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Field Occurrence and Petrographic Characteristics of Tertiary Volcanic Rocks and Associated Intrusions in and around Taiz City, Yemen

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Abstract Geologic and petrographic studies of Tertiary volcanic rocks and their intrusive bodies such as plutons, dykes and sills were carried out in and around Taiz city, Yemen with an aim to document their field occurrence and distribution as well as to study their mineralogical composition. This has an important bearing on the town planning in the city of Taiz as the existing buildings are collapsing due to the foundation problems. Studies on 110 exposures, carefully selected after field traverses revealed that the Tertiary rocks in the study region are mainly represented by typical bimodal mafic-felsic associations in the form of flows, plutons and dykes. Tertiary volcanic flows are characterized by alternating sequences of basic and felsic rocks and varicoloured volcaniclastic deposits which were all extruded and fed from fracturing and fissuring in the old rocks through which magma emerged in successive pulses, flooding the surrounding region. The basic flows (Tb1, Tb2 and Tb3) consist of jointed/massive basaltic rocks and volcaniclastic deposits while the felsic flows (Tr1 and Tr2) are comprised of jointed/massive rhyolite/dacite rocks and also varicoloured felsic volcaniclastic deposits. All these rocks show wide variations in their geological and petrographical characteristics such as colour, texture, heterogeneity, macro/microfractures, weathering/alteration, thickness, horizontal attitude, and intercalation with volcaniclastic deposits, repetition with depth in both vertical and horizontal directions. Volcaniclastic deposits are also characterized with great diversity in their types, colours, textural features, thicknesses, grain sizes, matrices, and degree of roundness of rock fragments and alternating and/or interlocking as well as intercalation laterally and vertically with basalt/rhyolite lava rocks. Volcaniclastic rocks were classified for the first time in the study area based on their particle sizes into different types. They range from strong, compact, welded rocks to weak, altered soils. The younger Sabir granitic pluton is represented by alkaline or peralkaline granites that are white to greyish white coloured massive, medium to coarse-grained, grading up to granite porphyry. Petrographic examinations of 52 thin sections representing the samples of basaltic lava flows, rhyolitic/dacite lava flows and younger intrusives under polarizing microscope have been carried to study their mineralogy. The dominant minerals in basaltic rocks are plagioclase, augite and olivine whereas rhyolitic rocks contain quartz, orthoclase and biotite. The main mineral constituents of younger granitic rocks are k-feldspar, quartz, hornblende and biotite. The mafic and felsic dykes almost resemble basalts and rhyolites/dacites respectively in their petrographical characteristics. XRD technique used for characterizing the minerals of volcanic soils revealed the presence of clay minerals namely montmorillonite and kaolinite as the major mineral phase in most of the samples whereas mica group of minerals such as muscovite, vermiculite and chlorite are present in minor amounts, in addition to talc, feldspar, calcite and halloysite.

Keywords *Taiz City in Yemen; Tertiary bi-modal Lava Flows; Volcaniclastic Characteristics; Colonnade Columnar Structures; Sabir Granite*

1. Introduction

In Yemen, during the Oligocene-Miocene period, stable conditions were persisted until the development of the Red Sea-Gulf of Aden which lead to a massive uplift along the rift boundaries, crustal thinning, extension and massive outpourings that resulted in the development of continental flood basalt provinces; Yemen Trap Series (YTS) and Yemen Volcanic Series (YVS). Obviously high heat flow was associated with crustal thinning and igneous intrusions. Extrusion and intrusive magmatic activity continued till the Quaternary. Yemen Trap Series (Geukens, 1966) are made up mainly of alternating lava flows (basalts, andesites or trachyte porphyries) and different types of tuffs. These basaltic, rhyolitic and ignimbritic successions attain a thickness in excess of 2500 m in the NE of Yemen (Al Subbary et al., 1993). The age of YTS ranges from Oligocene to Miocene (Al-Kadasi, 1994). Basalt of the Tertiary age is characterized by columnar, fine grained, porphyritic and intergrowth textures. The Quaternary Yemen Volcanic Series (YVS) are exposed bordering the Tertiary volcanics (YTS). Rhyolitic tuffs are of limited occurrence and the Quaternary basalts are fine grained and show porphyritic and intergrowth textures. Rhyolitic tuffs exhibit medium to fine grained porphyritic and myrmekitic textures. Earlier works on the bimodal volcanic rocks are largely limited to geological mapping of the Taiz and its surrounding areas (Kruck and Schäffer, 1991; DEY, 1997). Geology including petrogenesis of Sabir granitic rocks has been studied in detail than the surrounding volcanic rocks (Refaat et al., 1980; Shaalan et al., 1983; Youssef, et al., 1992; El-Gharbawy, 2011). Stratigraphy of a bimodal volcanic rocks and fault types present in Taiz area have been worked by Malek et al., (2014). The present paper documents geological and petrographical features of the Tertiary bimodal mafic-felsic suite represented by flows, plutons and dykes in addition to identification of mineral types in volcanic soils of Taiz and its surroundings.

2. Study Area

Taiz city is located in the southwestern part of Yemen in the watershed area of upper Wadi Rasyan. It lies mainly at the foot hill and slope regions of Sabir mountain in the northern highlands and bound by the latitudes 13°32' N - 13°44' N and longitudes 43°54' E - 44°10' E (Figure 1). The Taiz city and its vicinities are almost covered with product of the magmatism comprising mainly typical bimodal volcanic deposits, felsic plutonic rocks, mafic and felsic dykes as well as sills. The bimodal volcanic rocks encompass alternating sequences of volcanic lava flows and volcaniclastic deposits of varying composition from mafic to silicic types. The lava flows are believed to be extruded and fed from fracturing and fissuring in the old rocks through which magma emerged in successive pulses, flooding surrounding region. These sequences range in age from Oligocene to the lower Miocene (Beydoun et al., 1998). They form a part of the western volcanic margin of Yemen which is related to the Afar plume (Civetta et al., 1978; Capaldi et al., 1987; Chiesa et al., 1983, 1989).

The felsic plutonic rocks of Jabal Sabir belong to the alkaline or peralkaline suite of A-type granites (El-Gharbawy, 2011). These are produced by fractional crystallization of basic magmas (Capaldi et al., 1987; Chazot and Bertrand, 1995). Numerous mafic and felsic dykes and sills with different shapes and sizes have invaded the old volcanic sequences and felsic plutonic body. The Quaternary sediments in the study area are less (20.70% of total area) and are mainly represented by loess plane deposits that probably have been derived from the weathering of Tertiary volcanics, tuffs and ashes especially in Al-Janad plateau. They are composed mainly of silts, clays, sands and some gravels (Al-Qadhi, 2007).

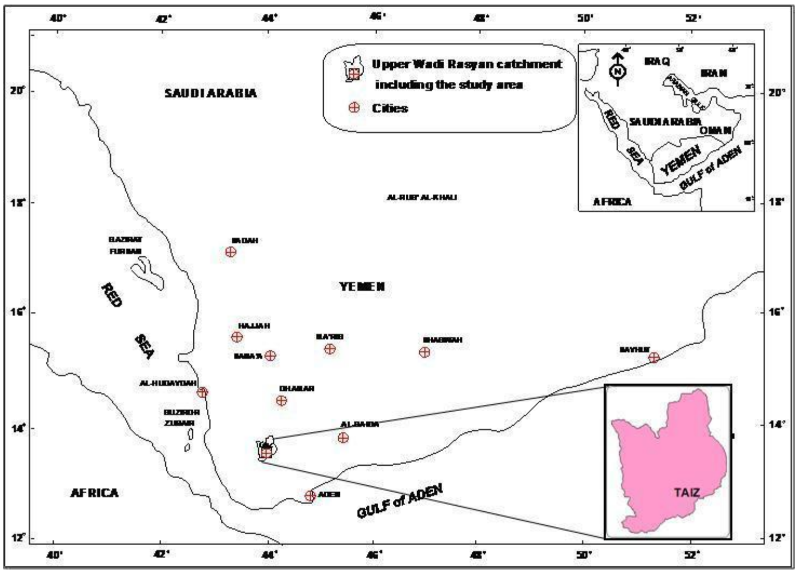


Figure 1: *Location Map of the Study Area*

The field studies in and around Taiz area reveal that the sequences of volcanic lava flows of YTS and YVS and associated volcaniclastic rocks can be considered to have erupted in five phases and in a repeated manner (Kruck and Schäffer, 1996; Dey, 1997; Malek et al., 2014). These form from bottom to top the following: (1) Tertiary lower mafic sequence phase (Tb1), (2) Tertiary lower silicic sequence phase (Tr1), (3) Tertiary middle mafic sequence phase (Tb2), (4) Tertiary upper silicic sequence phase (Tr2) and Tertiary upper mafic sequence phase(Tb3) (Figure 2). In the following sections, the geological settings and the petrographic characteristics of Tertiary bimodal mafic-felsic suite represented by flows (Tb1, Tr1, Tb2, Tr2 and Tr3), Sabir pluton and mafic and felsic dykes and sills are described.

3. Materials and Methods

A Geological map shows the distribution of rock units, their type and age relationship (Njue, 2010). Geological field mapping in the study area was carried out to document the distribution of Tertiary volcanic rock types, their field occurrences including structure, mineralogy and field relationship between the different litho-units. Initially, a geological map of the study area produced by Kruck and Schäffer (1991) on scale 1:250,000 were used as a base map. In order to prepare the medium scale map of the study area, in addition to Kruck and Schaffer (1991), remote sensing data was also used.

During the field traverses, volcaniclastic materials and fresh rock surfaces exposed along the road cuttings as well as on quarry surfaces were observed and studied. Geological features were documented in the field note book. Compass-clinometer and GARMIN 12 channel GPS were used respectively to record the attitude and location of the different lithounits. The coordinates of the outcrops were converted to Universal Transverse Mercator (UTM) with Transfo and then plotted in Surfer 8. Geological map of Taiz area published by Kruck and Schaffer (1991) was verified and necessary corrections in the geological map were made based on the field study and satellite images. In the field various Tertiary volcanic and magmatic intrusive rocks were distinguished. Different rock samples from the study area were collected from the 110 exposures with the help of a field hammer. 14 representatives volcanic soils (volcanic ashes) found between the different lava flows were characterized for their mineralogy by XRD analysis.

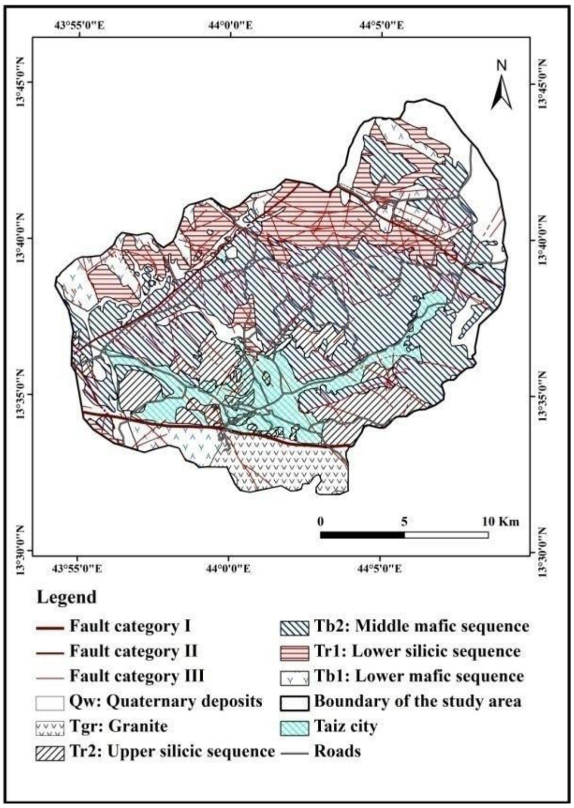


Figure 2: *Geological Map of the Study Area (modified after Kruck et al., 1991; DEY, 1997; Malek et al., 2014)*

Physical properties of the collected rock samples were studied with the aid of a magnifying lens. For the petrographic studies, 52 thin sections of different rock types were prepared in the laboratory by cutting the rocks using micro-cutting machine followed by reduction in the thickness of the rock slice to the required size using carborundum powder on a grinding wheel. The thin sections of the rocks were then mounted on a glass slide with the help of epoxy for their studies under petrological microscope. Photomicrographs were taken with digital camera to showcase the distinguishing and other optical characters of the minerals.

4. Results and Discussion

4.1. Tertiary Lower Mafic Sequence (Tb1)

Tb1 flows represent the lower most basaltic sequence of Tertiary volcanic rocks and the main activity which took place 29-20 million years ago (Civetta et al, 1978). This sequence is dated of Eocene age. In the study area, Tb1 comprises dominantly the basaltic lava flows and minor volcaniclastic deposits. They represent the volcanic products extruded primarily through the feeder dykes paralleling the axis of the Red Sea, and comprise either multiple or single cooling flow interbedded with centimeter to several meter thick basic volcaniclastic deposits. They are largely found scattered in the northwest border and to the west of Sabir mountain, covering 9% of the total area (see Figure 2). They occur deviated from horizontal attitude due to paleorelief peculiarities and/or riftogenic tectonic motions which are related to the development of the Gulf of Aden and opening of the Red Sea, or east African rift valley system. The basaltic lava flows which have developed joints owing to cooling have subsequently been filled with late hydrothermal alteration products. Further alterations have resulted in the development of angular fragments. Thus, the fresh to slightly altered basalt unit occurs as highly jointed, strong as well as very angular with sharp edges (eg, outcrop south of As-Salmani village). These jointed /massive rocks display varying colours ranging from dark grey in fresh surface to chocolate brown or dark reddish brown on outer weathered/altered surface. The rocks, after extraction in the form of crushed stone/aggregate, are being used as concrete and asphalt mix. In the same location, this unit is intercalated with basic volcaniclastics.

Megascopically, the Tb1 rocks at places display porphyritic texture wherein plagioclase and/or olivine phenocrysts are visible to the naked-eye in the hand specimens (Figure 3a & b). They are with or without vesicles. Vesicles do sporadically show infillings with secondary minerals, thus exhibiting amygdaloidal structure. Chalcedony is one of the common infilling as seen at station 92, east of Al-Mulayh village, Al-Hawban area. Phenocrysts of pyroxene (clinopyroxene) are also seen. Thin section studies of Tb1 rock shows that both olivine and clinopyroxene represent the main components and other accessory minerals are represented largely by iron oxides. Also, the cracked coarse phenocrysts of olivine in the fine groundmass are observed (Figure 3c & d). Iddingsite and/or serpentine, as an alteration product of olivine, are/is seen at the rims and along the cracks of phenocrysts. The microscopic study revealed the nature of the Tb1 flow to represent the composition of olivine basalt.

Almost at the top of Tb1 sequence, a continuous horizontal intrusive body is seen and it is overlain by Tr1 (ignimbrite flows) (Figure 4). In some places, the rock appears to show pseudo-schistosity caused by horizons of compact fine-grained volcanics. It is resistant to weathering so, lithological scarps several maters in height are formed. The lower boundaries of Tb1 with the underlying rocks is generally not obscured in the studied area, while the upper boundaries with lower silicic rocks (Tr1) are well exposed and sharp, commonly irregular in most of the localities. The upper boundary of highly weathered Tb1 is encountered at a depth of 11m from the ground surface in one of the bore well section near, Al-Ikam Ajud village, wadi Al-Burayhi, north of the study area (Figure 5).

