The geology and volcanological history of Mount Avital

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\textbf{ABSTRACT}


Phreatomagmatic (hydrovolcanic) structures are rare in the Golan Heights, probably due to the deep groundwater table in most of this area. The volcanic deposits in the Pleistocene complex of Mt. Avital document a shift from an initial period of dry strombolian eruptions to wet phreatomagmatic explosions. We present a new map of the volcanic complex Mount Avital at a scale of 1:10,000 and an analysis of the deposit distribution and sequence of events that led to the dry–wet transition. Dry activity commenced at the southern part of the complex (pouring of the ‘En Zivan basalt and buildup of the Avital cinder cone) and then migrated to the west (Avital basalts) and north (Bental cinder cone). The transition to wet activity occurred during the terminal stages of the buildup of the Bental cone and it concentrated in two vents at the central part of the complex. The reason for this transition is attributed to the diversion of the Quneitra creek eastwards into the Quneitra Valley, which caused an increase in the level of Lake Quneitra and the infiltration of its water into the magma conduit. This could be facilitated by a decrease in magma pressure in the conduit due to an intense magmatic activity. The phreatomagmatic activity was frequently interrupted by low water:melt eruptions that produced fine-grained scoria, which erupted from a small scoria cone where the access of water was restricted. The phreatomagmatic activity was followed by collapse in the southern and central areas of the complex, which produced the central depression of the Avital complex.

\textbf{INTRODUCTION}

The interaction between magma and surface water is a major process in the formation of volcanic landscapes. Maars, which are the second most common volcanic structures (Lorenz, 1986; Schmincke, 2003), are now commonly accepted as hydrovolcanic features (e.g., Wohletz and Sheridan, 1983; Lorenz, 1986). A significant amount of the observed volcanic eruptions start with hydrovolcanic ("wet") events, and then change to strombolian or basaltic ("dry") volcanic activity (e.g., Robin et al., 1994; Bourdier et al., 1997; Nakada et al., 1999). For example, most cinder cones in the Eifel volcanic field (western Germany), once assumed to be monogenetic strombolian features, contain basal hydrovolcanic deposits (e.g., Schmincke, 2003). Hydrovolcanism at terminal stages is less common, and when it occurs it is usually attributed to a reduction

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of magma pressure in the conduit or to the influx of groundwater or lake water into the magma system due to subsidence at craters or calderas (e.g. Decker and Christiansen, 1984; Mastin, 1997; Gutmann, 2002).

In the northern and eastern Golan, west of the Israel–Syria border, there are about 60 cinder cones, most of them of Pleistocene age. Unlike the Eifel, almost all of them do not show any evidence for an interaction of magma and surface water. Such evidence was found in just two structures, Birket Ram (Weinstein et al., 2004) and Mount Avital. In a recent work, Weinstein (2007) suggested that the relative absence of hydrovolcanism in the Golan is due to the depth groundwater level of the regional aquifer. At this depth (hundreds of meters below the surface, Dafny et al., 2003), the pressure of the rising magma does not allow the water an access into the conduit. Weinstein (2007) further suggested that the existence of hydrovolcanic deposits in Mount Avital is due to the infiltration of water from a nearby lake into the conduit.

In the present paper, we analyze the volcanic history of the Avital complex in the light of a new geological map of this area. We then elaborate on the above suggestion through a discussion of some quantitative aspects of the dry–wet transition and of the intercalation of hydrovolcanic and fine scoria deposits in the study area.

**VOLCANIC NOMENCLATURE**

The following nomenclature is used throughout this paper:

**Eruption mechanisms**

*Hydrovolcanism* or *phreatomagmatism* refers to volcanic explosions that occur due to the interaction of ascending magma with surface water, including groundwater, lake water, or seawater. *Hydrovolcanic* or *phreatomagmatic* deposits include those deposits that contain a certain amount of juvenile ejecta (even if just a few percent), where *juvenile* stands for volcanic particles that were formed from the magma involved in the eruption. On the other hand, *phreatic* deposits contain no juvenile material, just explosion-produced clasts of the surrounding rocks. *Strombolian* eruption is characterized by the intermittent explosion or fountaining of basaltic lava from a single vent. The products of this kind of eruptions are mainly *pyroclastic deposits*, which include *scoria* fragments and a variable content of volcanic *bombs* (see below). Strombolian eruptions commonly include short *lava flows* composed of columnar basalt.

