Peperites: Insight into the Submarine Eruptions within Walash Volcanosedimentary Group, Mawat Area, Iraqi Kurdistan Region

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Abstract—Peperites are volcanosedimentary materials generated by the mingling of magma and unconsolidated wet sediments. They have unique insights into submarine volcanism and the tectonic environments where they form. For the 1st time, the authors identified two types of peperites (blocky and fluidal) hosted by micritic limestone rocks in the Walash Volcanosedimentary Group of the Mawat area, Kurdistan Region–Iraq. They are designated as peperitic facies one and two (PF1 and PF2) and consist of black basaltic rocks mixed with chocolate-brown micritic limestone rocks. Their abundance demonstrates the contemporaneity of deep marine sediment deposition and submarine volcanism during Walash’s nascent arc. Despite hydrothermal alteration, the basaltic rocks retained their magmatic textures. Basaltic rocks comprise mainly albite, anorthite, diopside, hematite, and alkali-feldspar. Calcite dominates micritic limestone rocks, while quartz is minor. Based on geochemical data, igneous sections are basaltic rocks that have different juvenile clast morphologies, including blocky and fluidal types, and numerous magma-sediment relationships (Hanson, 1991). Peperite may extend its range from minor occurrences adjacent to igneous eruptions up to deposits with quantities of several km³ (Brown and Bell, 2007). Texturally, peperites have different juvenile clast morphologies, including blocky and fluidal types, and numerous magma-sedimentary relationships (Busby-Spera and White, 1987). Peperites may occur in any tectonic environment, where magmatism and sedimentation are contemporaneous, frequently in arc-related and other volcanosedimentary sequences (Hanson and Hargrove, 1999; Mueller, Garde and Stendal, 2000; Skilling, et al., 2002; Dadd and Van Wagoner, 2002; Templeton and Hanson, 2003; Nemeth, Breitkreutz and Wilke, 2004; Chen, et al., 2016; Fontboté, 2019; Mawson, White and Palin, 2020). Consequently, petrologists have defined peperites in different ways, some authors may mistakenly define this rock as sedimentary rock, while others more properly define peperites as a combined volcano-sedimentary succession (White, McPhie and Skilling, 2000; Skilling, et al., 2002; Brown and Bell, 2007; Chen, et al., 2016; Krobicki, 2018; Krobicki, et al., 2019; Memtittim, et al., 2020).

Index Terms—Mawat, Paleocene, Peperite, Primitive Arc, Volcanic Arc, Walash.

I. INTRODUCTION

The term “peperite,” comes after “peperino,” first used by Scrope, 1827 to describe clastic rocks from the Limagne d’ Auvergne region of central France (now considered the type locality for “peperite”). It comprises mixtures of wet sediment or lacustrine limestone and basalt (Skilling, et al., 2002). Peperite is a combined rock formed essentially in situ by the disintegration of magma which intrudes and mingles with unconsolidated or poorly consolidated, typically wet sediment (Busby-Spera and White, 1987; White, McPhie and Skilling, 2000; Skilling, et al., 2002; Brown and Bell, 2007; El Desoky and Shahin, 2020). However, most peperites described as basaltic extrusion involve relatively fine-grained sediment (White and Busby-Spera, 1987); Hanson, 1991; Boulter, 1993; Hanson and Wilson, 1993; Rawlings, 1993; Brooks, 1995; Goto McPhie, 1996; Hanson and Hargrove, 1999; Skilling, et al., 2002; Waichel, et al., 2007; Branney, et al., 2008; Palinkaš, et al., 2008; Chen, et al., 2013; Famelli, et al., 2021; Bann, Jones and Graham, 2022). While few exceptions involve basaltic extrusions into coarse-grained host sediment (Wilson, 1991; Squire and McPhie, 2002). Peperite may extend its range from minor occurrences adjacent to igneous eruptions up to deposits with quantities of several km³ (Brown and Bell, 2007).
Aziz (1986) studied the geochemistry and petrogenesis of the volcanic rocks within the Walash Volcanosedimentary Group (WVSg) for the first time, and he concluded that the volcanic rocks of the Walash composed of basalts and andesites, which display tholeiitic to calc-alkaline affinity, formed as a result of the subduction of the oceanic crust beneath the Iranian microcontinent. Previously, the $^{40}$Ar-$^{39}$Ar geochronological data suggested an age of 43–32 Ma for the volcanic rocks of Walash in the Mawat ophiolite complex (Aswad, et al., 2013). Despite the aforementioned studies for WVSg, it is reasonable to do more meticulous petrological studies as it is the most complex volcanosedimentary unit in the Iraqi Zagros Suture Zone (IZSZ).

The occurrence of basaltic pillow lava, peperitic rocks, and host micritic carbonate rocks together within the lower part of WVSg is designated as the peperitic facies (PF) in this study. The primary goals of our research are to use peperite and basaltic rock compositions obtained from the WVSg in the Mawat area to reconstruct the tectonic setting of the basaltic rocks within the aforementioned volcanosedimentary group. In addition to covering the occurrence and genesis of peperites in the Mawat area within WVSg.

II. Tectonic Setting of the Region

The Zagros orogeny is an active orogeny that includes the Arabian and Eurasian plates collided (Agard, et al., 2011; Austermann and Iaffaldano, 2013; Elias, Sissakian and Al-Ansari, 2018). Tectonically, the Zagros orogen is divided into four subparallel divisions, which are the Urumieh-Dokhtar Magmatic Arc; the Sanandaj-Sirjan Zone; the Zagros Fold-Thrust Belt and the Mesopotamian Foreland Basin (Alavi, 2004; Mohammad, et al., 2014; English, et al., 2015). Iraq also is a part of the Zagros orogeny. It is divided into different tectonic zones, which are Zagros Suture Zone (ZSZ), Unstable shelf, and Stable shelf. The studied area is located within the Penjween-Walash sub-zone, which is a part of the IZSZ (Jassim and Goff, 2006) (Fig. 1). Jassim and Goff, (2006) defined the Penjween-Walash subzone as a unit of the main (Central) Neo-Tethys, which consists of volcanosedimentary sequences formed during Cretaceous Ocean spreading in the Neo-Tethys and Paleogene arc volcanics and syn-tectonic basic intrusions formed during the ocean’s final closure. Thus, the oceanic sediments were deposited on both Arabian and Iranian microplates during the middle Paleocene. Later, Zagros orogeny was followed by the late Eocene 38 Ma continent-continent collision of the Arabian plate with the Iranian microcontinent. This collision was accompanied by large-scale magmatism and the formation of the Zagros Volcanosedimentary Group (WVSg).
Eurasia (Mohammad, et al., 2014). Furthermore, in the study area, the WVSG exposed in the Thrust Zone and the Mawat nappe stack consists of two allochthonous sheets, namely, the upper and lower allochthonous thrust sheets (Aswad et al., 2011; Aziz et al., 2011a). The lower allochthonous thrust sheet consists of Walash volcanosedimentary rocks, which undergo lateral transitions to the Naupurdan sedimentary group, thereby forming the Walash-Naupurdan allochthonous thrust sheet.