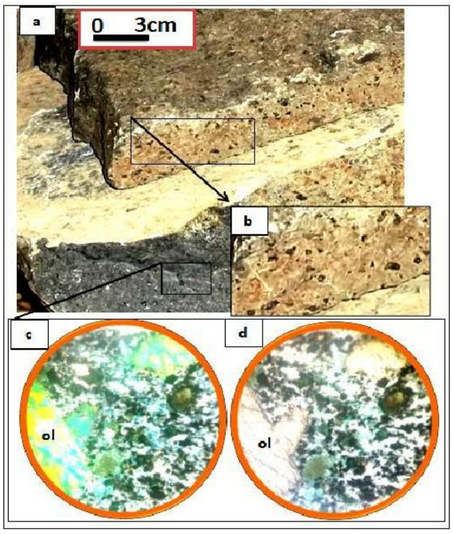


Figure 3: *Field photograph of basalt of Tb1 showing porphyritic texture with olivine phenocrysts (a) and Olivine-filled amygdules (b). Also, photomicrographs displaying cracked coarse phenocrysts of olivine (ol) in the fine groundmass (Figures c and d) (XL and PPL; 10X).*

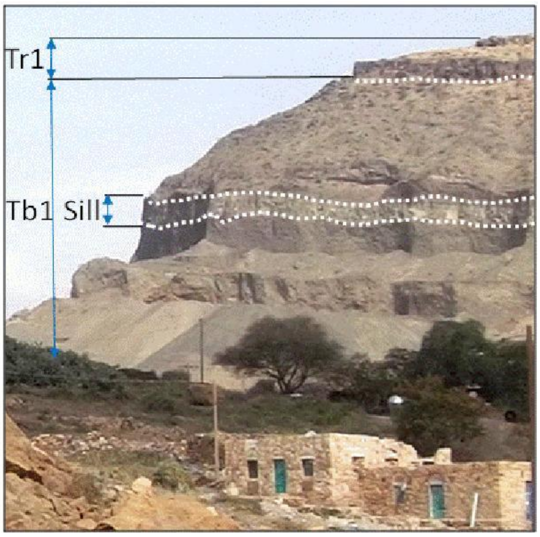


Figure 4: *Field photograph showing basalt flow (Tb1) with a sub-horizontal sill and overlain by ignimbrite of Tr1 sequence*

Figure 5: *Upper boundary of highly weathered Tb1 as seen in a bore hole located near Al-Ikam Ajud village, wadi Al-Burayhi, north of the study area*

4.2. Tertiary Lower Silicic Sequence Phase (Tr1)

The previous sequence (Tb1) is followed by Eocene - Oligocene felsic volcanic rocks (Tr1) which are exposed along the northern border of the study area with a dip of about 30° in SE direction. Thickness of these deposits reaches 200 m with an areal extent of 14.58% of the total investigated area. Topographically it forms high plateaus with escarpments or cliffs. In some places, Tr1 is forms cuesta-type almost horizontal morphology. Thus, Tr1 varies in its appearance from multi-sheet stratifications to domal mountains and hills (Figure 6).

Petrologically Tr1 is represented by jointed rhyolites/dacites, ignimbrites, rhyolitic tuffs, lapillistones, volcaniclastic breccias, and random pumice and obsidian. The higher amounts of volcaniclastic rocks in Tr1 sequence indicate that initially volcanism of silicic volcanic rocks was more explosive (Malik et al., 2014). They are generally hard, massive rocks although flow structures may also be seen, showing foliation, and cooling discontinuities. In Tr1 sequence, vertically change in lithology and colonnade columnar jointing features was observed. This feature is best studied along a rhyolite quarry located in the cliff-face at long Al-Steen road, Ad Daraj village in the northern part of Taiz city (Figure 7a). Here, the Tr1 stratigraphic sequence consists of three main alternating layers viz., from bottom to the top: 1) whitish yellow coloured welded rhyolitic tuff, ranging from fine-grained ash to lapilli, 2) yellow to reddish brown coloured massive, fine grained, highly welded ignimbrite showing flow band structure and 3) reddish yellow coloured colonnade columnar jointed rhyolite. The yellowish brown coloured weathered/ altered basaltic dyke shows discordant relationship with layers 1 and 2 and does not cut layer number 3 implying, it is younger to these layers and layer 3 wasn't emplaced coevally with both 1 and 2 layers (Figure 7b). However, intensive field studies on the boundary between the volcaniclastic rocks and rhyolite/dacite in several locations indicate that they were emplaced at least in part simultaneously.

Figure 6: *Cuesta topography with multi-sheet stratifications developed in the Tertiary lower rhyolite/ignimbrite flow (Tr1). Note the boundary between Tb1 and the Tr1*

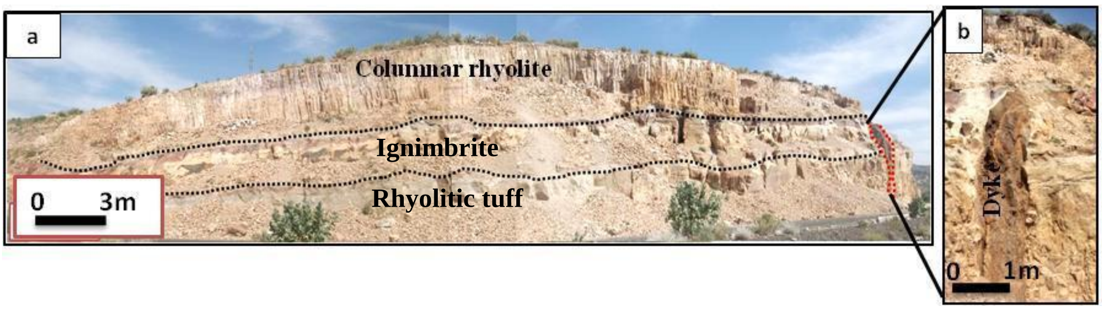


Figure 7: *(a) Field view of rhyolite lava flows with well-developed colonnade columnar jointing in the upper flow; (b) altered basaltic dyke older to colonnade columnar joints, near Ad Daraj village, Al-Steen road, north of Taiz city*

In some exposures, as at Aumam Mountain, the rhyolitic flows display colonnade shrinking joints which are varied in their shape and size along the flow direction than in the vertical section at the same location (Figure 8a). In the present day urban planning, the rocks of Tr1 rhyolitic lava flows are extracted by quarrying to use them as building stones (Figure 8b). At places, spherical weathering in the columnar rhyolite has produced spheroids as big as 1.80 m diameter. In addition, exfoliation, blocky and cavernous weathering features were also found in the same location (Figure 9).

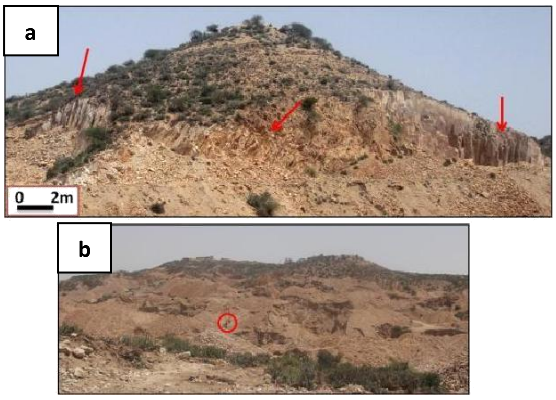


Figure 8: *View of lower Tertiary rhyolitic lava flows (Tr1) with colonnade columnar jointing showing the variation in the shape, size and the diversion direction of the colonnade columnar joints in the Aumam mountain area, NE of Taiz city. (b) Displays quarry sites which are used for extraction of build stones, in the same location. The scale is the Pulverizer (red circle)*

Figure 9: *Spherical weathering feature in columnar rhyolite at Aumam mountain, NE of Taiz city*

The Ignimbrites occur as flows and compact welded volcaniclastics with flattened and stretched fragments (Figure 10). At places, these rocks are seen as layer with columnar structure. Megascopically, the very important feature which was observed on most of the cut rock sample surfaces of the columnar rhyolites, ignimbrites and welded rhyolitic tuffs is the small pits or vesicles (1-7mm diameter); some of them are filled with powdery/hard white/black materials of secondary minerals. This feature is more frequent in the ignimbrites and welded rhyolitic tuffs than in the columnar rhyolites (Figure 11).

The ignimbrites at other places do not have pits or vesicles but contain flattened and stretched fragments known as fiammes. These fiammes are clearly visible in the hand specimens (see Figure 10) and their development is possibly due to the magmatic movement. The development of macrofractures on the surfaces of columnar rhyolite hand specimen are observed and these are filled with magnesium minerals (Figure 12a), while they are sometimes healed by hematite mineral as occurred in ignimbrite sample (Figure 12b).

In the field, clusters of thunder eggs (lithophysae) are also observed within welded rhyolitic lapillistone of the Tr1. This kind of clusters are clearly visible in the Ad Daraj village at Al-Steen road, to the north; where they form zones in the lower parts of rhyolitic lapillistone (Figure 13a & b) and near An Najaydah village in the northwestern part of the study area (Figure 13c). The size of concentric or star-shaped thunder eggs (lithophysae) varies from less than 1 cm to 8 cm. Another notable feature in most of Tr1 rocks is the stain like feature possibly created by iron oxides (hematization and limonite) during the alteration of Fe-bearing minerals (Figure 14a & b).

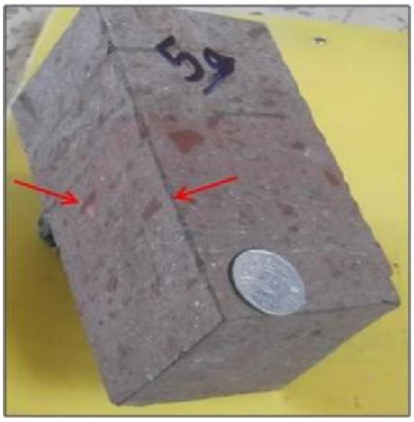


Figure 10: *Fiammes in welded ignimbrite, at middle of Aumam mountain, NE of Taiz city. Coin diameter 2.6 cm*

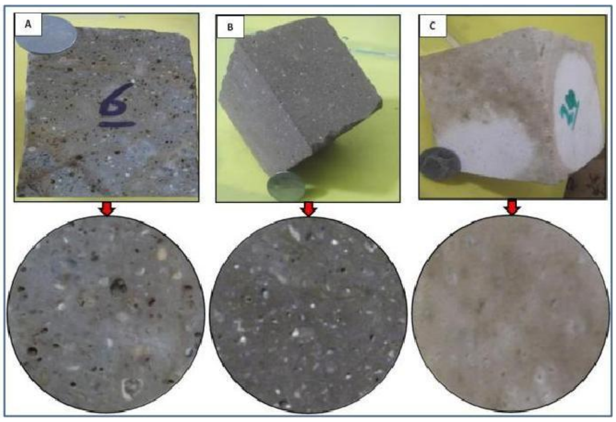


Figure 11: *Small pits or vesicles on the cut rock sample surfaces of the Tr1 flows. Note the size and density of these features are reduced from ignimbrites (a) to welded rhyolitic tuffs (b) to the columnar rhyolites (c). Coin diameter 2.6 cm*

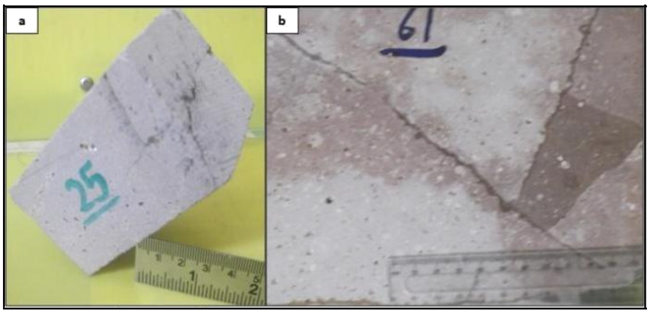


Figure 12: *Macrofractures filled with magnesium minerals in the columnar rhyolite, (a) and healed by hematite mineral as occurred in ignimbrite sample (b)*

Microscopic studies of jointed rhyolite/dacite of Tr1 reveal that most of the rock sections show porphyritic textures and on a minor scale, flow fabrics (Figure 15). They contain quartz grains, feldspar phenocrysts and biotite, opaque/Fe-oxide embedded in altered fine grained matrix of the same composition with or without clayey minerals. The ignimbrites in thin sections display pyroclastic textures and are composed of volcanic glass shards, rock fragments of vasicular basalt, quartz and opaque. These components are embedded in a glassy groundmass (Figure 16a & b).

Observed microfractures developed in the ignimbrites are normally filled with volcanic glass or/and secondary minerals while the vesicles or pits seen across the sections are either unfilled or partially filled with the secondary minerals (Figure 16 c & d).

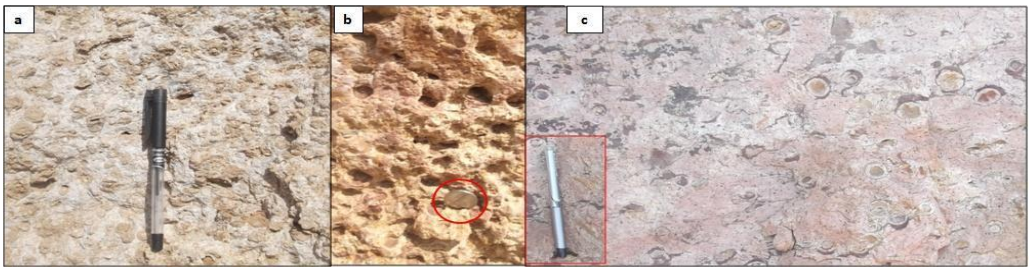


Figure 13: *Rounded lithophysae "thunder eggs" in the lower part of welded rhyolitic lapillistone of the Tr1 found near the Ad Daraj village on Al-Steen road to the north of the study area (a and b) and near An Najaydah village to the northwest of the study area (c). Pen lengths 16.7 cm and 14 cm in Figure a and Figure c respectively. Coin diameter 2.6 cm*

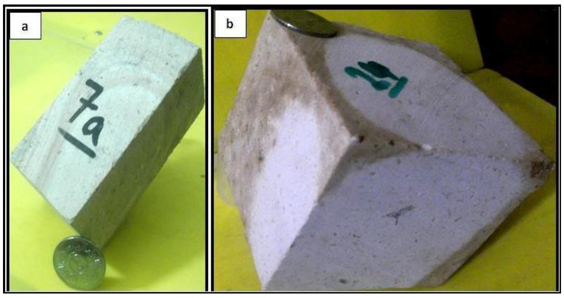


Figure 14: *(a & b) Iron oxide coatings in Tr1 rocks*

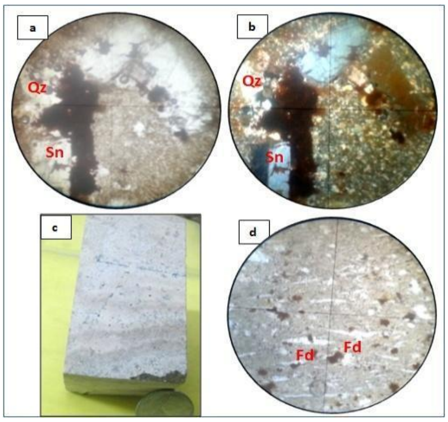
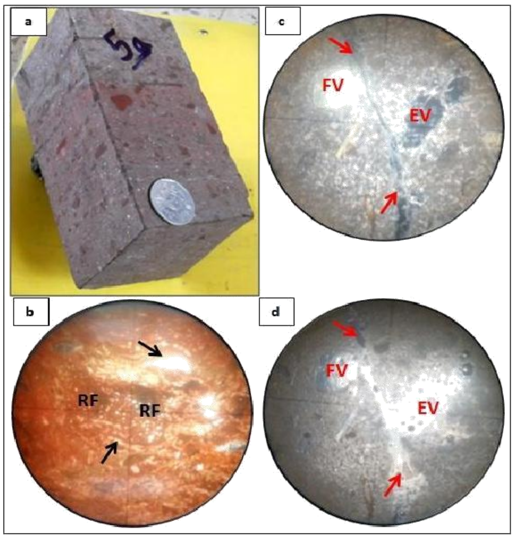


Figure 15: *Porphyritic texture in jointed rhyolite/dacite flows (Tr1) in PPL and CPL respectively (a and b) (10X) and (c and d) are showing flow fabric in hand specimen of rhyolite and in its thin section respectively. (in PPL and 10X). Coin diameter 2.6 cm (Fd= Feldspar, Qz= Quartz, and Sn= Sanidine)*

Mineralogy of tuffs of Tr1 sequence could not be made out as they are highly altered (Figure 17). They contain voids or vesicles which are at places filled with secondary minerals. In general, all thin sections studied of Tr1 rocks display the activity of hydrothermal solutions and consequent alteration of these rocks.



