograph of basalt showing the glomeroporphyritic texture where plagioclase (Pl) is present as phenocrystic aggregates. Minute grains of augite (Aug) are also seen. (Sample R-42) (Cross Nicol)

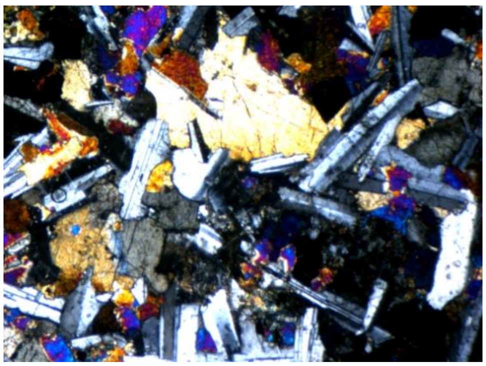

Fig. 15. Photomicrograph of dolerite showing the ophitic texture wherein grains of augite enclosing partly or completely the laths of plagioclase. (Sample R-36) (Cross Nicol)

D. Trachyte

The rock is light grey in, hard and compact showing porphyritic texture in the hand specimen. Microscopically it is fine-grained and invariably porphyritic. The groundmass is generally cryptocrystalline to microcrystalline with phenocryst of potash feldspar (mainly sanidine) which is highly altered. The groundmass looks turbid as a result of the alteration of feldspar. Augite is another essential mineral present as disseminated grains of variable size. The rock shows abundant acicular microlites of mafic minerals (Fig. 16). Accessory minerals present are biotite, hornblende, apatite and magnetite.

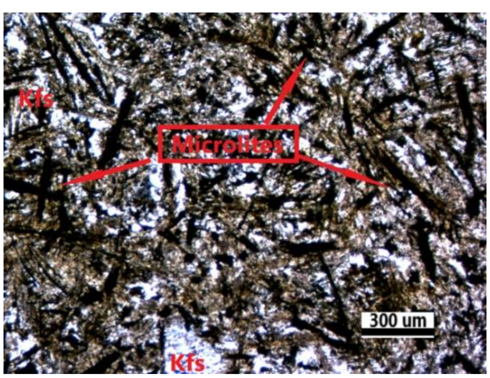

Fig. 36. Photomicrograph of trachyte showing abundant acicular microlites of mafic minerals. Altered phenocrysts of potash feldspar is also visible (Sample R-33) (PPL)

E. Carbonatized sandstone

The rock is light brown in colour, hard and compact, showing clastic texture. Microscopically the rock is fine to medium-grained having sub-rounded to rounded quartz grains which are embedded within the silico-carbonatitic cement (Fig. 17). Here the siliceous cement has been replaced by the fine-grained carbonatitic material at variable extent. The hot carbonatitic fluid has affected the quartz grains, as evident by the shattering of quartz grains (Fig. 18).

The carbonatitic fluid is having temperature ranges from 500 – 700^0C and very low viscosity i.e. around 0.005 Pas, even lower than the water (Tierney, 2002), therefore, the carbonatitic lava travelled to a greater distance from the point of eruption. Further, this low viscose fluid got penetrated into the pore spaces of Bagh sandstone, causing the soaking effect in the upper horizon and the original composition of sandstone got altered and became carbonatized sandstone or soaked sandstone. At places, the temperature and composition of carbonatite fluid have also caused the fenitization effect in sandstone and older metamorphic.