**Textural terms**

*Tuff* is a textural term that refers to volcanic deposits with particle size smaller than 2 mm, which may include both juvenile glassy particles and lithic clasts. *Lapilli* is a term used for volcanic tephra with particle size between 2 and 64 mm. It refers both to juvenile fine scoria and to deposits that consist solely of explosive lithic clasts. *Lapilli-tuff* refers to deposits consisting of both tuff-size and lapilli-size particles. *Scoria* is a general term for highly vesicular ejecta, usually with basaltic composition. *Volcaniclastic* deposits is a term used to include all deposits composed of particles (both *pyroclastic* and *phreatomagmatic*), as opposed to flows.

Volcanic *bombs* are rounded aerodynamic-shaped magmatic fragments larger than 64 mm in diameter, which being partially molten, acquired their shape during their travel through the air. The terms *lithics*, *accidental lithic clasts*, or *blocks* refer to rock pieces torn from the surrounding rock during the eruption. Phreatomagmatic tuff deposits usually contain variable amount of blocks, while bombs are restricted to strombolian deposits.

**Transport mechanisms and their related deposits**

*Fallout* deposits are composed of tephra that was vertically emplaced from a cloud of volcanic ejecta. They are characterized by parallel bedding and by relatively good sorting, and they may consist of fine-grained tuff-size as well as lapilli-size particles. *Base surge* deposits are produced by laterally-moving gas-rich volcanic currents. They are very common, usually dominant, in phreatomagmatic deposits. Base surges usually produce tuff- to lapilli-size thinly laminated deposits, which typically show flow structures such as cross-bedding, anti dunes, and wedging out of layers. *Cock’s tail* deposits are massive layers of poorly sorted breccia, with a high content of large lithic clasts that are produced by low-angle *debris jets*.

**THE GEOLOGY AND VOLCANIC FEATURES OF MOUNT AVITAL**

The landscape of the eastern Golan is dominated by two NNW-trending rows of cinder cones (Mor, 1973), each 30–35 km long (Fig. 1). Mount Avital is located at the center of the western row, east of the town of Quneitra. It is a large volcanic complex, which altogether covers an area of about 15–16 km² and includes four cinder cones, at least eight lava flows, and a large volume of phreatomagmatic deposits (Fig. 2a).
estimate the total volume of the volcanic products in the complex as 0.5–1.0 km$^3$, of which about half was produced by effusive eruptions (lava flows) and the rest by explosive activity. All lava flows and pyroclastic deposits share a basanitic composition, and they are highly enriched in incompatible elements (Weinstein et al., 1994).

The core of Mount Avital (Figs. 2a,b) consists of two large cinder cones (known locally as Tels), Tel Avital in the south and Tel Bental in the north, separated by a central large depression (hereafter: the Avital Valley). The depression is surrounded on its eastern and western sides by tuff rims (phreatomagmatic deposits). The remnants of another cone (hereafter the central cone) are observed at the northern part of the Avital Valley (Figs. 2b,c). Another parasitic small cone (Tel Kefel) is attached to the northwestern side of Tel Bental (Figs. 2a,b). Short but thick lava flows extend from the core of the complex to the south and west, altogether covering an area of about 8 km$^2$ (Figs. 2a,b).

Mount Avital is surrounded by lowlands (valleys) to the east, west, and south (Figs. 2b and 3). About 12 km$^2$ of the eastern valley (the Quneitra Valley) is blanketed by Mount Avital-derived explosive products (Dubertret, 1954; Mor, 1973), which are partly covered by alluvium.

**Scoria and the cinder cones**

In Mount Avital there are two types of scoria. The first type is a coarse scoria, which is restricted to the cinder cones or their remnants. The second type is a fine scoria, which occurs both on the slopes of the cones and in the eastern tuff rim (Fig. 3), as well as in the Quneitra Valley, up to more than 3 km from the mountain.

**Coarse scoria**

Tel Avital and Tel Bental are mainly built of bomb-rich coarse scoria. Tel Bental has a circular shape, but it is missing its western slope (Fig. 2a). Mor (1973) identified the remnants of this slope in hummocky features located west of the cone on top of the Bental Flow and suggested that the slope was fragmented and carried away with the lava flow. Tel Bental reaches an altitude of 1,165 m asl, which is 215 m above its base. With basal diameter of about 1,200 m, its height over diameter ratio (H/D) is 0.18, which is exactly the global average H/D ratio for cinder cones (Vespermann and Schmincke, 2000).