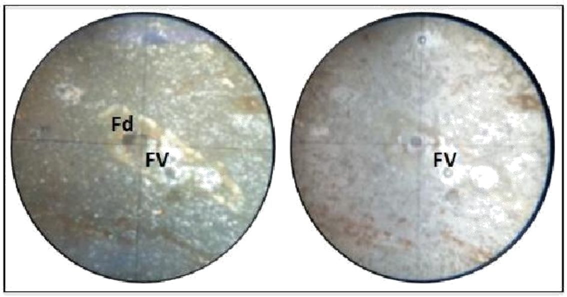


Figure 17: *Photomicrographs (3.5X) in CPL and PPL showing alteration of feldspar phenocrysts (Fd) set in intensely altered groundmass and vesicles filled with secondary altered minerals (FV) in tuff belonging to Tr1 sequence due to permeation of hydrothermal solutions*

Figure 16: *Hand specimen and photomicrograph (10X, CPL) showing pyroclastic texture in the Tertiary ignimbrites (Figures a and b). Note volcanic glass shards (black arrows), rock fragments (RF) of vascular basalt, quartz and opaque. Figures (c and d) exhibit microfractures filled with volcanic glass (red arrows), while the vesicles or pits are either unfilled (EV) or partially/fully filled (FV) with the secondary minerals (in PPL and CPL; 3.5X). Coin diameter 2.6 cm*

4.3. Tertiary Middle Mafic Sequence Phase (Tb2)

The Middle basic volcanics (Tb2) of Cenozoic are represented in Taiz area by basaltic lava flows and volcaniclastic deposits. Similar to Tb1 and Tr1, these are also extruded primarily through the feeders like - dykes. Some of sub-vertical N-S to NW-SE trending basalt feeders are exposed along Al-Steen road in the investigated area. These lava flows came as a second basic phase and overlie the first acidic phase (Tr1). They are considered Oligocene-Miocene in age (Kruck and Schaffer, 1991). In the study area, the rocks and deposits of Tb2 have a greatest areal extent in comparison to all other units with an areal extent of 39.61 % of total area and a thickness of about 100 m. They are widespread on a long middle zone extending from east to west (see Figure 2), topographically forming undulating plains inside Taiz plain and are dissected by major Wadis. The most striking feature of Tb2 is its occurrence as alternating sequence of more than one lava flow. These lava flows show different physical characteristics (colour, heterogeneity, discontinuity, thickness, horizontal attitude, weathering/alteration, intercalation and repetition with depth) in both vertical and horizontal directions implying variation in eruption type, mode of transport, distance travelled from the vent, temperature of the deposits, particle size, water content and paleorelief of older Tr1 sequence.

In some places, Tb2 lava flows are poorly exposed due to high weathering and consequent soil formation. The thickness of the soil cover does not exceed 10 m on the slope side of hills and increases to reach more than 30 m in valley bottoms.

The fresh and clear exposures of basaltic lava flows (Tb2) are seen along road cuts and some are seen as natural outcrops. Generally, in these outcrops, Tb2 are comprised of jointed basalts, massive basalts and/or volcaniclastic deposits. According to Fisher (1966) and Gillespie and Styles (1999), the volcaniclastic deposits can be classified as tuff-breccias, lapilli-tuffs, agglomerates and lapillistones based on their particles sizes. Locally, jointed basaltic lavas overlie volcaniclastics deposits of the same or different age and /or laterally intercalating with them. This kind of feature is observed in several places, particularly in the eastern parts of the study area such as NE Ash-Shu'ub village and in some outcrops occurring along Al-Rahidah road. For illustration of these features of Tb2, the excellent exposed section found near Al-Jibalah village in Al-Steen road was investigated. It consists of sequence of five layers (Figure 18) and from bottom to the top consists of the following: (1) reddish brown to dark greenish grey coloured massive basalt with more than 3 m thickness, (2) creamy white to reddish brown, unconsolidated to semi-consolidated volcanic ashes with a thickness of up to 6 m, (3) brown to dark grey colour jointed basalt flow with an irregular joint pattern (polyhedral blocks) and thickness varying from less than 1.5m to 5m, (4) brown to light grey colour poorly sorted volcanic agglomerates and (5) brown to greenish grey colour basalt flow with sub-vertical to irregular cooling joint pattern with a thickness of less than 1m to 2.40m.

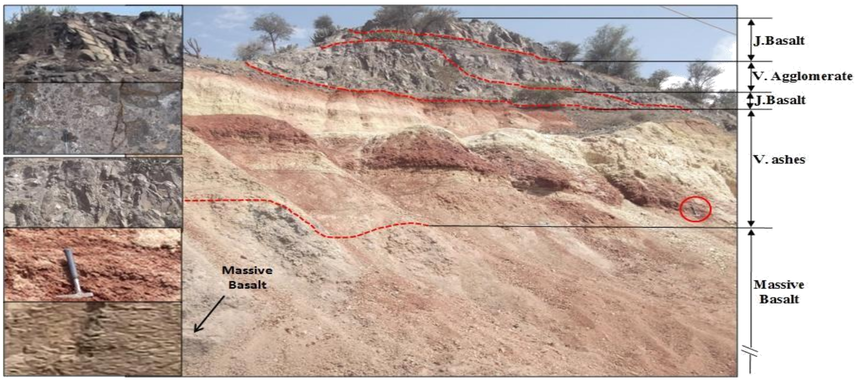


Figure 18: *Exposure of the Tertiary middle mafic sequence (Tb2), near Al-Jibalah village, Al-Steen road. Length of hammer 32.5 cm (inside of red circle)*

The second example has been taken to illustrate wide change in the physical characteristics of Tb2; vertically and laterally at the same location (Figure 19a-c). This example also includes correlation between the two sides, east and west of a road cut located to the west of Al-Mishhat village on Al-Steen road. For this reason, the representative vertical section at specified parts of the Tb2 sequence was taken on both trench sides for field description purpose. In the west side (Figure 19b, A-B section), the Tb2 sequence consists of the following from the bottom to the top: (1) Light reddish brown to dark grey coloured fine grained massive basalt flow with a thickness of about 3.5 m in this part and increases up to more than 10 m in other parts. These massive basalts have developed joints wherein the joint planes of the unfilled joints are stained by iron oxides. Some joints are filled with carbonate materials, quartz and angular fragments of basic rocks cemented by carbonate materials/calcite, especially near the dyke which cuts this layer (Figure 20).

In massive basalts, vesicles are small and tiny and vugs are of varied dimensions. These are partially or completely found filled with quartz and/or calcite minerals (Figure 21). The upper part of this layer has been subjected to weathering processes before the intrusion of the subsequent cycle basalt which formed the layer 2. The thickness of weathered zone ranges from 15 cm to 60 cm. (2) light reddish brown to dark grey coloured fine grained jointed basalt; this layer is injected through the sub-vertical feeder dyke and displays concordant relationship with the surrounding rocks. The angle of dip of this lava sheet ranges from few degrees to 47° in the SE direction and the lava sheet is obscured under the layer 3, with thickness ranging from 30cm to more than 3.5m. This lava sheet laterally shows change from randomly jointed basalt (close to dyke) to columnar basalt (in the SE direction). (3) Grey coloured welded and compacted volcanic pyroclastic rocks (lapilli-tuff) with 50 cm to 1.40 m thickness; it consists of angular to sub-angular basic rock clasts embedded in a matrix of volcanic ash and iron oxides. This layer is laterally interlocked with jointed basalt in other parts of this layer. (4) Light reddish brown coloured fine grained jointed basalt with a thickness ranging from 60 cm to 1.5 m is noticed at a distance from the current location. This flow is laterally discontinuous; where in, the jointed basalt may be laterally intercalated with volcaniclastics in some parts.

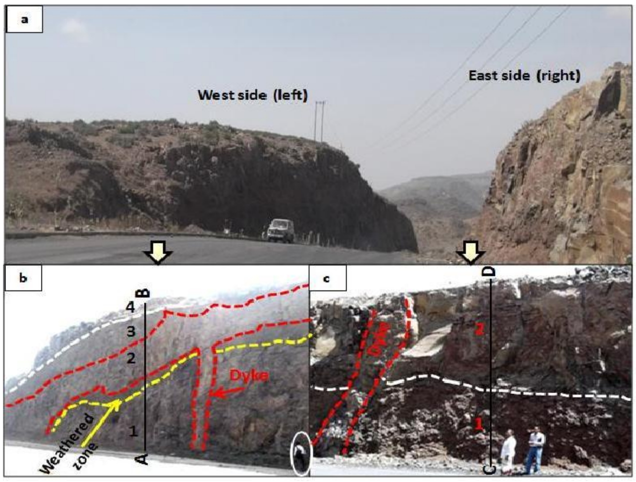


Figure 19: *a) The trench cut for laying road shows diverse features of Tb2 flow on either side. b) Western part consists of massive basalt (1); fractured basalt (2), lapilli tuff (3) and fractured basalt (4) Eastern side displays basaltic tuff breccia (c) (1) and fractured basalt (2) Note the presence a dyke and a sill on the western side*

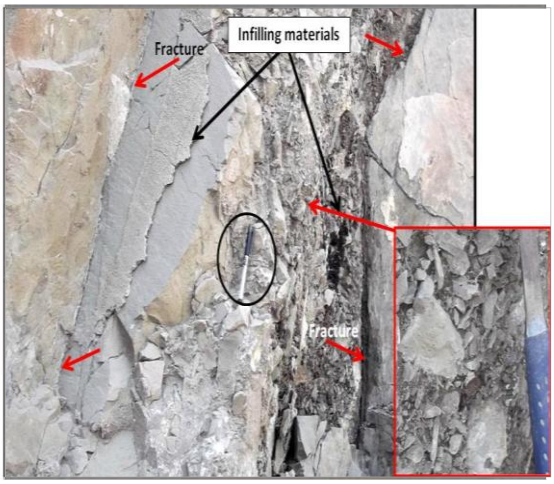


Figure 20: *Field photo showing carbonate formed along the joints of Tb2 rocks of western side of the trench*

The east side section of the road cutting displays a sequence of two layers (Figure 19c, C-D section) which are from bottom upwards are as follows: (1) Dark grey to light reddish brown coloured welded and/or interlocked, strong to medium strong volcanic pyroclastic rocks (tuff breccia); it is composed of small to medium, vesicular/ massive, angular, sub-angular to sub-rounded, intact to fractured clasts of basic rocks. These clasts are cemented by volcanic ashes, iron oxides and carbonate and silicate minerals (Figure 22). This layer is intercalated laterally with jointed basalt with thickness more than 2.50m. (2) Light reddish brown to light grey coloured fine-grained, highly jointed basalt; this layer is interbedded laterally with volcaniclastic deposits. The fractures are irregular, most of them stained with iron oxides and a few are filled with calcite and/or quartz or with admixture of these minerals and angular basic rock fragments.

Generally, in the investigated exposures of Tb2, the basaltic lava flows can be described as chocolate-brown to/or dark greenish grey coloured fine-grained, slightly to highly weathered, vesicular and porphyritic, in places with plagioclase and/or olivine phenocrysts as the dominant mafic minerals and pyroxene as a minor constituent. The jointed basalts are affected by the development of relatively random fractures in different directions. Locally, jointed basalts exhibit well-developed colonnade columnar jointing structures.

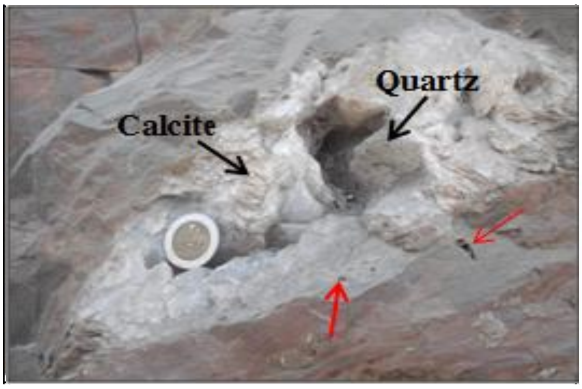


Figure 21: *Vugs lined with quartz and calcite on the eastern side of the trench*

Figure 22: *Tufff breccia, in the Tertiary middle mafic sequence (Tb2), on the eastern side (right) of the road trench. Pen length 16.7 cm (inside red circle)*

Highly fractured columnar basalt is seen near Uqush village (Figure 23), where the columns are of major discontinuous form and each column is highly fractured in different directions. The maximum and minimum spacings of columnar structures were measured between 1.38 m and 0.12 m south Qusaybah village, Al-Hamseen road and near Uqush village, Al-Steen road respectively. The columnar basalt, with persistence reaches to 3 m as seen in Wadi Al-Fula, North West of Al-Hawban area.

In most locations, the vesicles and cavities found in jointed basalt are either unfilled or entirely/ partially filled with secondary minerals such as calcite/crystallized quartz. The diameter of these cavities or vesicles varies from <2mm to as large as 35 cm.

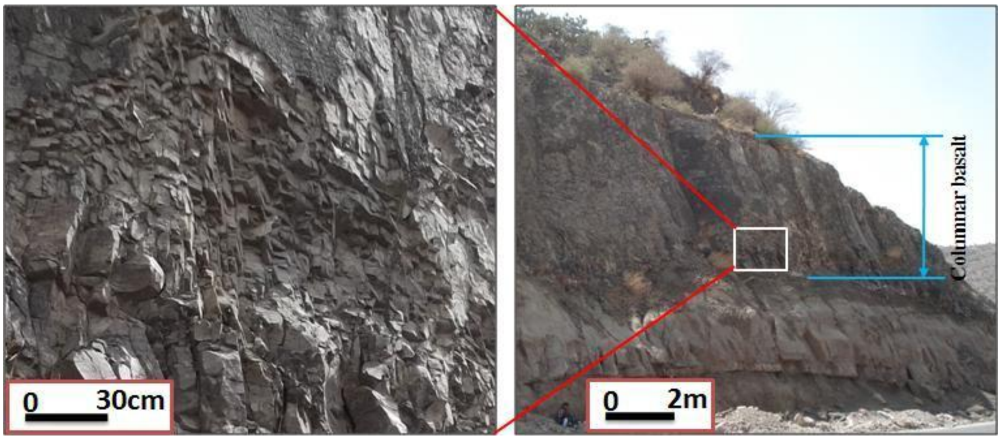
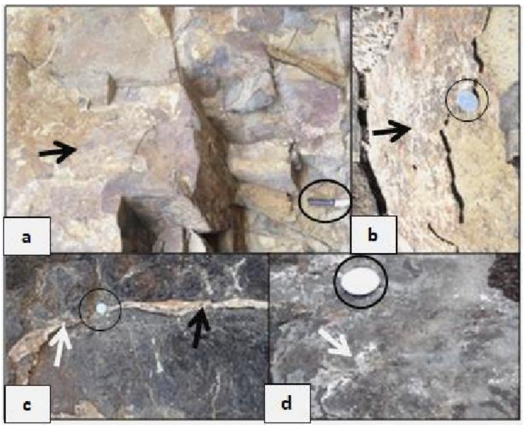


Figure 23: *Exposure of columnar basalt (Tb2) located near Uqush village. Note (inset) each column is affected by fractures in different directions*

The discontinuities in the basalt flows are either stained by iron oxides and/or filled with minarets and/or rock fragments. Sometimes, these materials take the form of thin sheets ranging in its thickness from <1mm (iron oxides in the form of films) to more than 20mm (carbonates and other minerals) (Figure 24a-c).

In some places, the carbonate materials which have filled the fractures are weathered and appear as white powdery materials in some fractures and weak thin sheets in other. The surfaces of fractures with a thin layer of micro or cryptocrystalline silicate minerals are rarely observed (Figure 24d). The fractures filled with angular rock fragments cemented by carbonate material/calcite are commonly found especially near dykes. The laminated jointed basalts are seen in the eastern part of Al-Mulayha village located in Al-Hawban area, and on the side of Taiz-Sana'a road nearly 300 m far from Hail's biscuit factory (Figure 25a). While the crushed jointed basalt was seen in the southern part of Al-Qurf village in Al-Howban area (Figure 25b).



