Olivine basalt and trachyandesite peperites formed at the subsurface/surface interface of a semi-arid lake: An example from the Early Miocene Bigadiç basin, western Turkey

Fuat Erkul *, Cahit Helvacı, Hasan Sözbilir

Dokuz Eylül Üniversitesi, Mühendislik Fakültesi, Jolojoji Mühendisliği Bölümü, 35100 Bornova, İzmir, Turkey

Received 3 June 2004; received in revised form 5 July 2005; accepted 18 July 2005

Abstract

Miocene successions in western Turkey are dominated by lacustrine, fluvial and evaporitic sedimentary deposits. These deposits include considerable amounts of volcaniclastic detritus derived from numerous NE-trending volcanic centres in western Turkey as well as in the Bigadiç region. Early Miocene syn-depositional NE-trending olivine basalt and trachyandesite bodies that formed as intrusions and lava flows occur within the Bigadiç borate basin. Olivine basalts occur as partly emergent intrusions, and trachyandesite dykes fed extensive lava flows emplaced in a semi-arid lacustrine environment.

Peperites associated with the olivine basalt and trachyandesites appear to display contrasting textural features, although all the localities include a large variety of clast morphologies from blocky to fluidal. Fluidal clasts, mainly globular, ameboidal and pillow-like varieties, are widespread in the peperite domains associated with olivine basalts, apparently due to large-volume sediment fluidisation. In contrast, fluidal clasts related to trachyandesites are restricted to narrow zones near the margins of the intrusions and have commonly elongate and polyhedral shapes with digitate margins, rather than globular and equant varieties. Blocky and fluidal clasts in the olivine basalt peperite display progressive disintegration, suggesting decreasing temperature and increasing viscosity during fragmentation. Abundance of blocky clasts with respect to fluidal clasts in the trachyandesite peperite indicates that the fluidal emplacement and low-volume sediment fluidisation in the early stages were immediately followed by quench fragmentation due to the high viscosity of the magma.

Size, texture and abundance of the blocky and fluidal clasts in the olivine basalt and trachyandesite peperites were mainly controlled by sediment fluidisation, pulsatory magma injection and magma properties such as composition, viscosity, vesicularity, and size, abundance and orientation of phenocrysts. Variousy combining these contrasting features to varying degrees may form diverse juvenile clast shapes in peperitic domains.

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Keywords: hypabyssal; peperite; semi-arid lake environment; Early Miocene; Bigadiç basin; western Turkey

* Corresponding author. Tel.: +90 232 3887866; fax: +90 232 3887865.
E-mail address: fuat.erkul@deu.edu.tr (F. Erkul).
1. Introduction

Magma–sediment interaction is common, especially in arc-related volcanic complexes accompanying continuous sedimentation in a subsiding basin (e.g., Hanson and Hargrove, 1999; Mueller et al., 2000; Dadd and Van Wagoner, 2002; Skilling et al., 2002; Templeton and Hanson, 2003). Sediment + igneous rock breccia is widely formed at the contacts between sediments and magma or hot volcaniclastic deposits. This lithofacies is distinguished as peperite, referring to a genetic name that describes a rock formed by mixture of unconsolidated, poorly consolidated or wet sediment and disintegrated magma (White et al., 2000; Skilling et al., 2002). Recognition of peperite is useful to establish emplacement mode of the igneous bodies, palaeoenvironmental reconstruction and relative contemporaneity of intruding magma and sedimentary host rock. Peperite might also be closely associated with hydrothermal systems and mineralisation due to magmatic fluid contributions into a basin and therefore their identification can be economically important (Delaney, 1982; McPhie and Orth, 1999).

Although peperite occurrences are common from submarine environments, subaerial examples are also known. Peperitic textures are formed by diverse volcanic processes in subaerial settings such as pyroclastic flows, phreatomagmatic eruptions and lava flows (Schmincke, 1967; Branney, 1986; Leat and Thompson, 1988; White, 1991; Rawlings and Sweeney, 1999; Hooten and Ort, 2002; Jerram and Stollhofen, 2002; Lorenz et al., 2002; McClintock and White, 2002; Zimanowski and Buttner, 2002). Controls on the formation of peperite and influencing factors based on field and experimental data are well documented in the literature (Skilling et al., 2002 and references therein). However, peperite occurrences identified in lacustrine settings are limited (e.g., Cas et al., 2001).

In this paper we describe peperites formed in association with olivine basaltic and trachyandesitic intrusive rocks emplaced in a semi-arid lacustrine setting. The lacustrine basin fill hosts the largest borate reserves in the world (Helvacı, 1995). The aim of this study is to compare the contrasting peperitic textures related to coeval syn-depositional intrusions of different composition. Emphasis is placed on mode of emplacement of the syn-depositional magmas, their interaction with lacustrine sediments, and hydrothermal systems in the Bigadiç borate basin. Field-based work included 1:25,000 scale geological mapping with description of the peperitic textures based on two dimensional outcrop-scale observations along road sections and small quarries. Outcrops lack tectonic overprints and major hydrothermal alteration, allowing insight into modes of magma emplacement and related peperite formation. XRF and ICP-MS analyses were also performed on representative samples from the syn-depositional intrusive and extrusive bodies and plotted onto geochemical discrimination diagrams in order to characterise their compositions.