The remnants of the central cone include three scoria structures (denoted 3a,b,c in Figs. 2b,c), all of which are built of coarse scoria. Structure 3a is a relatively large hill, adjacent to the southern slope of Tel Bental (Fig. 2b) and rising to 70 m above the Avital Valley floor, with northward-dipping layers of coarse scoria. Structures 3b and 3c are ~10 m high hummocky features built of coarse scoria with no clear layering.
Fig. 2. (a) Geological map of Mount Avital area mapped at 1:10,000 scale (revised from Mor, 1987a,b). Note that the alternating Fine Scoria & Tuff is also denoted AFST in the text; DTM map of Mount Avital area (vertical resolution of 5 m), with numbers denoting various parts of the complex discussed in the text: 1. Tel Avital, 2. Tel Bental, 3. central cone, 4. Avital Valley, 5. southern depression, 6. eastern lobe, 7. western lobe, 8. Quneitra Valley, 9. 'En Zivan Flow, 10. Avital Flow, 11. Shoulder Flow, 12. Channel Flow, 13. El Hashabi Flow, 14. Bental Flow, 15. western (tuff) rim, 16. northeastern (tuff) rim, 17. scoria landslide, 18. Odem Flow, 19. Tel Kefel, 20. Tel Kefel X', X, and Y are the locations of the sections shown in Figs. 5 and 7, respectively; numbers in italic are for altitude; (b) Panoramic photograph of the central part of Mount Avital, taken from the southern slope of Tel Bental (view to the south; numbers are as in (b) and the dashed line next to 4 shows the suggested location of the northern edge of Tel Avital).
The outline of Tel Avital is less clear. Its southern part is the most complete and reaches an altitude of 1,204 m asl (Figs. 2b,c), which is the highest peak in the complex. Both its eastern and western flanks are partly eroded and covered by tuff (east) or breached by basalts (west), while the northern part is almost entirely missing (Figs. 2a–c) and is now occupied by the southern part of the Avital Valley (950–960 m asl; denoted 4 in Figs. 2b,c). The northern outline of the cone is defined by an E–W-trending scoria ridge, which closes on this part of the Avital Valley (Fig. 2c). According to our restoration (Fig. 2b), Tel Avital’s external diameter would be 1,300–1,400 m. Assuming H/D ratio of 0.18, the cone’s height would be 240 m above its base, which is 1,250 m asl, 45 m above the southern summit. Mor (1973) suggested, alternatively, that Tel Avital occupied the whole area of the Avital Valley and that the central cone was actually the remnant of its northern flank. Weinstein (2007) argued that in such a case, the cone would have to be unreasonably high (about 360 m above its base, with its top at about 1,380 m asl). Moreover, it is not likely that Tel Avital occupied the whole area of the Avital Valley because no scoria was found along the western rim, between Tel Avital and Tel Bental (Fig. 2a). A large hill of scoria (#17 in Figs. 2b,c), north of the proposed location of Tel Avital, is a displaced block, probably a landslide from Tel Avital (Mor, 1973).

Fine scoria

The fine scoria is characterized by lapilli-size (typically, 1–2 cm), black, reddish, or yellowish, highly vesicular (typically ~60–70 vol%) particles. Larger scoria fragments are almost absent in the fine scoria, but it contains abundant large (up to >3 m) bombs (Fig. 4a), which are usually significantly less vesicular than the scoria. The fine scoria is bedded, with typical layer thickness of a few tens of centimeters. It covers the central cone, the southeastern and eastern slopes of Tel Bental, and the southern and eastern slopes of Tel Avital (Figs. 2a and 3) with typical thicknesses of 1–10 m. The thickest exposed section of fine scoria (30 m) occurs just east of the central cone. It is divided into two parts, separated by a thick lithified tuff breccia of phreatomagmatic origin (Fig. 2a). Further east, at the northern edge of the eastern rim, the intercalation of fine scoria and the phreatomagmatic deposits is on a finer scale (layers of tens of centimeters to a few meters thick, Fig. 7), denoted Alternating Fine Scoria & Tuff (AFST) in the geological map (Fig. 2a). Just trace amounts of fine scoria were found in the western part of the complex.

A large volume of fine scoria (at least 6 km$^2$, Mor, 1973; ca. 2 × 10$^7$ m$^3$) is found east of the complex, in the Quneitra Valley, where it is relatively finely layered (layers a few centimeters thick; Mor, 1973). Sections thin to the east and north (Qidron, 1969; Mor, 1973).

