Melt inclusions in pyroxene and plagioclase phenocrysts from Pavagadh igneous suite, Gujarat, India

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Abstract

A thick pile of felsic volcanics overlies eleven basic flows in Pavagadh. Mugearite seen as intrusive can be considered to be the last phase of the basic magmatic activity in Pavagadh. Rhyolite at the bottom portion of the hill may be a localized injection. The melt inclusions in pyroxene and plagioclase phenocrysts belong to the mostly evolved category. Three types of inclusions are identified on the basis of phase compositions. The temperature of homogenization (Th°C) of melt inclusions in pyroxene ranges from 950 - 1250°C and that in plagioclase ranges from 1000-1050°C. The Th°C of CO2 in inclusions ranges from 25-31°C in pyroxene and 27-31°C in plagioclase. The maximum and minimum densities estimated are 0.72 g/cm³ and 0.45 g/cm³, respectively and the pressure estimated is 4.2 kb for melt inclusion in olivine, 3.9 kb for melt inclusion in pyroxene and 3.5 kb for melt inclusion in plagioclase. The depth of entrapment of inclusion ranges from 11 to 14 kms.

Key words: Pavagadh Hill, Deccan Traps, Petrology, Melt inclusions

Introduction

Deccan Traps, one of the largest continental flood basaltic provinces in the world, is the result of a tumultuous outpour of lava beyond 10⁶ km³ in volume. It is confirmed that the peak of the Deccan eruptions occurred over a short time, between 69 and 65 Ma, probably coincident with Cretaceous/Tertiary boundary on the basis of 40 Ar/39 Ar ages (Kaneoka, 1980; Courtillot et al., 1988). These basalts are predominantly tholeiitic in nature. However nepheline normative mafic rocks, carbonatites and felsic rocks have also been reported from many parts of western India and along Narmada-Son valley (e.g. Sukeshwala and Udas, 1963; Krishnamurty and Cox, 1977; Bose, 1972). The origin and evolution of flood basalt have been topics of debate among petrologists for the past several years. Recent chemical and isotopic studies of Deccan Traps provide insight into various petrogenetic problems including the involvement of continental lithosphere and/or asthenosphere in the origin and evolution of flood basalts (e.g. Lightfoot and Hawkesworth, 1988; Greenough et al., 1998).

Chatterjee (1957, 1961, 1964) discussed the geology of Pavagadh hill including reporting of new varieties of rocks like rhyodacite, alkali-olivine basalt, mugearite and ankaramite. Discussing the petrogenesis, he concluded that except rhyolite all other rocks have an alkali-olivine lineage. Sinha and Tiwari (1964) and Tiwari (1971) regarded that the alkali olivine basalt with all its derivatives co-exists with the over-saturated normal basalt series at Pavagadh. Alexander (1980) proposed sialic contamination hypothesis for the origin of rhyolite in the present area. Mukherjee and Gupta (1989) reported seventeen horizontal flows in Pavagadh and postulated that the whole series resulted by fractionation in two episodes. Hari et al. (1991) proposed an alkali-olivine basalt parent magma for the mafic rocks in the area on the basis of melt inclusions in olivine phenocrysts. Hari (1991) reported twelve flows in Pavagadh area. Greenough et al. (1998) gave a new dimension to the whole series and proposed an asthenospheric origin for the entire Deccan basalt based on trace element geochemical studies. Recently Hari et al. (1999) reported one more new flow in the present area.

In this paper, an attempt has been made to give a detailed account of the field relations and fluid inclusion characteristics of the phenocryst minerals of the basic rocks in Pavagadh area.
Fig. 1. Map of Deccan Traps showing location of Pavagadh Hill.

**Field relations**

Pavagadh igneous complex, having a height of 820 m above M.S.L., occupies an area of about 35 sq.km in Gujarat, India (Fig.1). A variety of rocks ranging from olivine-rich basalt to quartz-rich rhyolites are exposed in this hilllock (Hari et al., 1991). These rocks are considered to be an outlier of Deccan Traps (Chatterjee, 1961) and represent a late (63.2 Ma) volcanic activity (Alexander, 1980). The complex overlies the Nimar sandstone belonging to Bagh formation of middle Cretaceous age. These sandstones are further underlain by middle Proterozoic rocks of the Champaran group with phyllite, slate, conglomerate, quartzite and grit (Krishnan, 1982). The exposures of these older rocks are not seen inside the series of the volcanic rocks constituting Pavagadh hill. Even though the broad stratigraphic position of the complex is well established, disparity among the field relation envisaged by various workers exists mainly due to the poor or inaccessible nature of exposures and steep escarpments which pose problems in the collection of samples and field data.