2. Regional setting

In western Turkey, the pre-Miocene basement rocks – Menderes Massif, Sakarya Zone, Lycian Nappes and the Bornova Flysch Zone, Eocene Başlamış Formation and Oligocene detrital rocks – have undergone extensional deformation since the late Oligocene, leading to the formation of NE-trending basins and E–W-trending grabens (Akdeniz, 1980; Seyitoğlu and Scott, 1991, 1992; Okay et al., 1996; Yılmaz et al., 2000; Bozkurt, 2001a,b; Bozkurt and Oberhansli, 2001; Özer et al., 2001; Seyitoğlu et al., 2002; Sözbilir, 2001, 2002a,b; Bozkurt, 2003; Özer and Sözbilir, 2003; Beccalletto and Jenny, 2004; Bozkurt and Sözbilir, 2004; Erdoğan and Güngör, 2004; Duru et al., 2004; Göncüoğlu et al., 2004; Koralay et al., 2004; Okay and Altiner, 2004; Okay and Göncüoğlu, 2004; Turhan et al., 2004; Purvis and Robertson, 2004, 2005a,b) (Fig. 1a). The NE-trending basins are cut by the E–W trending grabens, which likely formed under an N–S extensional regime existing since the Tortonian (Şengör and Yılmaz, 1981; Şengör et al., 1985; Şengör, 1987). The Gördes, Demirci, Selendi and Uşak-Güre basins have formed in NE-trending grabens that are bounded by oblique-slip faults (Şengör, 1987; Bozkurt, 2003) (Fig. 1b). One of the NE-trending basins, the Bigadiç borate basin, is located on the Bornova Flysch Zone of Late Cretaceous–Palaeocene age. The basin and its basement are restricted between the Sakarya Zone to the north and Menderes Massif to the south.
Widespread magmatic activity occurred during formation of the NE-trending basins and produced shallow-seated granitic intrusions and associated extrusive rocks (Yılmaz, 1989; Altunkaynak and Yılmaz, 1998; Karacık and Yılmaz, 1998). The Miocene successions in western Turkey are dominated by lacustrine, fluvial and evaporitic sedimentary deposits (Helvaci and Yagmurlu, 1995). The sedimentary deposits include considerable amounts of volcaniclastic detritus derived from numerous NE-trending volcanic centres in western Turkey as well as in the Bigadiç region (Seyitoglu and Scott, 1991; Seyitoğlu et al., 1992; Helvaci, 1995; Helvaci et al., 1993; Altunkaynak and Yılmaz, 1998; Genç, 1998; Karacik and Yılmaz, 1998; Helvaci and Alonso, 2000; Yılmaz et al., 2000; İnci, 2002; Bozkurt, 2003). Another common feature of the NE-trending basins is the presence of central volcanoes that cut or interfinger with basin fill deposits (Seyitoğlu and Scott, 1994; Seyitoğlu, 1997; Bozkurt, 2003; Purvis and Robertson, 2004, 2005a,b). Products of central volcanism include lava flows, pyroclastic and volcanogenic sedimentary rocks. These central volcanoes are thought to have been controlled either by an extensional tectonic regime within rift-type basins (Seyitoglu and Scott, 1994) or by strike-slip structures within pull-apart type basins (Bozkurt, 2003).

3. Local stratigraphy

3.1. Pre-basin fill units

The pre-basin fill units consist of the Late Cretaceous–Palaeocene Bornova Flysch Zone and the Early Miocene Kocaiskan volcanic unit (Figs. 2 and 3). The Bornova Flysch Zone is a NE-trending and 50–90 km wide chaotically deformed zone (Okay et al., 2001) (Fig. 1a). It comprises flysch-type sedimentary rocks including sandstone, shale and limestone with large recrystallised limestone olistoliths and ophiolitic tectonic slices.

The Kocaiskan volcanic unit is characterised by andesitic rocks that cover more than 800 km² and unconformably overlie the Bornova Flysch Zone.
The unit includes andesitic intrusions, lava flows, pyroclastic rocks and widespread volcanogenic sedimentary rocks (Erkul et al., in press(a,b)). The andesitic rocks mainly formed under subaerial conditions, producing a stratovolcano that was subsequently partly eroded and covered unconformably by the lacustrine basin fill deposits. For more information about pre-basin fill units, readers are referred to Okay and Siyako (1993), Helvacı (1995), Gündoğdu et al. (1996), Okay et al. (1996, 2001), Erkul (2004) and Erkul et al. (in press(b)).

3.2. Basin fill units

The Bigadiç borate basin consists of lacustrine clayey, calcareous and tuffaceous sedimentary rocks (e.g., lower limestone unit, lower tuff unit, lower borate unit, upper tuff unit, upper borate unit) that interfinger with coherent volcanic rocks (e.g., Sundurg volcanic unit, Gölçük basalt, Kayılar volcanic unit, Şahinkaya volcanic unit) (Fig. 2). Volcanism accompanied lacustrine sedimentation from approximately 20 to 18 Ma (Fig. 3). The lacustrine sedimentary rocks and syn-depositional volcanic rocks are grouped in the Bigadiç volcano-sedimentary succession (BVS) with a maximum thickness reaching up to 700 m. Readers are referred to Helvacı (1995), Gündoğdu et al. (1996), Erkul (2004) and Erkul et al. (in press-b) for detailed descriptions of the rock units within the BVS.

Lamination, syn-sedimentary slumps and dessication cracks are common sedimentary structures within
the sedimentary rocks (Helvacı and Orti, 1998; Helvacı and Alonso, 2000). The lacustrine sedimentary deposits in the Bigadiç borate basin are thought to have formed in intracontinental shallow lakes such as playas, perennial interconnected saline and ephemeral lakes in arid to semi-arid environments (Helvacı and Firman, 1976; Helvacı, 1995; Palmer and Helvacı, 1995, 1997; Floyd et al., 1998; Helvacı and Orti, 1998).

Felsic volcanic rocks, the Sındırçı volcanic unit, cover an area larger than 400 km² in the eastern and southern parts of the study area (Fig. 2). They comprise widespread lavas, autobreccias, welded and non-welded ignimbrites and ash-fall deposits. The lower tuff unit comprises interbedded crystal-rich volcaniclastic sandstone and vitric siltstone; they are thought to have been emplaced in both subaerial and lacustrine environments as debris flow and ash-fall deposits, respectively (Erkül, 2004). The crystal-rich sandstone is massive to planar stratified and made up of quartz, biotite, plagioclase and hornblende crystals, with pumice and minor limestone fragments derived from the underlying sedimentary rocks. The vitric siltstone is distinguished by its conchoidal fracture and comprises biotite fragments up to 0.5 mm and altered volcanic glass. The upper tuff unit is greenish in colour, and comprises variable amounts of pumice and lithic clasts in an ash-grade matrix. Distal parts of the unit are planar stratified, lack coarse-grained clasts, and consist entirely of volcanic glass. The upper tuff unit is interpreted to have formed by pyroclastic flow and fall processes within subaerial and lacustrine environments (Gündoğdu et al., 1996; Erkül, 2004). Both lower and upper tuff units locally contain zeolite minerals such as clinoptilolite.