Lava flows

The southernmost and the western parts of Mount Avital consist mainly of lava flows. The flows are usually a few hundred meters to 2 km long and up to 30 m thick, and they are typically covered by a wet Mediterranean oak forest (*Quercus boissieri* and *Quercus calliprinos*). The southernmost is the ‘En Zivan Flow (Figs. 2a,b), which dips southwards from 1,010 m asl at the foot of the southern slope of Tel Avital. The contact between this flow and the cinder cone is smooth; there are no signs of damage to the cone, and the scoria seems to cover the flow. Similarly, El Hashabi Flow, southwest of Tel Bental, does not breach the scoria cone. On the other hand, the Avital Flow, which is actually composed of two or three lava flows (Mor, 1987a,b), breaches Tel Avital at 1,115 m asl (Fig. 2a) and dips to the western lowlands, and the
Fig. 4. Pictures of volcanic deposits in Mount Avital: (a) a bomb in fine scoria with an impact sag and a small fault in the underlying fine scoria (southeastern quarries); (b) surges showing anti dune structures and filling local depressions (western rim); (c) a cliff of lithified tuff breccia (eastern Tel Avital); (d) lapilli fallout deposits, composed solely of lithic clasts; (e) disturbed tuff layers (southwestern part of the Quneitra Valley), probably a result of landslide; (f) surge deposits directly covering a clinker (western rim).
Bental Flow (actually, two lava flows; Weinstein et al., 1994) breaches Tel Bental at 1,000 m asl (Fig. 2a).

In this study we found that most of the western slope, between the Avital Flow and El Hashabi Flow, is also covered with basalts that extend from the complex core (Figs. 2a,b). At their highest point (1,070 m asl), these basalts form a “shoulder” on the northern flank of Tel Avital, where the lavas probably breached the original cone (Shoulder Flow, Figs. 2b,c). A lava flow, traced along an E–W channel 800 m northwest of the shoulder (Channel Flow, Fig. 2b), seems to derive from a vent close to the central cone at an elevation of 960 m asl. This implies that the basalts that cover the western part of the complex originated from several locations.

Unlike the western and southern parts, basalts are not exposed at the eastern part of Mount Avital. However, basalts were drilled at 960–1,020 m asl at the eastern slope of Tel Avital (Soudri and Bogush, 1971) and we relate them to the ‘En Zivan flow. Further north, basalts were not found down to 955 m asl in a borehole drilled at the northeastern rim (Fig. 3) (Qidron, 1969). There are no boreholes east of Tel Bental, but basalts are exposed in a channel at 940 m asl north of Tel Bental (Fig. 2b). In the Avital Valley, basalts were drilled at about 920 m asl (#5 in Figs. 2b,c; Mor, 1973), significantly lower than the nearby western flows (e.g., #11 and #13 in Fig. 2b).

**Phreatomagmatic deposits**

The phreatomagmatic deposits include ejecta composed mainly of lithic clasts, though they usually contain a few percent of volcanic glass. Grain size is usually in the range of tuff to lapilli (mm to cm scale), though accidental lithic clasts may be as large as 1 m. The dominance of lithic clasts, the angular and non-vesicular texture of the glass particles, and the frequent occurrence of base surges (see below) all support the work hypothesis that these deposits were produced by phreatomagmatic explosions (Weinstein, 2007). Following Mor (1973), we call these deposits Avital Tuff; however, unlike Mor (1973) and Mor et al. (1997), this definition does not include the fine scoria, which is discussed separately above.

The distribution of the phreatomagmatic deposits is shown in Fig. 2a. They are found almost all around the Avital Valley, up to 220 and 260 m above the valley’s floor at the top of Tel Bental and Tel Avital, respectively (Fig. 2a). In the western, northerwestern, and the northeastern rims, the deposits are found 0 to 50 m above the depression floor (Fig. 3), while in the rest of the perimeter they are usually restricted to the upper parts of the rims. In Tel Avital, the eastern part of the summit area is covered by phreatomagmatic deposits, which also cover the external eastern slopes down to the Quneitra Valley (Fig. 2a), while the western part of the summit and the southern slope is not covered by any phreatomagmatic deposits. In Tel Bental, the phreatomagmatic deposits are restricted to a small area on the upper part of the southwestern slope (Fig. 2a); they were not found at any other part of this cone. The thickness of the phreatomagmatic deposits is usually limited to a few meters, except for the western and the northeastern rims (Fig. 2a), where exposed sections reach more than 20 and 10 m, respectively (Figs. 3, 5, and 7), and extrapolating from borehole data, the total thickness could reach 70 and 50 m, respectively. Altogether, the phreatomagmatic deposits in Mount Avital cover an area of about 2 km² (Fig. 2a), assuming an average thickness of about 10 m, the volume of the phreatomagmatic deposits is estimated at $20 \times 10^6$ m³.
Large volumes of phreatomagmatic deposits were also found in the Quneitra Valley (Figs. 2a and 3) in association with the fine scoria, covering an area of up to 12 km² (Mor, 1973). With typical thickness of 1–3 m, it doubles the above-estimated volume of the phreatomagmatic deposits.

