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Petrography and Geochemistry of Scoria in Al Haikl Cone ''Thamar-Rada' Volcanic Field", Yemen

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Abstract The scoria rocks crop out at Al-Haikl cone, which lie at about 30 km east of Thamar City. The Al-Haikl cone is exposed in Thamar - Rada' volcanic field, within Quaternary Yemen Volcanic Series. Petrographic study shows that the scoria rocks are composed of groundmass with embedded phenocrysts of plagioclase, olivine, pyroxene and iron oxides. The scoria exhibit intergranular, intersertal, ophitic and subophitic relations. Geochemical analysis shows the majority of the studied scoria rocks have silica content ranging from 46.40 to 53.05 wt.%, with an average of 49.59 wt.%, and aluminum content has an average value of 16.55 wt.%. CaO have an average value of 8.41 wt.%. Iron oxides content has an average value of 10.98 wt.%, and K_2O has an average value of 1.29 wt.%. These suggest that the scoria rocks belong to the alkali basalt. Scoria is used as lightweight aggregate, as a source of Pozzolan for the manufacture of Portland - Pozzolan Cement, as well as having many industrial uses.

Keywords Scoria, geochemical, lightweight, concrete, aggregate

Introduction

The Al Haikl cone is a volcano located about 30km east of Thamar City. They are bounded by latitudes 14° 33' 20" - 14° 33' 46" N and the longitudes 44° 37' 09"-44° 38' 13" E. The study area is a part of the scoria deposits are outcrops in Thamar – Rada' volcanic field, this field is covered by Yemen Volcanic Group; Tertiary (basalt and rhyolites) and Quaternary basaltic volcano and Wadi deposits. Most scoria cones (also known as cinder cones) are appears as conical habits of ballistically-ejected fragments associated with many eruptive styles, but deposits exploited commercially are nearly all cinder cones. cinder cones are unconsolidated piles of scoria and cinder formed by subaerial eruptions.

Fresh cinder cones are typically conical, steep sided and open on one side where have flows were extruded [1]. Scoria is dark (black, red and brown) with thick vesicle walls that appear dull or stony and that may exhibit iridescence. Basaltic magmas tend to be more fluid than more silicic magma and as they near the surface, degas quickly without generating a stable vesicular structure. Even after vesicle formation, scoria particles may be fluid enough to collapse on impact or to adhere to each other, forminga dense mass rather than a friable, porous deposit [2,3].

In volcanology, the term scoria refers to dark vesicular material throughout a wide size range [4,5]. Scoria and cinder are typically basaltic to andesitic with a composition of approximately 50% - 60% SiO_2 [1]. Vesicles in cinder are larger and range from spherical to highly irregular in shape with much thicker walls and abundant interconnections. Scoria is vesicular volcanic ejected, essentially magma that has been frothed up by escaping gases. It is composed of heavier ferruginous lavas and is usually denser and darker in colour than pumice and has a higher crushing strength [2,6,7]. Scoria contains many phenocrysts of feldspars and various ferromagnesian minerals that crystallized in magma before eruption. Fragments of rock through which the magma has passed maybe entrained in the melt and wall rock maybe fragmented and admixed during an explosive eruption [1,8,9].

Scoria is a natural material of volcanic origin used as aggregate in lightweight concrete and block, it is also a source of Pozzolan for the manufacture of Portland- Pozzolan Cement, and it is an insulting material used for landscaping and gardening purposes, as well as having many industrial uses [10-14]. The aims of this study are examining the petrography and chemical properties of the scoria rocks to determine their mineralogical constituents, chemical behavior, textures and structures, and to define their economic potential.

Methodology

The methods of this study are including the field work and the laboratory analysis. The field work was carried out including define the scoria rocks, and collection of rock samples from different outcrops in the study area.

Petrographically, to determine the petrographic characteristics of the scoria deposits, a ten representative samples were collected systematically from the well exposed rocks sequences in the scoria deposits, and thin sections were prepared following the procedure listed in [15]. The rock samples were cut perpendicular to the bedding planes to recognize all the layers of the mineralogical constituents. The petrographic sections prepared in the central laboratories of the Geological Survey and Mineralogical Resources Board (GSMR) Sana'a, Yemen. Microphotographs illustrating the mineralogical constituent, crystal shape, textures and the structures of the scoria were taken.

Chemically, the chemical analysis was carried out for a ten selected scoria rock samples, investigating their major oxides. Major oxides were determined by X-ray fluorescence spectrometer (XRFS) techniques on a Philips PW2400 Automated Spectrometer. The analysis were carried out at the laboratories of Al-Amri in Saudi Arabia, and in the (GSMR) Sana'a, Yemen.

Geological Setting

Volcanic rocks within the Arabian plate take place throughout the western Arabian peninsula over a south - north distance of 3000 km, from Yemen through Saudi Arabia, Jordan and Syria [16]together they are one of the largest world’s alkali volcanic provinces, with approximate area of 180,000 Km² [17].

The "Yemen TrapSeries" Table (1) outcrops over a large area of western Yemen on the high plateau to the east of the Red Sea with smaller northern area south of Sadah center, with a total area of 50,000 Km² [17].

The "Yemen Volcanic Series" Table (1) includes two stages of volcanic activity; Late Miocene - Lower Pliocene volcanism and Pliocene - Quaternary volcanism. The Pliocene - Quaternary volcanism occur in various places in Yemen, that cover a total area of about 9,000 Km² in more restricted and disconnected occurrences on high plateau above the Yemen trap series (Fig. 1). It is divided into different fields: (a) Sana’a - Amran, (b) Marib - Serwah, (c) Thamar – Rada' (d) Shuqrah - Ahwar (e) Bir Ali - Balhaf (f) Qusayr - Sayhut, and Islands;also, that volcanism exists in the Red Sea as; Jabal At-Tair, Al-Zubair and Honaish Islands[18].