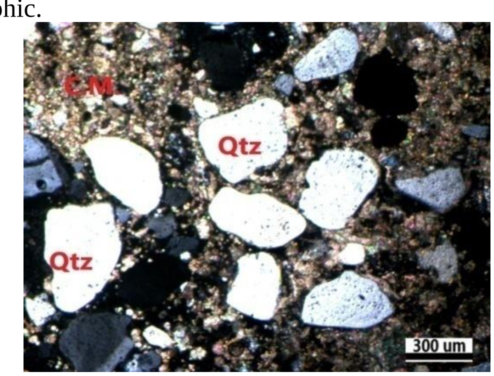

Fig. 47. Photomicrograph of carbonatized sandstone showing the sub-rounded to rounded grains of quartz (Qtz) embedded within the fine carbonatitic matrix (C.M.) (Sample R-8) (Cross Nicol)

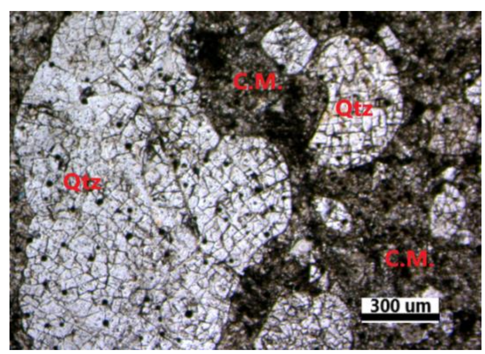

Fig. 58. Photomicrograph of carbonatized sandstone showing the sub-angular to sub-rounded grains of quartz (Qtz) which are enclosed by the carbonatitic matrix. All the quartz grains are shattered due to effect of hot carbonatitic fluid (C.M.). (Sample R-29) (PPL)

F. Tinguaite

The rock is hard, compact and greenish-black in colour. Under the microscope the rock is inequigranular and porphyritic in texture and has phenocrysts of both felsic and mafic minerals. The felsic phenocrysyts include both feldspar and feldspathoids which normally appear grayish but turn to pinkish due to alteration. Among the mafic phenocrysts augite, aegirine – augite and melanite are most conspicuous. Among the feldspar, orthoclase and albitic plagioclase are abundant and are highly altered. Nepheline is the most common feldspathoid and occurs as hexagonal or squarish crystals, which are invariably highly altered (Fig. 19). Acicular aegirine crystals often occur as a cluster in the light coloured groundmass. Aegirine – augite microphenocrysts are either prismatic or six-sided and are commonly zoned. Zoned melanite with a dark brown core and lighter margin (or vice-versa) occurs as sub-opaque, hexagonal to rounded isotropic crystals (Fig. 20). The groundmass is either glassy or fine-grained (cryptocrystalline), comprising of feldspar, aegirine, aegirine-augite and analcite. Apatite and magnetite are common accessory minerals in groundmass. At places, tinguaite also consist of fragments of carbonatitic material.

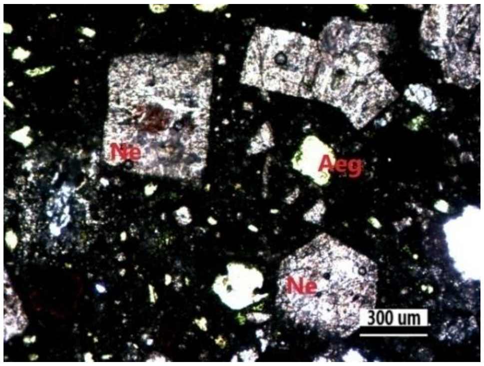

Fig. 69. Photomicrograph of tinguaite showing the porphyritic texture and hexagonal and squarish altered grain of nepheline (Ne) along with needle shaped and prismatic grains of aegirine – augite (Aeg) and augite (Sample R-9) (PPL)

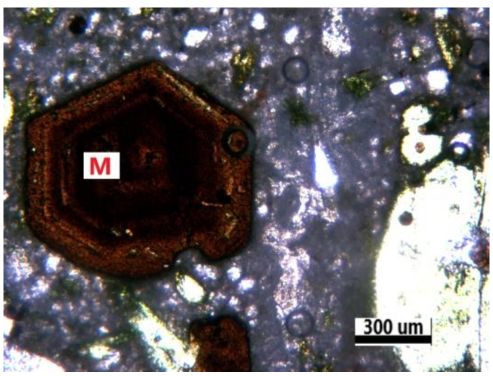

Fig. 20. Photomicrograph of tinguaite showing the melanite microphenocrysts (M). The melanite grains are showing zoning with dark brown core and light margin (Sample R-9) (PPL)