Weinstein (2007) described three types of phreatomagmatic deposits in Mount Avital, all of which are presented in a cross section through the western rim (Fig. 5). The first is a finely laminated tuff (and lapilli-tuff), which shows a variety of flow structures (Fig. 4b), and usually contains a certain amount of large accidental basaltic clasts. It is interpreted as deposits of base surges. The tuff is mainly composed of basaltic clasts (Fig. 6a) and to lesser extent scoria clasts (Fig. 6b), while glass is no more than a few percent. Glass particles are angular, non-vesicular shards, with typical fragment size of <1 mm, and they are usually palagonitized (Fig. 6c).

The second type of phreatomagmatic deposits consists of massive layers, a few tens of centimeters to 2 meters thick, of tuff breccia with a high content of large accidental clasts. Both the large clasts and the matrix are mainly basaltic, though scoria may comprise up to 30–40% of the smaller-size blocks and of the matrix. In a few cases, the clast population may be dominated by scoria. Some of the tuff breccias are strongly lithified, often forming small cliffs on the slopes facing the
Fig. 7. Section through the Alternating Fine Scoria & Tuff (AFST) unit in the northeastern rim (Y in Fig. 2b).
Avital Valley (Fig. 4c). Weinstein (2007) suggests that these are cock’s tail deposits, produced by low angle, relatively large volume debris jets.

The third type includes finely-layered lapilli deposits (Fig. 4d), which are almost solely lithic. Fragment size is mostly 0.2 to 10 mm, sometimes showing external reddish color due to alteration. Both large lithic fragments and fine ash (<0.2 mm) are rare. Based on the relatively good sorting and the almost complete absence of flow structures, Weinstein (2007) suggested that these are fallout deposits.

Dips in the phreatomagmatic layers vary around the complex (Mor, 1973), and they mostly reflect the dips of underlying structures. For example, on the southern slope of Tel Bental dips trend southward and on the eastern and western slopes of Tel Avital dips trend eastward and westward, respectively (Mor, 1973). However, the phreatomagmatic layers exposed on the western and northeastern rims, where the phreatomagmatic deposits attain large thickness, are probably showing original dips. Those on the western rim dip to the west, and at the northwestern rim they dip either to the southeast or to the northwest (Weinstein, 2007). On the northeastern rim, dips are either to the north-northeast or to the south-southwest (Fig. 7; Mor, 1973, fig. 24).

Avital Valley

The Avital Valley has the shape of a heart, elongated in the N20W direction, with a maximum length of 1,200 m and a maximum width of 700 m. It is leveled between 940 and 950 m asl, lower by 30–250 m than the surrounding structures (northern end of the western rim and Tel Avital, respectively). On the northeastern rim, dips are either to the north-northeast or to the south-southwest (Fig. 7; Mor, 1973, fig. 24).

Quneitra Valley

Amongst the lowlands around Mount Avital, the Quneitra Valley is the one that has the most relevance to our discussion, since it is covered by volcaniclastic deposits derived from the mountain (Mor, 1973; Goldberg and Goren-Inbar, 1990). The valley lies at 935–960 m asl, and it is bordered on its north, west, and south by the volcanic complexes of El Mahfi, Avital, and Bashanit, respectively, and by the Raqad depression to the east (Fig. 1). The lowest part of the valley (~935 m asl) is at its northeastern area, where a local depression has developed. The valley is currently drained by the Quneitra creek toward the northeast to the Raqad depression, which is separated from the Quneitra Valley by a topographic saddle that stands at 938–940 m asl.

The volcaniclastic succession of the Quneitra Valley usually includes fine scoria (the “black member” in Mor, 1973) covered by phreatomagmatic deposits (the “multi colored member” in Mor, 1973). Exposures are limited to local quarries, road cuts, and boreholes conducted for water exploration (Qidron, 1969). The total thickness of the exposed volcaniclastic deposits varies between a few meters and more than 20 m; the proportion of the fine scoria decreases toward the east and north (Mor, 1973), and it is absent at the northeastern part of the valley (Fig. 3). The volcaniclastic deposits overlie basaltic flows, which are typically found at a depth of 930–940 m asl (Fig. 3; Qidron, 1969; Soudri and Bogosh, 1971; Goldberg and Goren-Inbar, 1990; and this study). In the lowest area of the valley, the volcaniclastics are underlain by black clays.