<table>
<thead>
<tr>
<th>Event</th>
<th>Age (mil. yrs)</th>
<th>Source</th>
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</thead>
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<tr>
<td>Lower Tuff Unit</td>
<td>19.0 ± 0.4 (1)</td>
<td>Erkül et al. (in press(a,b))</td>
</tr>
<tr>
<td>Lower Tuff Unit</td>
<td>19.5 ± 0.4 (5)</td>
<td>Gündoğdu et al. (1989)</td>
</tr>
<tr>
<td>Lower Tuff Unit</td>
<td>19.8 ± 0.3 (5)</td>
<td>Krushensky (1976)</td>
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<tr>
<td>Lower Tuff Unit</td>
<td>20.3 ± 0.3 (3)</td>
<td>Helvacı (1995)</td>
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<td>Lower Tuff Unit</td>
<td>20.8 ± 0.7 (3)</td>
<td>Benda et al. (1974)</td>
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Fig. 3. Simplified stratigraphic column of the Bigadiç borate basin. Asterix illustrates K–Ar ages of a rock in millions of years. Numbers in parentheses indicate age data sources: (1) Erkül et al. (in press(a,b)), (2) Gündoğdu et al. (1989), (3) Krushensky (1976), (4) Helvacı (1995) and (5) Benda et al. (1974).

The uppermost volcanic unit in the BVS, the Şahinkaya volcanic unit, is located in the southern part of the Bigadiç area and represents the latest volcanism in the basin. The unit consists, from limited exposures, of basaltic andesite intrusive rocks, and massive and autobrecciated lava flows interbedded with thin-bedded ash-fall deposits. The BVS is unconformably overlain by Upper Miocene–Pliocene continental deposits. Only volcanic units related to the formation of peperite are described in detail below.

4. Peperite-related volcanic units

Peperite-related volcanic units within the BVS crop out intermittently along a 35-km-long NE-trending zone within the lacustrine sedimentary rocks. Two volcanic units are recognised based on their composition, the Gölcük basalt and the Kayırlar volcanic unit (Fig. 4). The Gölcük basalt is alkaline–subalkaline basalt and basaltic trachyandesite in composition, while the Kayırlar volcanic unit plots in the andesite and trachyandesite field (Fig. 4a–c, Table 1). Field relationships and K–Ar ages from the Gölcük basalt and Kayırlar volcanic unit indicate that they were emplaced synchronously (Erkül et al., in press(a,b)) (Fig. 3).

![Graphs showing geochemical discrimination diagrams for Gölcük basalt and Kayırlar volcanic unit](image-url)

Fig. 4. Representative samples from lavas of the Gölcük basalt and Kayırlar volcanic unit plotted on the various geochemical discrimination diagrams. (a) TAS variation diagram (after Le Maitre et al., 1989), (b) Zr/TiO₂ vs. Nb/Y classification diagram (Winchester and Floyd, 1977) and (c) SiO₂ vs. Zr/TiO₂ classification diagram (Winchester and Floyd, 1977). See also Section 4.2 for detailed description of the plagioclase- and sanidine-phyric trachyandesites.
4.1. Gölcük basalt

The Gölcük basalt comprises olivine basalt dykes and lava domes and is located in a 25-km NE-trending zone north of Gölcük to Babaköy and Çamköy (Fig. 2). North of Gölcük, an olivine basalt dyke intrudes the lacustrine sedimentary rocks of the BVS (Fig. 5). The dyke is up to 100 m thick, dips vertically and extends 4 km. The eastern contact of the dyke with massive and laminated limestone is sharp and linear, whereas the western contact is fault-controlled with the Kocaiskan volcanic unit. The dyke is highly vesicular. The vesicles are commonly filled by secondary minerals such as quartz, calcite and zeolites and constitute about 30–40 vol.% of whole-rock.

To the west of Çukurdere, lava domes are of small-volume and display circular and elliptical outlines in a plan view. Each lava dome covers an area up to 1 km². The inner part of the domes is massive and poorly vesiculated, but vesicularity increases toward the marginal contacts. The lava domes rarely contain shale and quartzite clasts up to 5 cm long derived from the underlying basement rocks. Upper contacts of the lava domes are concordantly overlain by massive and

<table>
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<th>XRF major- and trace-element analyses from Gölcük basalt and Kayırlar volcanic unit</th>
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<tr>
<td>TiO₂</td>
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<tr>
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| Trace elements (ppm)
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<td>Cu</td>
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<td>Pb</td>
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<tr>
<td>Zn</td>
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</tbody>
</table>

Fe₂O₃* = total iron, LOI = loss on ignition.

a Whole-rock major element analyses were completed at the Mineralogical–Petrographical and Geochemical Research Laboratories (MIPJAL) of the Geological Engineering of Cumhuriyet University in Sivas, Turkey using a Rigaku E-WDS-3270 X-ray fluorescence spectrometer. Sample preparation procedures and calibration standards are presented by Boztuğ (2000).