G. Carbonatite Breccia

The rock is reddish-brown in colour, compact, hard and having fragments of variable size. Microscopically rock is fine to medium-grained comprising small angular to sub-angular fragments (xenoliths) of older rocks. Rock is mainly composed of quartz and carbonate minerals. Quartz grains are variable in size and shape and generally unaltered. Corroded and broken grains of quartz are invariably present. At places the quartz grains show the effect of fenitization and replacement of quartz into albite or potash feldspar. The carbonate minerals are present as a groundmass and also as a microphenocryst and are generally calcite and ankerite in composition (Thin section examined staining with potassium ferricyanide and alizarine red S). Xenoliths (fragments) are invariably present and consist of phyllite, schist, quartzite, gneisses (older metamorphic) and older basalt (Fig. 21). Muscovite, apatite, plagioclase and iron oxides are present as accessory minerals. The groundmass is calcitic as well as ferruginous.

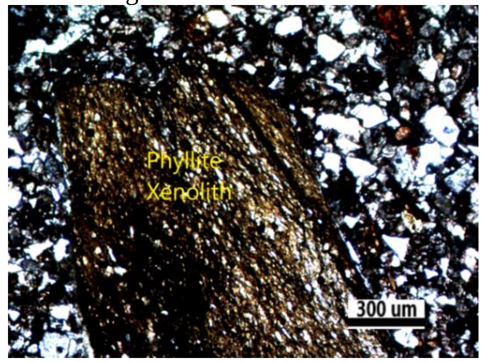

Fig. 21. Photomicrograph of carbonatite breccias showing the xenoliths of phyllite (older metamorphic) lying within the cryptocrystalline to microcrystalline silico-carbonatitic groundmass. (Sample R-11) (PPL)

H. Pyroclastic Rocks

The rock is hard, compact and grey, show a brecciated appearance. Microscopically the rock is generally fine-grained with fragments of variable size and shape. The fine-grained material is mainly composed of carbonatitic material. Carbonatitic material is cryptocrystalline to glassy and forming the groundmass and showing irregular flow banding (Fig. 22). The fragments are of carbonatite itself (juvenile clasts of carbonatitic magma) which are having a large amount of apatite (Fig. 23). Pyrochlore and cluster of rod-shaped and anhydral apatite are also present along with magnetite grains.

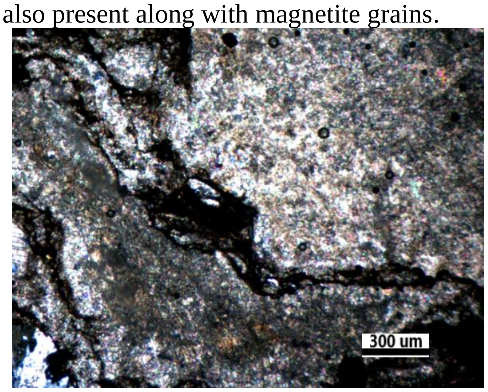

Fig. 22. Photomicrograph of pyroclastic breccias showing the cryptocrystalline to microcrystalline carbonatitic material with irregular flow bending (Sample R-6) (PPL)

I. Fine Grained Carbonatite (Alvikite)

The rock is grayish white, hard, compact and fine-grained. Microscopically it shows fine-grained, more or less equigranular texture and mainly composed of carbonate minerals (calcite/ankerite) with minute laths of aegirine and aegirine-augite (Fig. 24). Calcite grains are subhedral to anhedral in shape and at places, they are showing elongation. Aegirine is present as small laths and needles and is scattered throughout the rock. Grains of apatite and aegirine-augite are commonly present as accessory minerals. Few grains of pyrochlore and magnetite are also present (Fig. 25).