Peperite literature along the Zagros orogeny (Turkey-Iraq-Iran) is rare. Recently, Nouri et al., (2017) have recorded peperites within western Iran along the ZSZ. As well as Erkü, Helvaci and Sözbilir, (2006) recorded peperites within Miocene units in Western Turkey. The formation of peperites, which occurred by the interaction of lava with wet sediment, is a vitally significant environmental indicator. Nonetheless, few examples of this phenomenon have been comparatively documented, which happened during Archean successions (Beresford, et al., 2002; Wilson and Grant, 2006; Moulton, et al., 2011; Barnes and Van Kranendonk, 2014; Barnes and Arndt, 2019); Proterozoic succession (McPhie, 1993; Rawlings, 1993; Biske, Romashkin and Rychanchik, 2004; Sinha, et al., 2011; Constenius, et al., 2017); Palaeozoic succession (Brooks, 1995; Doyle, 2000; Cas, et al., 2001; Chen, et al., 2013; Zhu, et al., 2014; Chen, et al., 2016; Memtimin, et al., 2020; Bann, Jones and Graham, 2022); Mesozoic succession (Wilson, 1991; Wilson, 1993; Hanson and Hargrove, 1999; Templeton and Hanson, 2003; Hanson and, Nemeth, Breitkreutz and Wilke, et al., 2004; Palinkaš, et al., 2008; Asvesta and Dimitriadis, 2013; Krobicki, et al., 2019); Cenozoic succession (Erkü, Helvaci and Sözbilir, 2006; Martin and Németh, 2007; Busby, et al., 2008; Haller and Németh, 2009; Nouri, et al., 2017); and to the most recent Pleistocene succession around 43,000-12,400 years ago (Mercurio, 2011). However, it has also been pointed out by (Skilling, et al., 2002) that in ancient deposits, it may be difficult to differentiate fragments obtained from this process from those of tectonic origin. Despite this fact, the presence of peperite in oceanic island arcs may infer the primitive arc complex.

Although according to Jassim and Goff (2006) along Iraqi part of Zagros orogeny, the WVSG comprises from the base: Basal Red Beds, Lower Volcanics consisting of mafic, minor felsic lavas and frequently pillow lavas laterally adjacent to the sedimentary sequence (i.e., volcano-flysch unit), Middle Red Beds (±limestones), Upper Volcanics and finally the Upper Red Beds, peperites were not recorded in any sequences within whole succession of WVSG.

III. GEOLOGY OF THE STUDIED AREA AND FIELD INVESTIGATIONS

Peperites in the studied area are exposed at two locations along Mawat-Shasho road, which lies between longitudes 45° 25’ 21.10” E (PF1) – 45°27’11.21” E (PF2) and latitudes 35° 54’ 16.80” N – 35°55’29.65” N, respectively, and 1–4 Km away from East of Mawat town and 37 km north of Sulaimani city (Figs. 2b, 3-5). Stratigraphically, both sites are within the base of WVSG. The WVSG within the Mawat area covers almost 70 km². It is adjacent to the Mawat Ophiolite complex (Fig. 2). Along the Mawat-Shasho road, basaltic intrusions and its intermingling with deep-sea sediments have been observed at different locations in the basal part of the WVSG.

Based on the field investigations, the peperite-bearing successions in both PF1 and PF2 show variation in thickness at different sites and are widespread in the study area along the Mawat-Shasho section (Figs. 3-5). PF are discontinuously exposed on both the eastern and western sides of the Mawat-Shasho section. The distance between these two outcrops is about 6–7 km. PF1 and PF2 exhibit lateral lithological changes involving basaltic lava flows interlayered with deep marine succession involving micritic carbonate rocks occasionally associated with shale (a thrust product of basaltic pillow lava) beds. Two lithofacies types are recognized within peperites in the studied area (PF1 and PF2), both are illustrated in discussion section scenarios. Lithofacies Type 1 (PF1) is made up of coherent basaltic pillow lava that is sandwiched between peperites and micritic limestone rocks (Figs. 3, 4 and 6). While lithofacies 2 (PF2) comprises, coherent massive basalt intercalated with host micritic limestone rocks, closely packed vesicular pillow basalt, and peperites (Figs. 5 and 7). The host rocks for both lithofacies types (PF1 and PF2) are deep marine micritic carbonate rocks rich in planktonic Forams (Figs. 4 and 8).

PF1 in the field is characterized by blocky peperites and vesicular pillowed basaltic intrusions with well-layered, thick, and chocolate-colored micritic limestones. The jigsaw texture in the peperitic rocks is well exposed, especially in PF1 (Fig. 3). Even though PF2 is distinguished by fluidal peperites and vesicular to amygdaloidal pillowed basaltic intrusions with well-layered thick chocolate-colored micritic limestones (Fig. 5). In both PF1 and PF2 basaltic intrusions appear as grayish black having normal to the mega-pillow morphologies based on (Walker, 1992) classification and their rounded vesicles diameter range 1–5 mm are often filled with the secondary minerals such as calcite, chlorite, and quartz. The sedimentary rocks have attitudes of 240°/54°/NW, occur as layers to massive chocolate micritic limestones, and cover more than 30–50 m within PF (Fig. 4). Manganese mineralization is well exposed on the micritic limestones in the form of surficial pods (3–5 cm), small tubes, and dendritic structures within PF1, which may indicate the deposition of micritic limestone within a deep marine environment (Fig. 4).

IV. SAMPLING AND ANALYTICAL TECHNIQUES

The intensive fieldwork encompasses the meticulous collection of samples for peperites, basaltic rocks, and host micritic carbonate rocks, in addition to the comprehensive examination of the petrological and stratigraphical features of the PF. Almost 35 samples have been taken from PF. All 35 samples were cut for thin sections preparation (15 thin sections of basaltic rocks, 10 thin sections of peperite rocks,
and 10 thin sections of host micritic carbonate rocks) and for studying their internal structures, textures, mineralogy (modal analysis), and paleontology polarized light microscope were used.