Quaternary volcanism in Yemen have generated and developed through the post rift stage, volcanic cones, domes, sheet and lava flows are the characteristic output features of this volcanism and its related series [19].

The evolution of Thamar – Rada' volcanic field, is controlled by regional stress regime of the western Arabian plate and related to the Cenozoic development of the Red Sea [8].

Structurally, this field is heading to north west, parallel to the structural vectors construction of the Red Sea and the East - West direction, which show most of the crater volcanic eruptions. A variety of volcanic rocks occur in this field such as; rhyolite, ignimbrite, obsidian, vesicular and amygdaloidal basalt as well as various kinds of volcanic tephra.

The study area is a part of Thamar - Rada' volcanic field which located about 90 Km southeast the Sana’a City extends to southeast of Thamar City and spread to Rada' district, it cover an area of approximately 2,500 Km² **(Fig. 1)**. This field is considered as the newest volcanic field in Yemen, because of the presence of hot springs areas, such a Al-Lisi and Isbil mountains. Geologically the Thamar - Rada' volcanic field shows wide exposures of different types of basic and acidic volcanic rocks. The area is mainly composed of Quaternary volcanic rock sequence

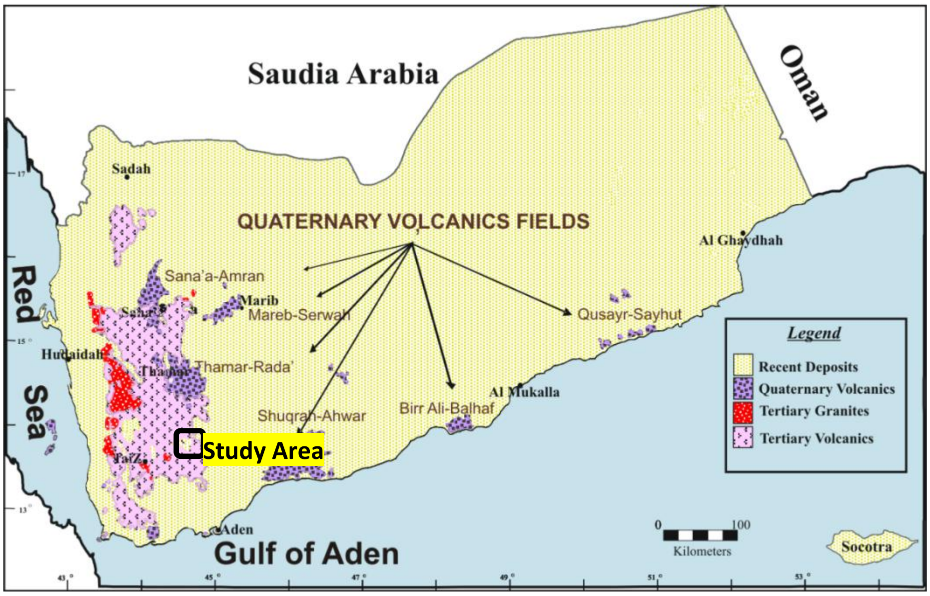


Figure 1: Geological map of Yemen showing Tertiary-Quaternary volcanic fields, modified after [20].

The studied scoria rocks belong to the Thamar - Rada' volcanic field stratigraphic evidence in Table (1) suggests that the sequence of volcanic events from the oldest to the youngest as summarize in Table (1).

Table 1: Stratigraphic column of Thamar - Rada' field sequence of volcanic evidence.

<table>
<tr><td rowspan="6">Quaternary</td><td colspan="4">Recent Sediments</td></tr>
<tr><td rowspan="8">Yemen Volcanic Group (YVG)*</td><td rowspan="7">Yemen "Volcanic" Series</td><td rowspan="3">Recent Basaltic Volcanic</td><td>Second Lava Flow</td></tr>
<tr><td>Scoria Cones</td></tr>
<tr><td>First Lava Flow</td></tr>
<tr><td colspan="2">Al-Lisi Volcanic</td></tr>
<tr><td colspan="2">Isbil Volcanic</td></tr>
<tr><td rowspan="3">Tertiary</td><td colspan="2">Thamar Basalt</td></tr>
<tr><td colspan="2">Thamar Ignimbrite</td></tr>
<tr><td colspan="3">Yemen "Trap" Series</td></tr>
</table>

* The term Yemen Volcanic Group (YVG) has crept into semi-formal use during 1990 - 1994 [21, 22, 23].

The study area is characterized by the presence of scoria cinder cone and explosive crater; as many of the horseshoe bendcones reflecting either the predominant wind direction during cone building (**Figs. 3 to 6**), or explosive removal of the side of the cones by directed volcanic blast **[24]**. The study cone is composed of basaltic scoria and Ejected material found on the foothills includes cinders, lapilli, pumps and blocks.

The Scoria cones locally known as "Hammat" are exposed mainly in the middle parts of the studied area (Figs. 3 to 6); they extend in east - west direction within the Dhamar - Rada' volcanic field [18].

The Yemen Trap Series (lower part of YVG) mainly outcrops in the northern and southern part of the study area (Fig. 2). It is made up mostly of basaltic and rhyolitic rocks, most of the rhyolitic rocks are ignimbrite. In the upper part of the "Trap" Series the occurrence of central activity is suggested by some felsic lava domes (Al-Lisi volcanic), a few of which had precursory explosions terming pumice ramparts.

The study area Al-Haikle cinder/scoria conelies within the upper part of Yemen volcanic series namely recent basaltic volcanicof Quaternary age Table (1), which are represented by central and fissure volcanism. The volcanism is characterized by widespread basaltic lava flows and spatter cones, extensive basaltic obsidians, and pumice in the Thamar-Rada' area. They are composed of three subunits:

(a) *First lava flows*: These lava flows are of fissure-type eruption and have strongly controlled by the existing morphology on account of their fluidity at the time of eruption.