On the basis of the recent investigation (Hari et al., 1999), eleven mafic and ultramafic flow units were recognized (Table 1; Fig.2). These flow units are overlain by rhyodacite, pitchstone, ignimbrite and volcanic ash. Towards the lower part of the hill, exposures of rhyolites are also noticeable.

Flow No.1 (fine-grained basalt) is exposed in the lower part of Pavagadh hill. This flow constitutes the small hillocks adjacent to the main hill where extensive quarrying is going on. Exposures of this flow are noticeable behind Pavagadh bus stand, near Atok gate, along Pavagadh-Machi road cutting, and at the Vishwamitri portion. Just above Machi, on either side of the pilgrim route and also near the first pillar of the rope way, exposures of porphyritic three phenocryst basalt (Flow No.2) are seen. This flow, with megascopically visible phenocrysts of olivine, pyroxene and plagioclase, is characterized by the presence of iddingsitization in the exposed portions. Ankaramite flow (Flow No.3), clearly exposed in the Bhadrakali plateau, is connected to the main line by a narrow ridge. Extensive iddingsitization and zeolitization are noticeable in this flow. Due to extensive iddingsitization, Chatterjee (1961) termed this rock as ‘iddingsite basalt’.

Above the ankaramite flow, a basaltic flow (about 35 m thick) is exposed (Flow No. 4) followed by hawaiite flow (Flow No.5). Exposure of thick compact basaltic flow (Flow No.6) similar to that of flow No.2 is seen at the site of the gate and also on the lower and upper portion of the ravine, which separates the lower ridge from the main hill (Fig.7). This flow continues up to the gate after the bridge.

Thick compact hawaiite flow (Flow.7), of about 30 m in thickness is exposed just above flow No.6. ‘Giant plagioclase phenocryst basalt’ flow (Flow No. 8) with very large plagioclase phenocrysts and prominent zeolitization and calcitization has a sharp flow boundary which clearly separates this flow from the seventh flow (Fig.8). The flow just above flow No.8 is a black coloured basaltic flow (Flow No.9). Two thick hawaiite flows (Flows No.10 & 11) are
Table 1. Flow Stratigraphy of Pavagadh Hill.

<table>
<thead>
<tr>
<th>Flow No.</th>
<th>Name of the rock</th>
<th>Approximate thickness (in meters)</th>
</tr>
</thead>
<tbody>
<tr>
<td>12</td>
<td>Rhyodacite, ignimbrite, volcanic ash</td>
<td>80, 10</td>
</tr>
<tr>
<td>11</td>
<td>Hawaiite</td>
<td>65</td>
</tr>
<tr>
<td>10</td>
<td>Hawaiite</td>
<td>55</td>
</tr>
<tr>
<td>9</td>
<td>Basalt</td>
<td>25</td>
</tr>
<tr>
<td>8</td>
<td>Giant plagioclase phenocryst basalt</td>
<td>30</td>
</tr>
<tr>
<td>7</td>
<td>Hawaiite</td>
<td>30</td>
</tr>
<tr>
<td>6</td>
<td>Three phenocryst basalt</td>
<td>35</td>
</tr>
<tr>
<td>5</td>
<td>Hawaiite</td>
<td>35</td>
</tr>
<tr>
<td>4</td>
<td>Basalt</td>
<td>35</td>
</tr>
<tr>
<td>3</td>
<td>Ankaramite</td>
<td>30</td>
</tr>
<tr>
<td>2</td>
<td>Three phenocryst basalt</td>
<td>30</td>
</tr>
<tr>
<td>1</td>
<td>Fine grained basalt</td>
<td>100</td>
</tr>
</tbody>
</table>

Alter Hari et al. (1999)

Table 2. Average modal percentage.