b The trace element analyses were performed using ICP-MS by ACME Analytical Laboratories Ltd. in Canada and powdered samples were fused by LiBO₂.
laminated clayey limestones while lower contacts are intrusive (Fig. 6a,c,e). Olivine basalt domes display at the upper contacts typical flow foliation, and contain sub-horizontal elongate vesicles (Fig. 6b). The intrusions at the lowermost part of the lava domes are characterised by a peperitic contact zone and up to 10-cm long flow-aligned elongate vesicles that are subvertical and more or less parallel to the contact with sedimentary host rock. The contact zone between the intrusive lower part and the lava domes is characterised by a breccia that comprises fluidal clasts surrounded by banded carbonate and silica as vug-infill (Fig. 6d). The olivine basalt is composed of phenocrysts of olivine, rare plagioclase and augite in an intersertal groundmass of plagioclase microlites and argilised volcanic glass. The olivine phenocrysts are usually subhedral to euhedral and are commonly altered to iddingsite and serpentine.
4.2. Kayırlar volcanic unit

The Kayırlar volcanic unit is located in the north-east of the study area, covering about 20 km² around Kayırlar and Doğançam districts (Fig. 2). The unit comprises trachyandesitic dykes and associated massive and autobrecciated lava flows. The dykes that fed extensive lava flows intrude massive limestone and are characterised by unidirectional subvertical flow foliations and phenocryst orientations. The dykes...
trend N40°E in direction, have a uniform width of about 100 m and extend about 1.5 km in the Doğançam area (Fig. 7). Subsidiary dykes, up to 1 m wide, and elongate bodies with fluidal contacts, also occur perpendicular to the NE-trending main dykes. Trachyandesitic lava flows form a lens-shaped body at least 6 km long that is intercalated with lacustrine sedimentary rocks. The maximum thickness of the lava flows is up to 400 m in the Kayırılar area. Subhorizontal flow banding and subvertical polyhedral columnar jointing are major diagnostic features of the lava flows at outcrop-scale. Autobrecciated lava flows form lens-shaped beds separating the volcanioclastic sandstones and overlying coherent lava flows. They are characterised by angular, partly in situ fragmented and monomictic clasts up to 20 cm long embedded in a lava–fragment matrix. The lower contact of the lava flows and autobreccias is only exposed in the Doğançam area where they conformably overlie crystal-rich volcanioclastic sandstones (Fig. 8a). The upper lava contact is sharply overlain by stratified silica-rich limestone containing abundant chert bands and nodules (Fig. 8b).

There are two contrasting trachyandesite compositions: plagioclase-phyric and sanidine-phyric. Trachyandesitic dykes and lava flows contain abundant ellipsoidal microcrystalline enclaves. The plagioclase–phyric trachyandesite is exposed in the Doğançam area, forming dykes and associated flows. It is commonly porphyritic with phenocrysts of euhedral to subhedral plagioclase, biotite, hornblende, clinopyroxene and minor quartz, apatite and opaque phases within hyalopilitic matrix formed by small microlites and volcanic glass. Phenocrysts make up to 50 vol.% of whole-rock. Microcrystalline enclaves display typical ophitic texture and consist of abundant plagioclase, clinopyroxene and hornblende. The sanidine-phyric trachyandesites occur as flows that are widely exposed in the southeastern part of Kayırılar. They differ from the plagioclase-phyric trachyandesite in containing up to 2–3 cm long sanidine and abundant corroded quartz phenocrysts. Mafic enclaves are oli-

![Fig. 7. Geological map of the Doğançam area illustrating peperite outcrops associated with the Kayırılar volcanic unit. See Fig. 2 for location of the map.](image-url)
vine basalt, showing similar mineralogic composition to the Gölcük basalt.

5. Field evidence for magma/wet sediment interaction

5.1. Peperitic textures associated with Gölcük basalt

Peperitic textures are only exposed at the lowermost contact of the olivine basalt domes with the massive limestone along a 30-m-wide zone, but are also associated with intrusions that fed the lava domes (Fig. 6). Olivine basalt clasts in the peperite domain are monomictic and have mixed morphologies such as blocky, fluidal and globular (Busby-Spera and White, 1987; Doyle, 2000; Skilling et al., 2002). They are variable in size, ranging from a millimetre to decimetres long, and are closely packed or dispersed within micritic limestone. Although micritic limestone as host sedimentary rock is massive in the peperite domain, it commonly displays planar and laminated stratification away from the intrusive contacts.

The dome-feeding intrusive bodies are surrounded by subsidiary lobe-shaped intrusions that are connected to the main body or isolated in the sedimentary host rock. Chilled margins are found along fluidal margins of the intrusions, lobes and clasts in the peperite domain. The lobes are subhorizontally oriented, enclosed by peperitic breccia and display folds that partially enclose massive limestone (Fig. 9a). Olivine basalt lobes are amygdaloidal up to 2 m long and a few decimetres thick. Vesicles are spherical or ellipsoidal up to 1 cm long and infills commonly
Fig. 9. Peperitic textures related to olivine basalts. (a) Polished slab from the longitudinal section of an olivine basalt lobe (b) showing folded flow pattern (broken line) with enclosed massive limestone (s). The lobe contains irregular, chilled (arrow) and brecciated margin (p), and hairline cracks (solid lines). (b) Dispersed tapered and platy lava clasts (b) with digitate margins within micritic limestone (ls). Clasts are highly vesicular and vesicles are filled by micritic limestone near the margin. Note also incomplete brecciation of the tapered clast (arrow). (c) Globular clasts with irregular margins surrounded by non-stratified micritic limestone. (d) Amoeboidal-shaped margins of vesicular olivine basalt clasts in micritic limestone. White circles indicate the micritic limestone-filled vesicles near the contact. Note progressive disintegration of the clasts along irregular cracks (arrow), grading to dispersed peperite. Hairline cracks may partially cut the fluidal clasts and form incomplete brecciation. Disintegrated clasts show both irregular and curviplanar margins. (e) Pillow-like lobe cut by hairline cracks parallel and perpendicular to margin. The lobe is gradually disintegrated from margin to host sedimentary rock and is surrounded by variably shaped, rotated and in situ fragmented clasts. (f) Vug-infill quartz and carbonate mineralisations within peperitic domain. In situ fragmented clasts are also surrounded by carbonate and silica (black arrow). b: basalt clast, v: vugs, q: colloform–crustiform veining. Note also the fluidally shaped margins of juvenile clasts (white arrow).
have a quartz core and carbonate rim. Some lobes were fragmented in situ and display jig-saw fit texture. The in situ fragmented clasts are variably shaped, but are predominantly platy and tapered with digitate margins. Platy and tapered clasts, reaching up to 40 cm long, are usually sparsely packed within micritic limestone. They locally grade into elongate clasts a few centimetres long derived from the margin (Fig. 9b). The orientation of the platy clasts, as well as hairline cracks filled by limestone, is more or less parallel to the margin of the lobes. Globular clasts are up to 3 cm in diameter and partly interconnected. Each clast displays fluidally shaped sharp contact with sedimentary host rock (Fig. 9c). Some clasts have spongy margins and are amoeboidal in shape; these are commonly intersected by hairline cracks with micritic limestone infill. Hairline cracks that irregularly intersect highly vesicular clasts partially form typical jig-saw fit textures. Amoeboid-shaped olivine basalts are progressively disintegrated into smaller, from a millimetre to 5 cm long, dispersed clasts displaying both fluidal and curviplanar margins (Fig. 9d). Vesicles at the marginal parts of the amoeboid-shaped clasts are filled with micritic limestone as a host rock.