(b) *Scoria cones*: The scoria cones (see Figs. 3 to 6) "locally known as Hammat", they extend in east-west within the Thamar-Rada' volcanic field. The scoria material is formed of vesicular fine to coarse fragments, black or reddish in color, and light in weight. They most commonly occur as isolated cones in large basaltic volcanic fields, but they also occur in nested clusters within complex tuff ring and as parasitic cones on polygenetic shield and stratovolcanoes, on which they are also essentially monogenetic elements [26,16].

(c) ***Second Lava Flow***: Numerous lava flows which were fed from parasitic vents located at the base of some Strombolian cones. The flow of lava from vents is mainly determined by its viscosity. The lavas which are normally fluid enough to flow away from the vent under gravity are basalts and some andesite.

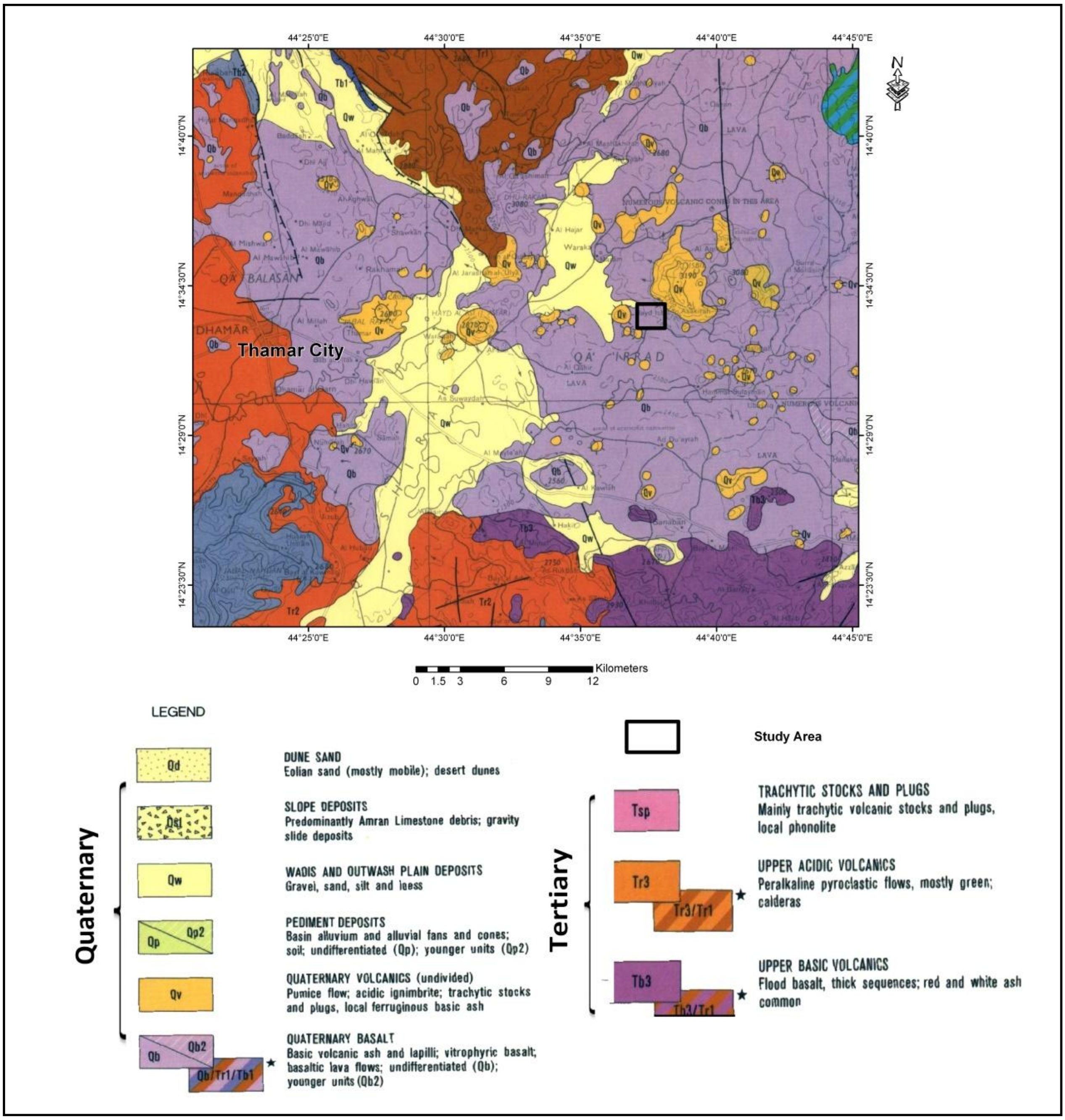


Figure 2: Geological map of south Sana'a region showing the studied localities of Al-Haikel cone east Thamar City. The map is adapted from the geologic map of Sana'a sheet, prepared by [25].

Figure 3: Photograph showing general side view of Al-Haikl cone

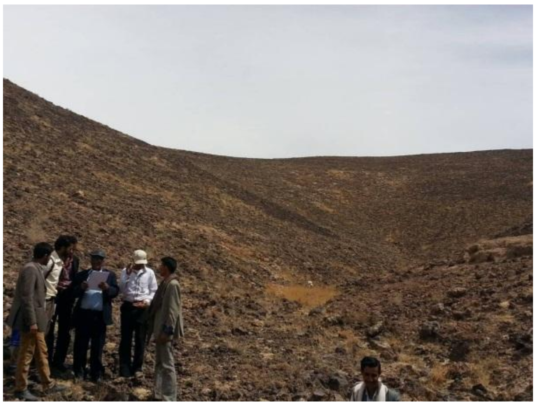


Figure 4: Photograph showing inside view of Al-Haikl cone

Figure 5: Photograph showing horseshoe morphologic shaped of Al-Haikl cone

Figure 6: Photograph showing scoria rocks of Al-Haikl cone

Results and Discussion

Petrographically, Petrography is an important tool to obtain insights into the petrogenesis of volcanic rocks. The scoria rocks are composed mainly of phenocrysts and groundmass. The phenocrysts are composed essentially of plagioclase, olivine and pyroxene. Other accessory minerals such as iron oxide and calcite are also present in small amounts. The groundmass contains the vesicles consists of volcanic glass, plagioclase laths, olivine, pyroxene and iron oxides. In the sections below, all principal minerals that were encountered during the thin section analysis will be discussed in terms of their abundance and specific textures.