<table>
<thead>
<tr>
<th>Name of the rock</th>
<th>Plagioclase</th>
<th>Clinopyroxene</th>
<th>Olivine</th>
<th>Diopsides + glass + secondary minerals</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mugearite</td>
<td>16.30</td>
<td>18.80</td>
<td>24.10</td>
<td>4.70</td>
</tr>
<tr>
<td>Mugearite (from the quarry)</td>
<td>6.20</td>
<td>14.60</td>
<td>20.30</td>
<td>14.30</td>
</tr>
<tr>
<td>Hawaiite</td>
<td>15.10</td>
<td>22.60</td>
<td>10.10</td>
<td>18.70</td>
</tr>
<tr>
<td>Giant plagioclase phenocryst basalt</td>
<td>32.16</td>
<td>14.17</td>
<td>26.80</td>
<td>2.10</td>
</tr>
<tr>
<td>Ankaramite</td>
<td>12.00</td>
<td>13.40</td>
<td>12.60</td>
<td>19.20</td>
</tr>
<tr>
<td>Fine grained basalt</td>
<td>22.30</td>
<td>10.60</td>
<td>19.10</td>
<td>26.20</td>
</tr>
</tbody>
</table>

Petrography

A brief petrographical description of some of the rocks are given in Greenough et al. (1998). Here, detailed description of all the rock types seen in the Pavagadh is presented, with the modal compositions in the Table 2.

**Fine grained basalt**

This rock is characterised by glomeroporphyritic aggregates of olivine and clinopyroxene set in a matrix of minute crystal and glass. Macrophenocrysts and microphenocrysts of olivine have mostly euhedral outline with sharp contact with the groundmass. The macrophenocrysts have maximum length of about 5 mm and breadth of about 2.9 mm, whereas the microphenocrysts have maximum length of about 1.6 mm and breadth of about 1.4 mm. Iddingsitization, serpentinization and rims of opaques around olivine grains are recognized. The Fo% varies from 86.3 to 74.7 in macrophenocrysts, and 85.5 to 66.5 from the core to rim in the case of microphenocrysts (Greenough et al., 1998).

Clinopyroxene of pale pinkish colour is seen both as phenocrysts and as a constituent of groundmass. Greenough et al. (1998) reported that the phenocrysts are diopside in composition and the groundmass grains are augite. The groundmass constitutes labradorite, augite, small granules of altered olivine, apatite, titanomagnetite, martite and glass. The parallel arrangement of labradorite laths in groundmass in some sections imparts a flow texture.

**Three Phenocryst Basalt**

'Three phenocryst basalt' which constitutes flow No.2 and 6, contains clusters of phenocrysts of calcic-plagioclase, clinopyroxene and olivine. The plagioclase grains are often zoned and the An content varies from 60 to 64. The maximum length of plagioclase phenocrysts is about
Fig. 3. Mugearite seen as intrusives in flow No.1 exposed in the stone quarry at the base of the Hill.

Fig. 4. “Caught up” patches of ‘fine grained basalt’ in mugearite.

Fig. 5. Angular fragments of ‘fine grained basalt’ in mugearite.

Fig. 6. Patches of ‘fine grained basalt’ in mugearite indicating various extends of assimilation. The colour of mugearite has changed due to contamination.
Fig. 7. Exposures of Flow No. 6 are seen in this portion of Pavadghul hill.

Fig. 8. Contact between flow No. 7 and 8. Contact line can be drawn very well on the basis of the physical appearance of the flows itself.

Fig. 9. Massive felsic flow units exposed at the top of the hill.

Fig. 10. Prominent flow structure seen in rhyodacite flow.

5.3 mm, and breadth is about 1.7 mm. The clinopyroxenes are Ca rich. They have idiomorphic outline and exhibit zoning in many cases. Calcite and zeolites are seen enclosed in few pyroxene grains. Olivine grains are larger with oval or rounded outlines. The maximum length and breadth noticed are 4.7 mm and 1.2 mm respectively. Serpentinization and iddingsitization are very common in the olivine grains. Poikilitic inclusions of pyroxene and olivine in one another are another noticeable feature. The groundmass consists of labradorite (An 58), augite, biotite, titanomagnetite, ilmenite, calcite and glass.

Ankaramite

Because this rock contains more clinopyroxene than olivine as phenocrysts, the term ‘ankaramite’ is suggested for this rock. Glomeroporphyritic aggregates of the clinopyroxene and olivine are common in this rock, with the former having larger size (maximum length is 4.9 mm and breadth is 2.6 mm) than the latter (maximum length is 3.3 mm and breadth is 1.9 mm). The clinopyroxene grains are Ca-rich and they exhibit zoning. The olivine grains are Mg-rich. The large olivine grains are altered to iddingsite and/or serpentine, whereas the small grains are fresh. Opaque and pyroxene grains are seen poikilitically enclosed in olivine. The groundmass consists of plagioclase (An 55), augite, biotite, titanomagnetite, ilmenite, hematite and glass.