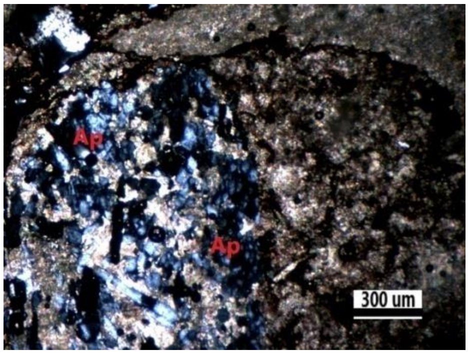

Fig. 23. Photomicrograph of pyroclastic breccias showing the juvenile clasts of carbonatite having large amount of apatite (Ap). The clast is surrounded by cryptocrystalline to microcrystalline carbonatitic material. (Sample R-6) (Cross Nicol)

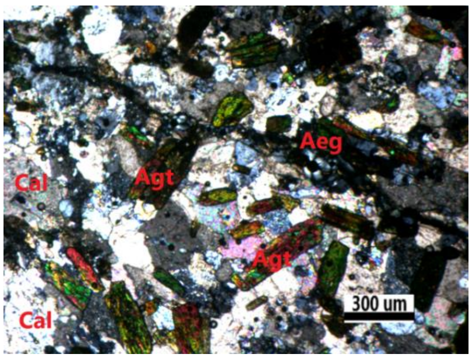

Fig. 74. Photomicrograph of alvikite showing subhedral to anhedral calcite (Cal) grains with laths and needles of aegirine (Aeg) and aegirine-augite (Agt) (Sample R-21) (Cross Nicol)

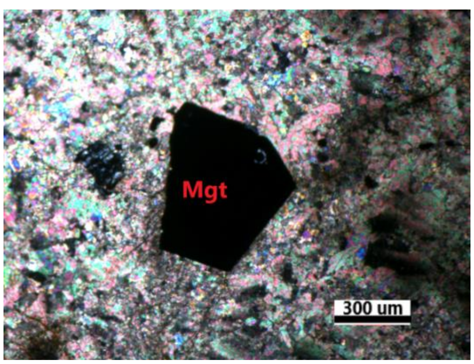

Fig. 85. Photomicrograph of alvikite showing euhedral grain of magnetite (Mgt) embedded within the cryptocrystalline to microcrystalline carbonatitic groundmass. (Sample R-7) (Cross Nicol)

J. Coarse Grained Carbonatite (Sovite)

The rock is white, hard and compact with large needles of aegirine or at places crystals of magnetite. Microscopically the rock is holocrystalline consisting medium to coarse-grained minerals of aegirine and calcite. Calcite grains are anhedral to subhedral in shape and show both straight and sutured contact. At places straight boundary and triple junction at the margin of grains is also seen (Fig. 26). Aegirine and aegirine-augite are present as large needle and lath shaped crystal embedded within calcite megacryst and also as clusters (Fig. 27). Minute grains of anhedral and rode shaped apatite and pyrochlore are found along the grain boundary as well as inclusion in the megacryst of carbonate calcite (Fig. 28). Scattered grains of magnetite and pyrochlore are also present in minor amount.

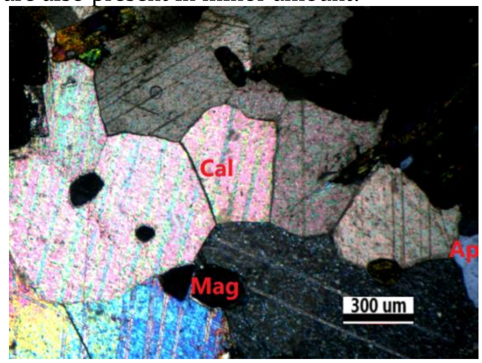

Fig. 26. Photomicrograph of sovite showing subhedral calcite grains (Cal), having straight boundary and triple junction at margins. Minute grains of magnetite (Mag) and apatite (Ap) are also present (Sample R-20) (Cross Nicol)