The fine scoria has characteristics similar to those observed in Mount Avital, but its particle size is finer and its bedding thickness less (typically <1 cm and a few centimeters thick, respectively; Mor, 1973), and it does not carry volcanic bombs. The phreatomagmatic deposits include lapilli-tuff and tuff; the average particle size is smaller than on Mount Avital, large accidental lithics are less frequent and smaller, and clay-rich tuff layers are commonly observed. Bedding is more regular and flow structures are less frequent than in Mount Avital. Sliding blocks with torn parts of tuff are found in the higher parts of the valley (Fig. 4e). Redeposited tuff was also reported from the deeper part of the valley, next to the Quneitra creek (Goldberg and Goren-Inbar, 1990).

Some of the tuff layers show laminar structures (varves), which could be of lacustrine origin. This is in accord with the suggestion of Dubertret (1954) that the Quneitra Valley was occupied by a lake at the time of the eruptions.

**STRATIGRAPHY AND SEQUENCE OF EVENTS IN MOUNT AVITAL**

Mor (1973, 1986, 1987a,b) suggested a relatively
Fig. 8. Sequence of the main events in the Avital complex: (a) Strombolian activity and buildup of the cinder cones of Tel Avital and the central cone; (b) effusion of Avital Basalt at the western part and buildup of Tel Bental at the northern part of the complex; (c) phreatomagmatic activity (Avital Tuff) and fine scoria eruptions; (d) landslides from Tel Avital and the central cone. Note that, although shown as coeval with pouring of the Avital Basalt, the strombolian activity in Tel Bental did not cease until after the phreatomagmatic activity commenced (see text). Also, it is probable that some Avital Basalt flows erupted at the terminal stages of activity, simultaneously or following the phreatomagmatic events.
simple sequence of events in Mount Avital (referring only to its southern and central parts), which included the buildup of a large cone (scoria, covered by tuff), followed by pouring of lavas and then by a passive collapse, which created the Avital Valley. Our observations suggest that the history of Mount Avital is more complicated and polygenetic (legend to Fig. 2a), including several generations of basaltic flows and cinder cone buildups. We suggest that the current morphology of Mount Avital, mainly of its central valley, was formed as a result of phreatomagmatic aggressive explosions. The sequence of events is elaborated below.

The earliest unit of the complex is the 'En Zivan Basalt, which includes the 'En Zivan Flow at the southern part of the complex, and probably the El Hashabi Flow northwest of the Avital Valley (Fig. 2a). At this stage, the Avital structure was centered at the southern part of the complex, where it gained an altitude of at least 1,010 m asl, compared with 940 m at the El Hashabi area. Post 'En Zivan activity started with a strombolian eruption that produced the Avital Coarse Scoria and built the structures of Tel Avital and the central cone (Fig. 8). The two cones are breached and covered by the Avital Basalt (Fig. 8). The above units are all covered by successions of fine-grained volcaniclastic deposits, which include the Avital Tuff, the Avital Fine Scoria, and the AFST facies (Figs. 2a, 3). Sections through Avital Tuff in the western rim and through the AFST in the northeastern rims are shown in Figs. 5 and 7, respectively. The scoria of Tel Bental (Bental Coarse Scoria) has no direct contact with Avital Basalt. However, the upper parts of the scoria intercalate with phreatomagmatic deposits of Avital Tuff. This implies that the last stage of the buildup of Tel Bental was coeval with the early stages of the Avital Tuff (see legend to Fig. 2a). The activity at this part of the complex terminated with the effusion of Bental Basalt, which breached the western flank of Tel Bental. The last event to occur in the complex was the collapse of Tel Avital and the Shoulder Flow, as well as of the central cone (Fig. 8). This is implied by the absence of phreatomagmatic or fine scoria deposits on the inner slopes of the two cones (Fig. 2a). The collapse could be accompanied by an effusion of the Avital flow, which, unlike the other Avital Basalt flows, is not covered by tuff.