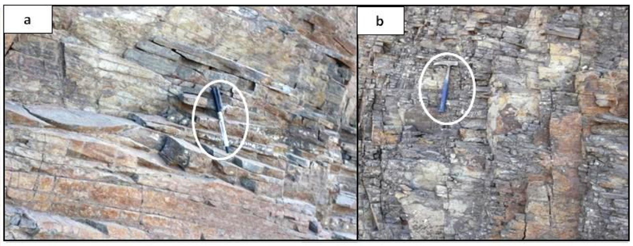


Figure 25: *Tertiary jointed basalts (Tb2) occurring as; a) laminated jointed basalt in Al-Hawban area to the east Al-Mulayha village, b) Crushed jointed basalt, in Al-Howban area to the south Al-Qurf village*

Figure 24: *Types of infilling material in the joints of basalt flows (Tb2); a) Iron oxide in the form of stain b) Iron oxides, carbonates minerals and fine soil found as sheets, c) Carbonate minerals, d) Cryptocrystalline silicates/ quartz. Knife length 14.6 cm (inside black circle), coin diameter 2.6 cm*

Basalts which show high density macro joints along horizontal and vertical directions join or cross each other. At places major joints have resulted in forming the tabular blocks. At times, these tabular blocks move down under the influence of gravity for which the term wedge slide is used. In general, the type of release surfaces which were identified in the jointed basaltic rocks are plane surfaces, concave surfaces, convex surfaces and inter-crossed surfaces. Small calcite veins, up to 1 mm thick were observed in both the hand specimens and thin sections of crushed basalts (Figure 26). These locations represent sites for extraction of crushed stone/aggregate which are being used for construction purposes. Megascopically; basalt in the hand specimens is greenish grey or light greenish black colour, generally show porphyritic texture with plagioclase and/or olivine as phenocrysts in a fine-grained groundmass (Figure 27). Rare occurrences of fine-grained aphyric basalts have been found in the study area.

Massive trachybasalts with trachy structure and aphanitic texture are seen in the upper Nqeel Al–Epil located to the southeast of the study area, where this lava flow is overlain by Tr2. In trachy basalts, assemblages of secondary calcite and/or quartz are found in small pockets. The amygdales are filled with glass, chalcedony/quartz, calcite, and zones of quartz-calcite while other vesicles are emptied due to weathering of feldspar crystals (Figure 28). Massive trachy basalts of Tb2 in Taiz area show pseudo-pillow structure at places implying the intensity of sub-aerial weathering (Figure 29).

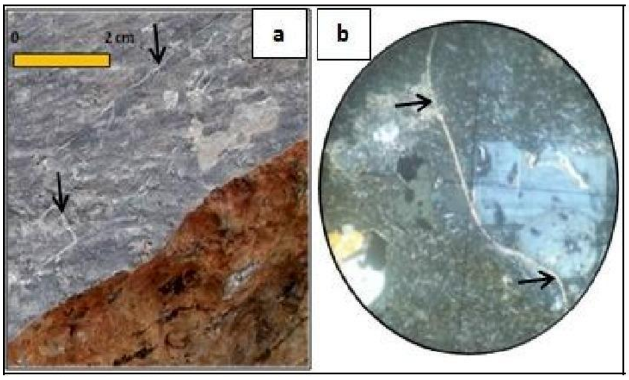


Figure 26: *Calcite vein in Tertiary Crushed jointed basalt in Al-Howban area to the south Al-Qurf village; a) In hand specimen, b) In thin section. (CPL and 3.5X)*

Figure 27: *Porphyritic texture in Tertiary jointed basalt flows showing olivine phenocrysts (black arrows) embedded in a fine-grained groundmass*

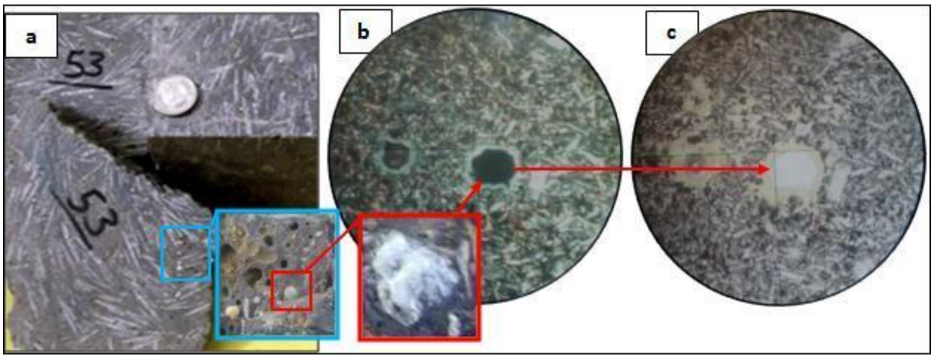


Figure 28: *Massive trachybasalt lava flow (Tb2) exposed at upper Nqeel Al–Epil to the southeast of the study area; a) Trachy structure and aphanitic texture in hand specimen. Note emptied vesicles due to release of feldspar /quartz/ calcite crystals by weathering. The amygdales filled with glass, chalcedony/quartz, calcite, or zones of quartz-calcite in thin sections (b and c and insets) (CPL and PPL; 10X). Coin diameter 2.6 cm*

Figure 29: *The pseudo-pillow structure in massive trachybasalt lava flow (Tb2) near upper Nqeel Al–Epil to the southeast of the study area*

In addition, the spherical weathering phenomenon is also observed in the basaltic lava flows as well as in some basic dykes at different sits. The highly spherical weathered basalt is seen in wadi Al-Qula, Al-Hawban area (Figure 30a), while moderately spherical weathered basaltic dyke is observed in Wadi Al-Malih, west of the study area (Figure 30b). The basaltic volcaniclastic deposits are also classified into tuff-breccias, lapilli-tuffs, agglomerates, lapillistones and volcanic ashes. These deposits are different in their types, colour, thickness, grain size, matrix, and degree of roundness of rock fragments and are interlocked laterally and horizontally. They range from strong, compacted, welded rocks to weak altered soils. This large diversity is a direct consequence of the wide range of emplacement and post-emplacement processes operation on volcanic flows (del Potro and Hürlimann, 2008).

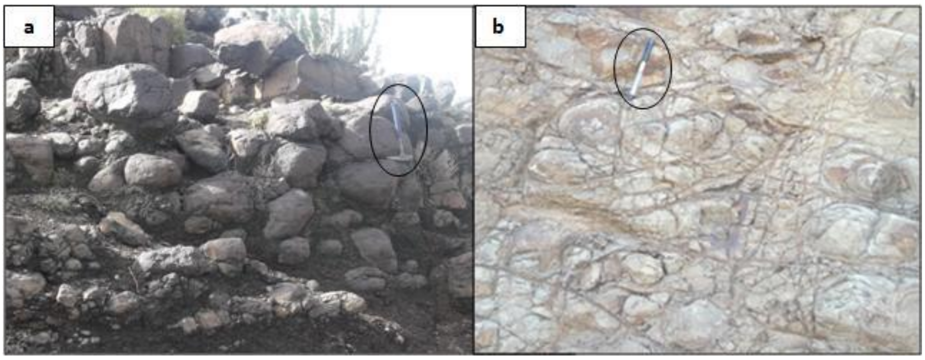


Figure 30: *a) Tertiary basaltic lava flows (Tb2) in the form of boulders due to spherical weathering phenomenon seen at wadi Al-Qula, Al-Hawban area, b) Onset of spherical weathering phenomenon in basaltic dyke, Wadi Al-Malih, west of the study area. Hammer length 32.5 cm, and the pen length 16.7 cm*

Tuff-breccias are dark grey to light reddish brown in colour welded and/ or interlocked, strong to medium weak. It is composed of small to large, vesicular/massive, angular, sub-angular to sub-round, intact to fractured clasts of basalt rocks. The bomb and/or block clasts range in volume from 25% to 75% (Figure 31a). They are cemented by volcanic ashes, iron oxides and carbonate minerals. Tuff-breccias often occur under jointed basalts or intercalated laterally with them within the Tb2 sequence.

Basaltic lapilli-tuffs are white, grey to reddish brown in colour, welded, strong to medium weak and compacted pyroclastic deposits. The bomb and/or block clasts (>64mm) represent <25% by volume, while lapilli (64-2mm) and ash (<2mm) together constitute less than 75% (Figure 31b). These deposits consist of angular to sub-angular and sub-round, vesicular/ amygdaloidal to massive clasts of basic rocks cemented by volcanic ash and iron oxides. Volcanic agglomerates are brown to light grey in colour, welded volcanic pyroclastics. The basic clasts are poorly sorted angular to subangular, rounded to sub-rounded, vesicular/amygdaloidal to non-vesicular, irregular interlocked and moderately strong. The size of these clasts is > 64mm (Figure 31c).

Basaltic lapillistones are pyroclastic rocks in which lapilli (64-2mm) constitutes > 75% (Figure 31d1). These are grey/light reddish brown in colour, welded and compacted, moderately strong pyroclastic rocks. They consist of angular to sub-angular and sub-rounded interlocked mafic clasts, cemented by volcanic ash and iron oxides/ or silicates and contain irregular voids between them. Some void surfaces are coated with silicates and carbonates as the lining material (Figure 31d2). Generally, in the study area, the volcanic ashes and iron oxides are more frequent matrix materials in the volcaniclastics.

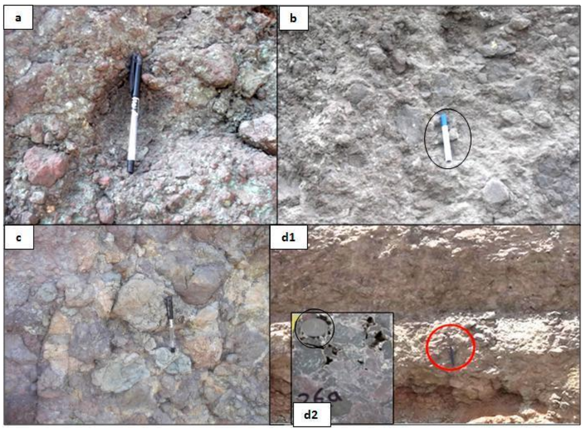


Figure 31: *Basaltic volcaniclastic deposits of Tb2; a) Tuff-breccia b) Lapilli-tuff, c) Volcanic agglomerate, d1) Lapillistone; Inset in Fig. d2 irregular, voids in rock clasts are emptied or partially lined with quartz. Hammer length 32.5 cm, pen length 16.7 cm, marker pen length 14.2 and the coin diameter 2.6 cm*

The volcaniclastics composited from un-welded and irregular interlocking clasts of two or more of volcanic materials are found at different sites such as, western side of Raheedh -Aden road, near intersection of Sana'a road with Aden road. In the exposures located near Nashit village and Al-Harrir areas, volcaniclastics are laterally and vertically intercalated with jointed basalt of Tb2. Usually, the jointed basalt occurs as lens in volcaniclastics. In the most investigated exposures of Tb2, the basalt flows are underlain by semi-consolidated volcaniclastic materials are found sandwiched between the volcanic sequences (Figure 32).

Due to this situation, the subsidence and landslides were observed in several locations in the study area such as near Al-Thawrah hospital and east of Al-Mulayh village, Al-Howban. In some places, the debris landslides have taken place as a consequence to the high degree of weathering volcaniclastics (Figure 33).

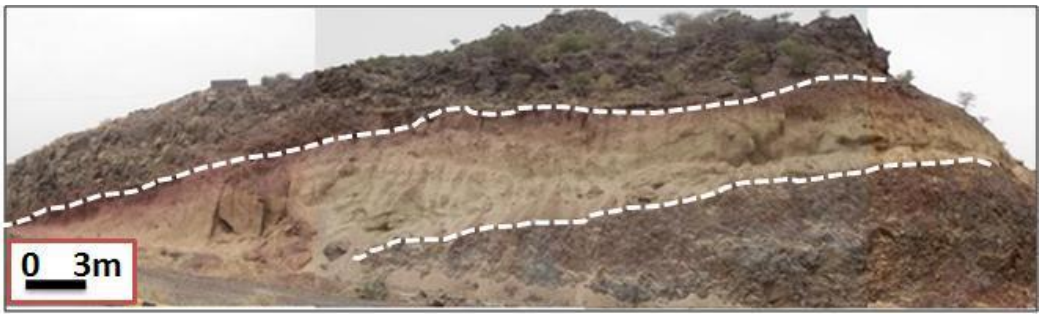


Figure 32: *Semi-consolidated volcaniclastic deposits sandwiched between the volcanic sequences*

Figure 33: *Field photographs showing the debris landslide in intensely weathered basic volcaniclastics-Tb2 located in the southeast NWRA, Ussayfra area. Note the horizontal displacement (about 1.4m) and the movement direction (EW) of landslide. Field notebook height 20 cm (inside white circle)*

Microscopically the jointed basalts of Tb2 flow show several features. They are generally porphyritic, where abundant feldspar and olivine and/or pyroxene phenocrysts are set in a fine groundmass of the same composition (Figure 34a). Most thin sections prepared from the samples of jointed basalt flows of Tb2, display glomeroporphyritic texture where crystal clots of varying sizes composed of plagioclase and /or olivine are found in fine groundmass (Figure 34b)

Occasionally, some phenocrysts define a flow fabric. The crystal phenocrysts of olivine are often altered at their rims and along fractures into iddingsite (Figure 34c). The microfractures intersecting the phenocrysts and the fine groundmass are also observed. They are filled with secondary minerals produced by alteration processes (Figure 34d).

Growth zoning in plagioclase with oscillatory variations in composition characterises is seen in some thin sections of these rocks (Figure 34e). Plagioclase with characteristic simple and lamellar and polysynthetic twins also is observed. Massive basalt in thin section shows trachytic texture or flow structure where the plagioclase phenocrysts are almost parallel in defined direction and embedded in fine-grained ground mass of plagioclase and iron oxides (Figure 35).

The vesicles/amygdales are observed within the trachytic-textured groundmass. The amygdales are filled with glass, chalcedony/quartz, calcite, or zones of quartz-calcite. The volcaniclastics in thin section are often consisting of clasts of trachybasalt cemented by volcanic ashes, iron oxides, malachite, glass or silicates (Figure 36). They contain emptied or filled vesicles and microfractures and veins also filled with secondary minerals.