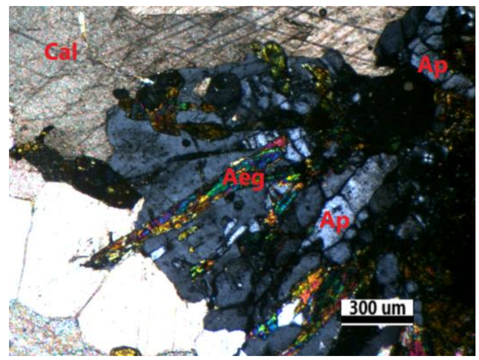

Fig. 27. Photomicrograph of sovite showing megacrysts of calcite (Cal) with cluster of needle shaped aegirine (Aeg) and elongated grains of apatite (Ap). (Sample R-20) (Cross Nicol)

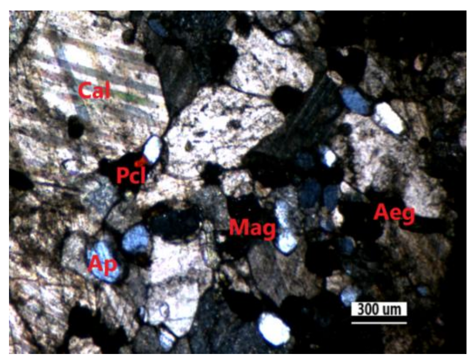

Fig. 28. Photomicrograph of sovite showing subhedral to anhedral calcite (Cal) grains having minute grains of pyrochlore (Pcl), aegirine (Aeg), magnetite (Mag) and cluster of apatite (Ap) (Sample R-41) (Cross Nicol)

IV. Fenitization

The fenitization is alteration of the original country rocks to metasomatic units (Zharikov et al., 2007). Cooling and crystallizing carbonatitic and alkaline melts expel multiple pulses of alkali-rich aqueous fluids which metasomatize the surrounding country rocks, forming fenites during the process of fenitization (Elliott et al., 2018). Fenitization is traditionally considered to involve the removal of silica (Brögger, 1921) and the addition of alkalis ($Na_2O + K_2O$) (Bardina and Popov, 1994).

In the present study area the effect of fenitization is observed both in the country rocks (Bagh sandstone) as well as in the older metamorphic. In a few samples of carbonatite breccia, the quartz grains show the effect of fenitization and have replacement of quartz into albite plagioclase (Fig. 29) or potash feldspar are observed.

Strong fenitization has been observed in the fragments of Bagh sandstone occur as clasts within the carbonatite breccia. Here the sandstone got fenitized due to the consequences of carbonatitic fluid (magma) and transformed into the rock of granitic composition. Fenitized rock is mainly composed of quartz, sanidine, plagioclase feldspar and mafic minerals (aegirine, aegirine-augite) with a small amount of apatite (Fig. 30). Similarly, the older gneiss xenolith also got fenitized and a large proportion of aegirine and aegirine-augite got developed (Fig. 31). The mineral composition of fenitized xenoliths supports the alkali – fenitization (dominated by Na).

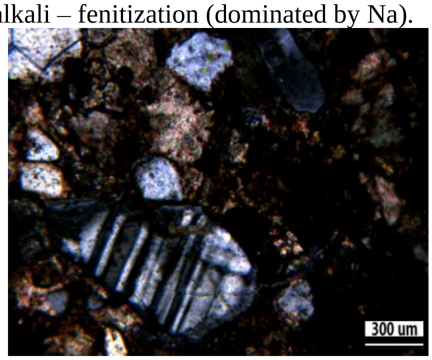

Fig. 29. Photomicrograph of carbonatite breccias showing the fenitization effect and replacement of quartz into albite plagioclase. (Sample R-11) (Cross Nicol)