Basalt

This rock with porphyritic texture has plagioclase (An 62-64) and augite as phenocrysts. This is the only basic rock which is devoid of olivine (Greenough et al., 1998). The phenocrysts set in a fine grained matrix constituted of labradorite (An 55), small amount of anorthoclase, augite, titanomagnetite and glass.

Giant Plagioclase Phenocryst Basalt

Large grain of plagioclase (An 52-64) ranging from a few mm to about 2.5 cm is the diagnostic character of this rock. The size of augite phenocrysts is very small compared to plagioclase phenocrysts. Some of the plagioclase grains
are seen altered to calcite. At places, few iddingsitized pseudomorphs of olivine grains are noticeable. The groundmass portion of this rock is glass rich. The minerals in the groundmass include labradorite, oligoclase, augite, opaques and glass.

**Hawaiite**

This light coloured rock contains white altered plagioclase grains of variable sizes. Some of the samples have spherulites of celadonite. Andesine and oligoclase grains are seen along with augite as phenocrysts. Plagioclase grains are partially altered to calcite. Opaques poikilitically enclosed in plagioclase grains are seen localized along the growth zones of the host minerals. The groundmass is composed of plagioclase (andesine-oligoclase), augite, small amount of altered olivine, titanomagnetite, ilmenite and glass. The percentage of opaque is high compared to other rocks in the area. Trachytic texture is common.

**Mugearite**

Variable degree of crystallinity and grain size is observable in these rocks. Mugearite from the lower part of the hill is medium grained with phenocrysts of clinopyroxene, olivine and plagioclase. Glomeroporphyritic texture is very common. The olivine is Mg-rich and in most cases, altered. Mugearite exposed above Machi is fine grained with a few augite phenocrysts. Therefore most of the phenocryst minerals seen in mugearite are suggested as ‘caught up’ minerals from the adjacent rocks entrapped at the time of intrusion of the mugearite magma.

The groundmass is composed of fine crystals occasionally with small amount of glass. Trachytic and sub-trachytic textures are noticeable. Plagioclase of oligoclase -andesine composition is the most abundant mineral and they have rectangular or fork edge outline. Augite, titanomagnetite, ilmenite, hematite and glass are the groundmass minerals in addition to plagioclase grains. Titanomagnetite is seen as subhedral equant grains whereas ilmenite and hematite are seen as laths, rod or as exsolution lamellae in titanomagnetite. Mesostasis is commonly noticeable.

**Felsic rock**

The felsic rocks, exposed at the top of the hill, i.e. rhyodacite, ignimbrite, pitchstone and obsidian have almost similar mineralogy, although megascopically they differ widely. Rhyodacite exhibits prominent banded or flow structure, whereas ignimbrite shows brecciated appearance. Albite, oligoclase, quartz, subordinate augite and fayalitic olivine are the phenocryst minerals in these rocks. Pitchstone is black coloured and obsidian is light coloured. Both these rocks have anorthoclase, in place of olivine, while other phenocryst minerals are as same as those in rhyodacite and ignimbrite. Rhyodacite and ignimbrite have a quartzo-felspathic groundmass along with glass, whereas pitchstone and obsidian have cryptocrystalline fine grained groundmass. Mosaic and spherulite textures are noticeable in the groundmass portion of rhyodacite.

The rhyolitic rocks exposed in the lower portion of the hill are with phenocrysts of quartz and K-feldspar, mainly anorthoclase, which set in a quartzo-feldspathic glassy groundmass characterized by mosaic texture. Chatterjee (1961) reported tridymite needles in the groundmass of rhyolite. He pointed out the mineralogical differences