Pillow-like lobes are up to 40 cm in diameter, and are enclosed within peperite domains (Fig. 9e). They have low vesicularity in the cores, increasing toward the margins. Hairline cracks, which are commonly filled by micritic limestone and quartz, occur parallel or perpendicular to the margins. Progressive disintegration toward the margin is common, generating platy and tapered clasts up to 20 cm long along the pillow-like lobes. Peperite breccias have also formed near the lobe cores due to penetration of sediment along fine irregular cracks.

Stockwork quartz and carbonate veins and vug-infills within peperitic contact zones, locally exposed in the southern part of Dastepe, characterise hydrothermal mineralization. Quartz and carbonate mineralisation is well-developed within the interconnected vugs that are surrounded by fluidally shaped olivine basalt clasts (Figs. 6d and 9f). Chalcedony and opaline silica are usually colloform–crustiform banded, and partly crystalline. The mineralisation only occurs within the peperitic zone and terminates at the contact between the olivine basalt and overlying limestone at the uppermost part.

5.2. Peperitic textures associated with Kayırlar volcanic unit

Peperitic textures around Doğançam area are only exposed along NE-trending plagioclase-phyric dykes (Fig. 7). A closely packed sediment–trachyandesite breccia comprises mainly blocky and minor fluidal clasts. It is closely associated with subsidiary dykes emplaced in a perpendicular direction to the NE-trending dykes, and is interpreted as peperite breccia. The 10-m-wide contact zone is also characterised by quartz veining and intense silicification of the sedimentary host rock, which is locally brecciated.

Subsidiary dykes exhibit both curviplanar and fluidal contacts with massive and silicified limestone host rock. Dykes with curviplanar margins were emplaced as subvertical bodies and contain irregular cracks a few centimetres wide filled by silicified limestone; they are enclosed by a breccia that contains blocky, angular, platy and tapered clasts. Clast size is commonly bimodal, ranging from a millimetre to a few centimetres and up to 10–30 cm long. Blocky and tapered clasts are usually aligned parallel to the mar-

Fig. 10. Peperitic textures related to plagioclase-phyric trachyandesites of the Kayırlar volcanic unit. (a) Partially in situ fragmented, tapered clast (arrow) detached from subsidiary dyke (td) intersecting intensely silicified and brecciated limestone (sl). Broken white line indicates sediment invasion along a fracture within the subsidiary dyke. (b) Mesoblocky clasts partly displaying in situ fragmentation. Mesoblocky clasts are enveloped by a few millimetres thick chalcedony rim. Note also fluidal margins of the mesoblocky clasts (black arrow) and planar curviplanar margins of the in situ fragmented blocky clasts (white arrow). (c) Assimilated limestone block (ls) within main trachyandesite dyke (td) displaying irregular contact relationships. (d) Close-up of the contact between the trachyandesite and the assimilated limestone block consisting of angular juvenile clasts with hairline cracks and partial jig-saw fit texture. (e) Polished slab near the contact between subsidiary dyke and sedimentary host rock, showing stratification and syn-sedimentary deformation such as clast rotation (rc), pipeline channels (pl) and slump structures within peperite domain. Host sedimentary rock surrounding the rotated juvenile clasts is composed of silicified (s) and micritic limestone (ml), showing syn-sedimentary deformation. Note also stratification of silicified and micritic limestone layers. (f) Silicified limestone-filled vugs surrounded by in situ fragmented polyhedral clasts. Central part of the limestone is more intensely silicified than that of margin. (g) Brecciated limestone with greyish silica matrix, partly enclosing blocky clasts with jig-saw fit texture.
gin of subsidiary dykes, and are disintegrated into smaller angular clasts forming jig-saw fit textures (Fig. 10a). Phenocrysts within the subsidiary dykes are also oriented parallel to the margins. Blocky clasts are commonly polyhedral with planar–curviplanar and digitate margins, and rarely connected to the dykes by fluidal necks (Fig. 10b). No chilled margins were recognised on the in situ fragmented blocky clasts. The margins of the blocky clasts are usually digitate, with millimetre-scale salients into the host rock. Hairline cracks filled by host rock are also common in the blocky clasts. Some of the blocky and tapered clasts are rimmed by 3–4 mm thick chalcedony. Platy clasts locally display random orientation, suggesting clast rotation.

The NE-trending intrusive body appears to contain large limestone blocks assimilated by the trachyandesite. Limestone blocks may reach up to 2 m in diameter, including altered trachyandesite clasts up to 10 cm long (Fig. 10c). We infer that trachyandesite magma was injected along fractures developed in massive limestone. The contacts between trachyandesite and assimilated limestone are irregular, and in places are lined with angular clasts displaying jig-saw fit texture (Fig. 10d).