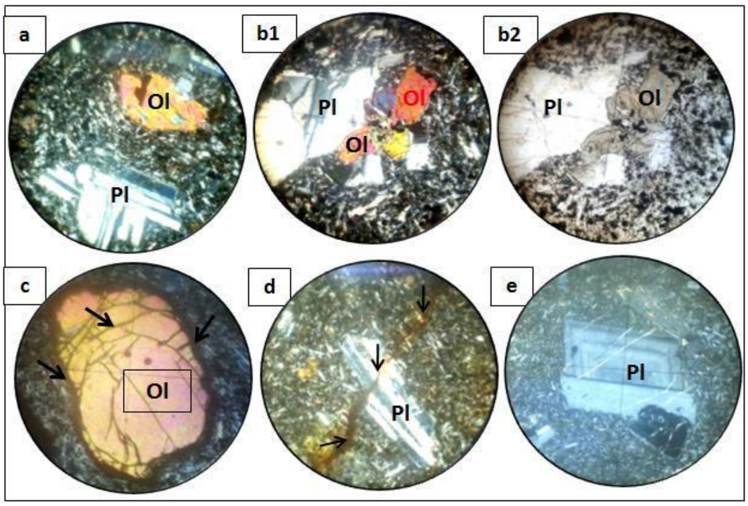


Figure 34: *Photomicrographs of Tertiary jointed basaltic rocks (Tb2); a) Porphyritic texture showing abundant feldspar and olivine phenocrysts in a fine groundmass of the same composition, b) Glomeroporphyritic texture, where crystals clots of different sizes composed of plagioclase and olivine are clustered in fine groundmass (in CPL (b1) and PPL (b2); 10X), c) Alteration of phenocryst olivine into iddingsite at its rims and along fractures (in CPL; 10X), d) Microfracture intersecting plagioclase phenocryst and the fine groundmass (in CPL; 10X) filled with iron oxides and e) Growth zoning in plagioclase with oscillatory variations in composition characterises (in CPL; 3.5 X). (Pl= Plagioclase, Ol= Olivine)*

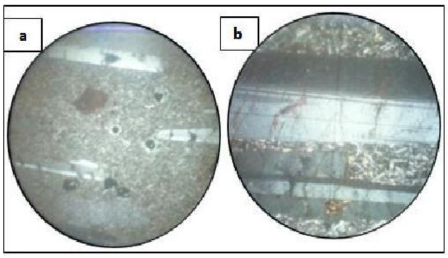


Figure 35: *(a and b) Photomicrographs show trachytic texture (flow structure) of Tertiary massive basalt (Tb2) (CPL; 3.5 X and 10X in respectively)*

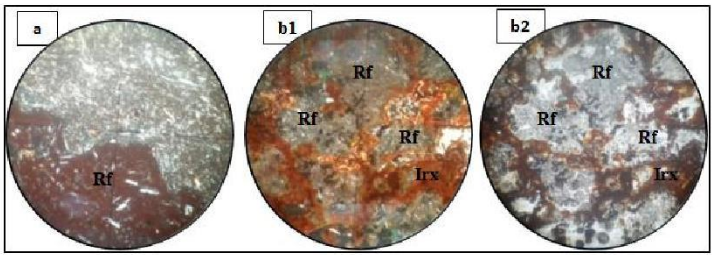


Figure 36: *Photomicrograph of Tertiary basaltic volcaniclastic rock Showing a) Large rock fragment of trachybasalt in volcanic agglomerate (CPL; 10X), (b1 and b2) Rock fragments of trachybasalt cemented by iron oxides and volcanic ashes in basaltic tuff-breccia (in CPL (b1) and PPL;10X). (Rf= Rock fragment, Irx= iron oxides)*

4.4. Tertiary Upper Silicic Sequence Phase (Tr2)

The Oligocene-Miocene upper silicic volcanic rocks (Tr2) are exposed along the northern part of E-W Sabir fault system as isolated domal mountains and plugs of different sizes and shapes. They cover an area of 14.47 sq.km of the total area (10.6%). Tr2 are represented by fine-grained porphyritic, yellow to gray, white, red, green and pink coloured jointed/massive rhyolites/dacites and/ or varicolored volcaniclastics of rhyolitic composition. Here, the volcaniclastic materials are also classified based on their particle sizes (Fisher, 1966; Gillespie and Styles, 1999) into ignimbrites, rhyolitic tuffs, rhyolitic lapilli-tuffs and rhyolitic lapillistones.

The most characteristic feature of Tr2 is its occurrence as alternating sequence of more than one lava flow with lateral and vertical variations as in the case of Tb2. Here, a number of exposures of Tr2 were selected and studied in detail. For example, the exposure of Tr2 sequence, located at Al-Hamseen road consists from the bottom to the top (Figure 37a): (1) white to reddish brown colour, un-welded to semi-welded felsic volcanic accumulated materials, including ash, random pumice and obsidian and lapilli tuff with more than 4.5m thickness. The semi-welded lapilli-tuff is laterally interbedded with un-welded other volcanic components. The lapilli-tuff is lithologically composed of fragments derived from sub-angular to sub-rounded silicic and basic surrounding volcanic rocks. Internal texture of the fragments, generally 2–64 mm in size, is homogenous; e.g. silicic and basic fragments are weak and they have been exposed to the same degree of weathering (Figure 37b), (2) light grey coloured massive welded rhyolitic lapilli-tuff with 0.50-1.6m thickness, (3) light grey to white coloured colonnade columnar jointing rhyolite with 0.60-3.80 m thickness, (4) reddish grey to white coloured massive welded rhyolitic tuff with 2-6 thickness and (5) chocolate colour in outer surfaces to light grey and white in inter surfaces, irregular colonnade columnar jointing rhyolitic lava with thickness ranging between 2-2.60 m. In this site, colonnade columnar jointing rhyolite shows porphyritic texture wherein the phenocrysts of quartz and plagioclase are embedded in altered fine-groundmass of the same composition and clay minerals. The minerals of this rock are highly affected by alteration hence the identifiable minerals for these components remains more difficult (Figure 38).

Reddish brown coloured, slightly weathered columnar ignimbrite bed is crossed by moderately to closely spaced vertical to sub-vertical columnar joints. This is emplaced on volcanic ash and tuff accumulations, with different colours, on the north east of the Al-Kahirah volcanic cone and it dips 42° in NE direction. The volcanic accumulated materials often occur welded by reddish brown to brown and gray coloured iron oxides with sandy size grained texture.

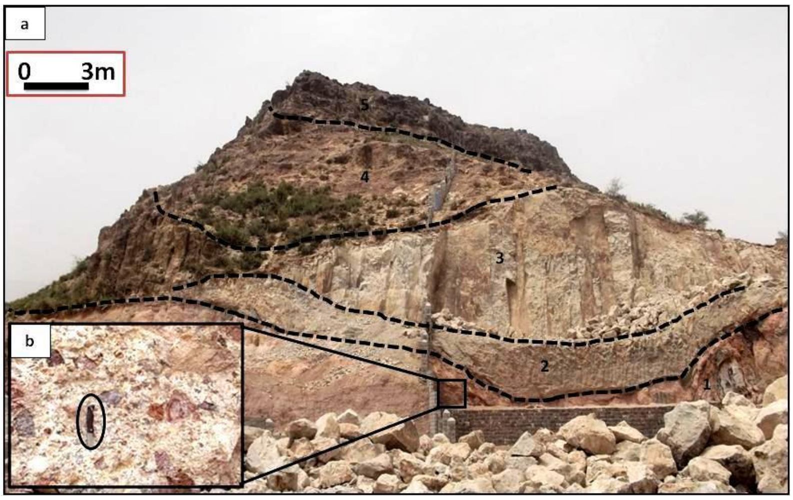


Figure 37: *Outcrop of the Tertiary upper silicic sequence phase (Tr2). Note a) Its occurrence as alternating sequence of more than one lava flow, b) Inset-the lapilli -tuff composed of fragments derived from surrounding sub-angular to sub-rounded silicic and basic volcanic rocks. Knife length 14.6 cm (inside black circle)*

Gabal Amid area located to the north of Taiz university exposes light grey (reddish brown on outer surface) coloured highly jointed voluminous rhyolite /dacite flow over the whitish grey coloured semi-volcanic tuff. In this site, the thickness of flow is various with an average of 7 m. The big blocks are formed by major joints and each block has also minor joints cutting each other thus forming small blocks of different sizes and shapes.

The columnar and tabular block shapes are more frequent. Rocks of this flow show porphyritic texture. Feldspar phenocrysts are fractured and the flow fabric is visualized. These crystals are affected by alteration and some minerals are totally altered into iron oxides. Most of the groundmass is generated from the produce of alteration process.

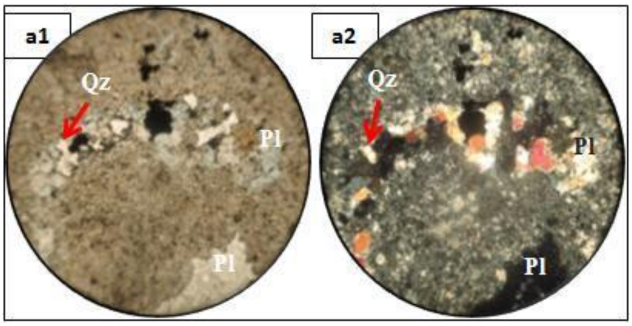


Figure 38: *Photomicrographs of porphyritic texture in columnar jointing rhyolite (Tr2), where the phenocrysts of quartz and plagioclase are embedded in altered fine-groundmass of the same composition and clay minerals (in PPL (a1) and CPL (a2); 10X), (Pl=Plagioclase, Qz= Quartz)*

The Tr2 sequence found at 0.5 km south of Al-Qurayn village, south east of the study area consists of the following sequence from bottom to the top (Figure 39a): (1) whitish grey coloured, massive, friable rhyolitic tuff with thickness exceeding more than 3m (Figure 39b).

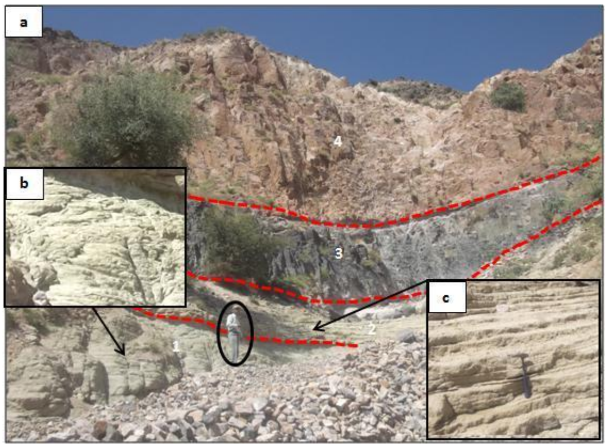


Figure 39: *Field photo of the Tertiary upper silicic sequence (Tr2) (a) near south of Al-Qurayn village, south east of the study area displaying massive, friable rhyolitic tuff (b), Tabular, saccharoidal textured rhyolitic tuff* (c) and the black coloured volcanic flow (layer3) represented by Pitchstone overlaid by columnar rhyolite (layer 4). Hammer length 32.5 cm.

This layer overlies Tb2 as observed in the surrounding region of the study area, (2) light greenish grey coloured, tabular, sand size grained texture, 1.40m thickness coarse rhyolitic tuff (Figure 39c). The most grain sizes are between 2 mm and 1/16 mm. The clasts composited of basic rocks with size more than 2mm are also found. Microscopically, it consists of quartz grains, k-feldspar and rock fragments. The matrix is composed of glassy and iron oxide minerals (Figure 40), (3) black to dark grey coloured fractured pitchstone with 3.5m thickness in this part and extended to more than 0.5 km and becomes obscured in the north east of this exposure. Microscopically, it shows perlitic fractures in the matrix of the glassy material (Figure 41). Other components are k-feldspar and sanidine, and (4) reddish brown (light grey inner) coloured, sub-vertical irregular columnar rhyolite. Folded flow bands in rhyolite are observed in this rock type.

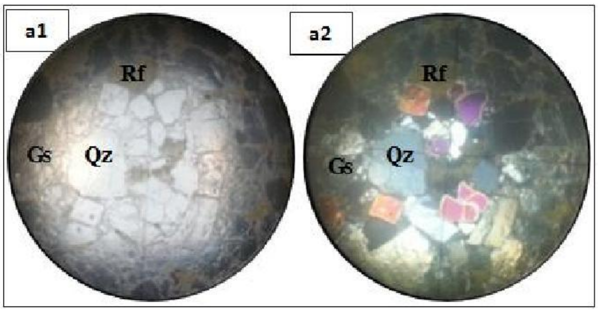


Figure 40: *Photomicrograph of tabular, saccharoidal texture, coarse rhyolitic tuff consisting of quartz grains, k-feldspar and rock fragments. The matrix is composed of glassy and iron oxide minerals. (PPL (a1) and CPL (a2); 3.5X). (Gs=Glass, Qz= Quartz, Rf=Rock fragment)*

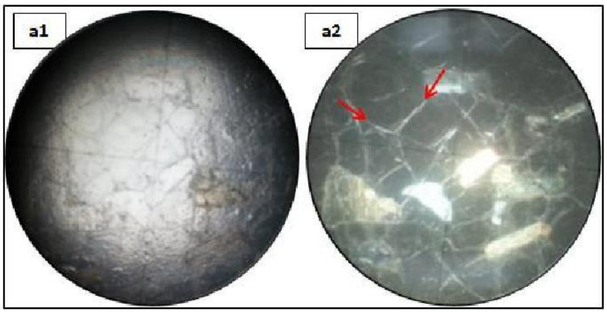


Figure 41: *Photomicrograph of the volcanic pitchstone showing perlitic fractures (red arrows) in the matrix of the glassy material. (in PPL (a1) and CPL (a2); 3.5X)*

In Jabal Zanikh located west Al-Kharabah village, the Tr2 flow is represented by light grey coloured rhyolite/dacite as big blocks of sub-vertical columns and exhibit more resistance for weathering forming ridges and steep slopes. In some parts of this exposure, the rhyolite/ dacite of Tr2 appears laterally change into white to reddish grey coloured, massive ignimbrite, while in other parts, some blocks of rhyolite/ dacite are unstable due to their occurrence over relatively weak, tabulated volcanic tuff. In hand specimen, this rock shows porphyritic texture, where feldspar phenocrysts are embedded in fine-grained groundmass. The small vesicles (not exceeding 7mm) are filled with secondary minerals. In most places, especially near fault zones the fractures developed in these rocks are stained by iron oxides generated by the dissolution of Fe and Mg bearing silicates (Figure 42). Folded flow bands in rhyolite were also observed (Figure 43).

Tr2 flows appear as light grey to reddish grey coloured, porphyritic columnar rhyolite in the south east of medical College, Al-Habil area (Figure 44a). Microscopically, it shows porphyritic texture and consists of phenocrysts of quartz and k-feldspar which are clustered to show glomeroporphyritic texture (Figure 44b). The groundmass is glassy, opaque and mainly composed of fine k-feldspars and quartz. The microfractures filled with iron oxides and called as transgranular fractures are travelling through some grains and groundmass (Figure 44c).

The vesicles filled with minerals (glass and calcite) are also seen. In the upper wadi Hasanat, south of the study area, the greenish grey to white colour rhyolite occurs overlying thin layer (average thickness 70 cm) of grey volcanic soil found over the thick layer of black to dark grey colour volcanic pitchstone.

Figure 42: *Permeation of Mg- and Fe- bearing solutions through fractures developed in Tr2 sequence of rocks. Pen length 16.7 cm (inside white circle)*

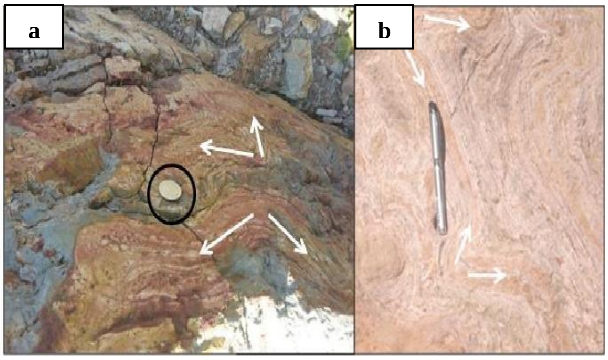
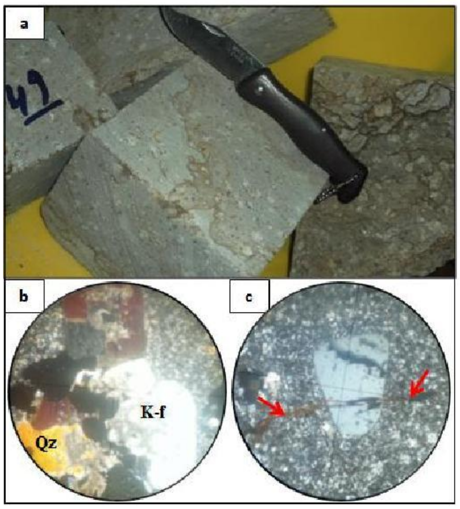


Figure 43: *(a & b) Folded flow bands in Tertiary rhyolitic lava flows (Tr2). Pen length 14 cm. Coin diameter 3.1*

The pitchstone contains inclusions of basic and acidic xenoliths from the neighboring country rocks and also crossed by basic dyke trending S60°E. Whole sequence of Tr2 in this location is dipped 41° SW. This sequence is laterally changed into light grey bedded semi-welded to welded volcaniclastics; this clearly appears in the east side of the investigated exposure. Microscopically, the rhyolite flow shows micrographic texture in granophyres, where crystal intergrowth is between quartz and k-feldspar (Figure 45a). The radiate intergrowths of quartz and k- feldspar is also seen, where these components are arranged about euhedral, equant plagioclase crystals (Figure 45b).