There are as yet no age determinations on rock samples from Mount Avital; therefore, we have no time constraints on the age of the various units or on the duration of the volcanic activity in the complex. Ages of basalts around the complex vary between 0.9–0.3 Ma (Heimann, 1990, Ziaei et al., 1990; Mor, 1993) Based on these and on morphological considerations, Mor (1986, 1987a,b) suggested that all units in the complex are younger than 0.4 Ma. Weinstein et al. (1994) suggested that the 'En Zivan Basalt could be older (0.8 Ma, like the nearby Dalwe Basalt; Mor, 1993). Several pieces of evidence suggest that the sequence of events starting with the eruption of Avital Basalt and the buildup of Tel Bental (Bental Coarse Scoria) and continuing through the whole section of the phreatomagmatic deposits, occurred within a very short time interval. The evidence includes: (1) surge deposits directly overlie a fresh top breccia (“clinker”) of an Avital Basalt (the Channel Flow) with no indication of erosion or pedogenic processes (Fig. 4f), implying that there was no significant pause in activity between the two eruptions; (2) two layers of lithified tuff breccia “sandwiched” by coarse scoria layers on the southern flank of Tel Bental, suggesting that the buildup of Tel Bental was coeval with the phreatomagmatic activity (or at least its early phase); and (3) the absence of paleosols within the phreatomagmatic section, implying a continuous phreatomagmatic activity.

We conclude that most of the units of Mount Avital volcanic complex were emplaced during a period of continuous volcanic activity. In the future, we intend to conduct a detailed radiometric dating of the basaltic flows, which will allow a finer tuning of the events in the Avital complex.

**LOCATION OF VENTS**

The volcanic activity often changed location in Mount Avital. In general, there was a northward migration of the locus of the “dry” (basaltic–strombolian) activity. The earliest known activity is the effusion of 'En Zivan Basalt centered at the southern end of the complex. This was followed by the strombolian activity that built the southern (Tel Avital) and the central cones, followed by the effusion of Avital Basalt at the southwestern and central parts of the complex and then by the events that built the northern cone (Tel Bental) and pouring of the Bental Basalt. However, the “wet” activity, which occurred simultaneously with the ongoing “dry” activity at the northern part, was centered at the area of the current Avital Valley (center of the complex), as discussed below.

Both the fine scoria and the phreatomagmatic deposits did not build topographic highs at their eruption site; therefore, it is more difficult to locate their vents.
The thick sections of fine scoria found around the central cone and on the nearby southeastern slopes of Tel Bental and the eastern slopes of Tel Avital imply that these ejecta probably erupted from the top of the central cone (FS vent, Fig. 9). The absence of fine scoria in the inner flanks of the Avital Valley further suggests that during their eruption both the central cone and Tel Avital were still relatively intact. The large extent of these deposits in the Quneitra Valley and its absence in the western slopes of the complex was probably determined by the prevailing westerly and northwesterly wind direction (Mor, 1973).

The distribution of the phreatomagmatic deposits is to some extent similar to that of the fine scoria. Their frequent occurrence around the Avital Valley implies that they erupted somewhere within the area of the Avital Valley. The absence of these deposits on the inner slopes of Tel Avital and the central cone
implies that they also erupted when the cones were relatively intact. Unlike the wind-driven fine scoria, the phreatomagmatic ejecta was mainly transported by base surges (Weinstein, 2007) and traveled radially from the vent, either downwards with the topography or upwards at low angle. Therefore, their absence on the southern slope of Tel Avital indicates that the eruption could not take place on top of that cone and that it occurred at the central or northern part of the current Avital Valley. The continuous cover of phreatomagmatic deposits on the western rim of the depression and on the western slope of Tel Avital and their occurrence on the southeastern slope of Tel Bental implies the existence of a vent in the northwestern lobe of the depression (vent PM1, Fig. 9). This is supported by the orientation of tuff layers on the western rim (Fig. 2a), which are dipping either toward or away from the northwestern lobe. However, this vent could not be the source for the deposits at the northeastern and eastern rims of the Avital Valley (Figs. 2a and 7), since the central cone (still intact during the phreatomagmatic eruption) would form a “shadow effect” and block the surges moving in these directions. Therefore, another vent (vent PM2) was probably located either south or east of the central cone. The absence of phreatomagmatic deposits on the southeastern and eastern slopes of Tel Bental (Fig. 2a) implies that vent PM2 was located south of the central cone (Fig. 9), which is close to an eruption site suggested by Mor (1973). Mor also suggested that another vent was located in the southern depression, mainly based on dips measured in tuff layers on the slopes of Tel Avital. As mentioned above, we consider these dips as topography-controlled rather than vent-controlled.

In summary, dry volcanic activity started at the southern part of Mount Avital and migrated to its northern part, while the transition to wet activity occurred at the central part of the complex, near the central cone.