Limestone as a host rock in the peperite domain is composed entirely of micritic calcite and is distinguished by white to creamy colours. It contains silicified and brecciated horizons near the intrusive contact. Although it is commonly massive, it may locally display stratification perpendicular to the dips of the dykes near their contacts, where blocky clasts are abundant. Stratified limestone is interbedded with silicified and clast-dominated horizons, which display syn-sedimentary deformation such as folding, load casts and 3 cm long pipe-like structures locally intersecting stratification (Fig. 10e).

Silicification of the sedimentary host rock, quartz veins and breccia zones is common, but is mainly restricted to the peperitic contact zone in the Doğançam area. Silicification usually occurs around breccia zones and blocky peperites. The in situ fragmented blocky clasts are enclosed by silicified limestone, locally as vug-infill displaying intense silicification parallel to margin of clasts in the core and less silicified at the margin of the trachyandesite clast (Fig. 10f). Intensely silicified parts of massive limestone contain a monomictic breccia zone with angular limestone clasts up to a few centimetres long. Breccia matrix surrounding the blocky clasts is made up entirely of angular silicified limestone clasts enveloped by dark coloured chalcedony (Fig. 10g). Limestone clasts in the breccia zone are polyhedral and rarely in situ fragmented. Colloform and crustiform quartz veining is widespread in intrusions, lava flows and contact zone. Stockwork-type quartz veining is also exposed in sanidine-phryic lava flows in the north of Kayılar area. Quartz veins a few centimetres thick consist of colloform–crustiform banded opaline and chalcedony.

6. Discussion

Extensive lacustrine successions and accompanying volcanism in the Early Miocene NE-trending Bigadiç borate basin provided appropriate conditions to form peperite. Syn-depositional volcanism is mainly represented by intercalations of felsic pyroclastic rocks with lacustrine sedimentary rocks. In this study, we have also described basaltic and intermediate magmas with peperitic margins within the semi-arid lacustrine succession in the Bigadiç borate basin. The major characteristics of the peperites are: (1) fluidal and blocky clasts enclosed by non-stratified host sediment (cf. Goto and McPhie, 1996), (2) chilled margins around fluidal clasts indicating contact with wet sediment or water (cf. Cas and Wright, 1987; McPhie et al., 1993), (3) in situ fragmented clasts forming jig-saw fit texture, (4) common irregular margins of magma clasts within the host sediment (cf. Doyle, 2000), and (5) secondary stratification of a mixture of juvenile clasts and host sediment due to sediment fluidisation. Development of peperite clearly indicates that the host sediment was wet and unconsolidated at the time of intrusion.

Although the host sediment is the same as the peperite domains in the Kayılar and Gölçük areas, syn-depositional olivine basalt and trachyandesite intrusions appear to have contrasting peperitic textures which may reflect difference in: (1) magma composition and viscosity (cf. Dadd and Van Wagoner, 2002), (2) vesicle and volatile content (cf. Doyle, 2000; Gifkins et al., 2002), and (3) size, proportion and alignment of crystals (cf. Hanson and Hargrove,
Olivine basalts are of small-volume, highly vesicular and contain a small amount of phenocrysts, whereas trachyandesites are voluminous, poorly to non-vesiculated and contain abundant phenocrysts with local preferred orientation. The different combinations of such contrasting intrusion properties are associated with diverse juvenile clast shapes in peperitic domains.

6.1. Emplacement mode of peperite-related syn-depositional volcanic units

The sharp and concordant upper contacts of the peperite-related volcanic units with lacustrine sedimentary rocks suggest that the Gölcük basalt and Kayırlar volcanic unit formed domes and lava flows emplaced in a subaerial environment. Hyaloclastite facies are not associated with either volcanic unit, suggesting that water level was more or less at, or immediately below, the sediment level at the time of magma emplacement. Lacustrine sedimentation resumed after emplacement of the syn-depositional volcanic rocks, and the limestone, now silicified, transgressively covered the volcanic ridges in response to ongoing subsidence of the basin. Emplacement modes of olivine basalts and trachyandesites also differ. Olivine basalts occur as small-volume emergent lava domes. Outer margins and the lowermost parts of the domes are intrusive, and lava flows show very limited extent on the sedimentary rocks. Trachyandesite dykes up to 100 m wide developed, in contrast, along fracture zones and fed extensive and thick lava flows emplaced in a subaerial setting.

Peperitic textures associated with the olivine basalts appear to have formed at the base of lavas along the ground surface. High vesicularity of the olivine basalt intrusions also suggests low confining pressure at shallow level (Goto and McPhie, 1996). The peperitic textures associated with trachyandesite dykes appear to have formed entirely in subsurface conditions. Absence of peperitic textures or hyaloclastites at the lower contact between the trachyandesite flows and the volcaniclastic sandstones clearly indicates that the sediment surface was dry after sedimentation of volcaniclastic layers that blanketed the limey mud and water level was probably below the sediment level at the time of lava flow emplacement. This is consistent with semi-arid climate, shallow-water and ephemeral lake environments previously inferred for the basin (Helvacı, 1995; Helvacı and Orti, 1998).

6.2. Formation of peperitic textures associated with olivine basalts

Peperitic textures associated with the Gölcük basalt occur along contacts of the partly emergent intrusions — similarly to those shown by White et al. (2000) — with sedimentary host rock. Irregular and fluidal clasts, as well as olivine basalt lobes, are thought to be closely associated with more mafic magma compositions and lower viscosity which may allow easier penetration of magma into the host sediment (Goto and McPhie, 1996; Dadd and Van Wagoner, 2002). The olivine basalt magmas probably had a high volatile content, low silica abundance (49.46–52.65 wt.%) and relatively low viscosity during formation of the fluidally shaped clasts and lobes. The presence of amoeboid-shaped clasts in the peperite domain also indicates dismembering of ductile, low-viscosity, and hence relatively hot, magma (cf. Squire and McPhie, 2002). Vesiculation has also partially controlled the formation of spongy margins in the fluidal clasts where the vesicles are filled by host sediment directly at the contact. The vesicle walls locally forming the margins of the fluidal clasts also indicate that the vesiculation occurred during fluidal emplacement and limey host was drawn into vesicles as magmatic gas in the vesicles cooled and condensed.