Twenty-six fresh samples have been selected for the mineralogical study. Among them, 20 samples were taken from peperitic rocks (basaltic rocks) and five samples from host micritic carbonate rocks, and one sample from thrust shale which is located between host micritic carbonate rocks and peperitic-basaltic rocks. All samples were grounded into powders for X-ray diffraction analysis at the University of Soran using a Panalytical X'Pert MRD machine. The samples were scanned using a Ni filter and K-Alpha1 radiation (1.54060 Å) at generator settings of 40 mA and 45 kV and recorded diffraction peaks are between 2Ѳ=5° and 2Ѳ=70°. Mineral patterns were identified using Match 3 software.

Within (PF1) 10 fresh samples from basaltic rocks and three samples from host micritic carbonate rocks and also 10 fresh samples from basaltic rocks and two samples from host micritic carbonate rocks within (PF2) have been selected for the whole rock geochemistry (major, trace and REE elements) analysis within ALS Laboratories in Seville, Spain.

At the geology department Research Laboratories at the University of Sulaimani, the slabbed whole-rock samples were prepared with a water-cooled diamond-blade saw to remove any weathered or calcified parts of the rock samples. All rock samples were powdered in hardened steel with a chromium-free tool steel vibrating cup mill by using PULVERISETTE 9 machine. Further sample preparations, such as pulverizing to get particle size <75 µm and lithium borate fusion before acid dissolution, have been done at ALS Labs. Whole-rock powders were analyzed by inductively coupled plasma-atomic emission spectroscopy (ICP) and Mass spectrometer (ICP-MS) methods for major, trace, and rare earth element (REE) abundances in the ALS laboratories using geochemical procedures (ME-ICP06; ME-MS81; ME-4ACD81). For major and trace element analyses, structural water was removed from sample powders by heating in a furnace at 1000°C for 30 min. Loss on ignition (LOI) was determined from 1 g of the powdered samples by heating in a furnace at 1000°C, and then the total weight change of the sample powder is calculated. Detection limits are <0.01% for major elements and 0.01–1 ppm for trace and REE elements, except for As and Cr, which have relative errors of 5 ppm. Mg numbers are calculated using the formula Mg# = (100* MgO/[MgO+Fe2O3] [molar]). Eu anomalies (Eu/Eu*) have been calculated as Eu/Eu* = ([Eu]ncn/[(Sm)cn x (Gd)cn])0.5 after McLennan (1989). The Chemical Index of Alterations

Fig. 2. (a) Location and geological map of the Mawat-Chwarta area of the study area after (Al-Mehaidi, 1974). (b) Detail geological map of the WVsg Mawat-Shasho section.
Fig. 3. Panoramic view and illustration of the PF1 outcrop within the Mawat area, comprising intercalation of the basaltic pillow with micritic limestone thick layers, blocky peperites, and coherent basaltic pillow lava. Numbers refer to the sampling locations.

Fig. 4. (a) Panoramic view (~70 m horizontal) of the PF1 outcrop. (b) Shale (thrust) contact between peperite and host micritic carbonate rocks. (c) Centimetric pods of volcanic clasts (white circles) within micritic carbonate rocks. (d) Reddish brown host micritic carbonate rocks. (e) Dendritic structures of manganese mineralization within host micritic carbonate rocks.
(CIA%) is also calculated using the formula CIA% = \frac{100 \times m. Al_2O_3}{m. Al_2O_3 + m. CaO + m. Na_2O + m. K_2O} after Nesbitt and Young (1982).

V. RESULTS

A. Petrography

Petrographically, both PF1 and PF2 are composed primarily of plagioclase (45–50%) and clinopyroxene (20–25%) phenocrysts, set in an aphanitic groundmass of the same minerals and associated with hematite (10%) and orthoclase (8%), nepheline and sphenite as accessory phases. Although PF1 and PF2 mineralogically are the same, they are showing different textures. PF1 samples tend to be more aphanitic in textures and are characterized by the presence of tachylite, in which skeletal grains of plagioclase (only the outer rim) set in the glassy groundmass (Fig. 9a). PF2 samples indicate more evolved magma and are characterized by porphyritic textures (Fig. 9c-f) in which boxy cellular plagioclase serves an initial mixing stage of magma. It indicates the typical volcanic texture of these rocks (Hibbard, 1995) and references therein (Fig. 9c and d). Amygdaloidal textures are clearly seen in both PF, vesicles are of circular and amoeboid forms and filled with secondary minerals, such as hematite, calcite, and dolomite. This might indicate hydrothermal alterations or submarine weathering in these volcanic rocks (Thompson, 1991) (Fig. 9a, b and e). Pyroxenes in PF1 samples are extremely altered while in PF2 samples, they are less altered (Fig. 9a and e). Despite the submarine hydrothermal alteration, the basaltic rocks in both PF1 and PF2 maintained their original igneous textures such as interstitial, glomerophyric, and interseral textures.

B. Mineralogy

Detailed mineralogical studies for the PF1, PF2, and host micritic limestone are shown in Table I. XRD analysis shows that the basaltic pillow lavas from PF1 and PF2 comprise major phases, such as albite, andesine, and diopside. While the minor phases comprise hematite, ilmenite, and titanite (Table I). As well as host micritic limestone rocks comprising calcite as major phases and quartz as minor. A 20 cm shale in PF1 (thrust product) is between peperites and host micritic limestone rocks. It comprises montmorillonite, quartz, calcite, and anorthite as major phases and pyroxene as minor phases.

C. Geochemistry

Within the studied area, 20 volcanic and five micritic limestones (host) rock representative samples from PF1 and PF2 were analyzed for geochemical classification and interpretation of the peperitic rock types. The major, trace, and REE concentrations of these volcanic and micritic limestone rocks in the PF are given in Tables II and III. Micritic limestone host rocks are characterized by a narrow range in SiO_2 (10.75–11.65 wt.%), CaO (45.3–46.7 wt.%) with LOI (36.0–36.8 wt.%). While the concentrations of Al_2O_3, Fe_2O_3, MgO, Na_2O, and K_2O are around 6 wt.%. The geochemical signature of these micritic limestone rocks indicates that the host carbonate rocks in both PF1 and PF2 are deposited in a deep-marine environment.