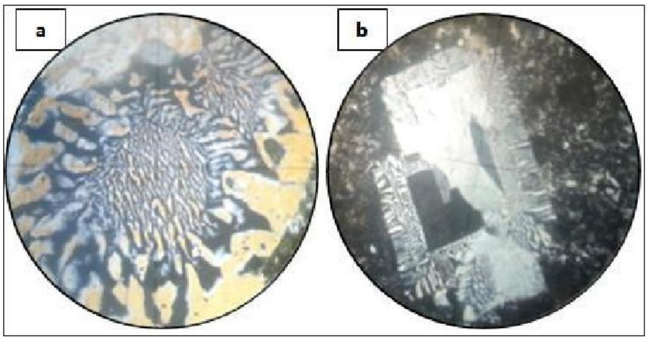


Figure 45: *a) Micrographic texture in granophyres in the Tertiary rhyolitic flow. Note the crystal intergrowth between quartz and k-feldspar. (in CPL; 10X), b) The radiate intergrowths of quartz and k-feldspar are arranged about euhedral, equant plagioclase crystals (in CPL; 10X)*

Figure 44: *Fe-oxide stained Tertiary columnar rhyolite (Tr2) showing porphyritic texture (a), and is composed of phenocrysts of quartz and k-feldspar that are clustered to form glomeroporphyritic texture (b in CPL; 10X) and (c) The transgranular microfractures filled with iron oxides (in CPL; 10X). (K-f=K-feldspar, Qz= Quartz). Knife length 14.6 cm*

The pitchstone in thin section shows hypocrystalline with perlitic cracks. The crystals of quartz, biotite and magnetite are embedded in glass which has spherical fractures and appear as circles. In Thabat area, at the north foot of Sabir mountain, white to chocolate colour, massive rhyolite appears overlaying the white welded rhyolitic tuff. It forms steep slope and hazardous zone dipping 46° to the NW. The welded rhyolitic tuff is massive and shows laminated structure vertically in some parts. This tuff laterally changes to light greenish grey, massive, weak rhyolitic lapilli-tuff with thickness more than 10 m (Figure 46). In the later, the basic clasts are cemented by volcanic ashes. In its upper part, the semi-stabled granitic blocks which have been rolled from Sabir Mountain are found.

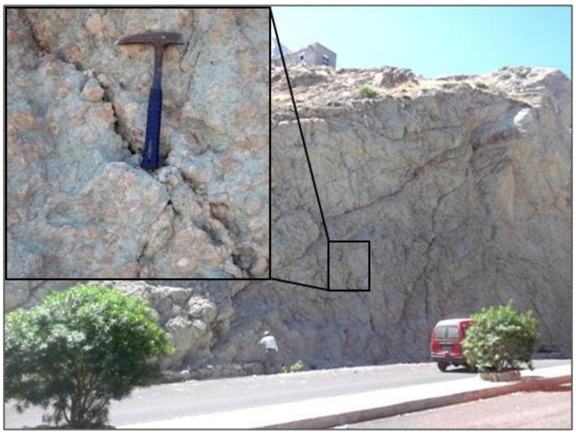


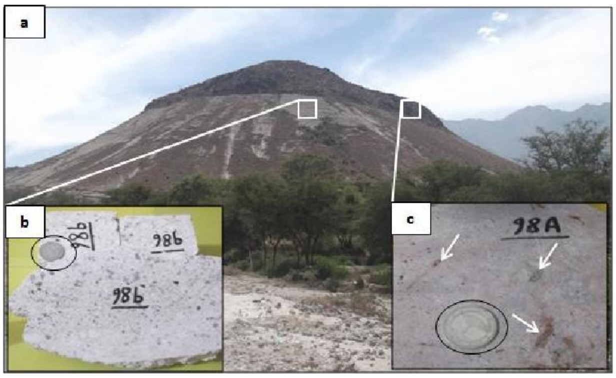
Figure 46: *Shows Tertiary rhyolitic lapilli-tuff of Tr2, Thabat area, south of Taiz city. Hammer length 32.5 cm*

This location represents the northern fault contact zone which is called as Sabir fault system trending E-W and separates the Jabal Sabir granitic mass from the surrounding Tertiary stratified volcanic rocks (see Figure 2). The reddish brown rhyolitic lava flows at Adanah village, to the south east of the study area occur as cap above white welded rhyolitic lapilli-tuff conical hill with slopes having dip angles ranging between 31° and 47° and thickness more than 60m (Figure 47a & b). This feature is also observed in several places at Adanah village. Macroscopically, in the hand specimens of Tr2 flow, the small vesicles are seen; some of them are found as having replaced other minerals (quartz or iron oxides) due to hydrothermal alteration while some other are empty (Figure 47c). Microscopically, the thin section of the rhyolitic lava flow-Tr2 shows vitrophyric and spherulitic textures (Figure 48). It is composed of phenocrysts of plagioclase, quartz, volcanic glass and opaque. These components are assembled in glassy groundmass. Also, the microfractures and vesicles are filled with quartz, glass or/and iron oxides.

The white welded rhyolitic lapilli-tuff forming the lower part of this sequence is composed of angular to sub-angular volcanic clasts of basic rocks and black volcanic obsidian embedded in volcanic ash (Figure 49a). In this location, welded rhyolitic lapilli-tuff appears in massive state, with scare joints, appearing as homogenous deposit, while at other places, lapilli-tuff occurs as bedded layers (Figure 49b).

At places, the lapilli-tuff/ignimbrite is reddish brown in colour and contains some fragments which are fattened and stretched forming so-called fiammes. Often it contains rectangular shaped vugs which reach up to 4cm in diameter filled with yellowish white coloured friable powdery material as seen in hand specimens. In some sites, the rhyolitic rocks occur as separated blocks forming instability zones on slope sides. They also exhibit variation in colour from chocolate on outer surfaces to white colour on the inner surfaces. These rocks are brittle, with rough outer surfaces. In the hand specimens of the rhyolitic rocks, some features like corrosion, macrofractures and alteration are observed. Generally, the rhyolitic tuffs display also lateral changes in their colour (creamy-white, whitish grey, yellowish grey and reddish brown), grain size, structure and hardness due to the changes in their components and the conditions of environmental deposition.

The rhyolitic tuffs form the middle or bottom of the Tr2 sequence in the most the investigated exposures and overlain by lava flows of rhyolitic/dacitic composition.



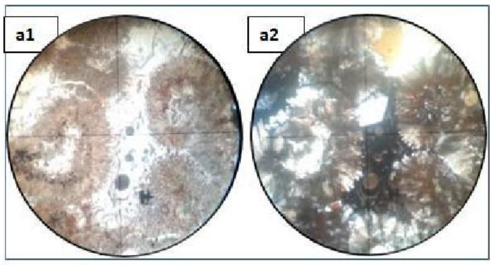


Figure 48: *Photomicrographs showing spherulitic texture exhibited by rhyolitic lava flow in PPL (a1) and CPL (a2): X3.5*

Figure 47: *a) Tertiary rhyolitic lava flows (Tr2), near Adanah village, to the south east of the study area consisting welded rhyolitic lapilli-tuff at the bottom (b) overlaid by rhyolitic flow containing small vesicles some of which emptied (white arrows in c). Coin diameter 3.1 cm*

Figure 49: a) Welded massive rhyolitic lapilli-tuff forming the lower part of the Tr2 sequence. Note angular to sub-angular volcanic clasts of basic rocks and obsidian (red arrows) embedded in volcanic ash; b) the rhyolitic tuff occurrence as bedded layers, near Al-Lasab village, south east of Taiz city.

In south face of Gabal Al-Darbah, Al-Masbah area located in Taiz city, the welded rhyolitic tuff (grains size is <2mm) appears as big blocks separated by sub-vertical discontinuities and emplaced on white, reddish brown and dark grey un-welded to semi-welded volcaniclastic deposits. In the lower volcaniclastics, very weakly cemented coarse grains of quartz mineral are aggregated formed friable layer in some zones. They are also occurred alternating with thin layers formed of sandy grain size of volcanic material in other parts (Figure 50a & b). This weak layer nearly extended horizontal formed unstable base and actually hazardous zone due to the nature this layer and the poor and unplanned construction on it (Figure 50c). The basic clasts and obsidian are also observed in volcaniclastics. In other locations, the welded rhyolitic tuffs display folded structures (Figure 51) and cavities with <10cm up to more than 7m in diameter (Figure 52).

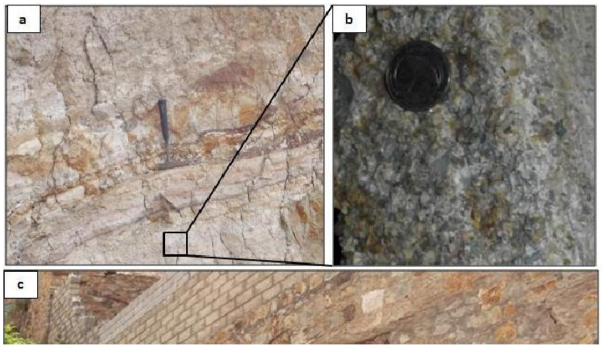


Figure 50: *Field photos showing un-welded to semi-welded volcaniclastic deposits (a) with a friable zone consisting dominantly quartz (b). This zone extends into human settlement area (c) causing instability to the civil structures*

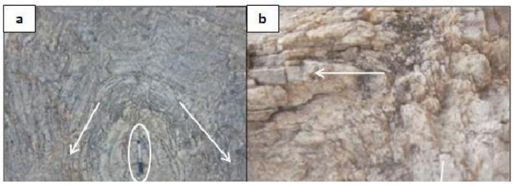


Figure 51: *(a, b) Folded structures in the welded rhyolitic tuffs belonging to Tr2. The pen length 14.3 and Coin diameter 3.1 cm*

In thin section, they show porphyritic rhyolitic texture where feldspar, quartz, subhedral biotite phenocrysts and iron oxides are embedded in the fine groundmass with same composition. Microfractures filled with iron oxides are seen and also vesicles/amygdales emptied or filled with minerals are observed. The flow structure was also seen.

Megascopically, the small vesicles commonly are observed on the surfaces of cut samples of rhyolitic volcaniclastic rocks, some of them are emptied and other are filled with white minerals (such as carbonate, glass, iron oxides minerals). These minerals can be/or cannot be peeled with a pocketknife such as sample 47p1 (Figure 53a) and sample 23 respectively (Figure 53b).

In places, the rhyolitic tuff is light greenish yellow to white grey in colour. It contains on crystals of quartz mineral in sandy grains size, and black, grey, light yellow rock fragments. The tuff in the block sample appears white or grey to white on the outer surface or brown material as stain, while on the fresh cut sample is white in colour. In other sites, the tuff appears the flow-structures composed from alternating bands of hard brown flows with relatively weak white detritus flows (Figure 54). These layers are intervened by friable brown dust material or emptied voids. Bands can be from few mms to 3 cm thick. In some places, the tuff appears as light reddish brown, massive blocks, compacted with grain sizes ranging between 2 to 64mm, corresponding to lapilli-tuff size. Black to dark grey sub-angler to sub-round clasts of basaltic rocks with diameters > 64 mm were also observed. The cavities with different sizes are found, particularly at the bottom of these blocks formed high potential of collapse hazard zone, especially, the blocks separated by discontinuities.

In thin section, rhyolitic tuff shows the pyroclastic texture, where it consists of basic rock fragments and shards of glass. The vesicles filled with minerals were also seen. The tuff can be contains different sizes of volcanic rock clasts such as lithic rhyolite /dacite and basalt; this indicating to the violent explosive nature of the felsic volcanism as observed that in wadi Al-Qadhi (Figure 55).

Figure 52: *(a, b) The cavernous structure developed in welded rhyolitic tuffs of Tr2. Hammer length 32.5 cm*

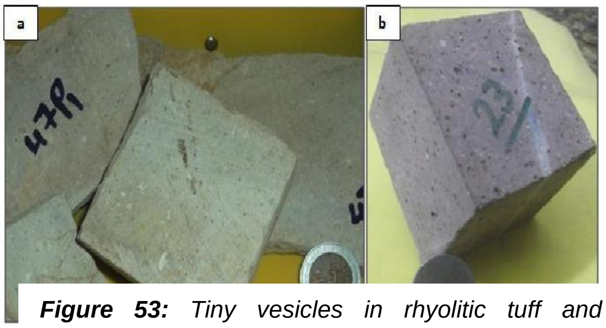


Figure 53: *Tiny vesicles in rhyolitic tuff and ignimbrite in respectively are filled with (a) white minerals which can be peeled with a pocketknife and (b) iron oxides minerals which cannot be peeled with a pocketknife. Coin diameters are 3.1 cm and 2.6 cm respectively*

The white rhyolitic tuff is exposed with average thickness more than 15 m in the north Hasanat, overlain by rhyolitic lava flow. Generally this tuff is welded, massive but may be contains on parts are either laminated (thickness <50cm) or have irregular joint systems. The block sample of this tuff is exhibited intact but after cut it; the macrofractures may be seen in its inner (Figure 56).

From alteration point of view, the effect of hydrothermal solutions on the joint surfaces is almost very less; this generally indicates that effect near the Sabir fault system or other fault systems is more and decreasing with increasing the distance far from those faults. Microscopically, the thin section of welded rhyolitic tuff reveals that sample primarily consists of plagioclase phenocrysts, quartz crystals and opaques embedded in highly altered fine grained groundmass.

Figure 54: *The flow-structures in rhyolitic tuff showing alternate bands of hard brown flows with relatively weak white detritus. Hammer length 32.5 cm. The pen length 14.3*

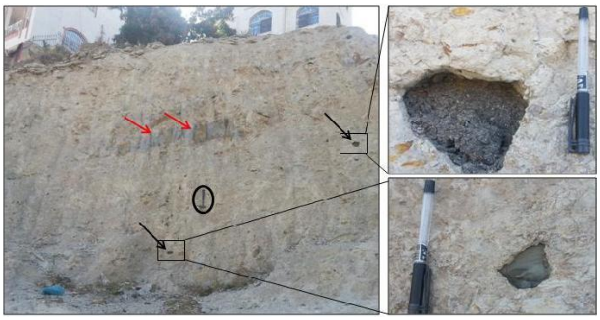


Figure 55: *Different sized volcanic rock clasts of rhyolite (red arrows) and basalt/andesite rocks (black arrows), in the Tertiary rhyolitic tuff (Tr2). The pen length 14.3*

The radiate intergrowths of quartz and k-feldspar are arranged about euhedral plagioclase crystals formed the granophyric texture. These textures are commonly observed in the rhyolite and rhyolitic tuffs belonged to Tr2. The pyroclasts-poor rhyolite is characterized by abundant feldspar and quartz phenocrysts in fine - grained matrix in comparison to pyroclasts-rich rhyolite (Malik, 2014).

Figure 56: *Macrofractures inside of the cut block sample of Tertiary rhyolitic tuff (Tr2) of Thabat area, south of Taiz city. Coin diameter 2.2 cm*

The effect of the weathering condition on Tr2 rocks is more clear through forms a number of accentuated ridges and knobs of pyroclasts-poor rhyolite and exhibiting cavities and spheroidal features which are observed in Gabal Al-Birarah, Madinat Al-Noor, wadi Al-Dehi and Gabal Al-Kahirah Castle.

4.5. Tertiary Upper Mafic Sequence Phase (Tb3)

The Tb3 represents the youngest and the uppermost lithological unit of Tertiary volcanic rocks which are confinedly exposed to the south eastern part, outside of the studied area. This sequence is erupted through re - novation of the old faults and fractures, mainly those in the NE-SW direction (DEY, 1997). It mostly comprises on compact basaltic lava flows, but also includes intercalated andesite, mafic conglomerate, tuff layers and red and white ash. It occurs as dykes and sills intruded into the various Tertiary rocks (e.g. volcanic rocks and granite intrusions). Microscopic observations show that most of the Tb3 are fine grained, nonporphyritic and rarely contains plagioclase phenocrysts (Malek et al., 2014).