Formation of blocky clasts followed the fluidal stage as indicated by in situ fragmentation of clasts with fluidal margins (Fig. 9d). Gradual disintegration of fluidal clasts along hairline cracks and combination of both blocky and fluidal clasts strongly suggest that the blocky clast formation was closely associated with gradually decreasing temperature, increasing viscosity and resulting quench fragmentation (Goto and McPhie, 1996; Dadd and Van Wagoner, 2002) (Fig. 11a). Fluidisation of the limey host was also another important factor for the generation of fluidal clasts during the early stages of olivine basalt emplacement. The main evidence for sediment fluidisation is the locally non-stratified nature of the calcareous sedimentary rocks which are dominated by laminated limestone away from peperite domains in the succession (cf. Kokelaar, 1982; Kano, 1989, 1991; McPhie,
Fig. 11. A summary diagram for the formation of peperitic textures associated with (a) Gölcük basalt and (b) Kayırlar volcanic unit. See text for explanation.
Hairline cracks intersecting fluidal clasts and sediment-filled vesicles near the outer surfaces of clasts are other diagnostic features of sediment fluidisation (Brooks et al., 1982; Boulter, 1993; Goto and McPhie, 1996; Dadd and Van Wagoner, 2002). Large blocky clasts, which are mainly tapered and platy varieties, are widely dispersed and rotated, and are found together with irregular fluidal clasts. Incomplete in situ brecciation of the sparsely packed blocky clasts suggests dispersion and rotation of the clasts after quench fragmentation (Fig. 9b). Formation of dispersed and rotated clasts has been mainly attributed to steam explosions (Kokelaar, 1982; Busby-Spera and White, 1987; Hanson and Hargrove, 1999), but no corroborative field evidence for steam explosions was recorded in the peperite domain. Dispersed platy and tapered clasts within the pore water-rich limey host may instead have been emplaced during forceful emplacement of the new magma pulses that disrupted the early formed peperite (Kokelaar, 1986). The presence of both fluidal and blocky clasts in the olivine basalt peperite can also be evidence for fluctuating magma rheology and thus perhaps multiple intrusive pulses (cf. Goto and McPhie, 1996; Squire and McPhie, 2002). Fluidal and irregular contacts can be generated by hotter pulses, with later pulses imposing stress on parts that have begun to cool and solidify, causing formation of clasts having mixed morphologies (Goto and McPhie, 1996).

6.3. Formation of peperitic textures associated with trachyandesites

Fluidal contacts of clasts and dykes are limited, and their paucity is not only related to magma rheology (i.e. high viscosity), but also local and low-volume fluidisation of the host sediment as evidenced by centimetre-scale pipe-like structures in the peperite close to the intrusive contact (Kokelaar, 1982; Busby-Spera and White, 1987). Laminated beds and slump structures found together with pipe-like structures are probably related to sediment fluidisation during initial intrusion of magma (Fig. 11b). The low-volume fluidisation resulted in sediment-filling fractures within dykes and millimetre-scale chilled margins at the irregular contact between magma and host rock. Sediment fluidisation continued through the early stages of quench fragmentation, which is indicated by nearly in-place clast rotation near intrusive contacts.

Mesoblocky clasts in the peperite domain are inferred to have formed during low-volume sediment fluidisation. Digitate margins and partly fluidal contacts with non-stratified host sediment are diagnostic features of a fluidal emplacement. Mesoblocky clasts with digitate margins are commonly rimmed by a chalcedony with a uniform thickness of a few millimetres. Insulation of a vapour film at magma–wet sediment interface probably occurred during formation of mesoblocky clasts and the chalcedonic rim defines preserved open spaces after removal of the vapour film. Open spaces as zones of weakness at magma–sediment interface were probably filled by hydrothermal solutions during quench fragmentation. Physical experiments also demonstrate that a vapour film layer acting as insulating barrier may promote passive quenching (Wohletz, 2002) and it was presumably preserved through initial stages of quench fragmentation. In this case, chalcedonic rim around juvenile clasts is a field evidence for vapour film development during fluidal emplacement of magma.

Fluidal emplacement was immediately followed by rapid cooling of magma forming jig-saw fit textures. Blocky clast formation and in situ fragmentation are thought to be controlled simply by quench fragmentation (Brooks et al., 1982; Kokelaar, 1982; Hanson and Hargrove, 1999; Doyle, 2000; Hooten and Ort, 2002). Quench fragmentation is inferred to have occurred due to the relatively high viscosity and decreasing temperature of the intruding magma. Mesoblocky clasts were also disintegrated by quench fragmentation into variable-sized blocky clasts displaying both planar–curviplanar and digitate margins (Fig. 10b). Fractures formed during cooling were filled by injection of mixture of host sediment with pore water and magmatic fluids during, or immediately after, quenching (cf. Brooks et al., 1982; Brooks, 1995; Kokelaar, 1982). Contribution of magmatic fluids into host sediment in the peperite domain is indicated by a hydrothermal breccia that comprises intensely silificified limestone and colloidal silica enclosing blocky clasts with jig-saw fit textures (Fig. 10g). Monomictic nature of the breccia suggests that partly consolidated limey hosts were breached and filled open spaces around rigid and quenched juvenile clasts.
Platy and tapered clasts formed during early stages of brecciation, and are generally oriented along the intrusion directions (Fig. 10a); this may be explained by a preferred alignment of phenocrysts that formed zones of weakness between crystals and groundmass. Digitate margins of the blocky and tapered clasts may also be evidence for internal heterogeneities, such as the size and abundance of phenocrysts (Doyle, 2000).