Meanwhile, the volcanic rock samples in both PF1 and PF2 occupy a narrow range of SiO_2 (43.63–47.57 wt.%), Al_2O_3 (16.05–17.85 wt.%), and Fe_2O_3 (10.15–11.35 wt.%) with relatively high Na_2O and CaO and low K_2O. Furthermore, the amounts of Cr_2O_3, MnO, P_2O_5, SrO, and BaO are <0.5 wt.%. Almost all samples are influenced by

Fig. 5. (a) Panoramic view of the PF2 outcrop near Shasho village. (b) Fluidal peperites. (c) Vesicular pillow basalt outcrop, white stars represent sampling locations. (d) Representative illustration for fluidal peperite outcrop of panoramic view (a). White stars represent sampling locations.
hydrothermal alteration (Fig. 9a-f). The alteration effects on the volcanic rocks are consistent with the high value of LOI (7.0–9.46%) and the high ratio of alkalies (Na$_2$O+K$_2$O).

The use of Harker diagrams reveals a discernible negative or positive correlation between the majority of major oxides and the increasing SiO$_2$ content. The observed correlations indicate the significant influence of fractional crystallization processes in the development of volcanic rocks within PF 1 and 2. The observed patterns in the concentrations of Al$_2$O$_3$, CaO, Na$_2$O, TiO$_2$, and Fe$_2$O$_3$ relative to SiO$_2$ indicate a potential process of fractionation involving diopside, plagioclase, sphene, and other iron-titanium oxides, as illustrated in (Fig. 10).

The low concentration of MgO observed in both sections PF1 and PF2 may be attributed to the absence of olivine and amphibole (specifically, Mg-hornblende). Besides, low TiO$_2$ concentrations of around 1% may reflect the eruption of basaltic submarine eruptions near frontal arc settings (Shuto, et al., 2015). Conversely, the greater concentrations of Fe$_2$O$_3$, as indicated by the elevated modal percentage of hematite, are evident in both PF1 and PF2.

The concentrations of trace elements, specifically Nb, Ta, and Ti, exhibit a distinct depletion characteristic in volcanic rocks found in PF1 and PF2. This depletion feature is believed to be an inherent characteristic of the source region of the island arc (Ryerson and Watson, 1987). Furthermore, the concentrations of compatible trace elements, such as chromium (Cr) and nickel (Ni), in the volcanic samples from PF1 and PF2 exhibit a range of (205–380 ppm) and (82–171 ppm), respectively (Tables II and III). As reported by (Humphris and Thompson, 1978), the observed values generally align with the Cr and Ni concentrations found in...
Zirconium (Zr) concentration serves as a reliable indicator of geochemical diversity, functioning as an independent index. It demonstrates a strong correlation with various other elements, thereby enabling the assessment of their mobility (Pearce, et al., 1992; Liu, et al., 2012; Wang, et al., 2016). Therefore, the utilization of Zr as a fractionation index allows for the identification of mafic fractionation processes involving pyroxene and/or olivine, as evidenced by the observed decrease in Cr and Ni (Fig. 11). The presence of a positive correlation between Zr and Y, as well as Zr and Nb, in conjunction with the presence of Ce, may suggest the absence of amphibole and monazite minerals. In general, there is a notable correlation between Zr and REEs (La, Ce, Nd, and Sm), which serves to confirm the immobile nature of these elements during hydrothermal or secondary alteration processes within PF1 and PF2 rock samples (Fig. 11).

All samples, that were plotted on the diagram (Zr/TiO$_2$–Nb/Y) after (Pearce, 1996), are in the basaltic field and show sub-alkaline characteristics (Fig. 12a). The magmatic nature classification diagrams, after (Miyashiro, 1974) and (Ross and Bédard, 2009), show all samples in the field of tholeiitic nature (Fig. 12b and c). All basaltic rock samples within both PF are characterized by the following elemental ratios: low Nb/Y (0.10–0.15), La/Yb (1.4–2.3), and Nb/La (0.61–0.77); adequately high Zr/Nb (23–30), Hf/Ta (12–22) and Th/Ta (2–5); relatively low contents of major elements, such as TiO$_2$ and P$_2$O$_5$ in contrast to the high ratios of FeO/MgO (Tables II and III). Furthermore, on well-known tectonic diagrams, such as Th/Yb versus Ta/Yb after (Pearce, 1982), Ce-Sr-Sm normalized ternary after (Ikeda, 1990), and
Zr-Ti-Sr ternary after (Pearce and Cann, 1973), these basaltic rocks are plotted in the fields of volcanic arc basalt and island arc tholeiitic basalt, respectively (Fig. 13a-c). Based on the primitive mantle-normalized multielement spider diagram (Fig. 14a), the basaltic rocks in both PF1 and PF2 show selective enrichment in Large-Ion Lithophile Elements (LILEs) (e.g., Rb, Ba, and K) and depletion in the High Field Strength Elements (HFSEs) (e.g., Ta, Nb, Nd, and Ti).

It compared with the field of island arc basalts (IAB) after (Perfit, et al., 1980). While on the REE chondrite-normalized diagram (Fig. 14b), these basaltic rocks are characterized by slight enrichment and with flat REE patterns. It compared with the average composition of IAB after (Elliott, 2003) and Izu-Bonin-Mariana arc basalts (IBM Arc) field after (Elliott, et al., 1997).

D. Paleontological Investigation
The authors concentrated on whole PF1 sections for paleontological investigations because the PF1 consists of well crops out of micritic carbonate sequences that sandwiched peperitic rocks in the area (Figs. 3 and 4). The distinguishable facies throughout peperites within WVSg indicated deep marine environments that lack benthonic foraminifera in contrast with the high percentage of planktonic foraminifera, especially Morozovella and Acarinina which they reflect the deep marine environment.
### Table I

**XRD Mineralogy (Major & Minor Phases) within PF1 and PF2 and Host Micritic Carbonate Rocks (MC). (BST. stands for Basalt)**