### Table 3. Major element concentrations in mugearite (in wt. %).

<table>
<thead>
<tr>
<th>Sample No.</th>
<th>GP225</th>
<th>GP236</th>
<th>GP237</th>
<th>GP238</th>
<th>GP239</th>
<th>GP243</th>
<th>GP247</th>
<th>GP250</th>
<th>GP256</th>
<th>GP257</th>
<th>GP262</th>
<th>GP285</th>
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<tbody>
<tr>
<td>SiO2</td>
<td>54.8</td>
<td>47.1</td>
<td>47.5</td>
<td>47.8</td>
<td>54.7</td>
<td>46.4</td>
<td>48.4</td>
<td>48.8</td>
<td>47.2</td>
<td>48.3</td>
<td>47.9</td>
<td>47.6</td>
</tr>
<tr>
<td>TiO2</td>
<td>2.16</td>
<td>2.16</td>
<td>2.6</td>
<td>2.04</td>
<td>2.12</td>
<td>1.92</td>
<td>2.16</td>
<td>2</td>
<td>2.48</td>
<td>2.2</td>
<td>2.36</td>
<td>2.48</td>
</tr>
<tr>
<td>Al2O3</td>
<td>13.6</td>
<td>14.9</td>
<td>15</td>
<td>16.1</td>
<td>13.5</td>
<td>14.3</td>
<td>14.4</td>
<td>15.1</td>
<td>13.9</td>
<td>13.9</td>
<td>14.6</td>
<td>14.3</td>
</tr>
<tr>
<td>Fe2O3*</td>
<td>11.89</td>
<td>11.64</td>
<td>11.71</td>
<td>10.87</td>
<td>11.96</td>
<td>11.3</td>
<td>12.04</td>
<td>13.55</td>
<td>14.4</td>
<td>12.04</td>
<td>12.66</td>
<td>14.73</td>
</tr>
<tr>
<td>MnO</td>
<td>0.15</td>
<td>0.13</td>
<td>0.13</td>
<td>0.12</td>
<td>0.15</td>
<td>0.15</td>
<td>0.15</td>
<td>0.12</td>
<td>0.17</td>
<td>0.14</td>
<td>0.14</td>
<td>0.2</td>
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<tr>
<td>MgO</td>
<td>3</td>
<td>3.4</td>
<td>3.53</td>
<td>3.17</td>
<td>2.82</td>
<td>4.63</td>
<td>4.91</td>
<td>3.5</td>
<td>5.03</td>
<td>4.02</td>
<td>4.46</td>
<td>4.47</td>
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<tr>
<td>Na2O</td>
<td>2.72</td>
<td>2.71</td>
<td>2.83</td>
<td>1.6</td>
<td>2.76</td>
<td>2.18</td>
<td>2.56</td>
<td>3.02</td>
<td>2.66</td>
<td>2.93</td>
<td>2.95</td>
<td>2.84</td>
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<tr>
<td>K2O</td>
<td>1.27</td>
<td>0.61</td>
<td>0.66</td>
<td>0.33</td>
<td>1.34</td>
<td>1.36</td>
<td>1.3</td>
<td>2</td>
<td>1.11</td>
<td>0.83</td>
<td>1.72</td>
<td>1.39</td>
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<td>P2O5</td>
<td>0.39</td>
<td>0.35</td>
<td>0.41</td>
<td>0.37</td>
<td>0.43</td>
<td>0.51</td>
<td>0.4</td>
<td>0.37</td>
<td>0.37</td>
<td>0.37</td>
<td>0.39</td>
<td>0.42</td>
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<tr>
<td>L.O.I</td>
<td>1.55</td>
<td>6.94</td>
<td>6.41</td>
<td>4.29</td>
<td>1.86</td>
<td>6.23</td>
<td>2.34</td>
<td>2.38</td>
<td>2.64</td>
<td>4.97</td>
<td>4.49</td>
<td>1.92</td>
</tr>
<tr>
<td>Total</td>
<td>99.03</td>
<td>98.94</td>
<td>99.64</td>
<td>98.31</td>
<td>98.78</td>
<td>98.78</td>
<td>98.64</td>
<td>98.98</td>
<td>99.28</td>
<td>100</td>
<td>99.91</td>
<td>99.71</td>
</tr>
</tbody>
</table>

Total Fe as Fe2O3*; L.O.I.=Loss on ignition
Analysis of GP225,GP285 and GP239 are taken from Greenough et al.(1998)
between the felsic rocks exposed at the top of the hill and in the lower parts of the hill.