6.4. Hydrothermal activity in the peperite domains

Magmatic fluid contribution is seen by the abundant quartz-carbonate veins and hydrothermal breccias within host sediment and magma bodies in the Gölçük and Kayırlar areas. Hydrothermal activity is mainly restricted to peperitic domains and locally lava flows. The timing of magmatic fluid contributions to the olivine basalt and trachyandesite peperite domains appears to differ. Olivine basalt peperites show no positive evidence for hydrothermal activity before or at the time of magma emplacement. Hydrothermal mineralization in the Gölçük area is characterised by vug-infill quartz and carbonate mineralisations around fluidal clasts (Figs. 6c and 9f). Formation of these large vugs may be attributed to the presence of steam generated from heating of the pore fluids (cf. Squire and McPhie, 2002). Steam-generated large cavities are inferred to have filled with hydrothermal fluids after peperite formation. However, termination of hydrothermal veins at the upper contact of olivine basalt domes strongly suggests that magma emplacement was immediately followed by hydrothermal fluid circulation in the peperite domain. In this case, steam-generated vugs in the peperite formation led to a highly permeable environment where hydrothermal fluids can circulate in the contact zone.

In the Kayırlar area, silicification and hydrothermal brecciation indicate spatial and temporal relationships between magma emplacement and hydrothermal activity. Considerable amounts of magmatic fluids appear to have fluxed the host sediment. This is evidenced by alternation of silicic and micritic limey layers and their syn-sedimentary deformation at the time of peperite formation (Fig. 10e). Moreover, no silica-rich horizons related to hydrothermal systems were defined within the lacustrine sedimentary rocks that predate the magma emplacement, implying that the magmatic fluid contribution was localised within the peperite domain and began during, or immediately before, peperite formation. Hydrothermal activity continued after peperite formation, and resulted in accumulation of a large amount of silica within the basin and formation of thick siliceous sediments on the uppermost part of the volcanic pile after volcanism. Hydrothermal activity after peperite formation produced intense quartz stockwork veining within the subaerial trachyandesitic lava flows.

7. Conclusion

Olivine basalt and trachyandesite peperites formed at the contacts between coherent magma bodies and lacustrine limestones in the Bigadiç borate basin have been described on the basis of clast shape, peperite textures and emplacement conditions. Olivine basalt and trachyandesite magmas display contrasting emplacement modes. Olivine basalts occur as partly emergent intrusions emplaced in a semi-arid, ephemeral lacustrine, environment. Trachyandesite dykes, in contrast, formed along narrow fracture zones and fed extensive lava flows emplaced in a wholly subaerial, post-lacustrine, setting. Water level of the lake was below the sediment level at the time of magma emplacement and the sediment surface was too compacted and/or dry for lavas to form basal peperites. The following subsidence of the basin due to crustal extension during the Early Miocene in western Turkey resulted in the deposition of lacustrine sediments over the volcanic ridges in the Gölçük and Kayırlar areas.

Peperite associated with the olivine basalt and trachyandesites includes a large variety of clast morphologies from blocky to fluidal. Fluidal clasts are widespread in the olivine basalt peperite domain. Fluidal clasts related to trachyandesites are, in contrast, restricted to a narrow zone near the margins of the intrusions and have commonly elongate and polyhedral shapes with digitate margins, rather than globular and equant varieties. Blocky and fluidal clasts in the olivine basalt display stepwise fragmentation, suggesting in turn decreasing temperature and increasing viscosity during fragmentation. Sediment fluidisation during fluidal clast generation played an important role in sustaining vapour films at the magma–sediment interface and hence suppressing steam explosions. Abundance of blocky clasts with respect to
fluidal clasts in the trachyandesite peperite indicates that the fluidal emplacement and low-volume sediment fluidisation in the early stages were immediately followed by quench fragmentation due to the high viscosity of the magma. Mesoblocky clast formation is also inferred to have been associated with fluidal emplacement during initial intrusion of trachyandesite magma.

Size, texture and abundance of the blocky and fluidal clasts in the olivine basalt and trachyandesite peperites were mainly controlled by sediment fluidisation, pulsatory magma injection and magma properties such as composition, viscosity, vesicularity, and the size, abundance and orientation of phenocrysts. Different combinations of these magma properties produced diverse juvenile clast shapes in peperitic domains.

In Gölcük area, olivine basalt emplacement was immediately followed by hydrothermal fluid circulation in the peperite domain, reflecting a highly permeable environment in the contact zone. In the Kayırlar area, hydrothermal systems were spatially and temporally associated with magma emplacement and resulting trachyandesite peperite formation. Hydrothermal activity was active during or immediately before peperite formation and continued throughout the emplacement of trachyandesite magma. This resulted in accumulation of a large amount of silica within the Bigadiç borate basin.

A model for the formation of economic borate deposits proposed by Helvacı (1995) and Helvacı and Alonso (2000) suggests that the borate mineralisation is closely associated with intrabasinal faults feeding hydrothermal fluids into the basin. The hydrothermal activity associated with syn-depositional volcanism in the Gölcük and Kayırlar areas is the first field evidence of such mineralisation within the western Anatolian borate basins. Therefore, investigation of the borate contribution related to these hydrothermal systems is a target of further work for understanding the mineralising potential of magmatic fluids in the region.

**Acknowledgements**

This study is a result of two different research projects supported by Dokuz Eylül University (Project no: 0922.20.01.36) and by the Scientific and Technical Research Council of Turkey (TÜBİTAK, Project no: YDABCAG-100Y044). This paper is also part of Ph.D. study of the first author. Durmuş Boztuğ and Sibel Tatar are acknowledged for providing major element analyses. The authors wish to thank authorities of the Eti Maden Company in Bigadiç for their logistic support. Yalçın Ersoy and Ökmén Sümer are also appreciated for their field assistance. The manuscript was greatly improved through reviews by referees Kelsie Dadd and Jim White.

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