<table>
<thead>
<tr>
<th>Sample</th>
<th>Location</th>
<th>Field description</th>
<th>Major minerals</th>
<th>Minor minerals</th>
<th>Sections</th>
</tr>
</thead>
<tbody>
<tr>
<td>JB1</td>
<td>Mawat</td>
<td>Basaltic-Peperitic rocks contacted with host micritic carbonate rocks</td>
<td>Diopside and Albite</td>
<td>Sodalite and Hematite</td>
<td></td>
</tr>
<tr>
<td>JB2</td>
<td>Mawat</td>
<td>Basaltic-Peperitic rocks 50 cm away from host micritic carbonate rocks</td>
<td>Albite, Andesine and Diopside</td>
<td>Calcite and Hematite</td>
<td></td>
</tr>
<tr>
<td>JB3</td>
<td>Mawat</td>
<td>Fresh pillowed basalt 10m away from Peperitic rocks</td>
<td>Albite, Augite and Anorthite</td>
<td>Hematite</td>
<td></td>
</tr>
<tr>
<td>JB4</td>
<td>Mawat</td>
<td>Fresh pillowed basalt 12m away from Peperitic rocks</td>
<td>Albite, Andesine and Hematite</td>
<td>Calcite and Ilmenite</td>
<td></td>
</tr>
<tr>
<td>JB5</td>
<td>Mawat</td>
<td>Fresh pillowed basalt contacted with host micritic carbonate rock</td>
<td>Albite, Calcite and Ilmenite</td>
<td>Hematite</td>
<td></td>
</tr>
<tr>
<td>JB6</td>
<td>Mawat</td>
<td>Fresh pillowed basalt 12.5m away from Peperitic rocks</td>
<td>Albite, Augite and Ilmenite</td>
<td>Calcite and Hematite</td>
<td></td>
</tr>
<tr>
<td>JB7</td>
<td>Mawat</td>
<td>Fresh pillowed basalt 13m away from Peperitic rocks</td>
<td>Albite, Andesine, Augite and Ilmenite</td>
<td>Calcite and Hematite</td>
<td></td>
</tr>
<tr>
<td>JB8</td>
<td>Mawat</td>
<td>Fresh pillowed basalt 14m away from Peperitic rocks</td>
<td>Albite, Andesine and Ilmenite</td>
<td>Calcite and Hematite</td>
<td></td>
</tr>
<tr>
<td>JB9</td>
<td>Mawat</td>
<td>Fresh pillowed basalt 15m away from Peperitic rocks</td>
<td>Albite, Andesine, Augite and Ilmenite</td>
<td>Calcite and Hematite</td>
<td></td>
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<tr>
<td>JB10</td>
<td>Mawat</td>
<td>Fresh pillowed basalt 16m away from Peperitic rocks</td>
<td>Albite, Diopside, Anorthite and Ilmenite</td>
<td>Hematite</td>
<td></td>
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<tr>
<td>JB11</td>
<td>Mawat</td>
<td>Host Micritic carbonate rock, Right side of peperitic rocks</td>
<td>Calcite</td>
<td>Coloite and Quartz</td>
<td></td>
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<tr>
<td>JB12</td>
<td>Mawat</td>
<td>Host Micritic carbonate rock, Left side of peperitic rocks</td>
<td>Calcite</td>
<td>Quartz</td>
<td></td>
</tr>
<tr>
<td>JB13</td>
<td>Mawat</td>
<td>Host Micritic carbonate rock, Left side of peperitic rocks</td>
<td>Calcite</td>
<td>Quartz</td>
<td></td>
</tr>
<tr>
<td>Shale</td>
<td>Mawat</td>
<td>20 cm Thick Shale rock contacted with samples 1MP and 1MPF</td>
<td>Montmorillonite, Quartz, Calcite and Anorthite</td>
<td></td>
<td></td>
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<tr>
<td>JB14</td>
<td>Shasho</td>
<td>Vesicular- amygdaloidal basalt- Peperite</td>
<td>Albite and Diopside</td>
<td>Ilmenite and Hematite</td>
<td></td>
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<tr>
<td>JB15</td>
<td>Shasho</td>
<td>Vesicular- amygdaloidal basalt- Peperite</td>
<td>Albite and Diopside</td>
<td>Ilmenite and Hematite</td>
<td></td>
</tr>
<tr>
<td>JB16</td>
<td>Shasho</td>
<td>Vesicular- amygdaloidal basalt- Peperite</td>
<td>Albite and Diopside</td>
<td>Ilmenite and Hematite</td>
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<td>JB17</td>
<td>Shasho</td>
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<tr>
<td>JB24</td>
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<td>Micritic carbonate rock, within peperitic rocks</td>
<td>Calcite</td>
<td>Quartz and Coloite</td>
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<td>JB25</td>
<td>Shasho</td>
<td>Micritic carbonate rock, within peperitic rocks</td>
<td>Calcite</td>
<td>Quartz</td>
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### Table II

**Whole-Rock Major, Trace, and REE Concentrations (ICP-MS) of PF1 Rock Samples in the Mawat Area**

**Pepetritic Facies**

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<tr>
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<tr>
<td>Lst. Mic.</td>
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<tr>
<td>Lst. Mic. Lst.</td>
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<td>Mean Precision</td>
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</tr>
</tbody>
</table>

**Oxides (Wt.%)**

- **SiO₂**
- **Al₂O₃**
- **Fe₂O₃**
- **CaO**
- **MgO**
- **Na₂O**
- **K₂O**
- **Cr₂O₃**
- **TiO₂**
- **MnO**
- **P₂O₅**
- **SrO**
- **BaO**
- **LOI**
- **TOTAL**
- **Mg#**
- **CIA%**
- **Trace (ppm)**

- **Ag**
- **As**
- **Cd**

(Contd...)
with tropical to subtropical climate condition (BouDagher-Fadel, 2015).

Ten samples were dated using planktonic foraminifera, five samples were from peperitic rocks taken from the contact of basaltic-carbonate clasts (basal peperites). The other five samples were taken from host micritic carbonate rocks. Both of these section samples gave us the same planktonic foraminiferal assemblages permits the recognition of 15 species and subspecies in the studied sections (Fig. 8) including Morozovella praegangula; Morozovella apathesma; Morozovella angulata; Morozovella subbotinae; Morozovella accuta; Morozovella occlusal; Morozovella cf. apathesma; Morozovella velascoensis; Morozovella aequa; Acarinina nitida; Acarinina soldadoensis; Subbotina cancellate; and Globanomalina chapmani. To recognize these species, a lot of sources were used including (Cushman, 1925; White, 1928; Parr, 1938; Morozova, 1939; Toulmin, 1941; Cushman, 1942; Martin, 1943; Bronnimann, 1952; Loeblich Jr. and Tappan, 1957; Blow, 1979; Olsson, et al., 1999; Berggren, et al., 2006). The stratigraphic distribution of these planktonic foraminiferal assemblages permits the recognition of 15 biozones, two dominant biozones (P3 and P4) after (Wade, et al., 2011) have established in WVSg (Middle Paleocene). The
## TABLE III