Microscopically, the rock samples are variably vesicular, amygdaloidal and almost fine grained to coarse grained. The samples are characterized by the presence of glass in the groundmass and most of them are hypocrystalline. Most scoria samples are vesicular, containing more than 50% of the material mass. They are of different shapes as spherical, void and irregular. They show different textures as vesicular, hypocrystalline, ophitic and subophitic textures (Figs. 7, 8); they also have intergranular to intersertal textures(Figs. 9,10) and glomeroporphyritic textures of plagioclase and pyroxene, porphyritic texture in which the phenocrysts are clustered in clots called glomeroporphyritic (Fig. 11).

Plagioclase is present as euhedral to prismatic phenocrysts, while microlites show a distinct tabular shape. The plagioclase has polysynthetic twinning features, (Fig. 12). Plagioclase crystals ranges in size from 0.1-3 mm phenocrysts in a porphyritic texture, and from 0.05 mm in lath groundmass (Fig. 13). It is present in relative percentages ranges from 10% up to 40% of the whole rocks. Plagioclase phenocrysts sometimes occurs as clots displaying a glomeropyrphritic texture (Fig. 11). Generally, the relief of plagioclase is quite high, so this is a calcium-rich plagioclase [2,27]. Optical measurements indicate that the plagioclase compositions are generally in the range of An 61% (labradorite), which is characterized by broad twin lamellae under cross-polarized light. Some phenocrysts show evidence of fracture and breaking turbulent transport.

Olivine phenocrysts occur as subhedral and sometimes as euhedral form. These minerals occur as phenocrysts, and as groundmass. The olivine crystals range in size from 0.03-0.3 mm in the groundmass, and from 0.3- 1 mm phenocrysts in a porphyritic texture (Fig. 13). The modal percentages of the olivine range from 1 - 10%. More than one generation of olivine were observed: the first generations were the phenocrysts, which appear as highly cracked crystals, whereas the second generation produced small scattered crystals associated with pyroxene (augite) occupying the spaces within the plagioclase, which is characterized by intergranular texture. Olivine phenocrysts are partially or completely converted into strongly colored reddish brown along their cracks and boundaries, known as iddingsite (Fig. 14).

Pyroxene was recognized as subhedral to euhedral phenocrysts in some samples as prismatic crystals (Fig. 13). These minerals occur as phenocrysts or microphenocrysts, also occur as groundmass. The pyroxene relative size range from 0.04 mm lath in the groundmass and up to 2 mm phenocrysts in porphyritic textures. The modal percentages of the pyroxenes range from 1 - 12%. They are identified as pyroxene (augite). Augite crystals are colorless to pale brown and brown in some specimens.

Volcanic glass is present in the studied rock samples, as dark volcanic glass with dusty iron oxide between plagioclase laths, manifesting an interstitial texture (Fig. 10).

Iron oxides (opaque minerals) are present in considerable amounts, being in the form of discrete crystals that exhibit various form. It occur as very fine grain connected with the interstitial texture of the groundmass (Fig. 14).

Void and vesicles in the Al-Haikl cone scoria rocks constitute between 10 - 60% of the material mass, and appear which different shapes such as spherical, void and irregular (Fig. 15). In some altered scoria, the vesicles are totally or partially filled with secondary minerals (carbonates). Some of the vesicles are interconnected, while others are not connected.

According to **[10]**, the petrography of the scoria and the deleterious material content were found to be acceptable by ASTM standards, but grading analyses indicated it would need to be processed before use. For the main purpose of study the petrography of the aggregate is to identify an existing particles sensitive to chemical reactions. Amounts of minerals or forms of silica are known to be reactive with alkalis. These are intermediate to acid (silica-rich) volcanic glass. Since the volcanic glass constituting the scoria is basic (silica- deficient), it can be assumed to be non-reactive with alkalis.

Geochemically,the chemical analyses of a ten selected rock samples representing the scoria rock for major oxides, have been carried out at the laboratories of the Geological Survey and Mineral Resources Board, Sana'a, Yemen and in the laboratories of Al-Amri in Saudi Arabia, The analytical data of the scoria samples are listed in **Table** (**2**).

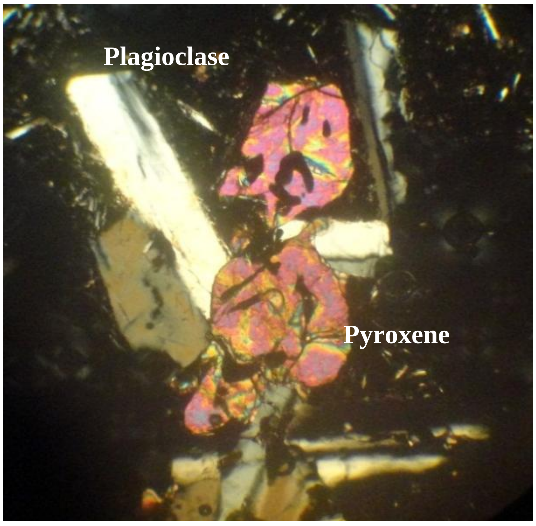


Figure 7: Photomicrograph showing ophitic texture, pyroxene enclosing plagioclase, (C.P. x80).