4.6. Volcanic Soils

In Taiz area, Tertiary volcanic units are underlain or intercalated with varicoloured semi-unconsolidated accumulated volcanic materials. The powder X-ray diffraction (XRD) studies on volcanic ash (volcanic soils) reveal sharply defined reflections (Figures 57-60). The mineralogical search carried out by adopting the standard procedure revealed that clay minerals namely montmorillonite and kaolinite as the major mineral phase in most of the samples with minor amounts of mica group of minerals such as muscovite, vermiculite and chlorite, in addition to talc, feldspar, calcite and halloysite. Quartz is present in almost all the soil samples.

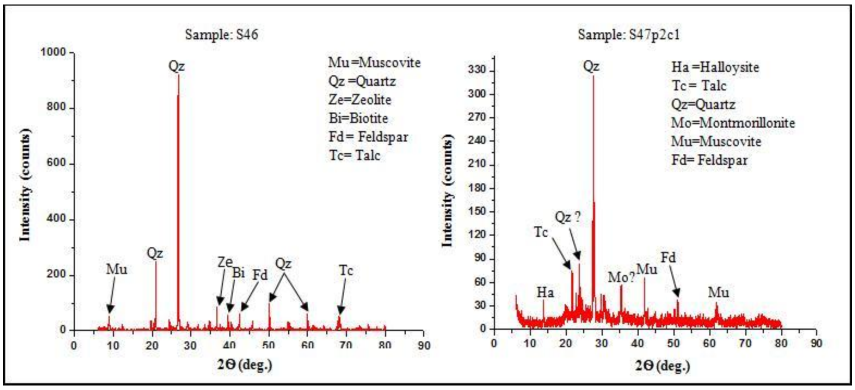


Figure 58: *XRD patterns of S46 and S47p2c1volcanic soil samples*

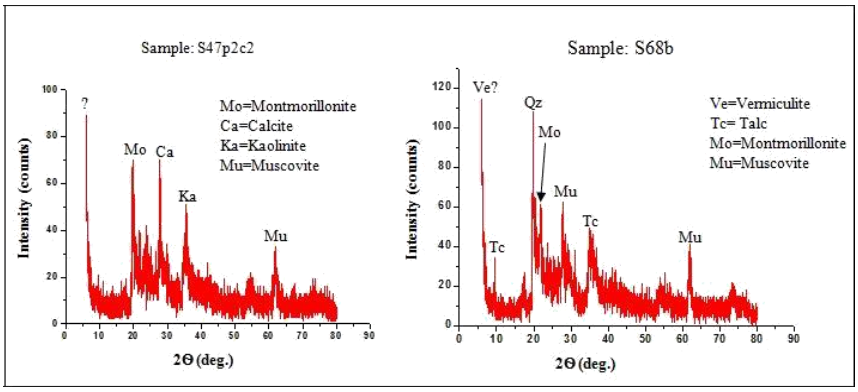


Figure 59: *XRD patterns of two volcanic soil samples (S47p2c2 and S68b)*

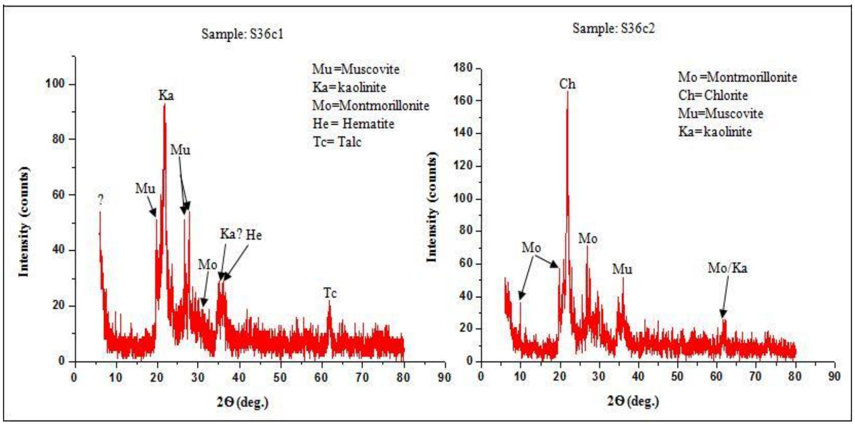


Figure 57: *XRD patterns of two volcanic soil samples (S36c1, S36c2)*

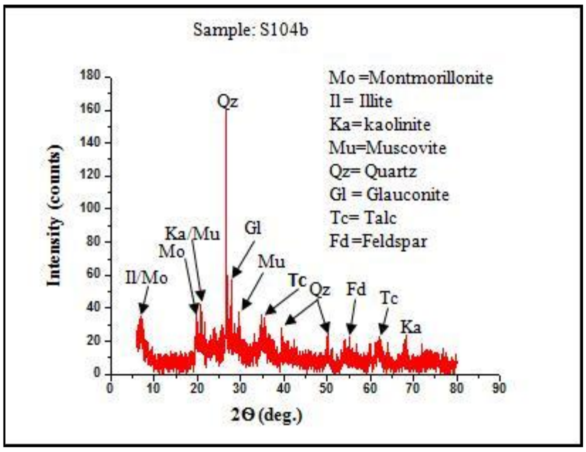


Figure 60: *XRD pattern of S104b volcanic soil sample*

4.7. Younger Intrusives

Sabir Granitic Pluton

Jabal Sabir granite body dated to Miocene age (Shaalan and Zalata, 1983) is one of the Tertiary intrusive bodies exposed in various locations, especially in the south and along the western escarpment slopes of Yemen highlands, parallel nearly to the general trend of the Red Sea. The Jabal Sabir granite is emplaced as laccolithic body inside the older stratified Tertiary Yemen volcanic rocks, forming the dominant morphological feature (Sabir Mountain) overlooking the city of Taiz in the southern part of the study area (see Figure 2). It is characterized by high lands, steep slopes and deep valleys. Physical weathering of varying intensities has produced different sizes of granitic blocks and boulders along the slope sides. At places deep valleys have been filled by the granitic boulders. The waterfalls and channels are the dominant features in the Sabir area. Tertiary granite contacts with the surrounding Tertiary volcanic rocks covered by the Quaternary deposits are although sharp, it is distinct in some places. Along northern contact, the fault breccia is observed. It is composed of angular to sub-angular and sub-rounded blocks of basic and granitic clasts which are cemented by carbonate material (Figure 61).

The Tertiary granitic masses consist mainly of alkaline or peralkaline granite, white to greyish white coloured, massive, medium to coarse-grained with grading up to granite porphyry and almost < 5% of dark minerals. They belong to the alkaline or peralkaline suite of A-type granites (El-Gharbawy, 2011). These are produced by fractional crystallization in the basic magmas (Capaldi et al., 1987; Chazot and Bertrand, 1995).

Microscopic studies of Sabir granitic rocks reveal that the main rock forming minerals are k-feldspar (orthoclase, perthite, and perthitic microcline), quartz, hornblende and biotite with accessory minerals zircon and other opaque minerals (Figure 62a). K-feldspars are the most common and occur as subhedral to lath-shaped crystals. It shows narrow lamellae of albite forming a braided pattern in an orthoclase host. In some thin sections, the microperthitic texture is observed (Figure 62a &b).

The micrographic texture is also seen where the intergrowth is between quartz and plagioclase minerals. Quartz appears as anhedral to subangular grains.

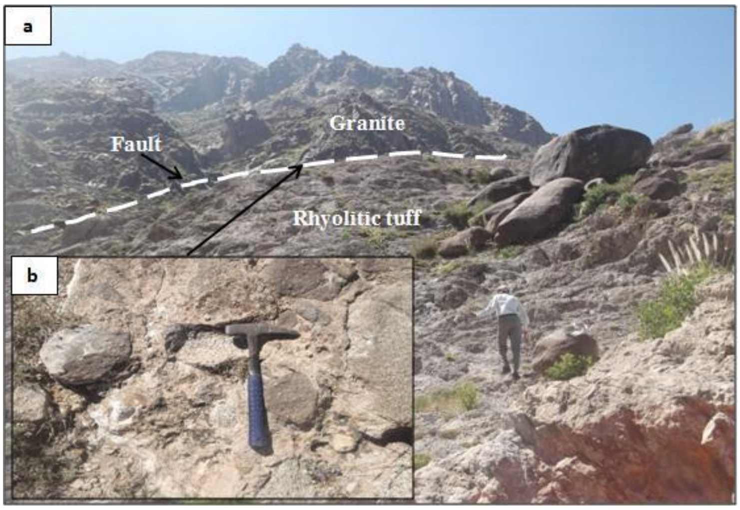


Figure 61: *(a) Field photo shows part of the E-W Sabir fault system along the northern contact between Tertiary Sabir granite and the surrounding Tertiary volcanic rocks (Tr2) and (b) The occurrence of fault breccia composed of angular to sub-angular and sub-round rock fragments of basic and granitic clasts which are cemented by carbonate material, Hammer length 32.5 cm.*

In some thin section, interlocked aggregations of quartz grains, biotite, hornblende crystals and opaque minerals are seen. Most of the feldspar and quartz crystals are large in size. This is characteristic of almost all the different granitic samples. Biotite is less common and present as subhedral to anhedral grains and shows pale to dark brown pleochroism.

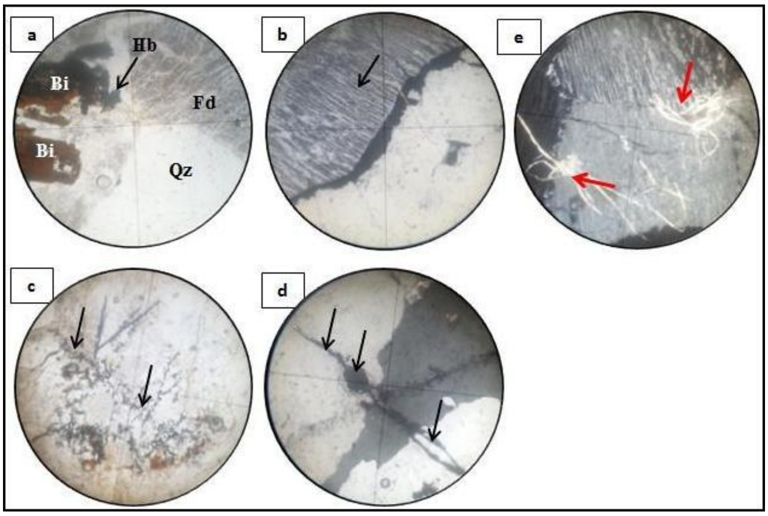


Figure 62: *Photomicrographs of Sabir granitic rock (a) containing k-feldspar(Fd), quartz (Qz), hornblende (Hb) and biotite (Bi) with opaque minerals under plane polarised, 10X, (b) showing microperthitic texture, under crossed nicol, 10X, and microfractures, veins and cavities that are filled with calcite and iron oxides (c, d) under crossed nicol 10X. The microviens are filled with calcite (red arrows) under crossed nicol (e) 10X*

Usually, it occurs as elongated irregular skeleton and contains small inclusions of quartz grains. Locally, the biotite crystals are partly magmatically corroded. In some thin sections, the muscovite has also been seen.

The zircons are present in some thin sections, occurring as rounded grains. Generally, Sabir granitic rock samples in these sections are characterized by microfractures, veins and cavities that are nearly filled with minerals especially calcite, iron oxides and quartz (Figure 62c & d). The microveins are filled with calcite and are seen almost in all the thin sections (Figure 62e). The granite (syenite) hand specimens taken from Thabat area appear to be relatively coarser than some of the other samples. Granite of this area is characterized by coarse grained texture with phenocrysts of white plagioclase and quartz.

Individual grains of both the plagioclase and quartz measure a length of about 2cm. Biotite and hornblende grains are visible to the naked-eye in the hand specimens (Fig.63a). The miarolitic cavities occupied by euhedral crystals of quartz, alkali feldspar and chalcedony are also found in hand specimens of granite (Figure 63b).

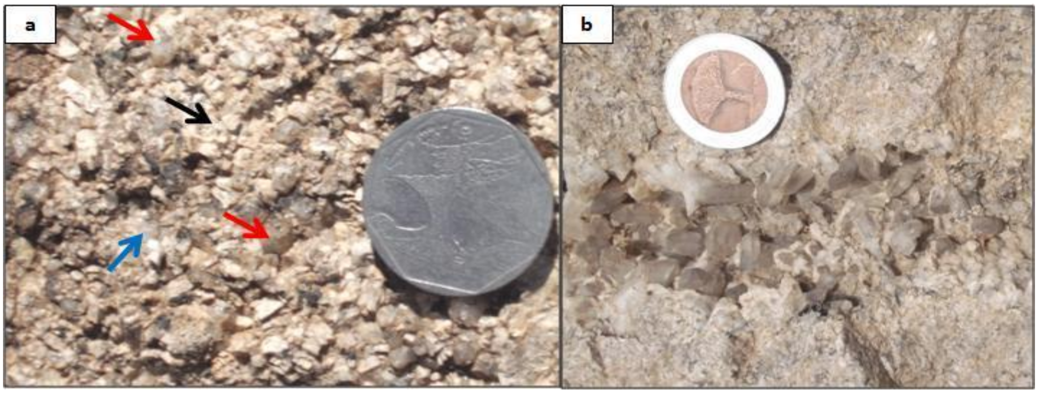


Figure 63: *Coarse grained texture with phenocrysts of white plagioclase (black arrow) and quartz (red arrows) with lengths up to 2cm and 2.1cm, respectively in the granite hand specimen (a) (Coin diameter 2.6 cm). Note the biotite is also observed (blue arrow) and the miarolitic cavity occupied by euhedral crystals of quartz, alkali feldspar and chalcedony in hand specimen (b) miarolitic cavities occupied by euhedral crystals of quartz, alkali feldspar and chalcedony, Sabir granite. Diameter of coin is 3.1cm*

Megascopically, biotite is the main ferromagnesian mineral. Microscopically, the syenite samples are characterized by myrmekitic texture (intergrowth texture) where intergrowth is seen between quartz and plagioclase. This forms embayments in the microcline crystal. Generally, the granitic rocks are easily identifiable in the study area by their macro features such as texture in situ, structure, joint discontinuities and degree of weathering. The texture varies from medium to coarse-grained and often graded up to granite porphyry. In the hand specimens the pinholes (<1mm to 1cm in diameters) are observed; some of them are empty and others are filled with secondary minerals.

In places, the granite appears as beds alternating with basic dykes or layers of same composition (Figure 64). In other sites, these beds of granite appear slightly deformed wherein cataclinal joints have developed well and granitic body is altered, especially near the dykes (Figure 65). Granites are disjointed, which occur either as systematic sets of joints or occur randomly. The orientation of these discontinuities with different spacing, are planar and curved. In each investigated site, the discontinuities display various geometrical relationships to each other. These relationships define the size and shape of the blocks formed between those discontinuities. The discontinuities in the granitic blocks have produced different sizes and shapes including triangular and rectangular blocks as seen in the north of Al-Mihal village (Figure 66a).

Granite occurring in the form of domes show pile of disjointed boulders and have suffered intense alteration along the fractures resulting in the oblate form of the boulders (Figure 66b). Here the effect of the weathering doesn't extend into the rock but is restricted to the surface. However, brown coloured coatings due to iron oxide has extended into the inner parts of the rock along the fractures and weak planes Figure (67a &b). The effect of this phenomenon has reduced the strength of the rocks (Figure 67c). Granites contain xenoliths of various rocks as seen in different locations (Figure 68).