<table>
<thead>
<tr>
<th>Peperitic Facies</th>
<th>PF2</th>
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</thead>
<tbody>
<tr>
<td>Rock type</td>
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<tr>
<td>SiO2</td>
<td>44.56</td>
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<tr>
<td>Al2O3</td>
<td>16.40</td>
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<tr>
<td>Fe2O3</td>
<td>10.55</td>
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<td>CaO</td>
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<td>MgO</td>
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</tr>
<tr>
<td>Na2O</td>
<td>3.64</td>
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<tr>
<td>K2O</td>
<td>1.28</td>
</tr>
<tr>
<td>Cr2O3</td>
<td>0.03</td>
</tr>
<tr>
<td>TiO2</td>
<td>1.15</td>
</tr>
<tr>
<td>MnO</td>
<td>0.15</td>
</tr>
<tr>
<td>P2O5</td>
<td>0.16</td>
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<tr>
<td>SiO</td>
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<td>BaO</td>
<td>0.02</td>
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<tr>
<td>LOI</td>
<td>8.74</td>
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<td>TOTAL</td>
<td>102.21</td>
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<td>Mg%</td>
<td>56.85</td>
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<tr>
<td>CI%</td>
<td>35.56</td>
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</table>
| Trace (ppm)     | (Contd...)
VI. Discussion

A. PF in WVSg

As a first attempt, in this paper, two kinds of PF have been recognized in the WVSg. However, to define any PF in any tectonic setting, two principal rules of (White, Mchpie and Skilling, 2000; Skilling, et al., 2002) must be fulfilled: (1) The presence of unconsolidated wet sediment or poorly consolidated sediment; (2) The confirmation of hot magma and its in-situ disintegration and intermingling with the host sediment. Regarding WVSg, the PF1 and PF2 possess the two principal rules as they are clearly seen in the fields. Thus, volcanic rocks and peperites are ubiquitous components within the WVSg of all studied sections in the Mawat area.

TABLE III

(Continued)

<table>
<thead>
<tr>
<th>Peperitic Facies</th>
<th>PF2</th>
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</thead>
<tbody>
<tr>
<td>Sample number</td>
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<tr>
<td>Rock type</td>
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<td>W</td>
<td>1</td>
</tr>
<tr>
<td>Y</td>
<td>24.5</td>
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<tr>
<td>Yb</td>
<td>2.67</td>
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<td>Zr</td>
<td>86</td>
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<td>Eu/Eu*</td>
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<td>(La/Sm)N</td>
<td>0.87</td>
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<td>(La/Yb)N</td>
<td>1.09</td>
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<tr>
<td>(Tb/Yb)N</td>
<td>1.08</td>
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</table>


peperitic rocks in WVSg were dated to 60 million years ago, corresponding to the Selandian stage of the Middle Paleocene, based on the presence of a Morozovella assemblage zone.

Fig. 10. Harker diagram SiO$_2$ based versus major elements (Wt.%) for the basaltic rock samples from PF1 and PF2 within WVSg.
The peperite-bearing successions in WVSg have varying thicknesses at several places across the research area, which includes the PF1 and PF2 study areas (Figs. 3-5). Their deposits are exposed in a discontinuous fashion across the entirety of the Walash volcanic arc basin (Fig. 2b), including both its eastern and western sides of the WVSg. Peperite-bearing successions are often made up of basaltic lava flows that have intruded carbonates and volcanoclastic, as their primary constituents. A deep carbonate sequence has been found in both the eastern and western sides of the PF (Figs. 3-5). This succession displays a lateral lithological change as it moves right and left flanks. In general, both PF 1 and 2 are composed of basaltic lava flows that are interlayered with deep marine-rich planktonic rocks that consist of micritic carbonate horizons.

Fig. 11. Binary plots of Zr (ppm) vs selected trace and REE elements (ppm) for the volcanic rocks within PF1 and PF2. Symbols are the same as in Fig. 10.

### Table IV

**Walash Peperite Major-Trace Elemental Ratios Comparison to the WPB-MORB and ARCB-NMORB after (Condie, 1989).**

<table>
<thead>
<tr>
<th>Major-Trace elemental ratios</th>
<th>WPB-MORB</th>
<th>ARCB-NMORB</th>
<th>Walash Peperite</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nb/La</td>
<td>&gt;1</td>
<td>≤1</td>
<td>0.47-0.77</td>
</tr>
<tr>
<td>Hf/Ta</td>
<td>&lt;5</td>
<td>≥5</td>
<td>12-22</td>
</tr>
<tr>
<td>Ti/Y</td>
<td>≥350</td>
<td>&lt;350</td>
<td>240-281</td>
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<tr>
<td>Ti/V</td>
<td>&gt;30</td>
<td>≤30</td>
<td>27-31</td>
</tr>
<tr>
<td>TiO₂%</td>
<td>&gt;1.25</td>
<td>≤1.25</td>
<td>1.04-1.2</td>
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<tr>
<td>Ta(ppm)</td>
<td>&gt;0.7</td>
<td>≤0.7</td>
<td>0.1-0.2</td>
</tr>
<tr>
<td>Nb(ppm)</td>
<td>&gt;12</td>
<td>≤12</td>
<td>2.4-3.7</td>
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</tbody>
</table>

WPB: Within Plate Basalt; MORB: Mid Oceanic Ridge Basalt; NMORB: Normal Mid Oceanic Ridge Basalt; ARCB: Arc Basalt.

### Table V

**Walash peperite Major-Trace Elemental Ratios Comparison to the NMORB and ARCB after (Condie, 1989).**

<table>
<thead>
<tr>
<th>Trace elemental ratios</th>
<th>NMORB</th>
<th>ARCB</th>
<th>Walash Peperite</th>
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<tbody>
<tr>
<td>Th/Yb</td>
<td>≤0.1</td>
<td>&gt;0.1</td>
<td>0.13-0.2</td>
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<tr>
<td>Th/Nb</td>
<td>&lt;0.07</td>
<td>&gt;0.07</td>
<td>0.11-0.2</td>
</tr>
<tr>
<td>Nb/La</td>
<td>&gt;0.8</td>
<td>≤0.8</td>
<td>0.47-0.77</td>
</tr>
<tr>
<td>Hf-Th</td>
<td>≥8</td>
<td>&lt;8</td>
<td>4.33-5.88</td>
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</table>

NMORB: Normal Mid Oceanic Ridge Basalt; ARCB: Arc Basalt.
Two types of peperite occur in the Mawat-Shasho area, these include (a) PF1 characterized by blocky peperite related to the rapid submarine eruption of basaltic rocks into wet, unconsolidated deep-marine sediments (host micritic limestone) (Figs. 3, 6, and 9). (b) PF2 is characterized by fluidal peperite associated with the more evolved palagonitized basaltic lava flows into wet, unconsolidated deep-marine sediment (Figs. 5, 7 and 9e, f). Base lithology extension of the Walash arc and PF in the Mawat area was compared with the similar peperites and their extended range from minor occurrences adjacent to igneous extrusions up to deposits with quantities of several km$^3$ within Mull lava field of NW Scotland by (Brown and Bell, 2007). In this way, the Walash arc base distance may extend to several kilometers based on petrological field evidence.