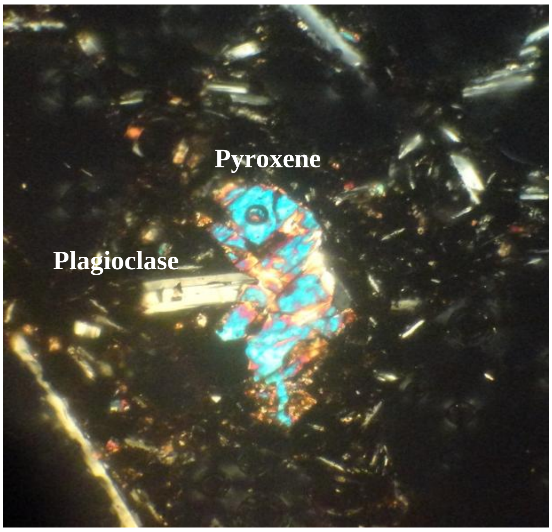


Figure 8: Photomicrograph showing subophitic texture, where plagioclase crystals are partly enclosed with pyroxene, (C.P. x80).

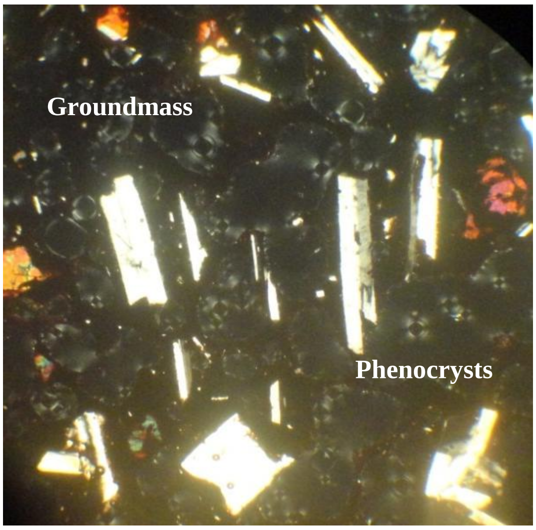


Figure 9: Photomicrograph showing intergranular texture, plagioclase phenocrysts imbedded in groundmass of pyroxene, olivine and iron oxides, (C.P. x40).

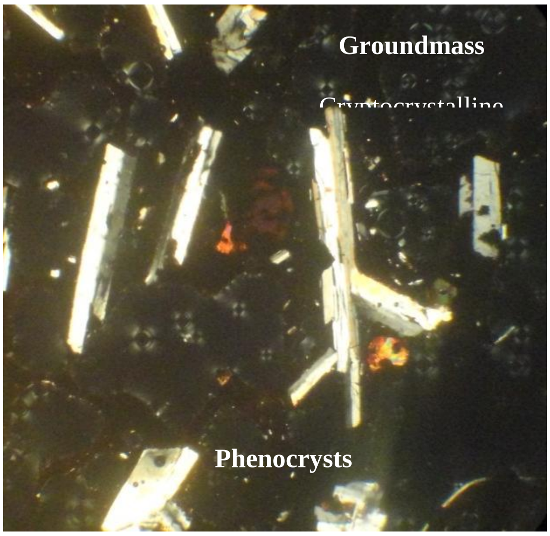


Figure 10: Photomicrograph showing intersertal texture, plagioclase phenocrysts imbedded in groundmass of glass and cryptocrystalline crystals, (C.P. x40).

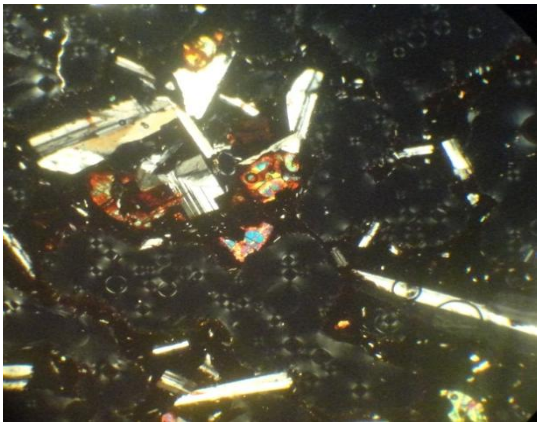


Figure 11: Photomicrograph showing glomeroporphyritic texture, (C.P. X 40).

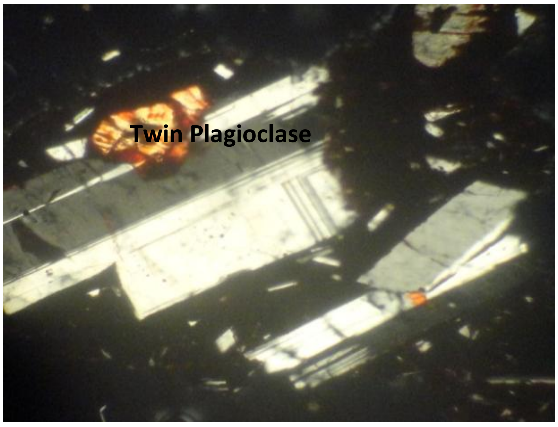


Figure 12: Photomicrograph showing twin feature of plagioclase, (C.P. x80).

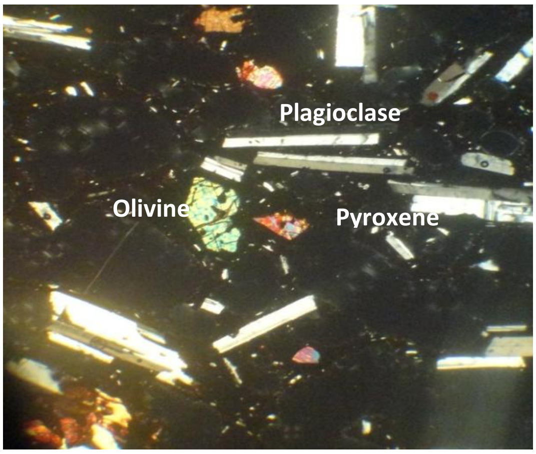


Figure13: Photomicrograph showing plagioclase, pyroxene and olivine phenocrysts imbedded in groundmass, (C.P. x40).