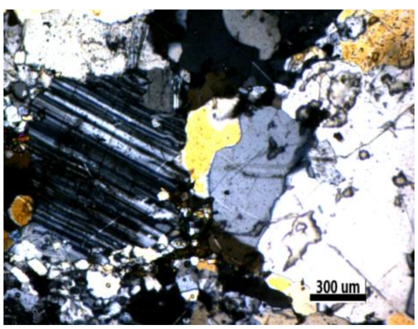

Fig. 30. Photomicrograph of fenitized xenolith showing granitic texture in which laths of plagioclase, anhedral quartz grains and altered sanidine are seen. (Sample R-5) (Cross Nicol)

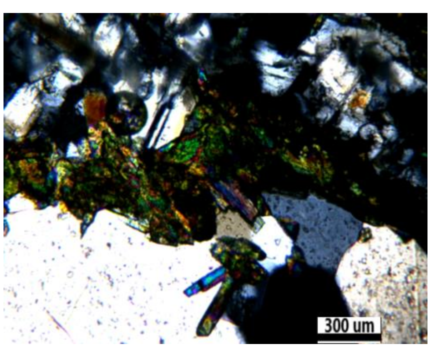

Fig. 31. Photomicrograph of fenitized xenolith showing the elongated and needle shaped aegirine and aegirine-augite present as segregated patches along with feldspar and quartz (Sample R-5) (Cross Nicol)

V. DISCUSSION ON EMPLACEMENT OF CARBONATITE MAGMA

According to Sukheswala and Borges (1975) and Viladkar and Gittins (2016), the carbonatite magma in the present study area occurred as sill like intrusion between lower Bagh sandstone and overlying Deccan basalts. The carbonatitic magma has penetrated the upper part of the Bagh sandstone, without penetrating the basalt cover (Deccan basalt). According to them, the carbonatite magma was intruded at a high temperature and pressure, resulting in the formation of carbonatite breccia enclosing fragments of sandstone and older metamorphic rocks. The carbonatite intrusion has not caused any disturbance in the lower part of sandstone horizons and Deccan basalts. Further, the soaking of carbonatite fluid in sandstone was probably because that the upper part of the sandstone was water logged, less consolidated and more porous than the lower strata. Further, towards the top the carbonatite fluids collected in pools and crystallized there as pockets (Sukheswala and Borges, 1975). The age of Siriwasan carbonatites is place at 63 $\pm$ 2 Ma i.e. at the around the closing stage of Deccan Trap volcanic episode (Viladkar and Gittins, 2016).

However, the detailed field and petrographical studies by the present authors generate a difference of opinion regarding the types and emplacement history of carbonatitic magma in the area. There are a few observations pointed out by the present authors that have been either ignored or missed by the earlier workers.

- If the carbonatite magma forcefully intruded as sill in between the Deccan traps and Bagh sandstone then, why was only the Bagh sandstone horizon got affected? Further, why did the overlying Deccan basalt which was in close contact with sandstone remain unchanged?
- For the injection of such enormous carbonatitic magma as a sill, adequate space/opening is usually required. However, the field relationship indicates that in a major part of the area, there is no capping of Deccan basalt over the carbonatite breccia. Only at few places a contact has been observed and that is also a sealed contact between Bagh sandstone and Deccan basalts.
- It has been suggested by the earlier workers that at the time of injection of carbonatitic magma, the Bagh sandstones were not fully consolidated, causing the soaking of carbonatitic fluid in sandstone. This statement is not convincible because it is considered that the Bagh sandstone in and around the area was deposited during Late Cenomanian to Early Turonian i.e. around between 96 to 90 Ma (Keller et al., 2021) and the age of carbonatites is considered as 63 $\pm$ 2 Ma (Viladkar and Gittins, 2016). It means there is a gap of more than 25 million years which is quite enough for the consolidation of a sediment formation.
- Suppose if we accept the observations of earlier workers that the Bagh sandstones were not fully consolidated at the time of carbonatitic magmatism, then why not the basaltic flows (Deccan Traps) that started eruption earlier (the first phase of Deccan trap basalt erupted during the Late Maastrichtian i.e. around