Major and trace elements in mugearite

Major element concentrations of mugearite rocks are given in table 3 and trace element concentrations in table 4. The details of analytical procedures are given in Greenough et al. (1998). The major element geochemistry clearly depicts the existence of wide variations in these rocks. The SiO₂ varies from 46.4 to 54.8 wt.%, and Al₂O₃ from 13.50 to 16.10 wt.%. Large variation are noticeable in Fe₂O₃ (10.87 to 14.73 wt.%), in CaO (7.14 to 11.62 wt.%), and in MgO (2.82 to 5.03 wt.%). The high SiO₂ contents in GP 225 and GP 239 may be due to the presence of sec-
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Secondary minerals such as quartz, zeolites, etc. Large variations are noticeable in almost all trace elements. The lowest LIL elements (Li, Rb, Cs, Br, Ba and Be) concentration is noticeable in GP 238 and highest in GP 239 (except Ba; maximum 483 ppm in GP 250). The lowest LREE concentration is noticeable in GP 247 and HREE in GP 285. However, GP 239 exhibits highest LREE and HREE values. High L.O.I. in the samples indicates weathering and/or alteration processes. The Al₂O₃ enrichment and the K₂O depletion in higher L.O.I samples may be due to leaching during weathering and/or alteration process. Variable inclusions in mugearites from country rocks suggest assimilation during the passage of mugearite through various fissures and fractures of pre-existing rocks. For example, even though GP 238 and GP 239 are taken from adjacent localities, the large variation in the geochemistry is found. However, further data including bulk and mineral chemistry...
Fig. 16. Photomicrograph of irregular shaped primary melt inclusions in pyroxene phenocrysts of "three phenocryst basalt". These inclusions contain a number of daughter minerals. Note the distortion of the shape of spherical bubble due to the pressure exerted by the silicate glass globule and the opaque. Parallel nicols. Bar indicates 50 μm.

Fig. 17. Photomicrograph showing the co-existence of CO₂ inclusions and Type IIIb inclusion in plagioclase grain of basalt. Parallel nicols. Bar indicates 50 μm.

Fig. 18. Photomicrograph of melt inclusion of Type IIIa in labradorite grains in "basalt". Parallel nicols. Bar indicates 50 μm.

Fig. 19. Photomicrograph of dark iron globules in devitrified glass depicting silicate-liquid immiscibility. Parallel nicols. Bar indicates 50 μm.

Fluid inclusion studies

More than 50 doubly polished rock wafers with varying in thick ranging from 0.1 to 0.4 mm were carefully prepared. The thickness of the plates depended on the transparency of the phenocryst minerals studied. The general distribution pattern of inclusions and their phase compositions were studied using a normal petrological microscope under varying magnifications. Due to the friable nature of mugearite, high degree of alteration in plagioclase phenocrysts, and near absence of melt inclusions in hawaiite, giant plagioclase phenocryst basalt and felsic rocks, the inclusions inside the phenocrysts of these rocks could not be studied.

Phase-wise classification

In order to characterize the inclusions in clinopyroxene and plagioclase phenocrysts in a detailed way, the following categories of inclusions based on their phase composition are recognized.

Type I: These are single phase inclusions which contain a homogeneous fluid phase of near pure carbon-dioxide composition which completely fills the cavity at...
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room temperature. Such inclusions are either larger primary inclusions (Fig.11) or small pseudo-secondary trails.

Type II: Multiphase inclusions containing one or more tiny solids (daughter crystals) together with silicate glass (brownish devitrified aggregate) and a fluid bubble (which is spherical in the form or compressed between the glass and daughter crystals and/or against the walls) (Fig.12-16). All these inclusions studied here belong to the evolved or slightly evolved category of Linqui and Clocchiatti (1985). They often represent the primary inclusions in the present study and are similar to silicate melt inclusion reported from various igneous suits (e.g. Roedder, 1985), including some phenocrysts of Deccan traps (Santosh et al., 1988; Hari et al., 1991).

Type III: Some of the silicate melt inclusions are devoid of crystalline daughter crystals, but comprise mostly devitrified glass together with opaques. Many of the samples contain this category distributed along the growth zones of the host minerals (Fig.17). A fluid bubble is often associated (designated as sub-category IIIa), but sometimes they comprise an assemblage of only silicate glass + opaque (designated as sub-category type IIIb). As type IIIb inclusions are devoid of glass bubble, they can be considered to be of non-evolved type.