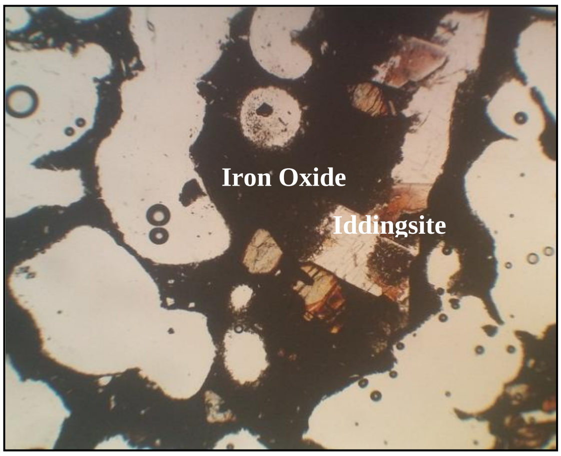


Figure 14: Photomicrograph showing converted olivine into iddengsite mineral and iron Oxide, (P.P. x40).

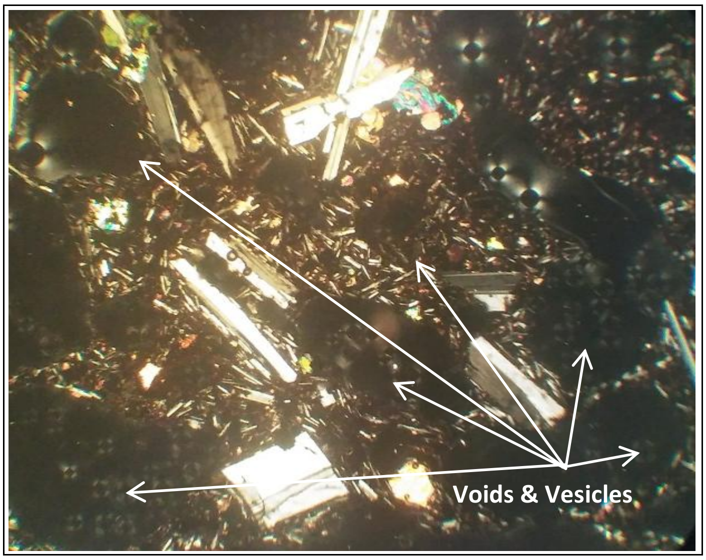


Figure 15: Photomicrograph showing rounded to subrounded vesicles of scoria, (C.P. x40).

Table 2: Chemical analysis show the major oxides percentages of the selected Scoria samples of Al-Haikl cone locality

Sample	Major Oxides Wt.%											
No.	SiO_2	TiO_2	Al_2O_3	Fe_2O_3	MnO	MgO	CaO	Na_2O	K_2O	P_2O_5	LOI	Total
Srh-1	51.12	1.64	16.63	10.43	0.16	5.65	7.20	3.00	1.64	0.27	2.22	99.96
Srh-2	47.72	2.12	16.64	14.20	0.20	5.24	7.91	3.50	1.50	0.53	0.38	99.94
Srh-3	50.71	1.11	17.05	8.98	0.16	10.11	6.12	3.46	0.94	0.23	1.12	99.99
Srh-4	50.10	2.00	16.40	10.50	0.19	5.50	8.90	3.53	1.52	0.49	0.94	100.07
Srh-5	49.25	1.80	17.20	10.60	0.17	4.95	9.75	3.60	1.00	0.38	1.15	99.85
Srh-6	48.40	1.86	16.60	11.25	0.19	5.90	9.38	3.15	1.35	0.50	1.20	99.78
Srh-7	52.03	2.02	16.06	10.35	0.01	5.30	8.21	3.40	0.98	0.32	1.00	99.68
Srh-8	46.40	2.23	17.00	12.40	0.19	5.92	8.55	3.85	1.61	0.55	0.91	99.61
Srh-9	47.15	2.24	16.85	12.03	0.18	6.07	9.74	2.90	1.34	0.48	0.97	99.85
Srh-10	53.05	1.35	15.06	9.01	0.10	6.80	8.31	3.45	0.98	0.29	1.00	99.40
Minimum	46.40	1.11	15.06	8.98	0.01	4.95	6.12	2.90	0.94	0.23	0.38	99.40
Maximum	53.05	2.24	17.20	14.20	0.20	10.11	9.75	3.85	1.64	0.55	2.22	100.07
Av.-Srh	49.59	1.83	16.55	10.98	0.16	6.14	8.41	3.38	1.29	0.40	1.10	99.86

The major elements of scoria rock in the Al-Haikl cone locality **Table** (**2**), indicated that SiO_2 oxide is variegated from 46.40 - 53.05 wt.% with an average of 49.59 wt.%, Al_2O_3 is variegated from 15.06 - 17.20 wt.% with an average of 16.55 wt.%, Na_2O is variegated from 2.90 - 3.85% with an average of 3.38 wt.% and K_2O is variegated from 0.94 - 1.64 wt.% with an average of 1.29 wt.%. Whereas Fe_2O_3 varies from 8.98 - 14.20 wt.% with an average of 10.98 wt.%, MgO varies from 4.95 - 10.11 wt.% with an average of 6.14 wt.%, CaO varies from 6.12 - 9.75 wt.% with an average of 8.41 wt.%, TiO_2 from 1.11 - 2.24 wt.% with an average of 1.83 wt.%, and P_2O_5 varies from 0.23 - 0.55 with an average of 0.40 wt.%.

Eventually the average of silicon oxide concentration is 49.21%, these indicated that, the source of the scoria rocks in Al-Haikl cone locality is basaltic magma. Major oxides through the studied samples Al_2O_3, total alkalis (Na_2O + K_2O) and CaO increase with increasing SiO_2, whereas MgO, Fe_2O_3 (astotal iron) and TiO_2 decrease, Fe_2O_3 and TiO_2 are clearly positively correlated and show slight different trends.