Accurate and effective volcanic age estimates necessitate a meticulous differentiation between primary and secondary volcanic deposits and volcanosedimentary rocks. Primary volcaniclastic deposits and volcano-sedimentary rocks are non-reworked deposits formed directly from volcanic eruptions (i.e., pyroclastic, autoclastic, hyaloclastic, and peperitic) (White and Houghton, 2006; Sohn and Sohn, 2019). They are distinguished from other volcaniclastic deposits that are not directly related to eruptions but are reworked, modified, and redeposited by surface or gravitational processes (e.g., tides, waves, currents, or non-eruptive gravitational density flows in the oceanic realm) and are classified as epiclastic or secondary (White and Houghton, 2006).

Contemporaneous and non-reworked beds of peperitic rocks have been found throughout the whole section of Mawat-Shasho. According to (Nayudu, 1971), it is conclusive that fossils can be discovered in primary volcaniclastic piles, even in solid basalts. When there is a good record of foraminiferal assemblages with chronostratigraphic value, such as planktonic forams, biochronostratigraphic methods can be used to date volcanic events. Dating peperitic rocks with the presence of short-geologic-range planktonic Foram species, including specifically Morozovella praeangulata and Morozovella angulata (ranging only 1–2 Ma), is vital and helpful to understand the contemporaneous idea behind the eruption of submarine volcanism into wet, unconsolidated sediments throughout the Walash volcanic area. In this

Fig. 12. Rock classification and characteristics of volcanic rocks within PF1 and PF2 (a) Zr/TiO$_2$ versus Nb/Y of (Pearce, 1996) after (Winchester and Floyd, 1977). (b) SiO$_2$ versus (FeO/MgO) diagram of (Miyashiro, 1974) and (c) La versus Yb after (Ross and Bédard, 2009), showing the tholeiitic nature of the PF1 and PF2 volcanic rocks.
particular instance, we used planktonic fauna to date volcanic rocks (contemporaneous with the age of deep-marine micritic carbonate rocks) within PF due to the absence of normative zircon and numerous problems within hydrothermally altered volcanic rocks, including grain size and freshness of phenocrysts; whole rock low K content and low K/Ca content; common replacement of crystalline plagioclase and other K-rich phenocrysts. The aforementioned obstacles represent particular difficulties for dating these volcanic rocks using U-Pb and Ar/Ar dating geochronological methods, respectively.

The results indicate that the presence of basaltic rocks, peperites, host micritic carbonate rocks, and shales with some volcaniclastic rocks as well as mélange of mentioned rocks are robust to the presence of a complex primitive volcanic arc in the studied area. Furthermore, because volcanic arcs are large and geologically comprise heterogeneous structures (Stern, 2010), different perspectives of geoscience have been used in this research, such as field investigations, geochemistry, sedimentology, and paleontology. All mentioned tools together will explain the contemporaneity of the basaltic rocks with deep marine sediments in both PF1 and PF2 and based on a precise paleontological study the peperitic rocks dated to the Middle Paleocene, that is, 60 Ma. This age represents the beginning of submarine eruptions in the initial volcanic arc stage within WVSg. These peperites and initial arc volcanic rocks were formed by the subduction of the Arabic Plate beneath the Iranian Plate (Fig. 16).

**B. Geochemical Signatures and Tectonic Implications**

The peperite concept has changed greatly since its original application, and how and where the peperite form is still a lively topic of debate. The authors precisely prepared volcanic rock samples for geochemical analysis by removing all altered and weathered parts, thus the chemical index of alteration (CIA) value is consistent with fresh basaltic rocks after Nesbitt and Young (1982) and ranging between (33.33–40.0)%.

Besides, a minor amount of nepheline in these basaltic rocks may refer to the assimilation of the basic magma with carbonate rocks (Iacono Marziano, et al., 2008), and this will allow the magma to be rich in Na and nepheline.
Fig. 14. (a) Multi-element spider diagram normalized to the primordial mantle (normalizing values are from [Wood, et al., 1979] and IAB field after [Perfit, et al., 1980]). (b) Chondrite-normalized REE patterns (normalizing values are from [Sun and McDonough, 1989]) for the basaltic rocks within PF1 and PF2 (average composition of IAB is from [Elliott, 2003], IBM Arc: Izu – Bonin – Mariana arc basalts field after [Elliott, et al., 1997]).

Considering altered arc volcanic rocks, the diagram (Zr/TiO$_2$-Nb/Y) can be used to replace the total alkali-Silica diagram (Winchester and Floyd, 1977; Pearce, 1996; Hastie, et al., 2007). It is not reasonable to use (Winchester and Floyd, 1977) classification, because it is not robust in classifying altered volcanic rocks (Hastie, et al., 2007). Thus, to determine the classification of mafic volcanic rocks from PF1 and PF2, the data were plotted on a Zr/TiO$_2$ versus Nb/Y diagram, as shown in Figure 12a. All samples fell within the basaltic field and exhibited sub-alkaline characteristics. Furthermore, their tholeiitic nature is obvious from petrochemical discrimination diagrams of SiO$_2$ versus (FeO/MgO) after Miyashiro (1974) and La versus Yb after Ross and Bédard (2009) (Fig. 12b and c). Basaltic rocks within both PF are characterized by the following elemental ratios: low Nb/Y (0.10-0.15), La/Yb (1.4–2.3), and Nb/La (0.61–0.77); adequately high Zr/Nb (23–30), HF/Ta (12–22) and Th/Ta (2–5); relatively low contents of major elements like TiO$_2$ and P$_2$O$_5$ (Tables II and III) in contrast to the high ratios of FeO/MgO, which are diagnostic features of subalkaline (tholeiitic) rocks in primitive arc basalts (Miyashiro, 1974; Winchester and Floyd, 1977; Condie, 1989; Ross and Bédard, 2009).