Inclusions in clinopyroxene

Type II inclusions are the most common inclusion in clinopyroxene phenocrysts of ‘fine grained basalt’, ‘three phenocryst basalt’, ‘ankaramite’ and ‘basalt’. These in-
Inclusions have rectangular, elongated or irregular outline and the fluid bubble occupying 30-40% of the total volume of the cavity appears to be of shrinkage origin (Fig.12-16). The size of the inclusions varies widely, i.e. from 30 μm to 120 μm. The vapour phase inside the inclusions is seen attached to opaque phase in many cases. Most of the inclusions contain more than one opaque crystal. In the clinopyroxene grain in 'three phenocrysts basalt' the gas bubble inside the type II inclusion is seen compressed by the glass globules and other daughter crystals and even the spherical shape of the bubble is seen distorted (Fig.15). Type I pseudo-secondary array of carbonic inclusions with small cavities are seen co-existing with type II melt inclusions. The daughter crystals inside the type II inclusions (melt inclusions) were identified as olivine, clinopyroxene, plagioclase and opaques including titanomagnetite (square shaped), ilmenite (lath shaped) and globules of sulphide. These were identified on the basis of the procedure given by Roedder (1985) and Shepherd et al., (1985) and comparing with melt inclusions elsewhere (e.g. Belkin et al., 1985; Metrich and Clocchiatti, 1989 etc.).

**Inclusions in Plagioclase**

Large type I CO₂ inclusions up to 40 μm were noted to occur commonly as isolated primary inclusions in the labradorite phenocrysts of 'three phenocrysts basalt' (Fig.11). Minute carbonic inclusions sometimes array, pinching out within the crystal constituting pseudo-secondary array.
Melt inclusions in pyroxene and plagioclase phenocrysts from Pavagadh igneous suite, Gujarat, India

dary category. Iron-rich globules associated with devitrified glass typifying silicate-liquid immiscibility texture (Fig.19) were also observed. This type of texture has been reported by Santosh et al. (1988) from plagioclase phenocrysts in the tholeitic basalts of Deccan traps to indicate silicate liquid immiscibility. The labradorite phenocrysts in "basalt" contain Type I, Type IIIa and Type IIIb inclusions. One of the characteristic features is that the genetic co-existence of silicate melt and CO₂ is apparent here (Fig.17). The Type IIIa (Fig.18) inclusions are small in size (c.a.30 μm) and only in a few cases the gas bubbles are clearly perceptible. In many cases, Type IIIb inclusions are either arranged along the growth zones of the mineral or are concentrated towards the core of the mineral. Type I inclusions are either hand in hand with type IIIa inclusions or are isolated primarily. These Type IIIb inclusions can be considered to be of non-evolved category.

Microthermometry

High temperature heating experiments of the melt inclusions were carried out using Leitz-1350 heating stage mounted on the Leitz-Ortholux microscope. The heating stage was calibrated for high temperature runs with a precision of ±1°C using synthetic standards. At high temperature, the visibility of the phase changes inside the inclusions is sometimes considerably hampered. Therefore the temperature of homogenization in such cases could not be noted exactly and those data are exempted from presentation and discussion here. Freezing runs for identifying the volatile phases were carried out using CHAIXMECA microthermometer calibrated with a precision of ±0.3°C, using natural standards of pure carbon dioxide. The temperature of melting and temperature of homogenization of CO₂ inclusions occurring mostly as pseudo-secondary arrays could not be found out due to their smaller sizes, thereby the exact composition of these volatile phases could not be ascertained.

During heating, the pattern of changes inside melt inclusions in clinopyroxene is similar to that of the inclusion in olivine. The fusion of the devitrified glass took place in the initial stages of heating followed by slow melting of opaques, plagioclase, clinopyroxene, olivine and finally, the disappearance of the bubble. The melt inclusions in clinopyroxene of ankaramite homogenized between 950°C and 1200°C with the peak homogenization between 1050°C and 1100°C. The homogenization temperature of the inclusion inside clinopyroxene of the 'three phenocrysts basalt' ranged from 1000°C to 1200°C and that of the 'basalt' ranged from 1000°C to 1250°C (Fig.20 A, B & C). The temperature of homogenization of the melt inclusion in plagioclase phenocrysts could be noted only from the 'basalt'. During heating, the fusion of silicate glass followed by melting of opaques and finally the disappearance of the bubble was noticeable in these inclusions. The homogenization temperature ranged from 850°C to 1200°C with a peak homogenization between 1000°C and 1050°C (Fig.21).

![Liquid homogenization curve](image)

**Fig. 24.** Plot on temperature of homogenization of CO₂ verses density of CO₂ (After Roedder,1965). The maximum density estimated is 0.72 g/cm³ and minimum is 0.45 g/cm³. The peak Th°C of CO₂ indicate an average density 0.70 g/cm³.