67 Ma) than the carbonatitic fluid, has affected (soaking of basaltic fluid) the Bagh sandstone?

- Regarding the presence of carbonatites in the area as pockets, it has been suggested by earlier workers that "towards the top, the carbonatite fluids collected in pools and crystallized as pockets". Then how the coarse-grained carbonatites (Sovite) can be crystallized by such a process at the surface? Further, what about the alvikite intrusions found within the carbonatite breccia?
- What about the pyroclastic rocks (volcanic breccia) which are found as distinct litho-unit in the area, having cryptocrystalline texture, flow structure and carbonatitic composition?

Considering the general appearance and nature of outcrops of various lithounits in the field, at first instance it emerge that the Bagh Group of rocks (sandstone, intercalated limestone and shale) are the oldest rock unit in the area which are overlain by the Deccan trap basalts. The carbonatite breccias and carbonatites appear as sill like intrusion between the sandstone of Bagh Group and Deccan basalts. However, the detail field studies by the present author and the megascopic characters of carbonatites and carbonatite breccias and their field relationship indicate that there should be at least three episodes of carbonatitic magmatism. The older episode was of extrusive nature coupled with intrusive (sovite pockets), followed by intrusive dykes (alvikite) and the third phase was again of extrusive type (pyroclastic breccia). The tinguaite was older than Deccan basalts while the trachyte and dolerite are younger rock units. The generalized geological succession as it appears in the study area is as under:

Dolerite dykes
Trachytes
Deccan Basalts
Pyroclastic breccia
Alvikite intrusions
Carbonatite breccia (extrusive phase), Sovite and Tinguaite
Bagh Group of Sedimentary Rocks

Conclusion

After the detailed field studies and petrography of the carbonatites and associated rocks of the area it can be concluded that there should be at least three episodes of carbonatitic magmatism of different time periods. The older episode was extrusive coupled with intrusive pockets and the later events were intrusive (alvikite) and extrusive (pyroclastics). The first event of carbonatite magmatism possibly occurred before the Deccan volcanism and after the deposition of Bagh sediments. During the first episode, the carbonatitic magmatism was explosive in nature. During the explosion, the fragments of country rocks and older metamorphic rocks with the carbonatite lava were thrown out into the air and fell on the surface of Bagh sandstone with carbonatitic fluid, forming the carbonatite breccia. Concurrently with the eruption, there were the intrusion of sovite (coarse-grained carbonatite) and tinguaite in form of pockets and dykes. In second phase there was the intrusion of alvikite in form of dykes within the carbonatite breccia. Later on there was again explosive carbonatitic magmatism occurred that was consisting the juvenile clasts of earlier carbonatites, forming the pyroclastic breccia. Dassarma and Sinha (1975) have also mentioned these rocks as "Reworked Pyroclastic Beds". Sukheswala and Borges (1975) have also commented that these rocks "resemble as an igneous breccia". Moreover, Srivastava (1997) named these pyroclastic rocks (exposed near villages Nakhal and Manka) as "agglomeratic flows".

The Deccan volcanic event occurred after these episodes. The age of 71 $\pm$ 3 Ma for carbonatite magmatism in the area as advocated by Veena et al., (1993) validates our observation. Viladkar and Gittins (2016) however, have assigned age of 63 $\pm$ 2 Ma and suggested that at the closing phase of Deccan volcanism, the episode of carbonatitic magmatism took place. But during the detailed field studies, the authors have not encountered any carbonatite intrusion within Deccan basalts in the area. The trachyte and dolerite dykes are the post – Deccan magmatic phase.

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