Using Condie (1989) basaltic trace elemental ratios, a comparison is made between the Walash peperite and the various types of basalt, such as Within Plate Basalt-Normal Mid Oceanic Ridge Basalt (WPB-NMORB) and Arc Basalt-Normal Mid Oceanic Ridge Basalt (ARCB-NMORB). The trace elemental ratios of Walash peperite are in agreement with those of ARCB and NMORB (Table IV). It should be noted that the ARCB and NMORB are difficult to

Fig. 15. Biozonation study for Paleocene peperitic rocks (PF1) within WVSg. Ages after (Cohen, et al., 2021)

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**Table I**

<table>
<thead>
<tr>
<th>Age (Ma)</th>
<th>Epoch</th>
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<tbody>
<tr>
<td>65-66</td>
<td>Early</td>
<td>Danian</td>
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</tbody>
</table>
| 64-65    | Early | Paleocene
| 63-64    | Early | Selandian|
| 62-63    | Early | Thanetian|
| 61-62    | Early | Eocene
| 60-59    | Early | Ypresian|
| 58-57    | Early | ?
| 56-55    | Early | ?
| 54-53    | Early | ?
| 52-51    | Early | ?
| 50-49    | Early | ?

**Table II**

- **Species found in Peperitic rocks only**
- **Species found in Mic Carbonate rocks only**
- **Same Species found in both Peperites and Mic Carbonate rocks**

**Table III**

- **Morozovella praesangula**
- **Morozovella apenthosa**
- **Morozovella angulata**
- **Morozovella subbotinae**
- **Morozovella acuta**
- **Morozovella obtusa**
- **Morozovella cf. apenthosa**
- **Morozovella velascoensis**
- **Morozovella aqua**
- **Acarinina nitida**
- **Acarinina soldadoensis**
- **Sabotina cancellata**
- **Globorotalia chapmani**
differentiate in general; however, using several different ratios of trace elements, such as Th/Yb, Th/Nb, Nb/La, and Hf/Th (Tables IV and V), it is possible to overcome this issue (Condie, 1989).

Using trace elemental ratios, such as Nb/Th and Zr/Nb, the arc basaltic source for Walash peperites can be distinguished from the NORMB basaltic source (Fig. 17). According to Condie (2005), arc basalts may have similar Zr/Nb ratios, but they are quite different in Nb/Th ratios. Thus, arc basaltic sources for Walash peperite on an Nb/Th–Zr/Nb plot seem robust. Furthermore, the headed arrows are quite consistent with the Walash volcanic data, which indicate subduction-related derived fluid effects (Condie, 2005).

Based on the primitive mantle-normalized multielement spider diagram (Fig. 14a), the basaltic rocks in both PF1 and PF2 show selective enrichment in LILEs (e.g., Rb, Ba, and K) and depletion in HFSEs (e.g., Ta, Nb, Nd, and Ti) indicate an arc volcanic feature (Saunders and Tarney, 1979) and compared with the field of IAB after (Perfit, et al., 1980). While on the REE chondrite-normalized diagram (Fig. 14b), these basaltic rocks are characterized by slight enrichment and with flat REE patterns which is consistent with the same normalized ratio of (La/Yb) ≈1 for IAB (Perfit, et al., 1980; Philpotts and Ague, 2022). As well as, the absence of the negative Europium (Eu) anomaly suggests that the plagioclase role is insignificant during magma evolution in the area (Slovenec, Lugovic and Vlahovic, 2010; Philpotts and Ague, 2022). Furthermore, in Figure 14a and b, these basaltic rocks were compared and consistent with the average composition of IAB after (Elliott, 2003) and Izu-Bonin-Mariana arc basalts (IBM Arc) field after (Elliott, et al., 1997).

However, PF1 and PF2 basaltic rocks have a geochemical affinity to normal island arcs. In the Sr/Y versus Y diagram (Fig. 18a), basaltic rocks were plotted in the normal island arc magma field suggesting a high concentration of Y with low concentration ratios of Sr/Y. This low ratio of Sr/Y suggests partial melting or fractionation at lower pressure (<≈1 GPa.), in addition, the absence of garnet ± amphibole will cause Y to behave incompatibly, and simultaneously stable plagioclase absorbs Sr as a result, a melt with low Sr/Y will form (Lieu and Stern, 2019). Based on these incompatible trace ratios and tectonic models of Lieu and Stern (2019), we infer that basaltic rocks in the PF1 and PF2 were generated by the partial melting of subducted slabs deep within 30 km and accompanying derived fluids above the subducted slab.
Furthermore, positive Sr, Ba, and K and negative Nb and Ta anomalies indicate magma generated at the subduction zone (Pearce, 1983). Peperites uniquely suggest a tectonic signature for the submarine eruptions into host sediments. However, their identification indicates contemporaneous magmatism and sedimentation. It helps to reconstruct facies architecture, paleoenvironmental conditions, and tectonic settings. In this circumstance and using available data, the PF1 and PF2 volcanic rocks yielded a primitive arc setting. As well as, their formation in the spreading center of the Island basalts suggest their eruption might happen at the initial arc stage of the volcanic arcs in the arc fronts (Fig. 6, 7, 16).

VII. Conclusions

Peperitic rocks in WVSg are classified into blocky and globular (fluidal) peperitic rocks based on field investigations and textural evidences. In contrast to previous interpretations of the Walash stratigraphy base unit as volcaniclastics, detail mapping and petrological study during this work have revealed a coherent stratigraphy of volcano-sedimentary made up of intrusions of basaltic pillow lavas into micritic carbonate sequence. The newly mapped unit nominated as PF, outcropped in two locations consequently as PF1 and PF2, are texturally classified as blocky and fluidal peperitic rocks, respectively. Volcanic intrusions in the PF classified as basaltic rocks showing tholeiitic magma series based on geochemical signature and positive Sr, Ba, and K and negative Nb and Ta anomalies indicate magma generated at the subduction zone. Dating of the host micritic carbonates and sedimentary clasts in contact with the basaltic rocks within the base of the Walash arc (Fig. 7).
suggests a spreading center of arc front at the early stage of the Walash volcanic arcs.

In summary, for the first time, we have reported the simultaneous occurrence of basaltic pillow lava and deep-marine mafic carbonate rocks using comprehensive and precise field investigations, petrological, geochemical, and biostratigraphical studies. The identified peperites present within the WVSg indicate simultaneous volcanism and sedimentation and that the Neo-Tethys was still open throughout the Paleocene (~60 Ma).

Acknowledgments

The authors are grateful to Dr. Yadolah Ezampanah from Bu-Ali Sina University (Hamadan, Iran) and Professor Dr. Khalid M. I. Sharbazhери from Sulaimani University (Sulaimani, Kurdistan Region-Iraq) for their help in recognizing and identifying the planktonic species.

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http://dx.doi.org/10.14500/aro.11363


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