![Pressure-temperature diagram](image)

**Fig. 25.** Pressure of entrapment of inclusion estimated from temperature of homogenization and density of inclusions. The pressure-temperature diagram after Touret and Bottinga (1979).
Before heating, the inclusions were deeply frozen to estimate the composition of gas bubble. In most of the inclusions, a bubble froze to a solid aggregate at a temperature below -70°C, and on slow warming, sudden melting occurred between -56°C and -57.2°C in the clinopyroxenes (which are from three phenocryst basalt, fine grained basalt, ankaramite and basalt) and between -56 and -57.4°C in plagioclase (which are from three phenocryst basalt and basalt) (Fig. 22 A & B). In both cases, the peak melting is around -56.6°C ascertaining that the bubble is pure carbon dioxide. Several inclusions show slight depression in melting temperatures indicating that some additional phases are present with carbon dioxide. Bergman and Dubessy (1984) pointed out that traces of CO along with CO₂ in the melt inclusion can lower the temperature of melting. The common fluids associated with CO₂ in the melt inclusions are CH₃, N₂ and SO₂ (e.g. Linqui and Zu-Chin, 1990). On warming the inclusions, the carbon dioxide homogenizes into liquid phase between 25°C and 31°C in the case of clinopyroxene and between 27°C and 31°C in the case of plagioclase from ‘basalt’ (Fig. 23 A & B).

**Discussion**

From the microthermometric data on the various categories of inclusions, it is possible to deduce the density, pressure, and depth of entrapment of the inclusions in the phenocryst minerals of basaltic rocks from Pavagadh hill, in conjunction with the data on melt inclusions from olivine phenocrysts (Hari et al., 1991) from ‘fine grained basalt’, ‘ankaramite’ and ‘three phenocryst basalt’. From the present study it is further confirmed that CO₂ was probably one of the dominant gaseous phase in the system throughout the crystallization history of the minerals. On the basis of the temperature of homogenization of CO₂ in the three minerals, the maximum density estimated is 0.72 g/cm³ and the minimum is 0.45 g/cm³ (Fig. 24).

If we assume that a series of basaltic rocks in Pavagadh complex was produced from one magma reservoir and that the CO₂ fluid entrapped in crystallizing minerals in the magma reservoir had a mean density of 0.70 g/cm³, (as estimated by peak homogenization temperatures of phenocryst minerals), then the fluid density can be correlated to the depth of entrapment under the assumption that the dominant pressure during entrapment was hydrostatic due to magma column. The depth of entrapment can be deduced from the density of CO₂ within the inclusion and the trapping temperature (density versus depth of trapping diagram after Belkin et al., 1985). The average density of 0.70 g/cm³ and the range of homogenization temperature of melt inclusions (1000-1200°C) in the present case gives an estimate that the entrapment took place at a depth between 11 and 14 kms.

The trapping pressure of the inclusions can be obtained from the homogenization temperature of carbonic phases and silicate phases in the melt inclusion based on CO₂ equation of state barometry (Tourret and Bottinga, 1979). The pressure of entrapment in the inclusions obtained by intersecting the Th °C of melt inclusions in different minerals with the CO₂ isochore of 0.70 g/cm³ varies slightly in different minerals (Fig. 25). It is estimated that the entrapment of the melt inclusions in olivine minerals took place at 4.2 kb based on the data from Hari et al. (1991), the inclusions in the clinopyroxene at around 3.9 kb, and inclusion in plagioclase at 3.5 kb.

**Conclusions**

1. The rhyolite at the lower part of the Pavagadh hill may be “insitu” and a product of localized injection.
2. The melt inclusions in the phenocrysts of olivine, pyroxene and plagioclase are mostly “highly evolved” even though a few of “slightly evolved category” are also seen.
3. The Th °C of melt inclusions ranges from 1040-1240°C in olivine (Hari et al., 1991), 950 - 1250°C in pyroxene and 850 - 1200°C in plagioclase. On the basis of the homogenization of CO₂, a density of 0.70 g/cm³ is estimated. The entrapment of the melt inclusion in olivine took place at about 4.2 kb, the inclusions in pyroxene at about 3.9 kb and the inclusion in plagioclase at about 3.5 kb pressure.

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**References**