In the a variation diagrams; the major oxides such as; Al_2O_3, total alkalis (Na_2O+K_2O) and CaO increases with SiO_2 (**Fig. 16**), whereas MgO, Fe_2O_3 and TiO_2 decreases against silica (**Fig. 17**).

The studied scoria samples are chemically classified using total alkali silica (TAS) diagram **[28]**. On this diagram (**Fig. 18**) the all scoria samples plot in the basaltic field.

On the alkali versus SiO_2- diagram **[29]**, the most samples defined alkaline nature and partially subalkaline (**Fig. 19**), due to alkaline elements are tent to be mobile than others elements.

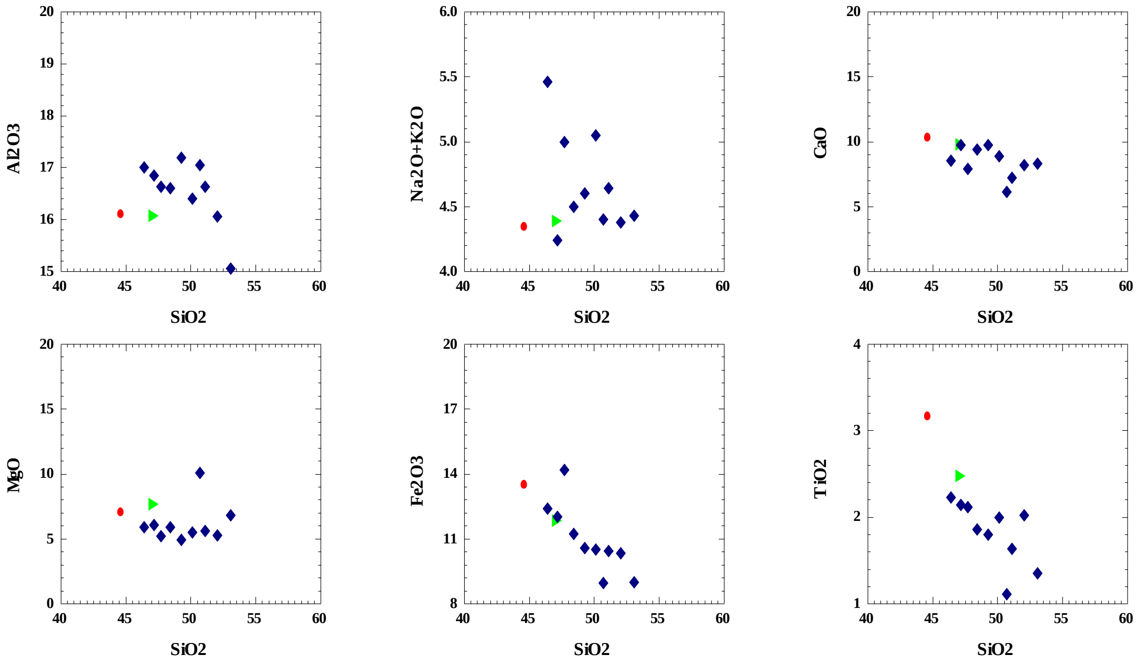
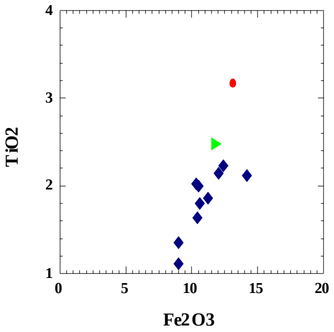


Figure 16: Variation diagrams; the SiO_2 versus Al_2O_3, (Na_2O+K_2O), CaO, MgO, Fe_2O_3 and TiO_2



Legand

Srh- Study Samples of scoria.

Av. Harat scorai –Saudi Arabia.

Av. Harat Basalt -Saudi Arabia.

Figure 17: Variation diagram; the Fe_2O_3 versus TiO_2

On the AFM-diagram [29], the all scoria samples fall within the calc-alkaline volcanic rocks field (Fig. 20) except tow samples; the Srh-2 due to its have the highest concentration of Fe_2O_3 (14.20 wt.%), where is the Srh-3 due to its have the lowest concentration of Fe_2O_3 (8.98 wt.%) and highest concentration of MgO (10.11 wt.%) between other analytical scoria samples Table (2). On the other hand, all scoria samples plot within the field of continental basalt (Fig. 21) in the diagram of [30].

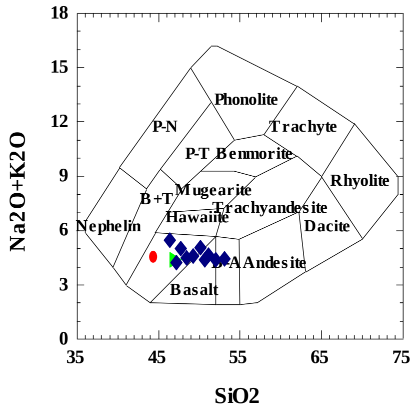


Figure 18: Total (Na_2O+K_2O) - SiO_2 diagram showing geochemical classification of Al-Haikl scoria rocks, after IUGS [28].

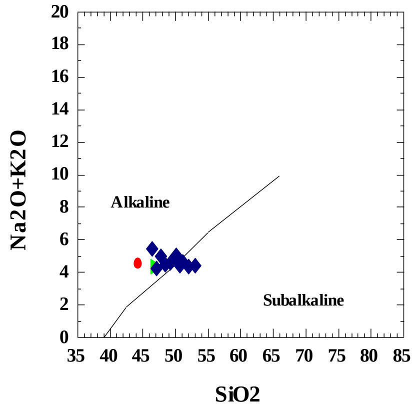


Figure 19: SiO_2 versus Na_2O+K_2O, diagram showing geochemical composition of Al-Haikl scoria rocks, after [29].