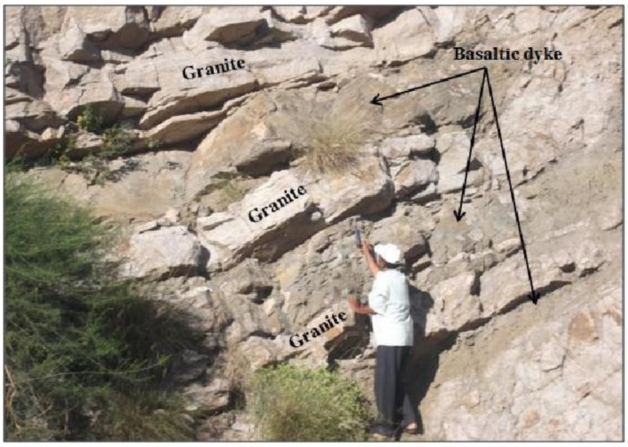


Figure 64: *Granite showing cataclinal joints and alternated with basic dykes or layers of same composition, east of Dar Al-Nasr, Sabir area. Hammer length 32.5 cm*

Figure 65: *Granite exposed as slightly deformed layers which may be caused by intrusion of the basic dyke through them (red arrow). Note highly alteration of granite near the basic dyke*

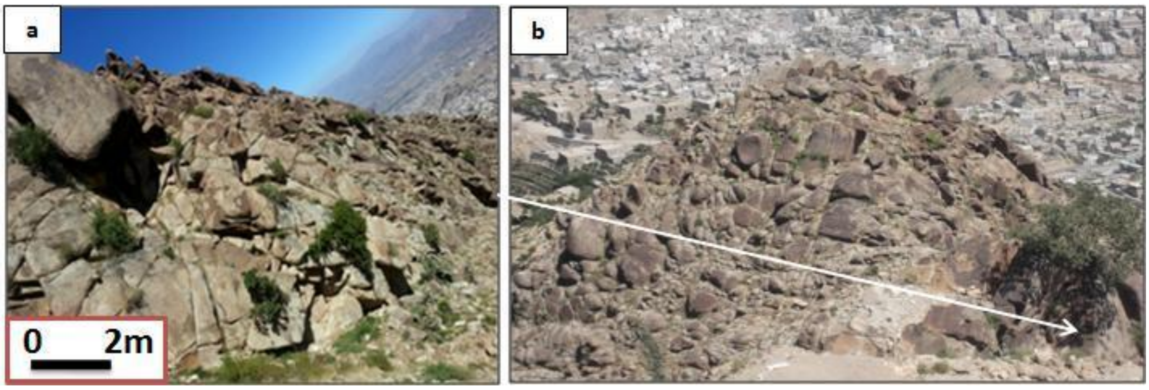


Figure 66: *(a) Shows the variation in the sizes and shapes of granitic blocks formed by discontinuities and (b) Dome formed of granitic boulders of granite. Note concentration of weathering processes along the fractures and eliminating the block edges, north of Al-Mihal village, Sabir area.*

The abundance of xenoliths from the neighbouring country rocks and porphyritic texture of the Jabal Sabir granite body indicate shallow depths of intrusion (El-Gharbawy, 2011). Generally, granites are almost affected by all weathering grades e.g. from fresh weathering to complete weathering (Figure 69). The spherical and cavernous weathering is one of characteristic features of Sabir granitic rocks. The caverns with various sizes and shapes were observed in different locations. They have spherical or elliptical shapes, arched-shaped entrances, concave inner walls, overhanging edges and gently sloping-covered floors (Figure 70).

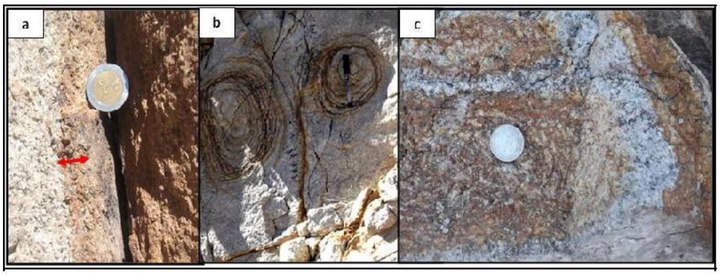


Figure 67: *Photographs showing the effect of weathering/ alteration on granite in Sabir area; (a) The effect is restricted to the surface of granitic rock (diameter of coin is 3.1cm), (b) The extension of iron oxide solutions effect into interior of rock. Note the whirling paths for the injected iron oxide solutions through fractures and weak parts of rock (pen length 14.3cm) and (c) The strength and hardness of granitic rock is reduced by alteration caused by hydrothermal solutions. Diameter of coin is 2.6cm*

Figure 68: *Xenolith of basalt in granite rock exposed in the north west of Zaid's Hotel, Sabir area. Pen length 14.3 cm*

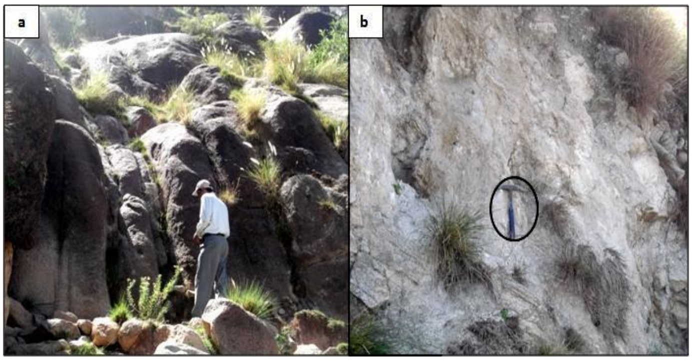


Figure 69: *Weathering grades in granite; (a) Fresh granite, in Salah area and (b) Highly weathered granite at the foot of the Gabal Sabir, near Al Damkha area. Hammer length 32.5 cm*

Figure 70: *Field photograph shows the spherical and cavernous weathering on Sabir granitic rocks*

4.8. Mafic and Felsic Dyke and Sill Intrusions

Numerous basic and felsic dykes cut through the concordant and discordant bodies represented respectively by flows (basalts, rhyolites/dacites and volcaniclastic deposits) and Sabir granitic pluton. These are injected during different volcanic phases and along fault trends, the majority of them trend in the NW-SE and NE-SW directions, and few in the E-W direction. The dykes with basic composition are more predominant than acidic dykes in the study area (Al-Qadhi, 2007). The basic and felsic dykes show resemblance to basalts and rhyolites/dacites respectively in their petrographical characteristics. In some places, the dykes followed Tr2 form i.e., occur in the form of blocky ridges, often rising more than 10m above the surrounding landscape and with an areal extent of more than 8 km in length. For example, a large NE-SW dacitic dyke located at Al-Sufi village, Al-Hawban area is seen like a pillar as it has been left standing after softer Tb2 country rock eroded away. It is well jointed and appears as bedded layers.

The dyke contains cavities of various sizes and shapes and these are concentrated along bedding planes (weak planes) (Figure 71a). Microscopically, the dyke rock shows porphyritic texture where feldspar and quartz phenocrysts are embedded in holocrystalline groundmasses of same composition and opaques. Opaque minerals in matrix are altered to hydrous Fe-oxides (Figure 71b).

In the most investigated exposures (in more than 10 stations) especially along Al-Steen and A-Hamseen roads, the younger dykes are characterised by fractures and/or features of weathering/alteration, particularly the basic types. In some places the dykes of basalt have been weathered to form trenches (Figure 72a). The composite basic dykes were also observed in the Wadi Al-Malih and west of Nashit village, located in the northern part of the study area (Figure 72b).

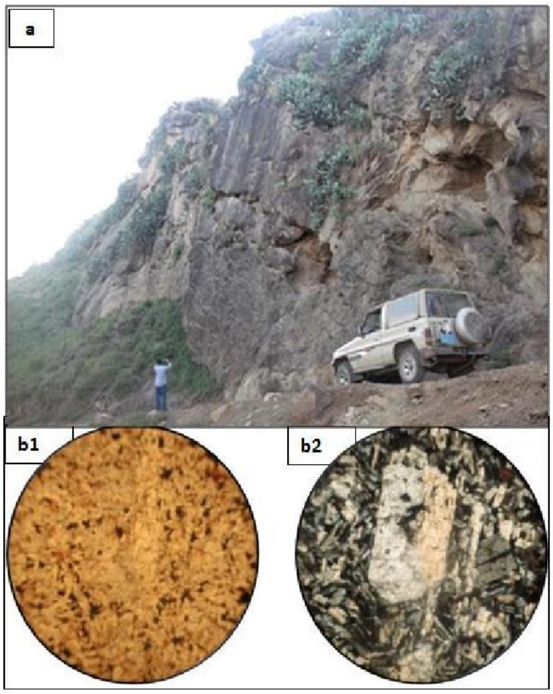


Figure 71: *(a) Large NE-SW trending dacitic dyke intruded through Tertiary basaltic rocks (Tb2) and forms prominent, blocky ridge, rising more than 10m above the surrounding landscape, near Al-Sufi village, Al-Hawban area and (b) The porphyritic texture in dacitic dyke, where feldspar and quartz phenocrysts are embedded in holocrystalline groundmasses. (in PPL (b1) and CPL (b2) 3.5X)*

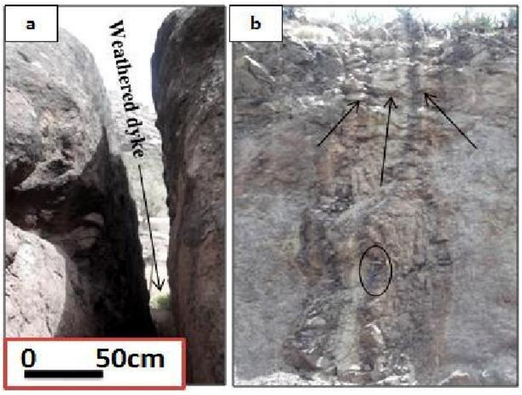


Figure 72: *(a) Trench formed by the weathering of basaltic dyke intruded into basaltic lapilli-tuff, Al-Saeed quarter, Al-Hawban area and (b) Composite basic dyke, west of Nashit village, north of the study area. Hammer length 32.5 cm*

Some dykes with fault displacement were found in granite (Figure 73). The sills are also observed in many location and these are injected through feeder like dykes.

Figure 73: *Basic dyke cut the highly weathered granite of Sabir, displaced by small normal fault, east of Al-mihwar village, Sabir area. Hammer length 32.5 cm*

5. Summary and Conclusions

Taiz city and its surrounding areas in Yemen are largely covered with product of the Tertiary magmatism comprising typical bimodal mafic-felsic associations and are represented by flows, plutons, dykes and volcaniclastic deposits of variable composition. The magmatism is related to the continental rifting and break up processes associated with Afar mantle plume. All lava flow sequences are believed to be extruded and fed from fracturing and fissuring in the old rocks through which magma emerged in successive pulses, flooding the surrounding region. The occurrence of the Tertiary volcanic rocks as bimodal mafic- felsic with alternating sequences (Tb1, Tr1, Tb2, Tr2 and Tb3) and with distinctive lithological and stratigraphic characteristics and separated from one another by well-developed unconformities is the characteristic geological feature of these rocks. The alternating layers have widely different characteristics such as colour, heterogeneity, discontinuity, thickness, horizontal attitude, intercalating with volcaniclastic deposits, repetition with depth even within the same site, in both vertical and horizontal directions, depending on eruption type, mode of transport, distance travelled from the vent, temperature of the deposits, particle size, water content and paleorelief or riftogenic tectonic motions which are related to the development of the Gulf of Aden and opening of the Red Sea, or east African rift valley system.

Generally, in the study area, the Tb1 and Tb2 sequences are represented by jointed/massive basalt lave flow rocks which are interbedded/ alternated/ intercalated with volcaniclastic deposits. The Tertiary upper mafic sequence phase (Tb3) is exposed outside the investigated area and is also represented by the basaltic rocks. Megascopically, these rocks are characterized by porphyritic textures due to the presence of the plagioclase and/or olivine phenocrysts which are visible to the naked eye on the hand specimens. Presence of calcite veins, trachy structure and aphanitic texture are characterized features for massive trachybasalt. Microscopically, a variety of textures have been observed in the Tb1 and Tb2 thin sections including porphyritic, glomeroporphyritic and trachytic texture or flow structure. The microfractures intersected the phenocrysts and the fine groundmass, the alteration of olivine phenocrysts at their rims and along cracks into iddingsite, growth zoning in plagioclase with oscillatory variations in composition characterises and the vesicles/ amygdales structures all these features were seen in thin sections.

The Tr1 and Tr2 sequences are comprised of jointed/massive rhyolitic/dacitic/ pitchstone lave flows and domes which are also intercalated or interbedded/ alternated with the silicic volcaniclastic materials. Felsic volcanic rocks (Tr1 and Tr2) are exposed to forms characteristic geomorphological features as ridge of domal mountains and hills, high plateaus with escarpments or cliffs sides and resistant cuestas. Petrographically, the jointed rhyolites/dacites show various textures; porphyritic, micrographic, radiate, glomeroporphyritic, vitrophyric and spherulitic textures. Identification of minerals present in the Tr1 and Tr2 was not possible due to the effect of hydrothermal solutions and alteration. The pits and/or vesicles of varying sizes with or without secondary minerals are found in the hand specimens of the columnar rhyolites, ignimbrites and welded rhyolitic tuffs. The microfractures filled with volcanic glass or/and secondary as iron oxides and called as transgranular fractures travel through some grains and groundmass.

The volcaniclastic deposits are characterized with great diversity of their type, colour, textural features, thickness, grain size, matrix, and degree of roundness of rock fragments and interlocking, intercalating laterally and vertically with basalt/rhyolite rocks. They range from strong, compacted, welded rocks to weak, altered, soils. In the investigated exposures, the basaltic volcaniclastic deposits are represented by tuff-breccias (>64mm wherein bomb and/or block clasts ranges from 25% to 75 %), lapilli-tuffs (a mixture of both lapilli (64-2mm) and ash (< 2mm) put together <75% and the bomb and/or block clasts are <25%) from 25% to 75 %), lapillistones (lapilli is >75 %), agglomerates (bomb and/or block clasts volume is >75 %), tuffs (ash grains<2mm) and volcanic ashes. The Ignimbrites are also common in the study area. Microscopically, the basic volcaniclastics in thin section are often consisting of clasts of trachybasalt cemented by volcanic ashes, iron oxides, malachite, glass or silicates. They contain emptied or filled vesicles and microfractures and veins also filled with secondary minerals. The silicic volcaniclastic materials consist of ignimbrites, rhyolitic tuffs, rhyolitic lapilli-tuffs and rhyolitic lapillistones.

The volcanic ashes and iron oxides are more frequent matrix materials in the volcaniclastic materials. Both mafic and acidic types are underlain or /and intercalated with varicoloured volcanic ashes (soil). In the volcanic soils, the major clay minerals namely montmorillonite and kaolinite are identified by XRD analysis in addition to minor amounts of mica group of minerals such as muscovite, vermiculite and chlorite. Other minerals found in volcanic soils are talc, feldspar, calcite and halloysite.

The felsic plutonic rocks are represented by alkaline or peralkaline granites called Jabal Sabir granites. It consists of, white to greyish white, massive, medium to coarse-grained with grading up to granite porphyry and almost <5% of dark minerals. The main minerals constituted these granitic rocks are k-feldspar, quartz, hornblende and biotite. Petrographically, the study of thin sections of Sabir granitic rocks indicates that the main minerals are k-feldspar (orthoclase, perthite, and perthitic microcline), quartz, hornblende and biotite with accessory minerals zircon and other opaque minerals. The spherical and cavernous weathering is one of characteristic features of Sabir granitic rocks. The caverns with various sizes and shapes were observed in different locations. Numerous basic and felsic dykes cut through the surrounding older Tertiary igneous rocks represented by flows (basalts, rhyolites/dacites and volcaniclastic deposits) and Sabir granitic pluton. They are injected during different volcanic phases and along fault trends. The dykes with basic composition are more predominant than acidic dykes in the study area. The basic and felsic dykes show resemblance to the basalts and to the rhyolites/dacites respectively in their petrographical characteristics. The Tertiary rocks of Taiz area have been affected by the permeation of magnesium and iron-bearing solutions along their discontinuity surfaces implying the instability of the rocks caused due to the intensity of alteration the rocks.

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