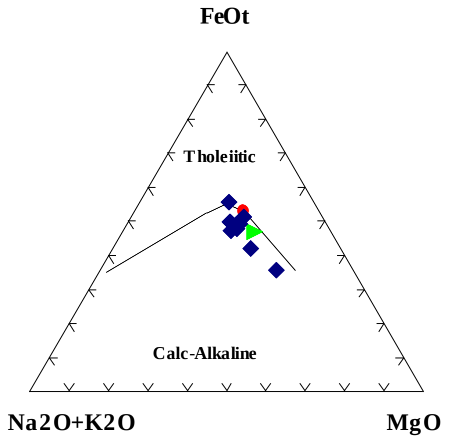


Figure 20: Ternary AFM (Na_2O+K_2O, FeOt, MgO) diagram showing geochemical composition of Al-Haikl scoria rocks, after [29].

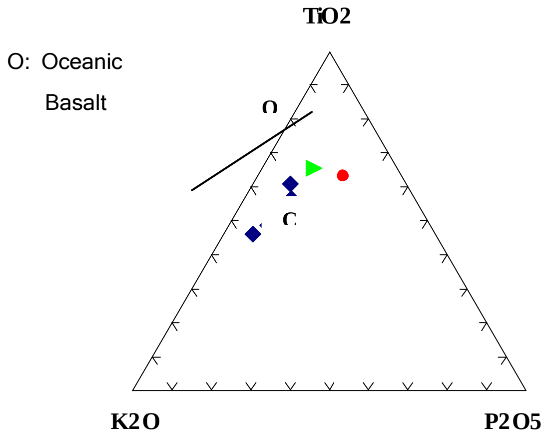


Figure 21: $TiO_2 – K_2O – P_2O_5$ discrimination diagram showing geochemical composition of Al-Haikl scoria rocks, after [30].

The results of chemical analysis of Al-Haikl scoria rocks are concludes and compared with the scoria rocks of the Harat (Saudi Arabia) and with Roma (Italy) Table (3), that refer to the similarity somehow of the Al-Haikl scoria rocks with those of Harat – Saudi Arabia and with Roma – Italy (Fig. 22).

Table 3: Average of study scoria samples with averages of scoria of the world

Average	SiO_2	TiO_2	Al_2O_3	Fe_2O_3	MnO	MgO	CaO	Na_2O	K_2O	P_2O_5	Total
Srh- Al-Haikl Scoria.	49.59	1.83	16.55	10.98	0.16	6.14	8.41	3.38	1.29	0.40	99.86
* Harat Saudi-Arabia.	44.85	3.13	16.05	13.37	-	6,8	10.1	3.59	0.73	1.19	99.79
* Roma, Italy.	44.65	-	18.65	10.7	-	2.9	10.9	3.8	4.65	6.85	103.1

* After**[31]Habib et al., (2001).**

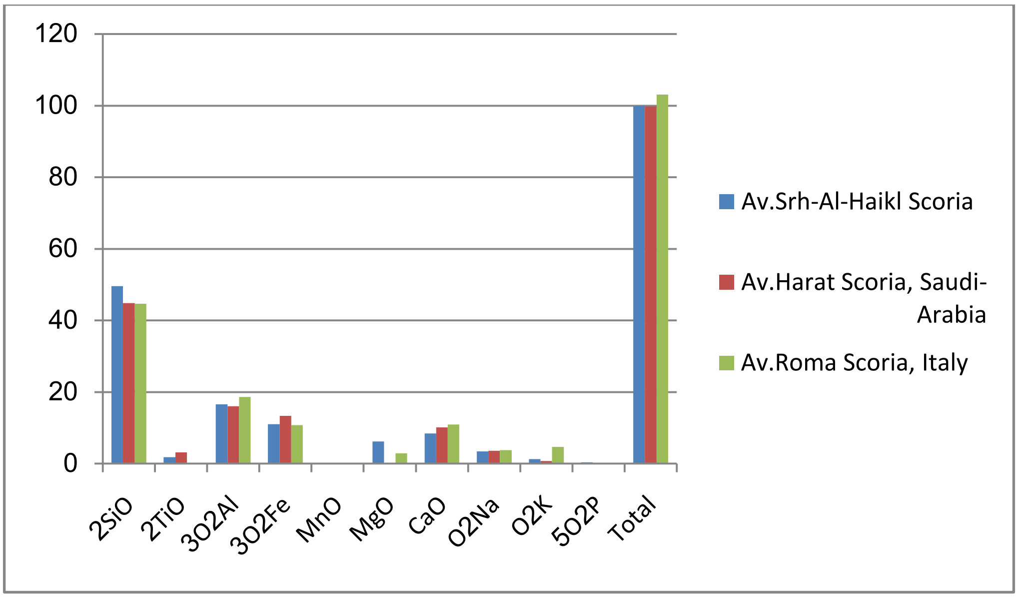


Figure 22: Histogram diagram showing average content of study samples against Harat Rahat in Saudi Arabia.

Conclusion:

The scoria rocks in the Al-Haikl volcanic cone are generally of a basaltic composition with vesicles, a glassy matrix and some phenocrysts.Most scoria samples are vesicular containing up to 60% vesicles. Scoria consists mostly of plagioclase, olivine and pyroxene.

The chemical analysis show that the percent of silica range from 46.40 wt.% - 53.03 wt.% and aluminum content has an average value of 16.55 wt.%. The percentages of iron, magnesium and calcium oxides refer to the presence of olivine, pyroxene and Ca-feldspar minerals in the studied scoria samples. While the aluminum, sodium and potassium oxides refer to the feldspar minerals. Scoria of Al-Haikl volcanic cone can be used as aggregate in lightweight concrete also as an additive to Portland Cement.

Recommendations

The present study recommends that the physical properties of the scoria such as bulk density, specific gravity, compressive strength and absorption should be used to analyze before use.

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