**DISCUSSION**

**The cause for the dry–wet transition**

The volcanic record in Mount Avital shows a transition from a dry, strombolian-style to a wet, phreatomagmatic activity. Weinstein (2007) discussed the rarity of phreatomagmatic structures and deposits in the Golan (unlike other areas in the world) and concluded that this is the result of the deep regional aquifer (Dafny et al., 2003). The small local aquifers that are very common in the Golan surface basalts (usually underlain by a confining paleosol, Mor, 1973) could not be the source for water in the phreatomagmatic activity since the water volumes they carry are too little to produce an effective water–magma interaction. Weinstein (2007) further attributed this transition to the infiltration of water from a lake that existed in the nearby Quneitra Valley (hereafter: Lake Quneitra; Dubertret, 1954). This suggestion is examined and elaborated below in light of the topography of the Quneitra Valley.

According to Mor (1973), the emplacement of the Odem Flow north of Tel Bental (Fig. 1) dammed water in the Quneitra Valley (Figs. 1 and 2b) and formed Lake Quneitra. However, the base of the Odem flow at this area is at ca. 950 m asl, while the known lowest point of the sub-tuff basalt in the Quneitra Valley is at 930 m asl (2 km east of Tel Bental, Goldberg and Goren-Inbar, 1990), and we have no reason to believe it was significantly higher during the last 100–200 kyr. This implies that a lake could exist in the valley prior to the emplacement of the Odem flow, assuming that no significant changes have occurred in the topography of the valley since the eruptions took place. Nevertheless, the Odem flow did cause a change in the course of the Quneitra creek, which previously drained the area north of the Quneitra Valley westward (toward the Jordan River) and consequently added its water to Lake Quneitra.

The level of Lake Quneitra was limited by the altitude of the topographic saddle that separates the Quneitra Valley from the Raqad depression (Fig. 1), which currently stands at 938–940 m asl. The area of the Quneitra Valley, which is currently lower than 938 m asl is roughly 2–3 km², and we arbitrarily assume that it was twice as much (~5 km²) before the emplacement of the volcaniclastic deposits. The current average flux of the Quneitra creek is about 2–3 × 10⁶ m³/yr. This, probably, did not change much since the middle Pleistocene, since precipitation in the area hardly changed (Bar Matthews, pers. comm., 2006) and there were no post-tuff volcanic activity or tectonics that could significantly change drainage basins. Therefore, Lake Quneitra’s level could rise by about 0.5 m within the first rainy season after the change in the course of the creek.

We suggest that the addition of water due to the diversion of the Quneitra creek caused the lake level to rise and to cross a topographic sill that separated the area of the volcanic activity from the Quneitra Valley. Consequently, lake water could come in contact with the magma either at the surface (if activity was already taking place at the time) or, more probably, find its way...
into the magma conduit through fractures and induce the phreatomagmatic activity. The above threshold had to be somewhat lower than the maximum level of the lake (938 m asl). Pre-phreatomagmatic basalts stand higher than 1,000 m asl at the southeastern part of the complex and at 940 m asl at the northern foot of Tel Bental, while in the central part of the complex basalts, are found in a relatively low position (920 m asl in a borehole drilled southwest of the central cone, Mor, 1973) and were not found in exposures and in a borehole at the northeastern tuff rim. We suggest that the water got access into the magma conduit through the northeastern corner of the current Avital Valley (Fig. 9), where it is also now the lowest point along the eastern side of the complex. The water could also possibly migrate through the basaltic basement, but this would still be limited to the uppermost flow (a few meters), since it is usually separated from the underlying flows by an impermeable paleosol. Once the shift to phreatomagmatic eruptions took place, phreatomagmatic deposits started accumulating in the Quneitra Valley, which caused a further rise in the lake level and an additional influx of water into the magmatic system.

Another possibility, suggested by Weinstein (2007), is that the trigger for the transition to wet activity was the outpouring of Avital Basalt and the buildup of Tel Bental, which reduced pressure in the magma conduit and allowed lake water in. This suggestion should be corroborated by future age determinations of the basalts in the complex.

Water/melt ratios

There is some disagreement in the experimental literature about the optimal water/melt ratio for a phreatomagmatic explosion to occur, and the values vary between 0.05 and 0.3 (mass ratios; e.g., Wohletz, 1983; Zimanowski et al., 1991; Wohletz et al., 1995; Morrissey et al., 2000; Fig. 10). A smaller ratio cannot produce a strong enough explosion to cause fragmentation of the magma, and will usually result in a strombolian-type eruption. The amount of phreatomagmatic products in Mount Avital and the Quneitra Valley is estimated at 40–50 × 10⁶ m³ or 80–100 × 10⁹ kg (using a rough bulk density of 2000 kg/m³). Assuming an average fraction of 5% juvenile material, we arrive at 4–5 × 10⁹ kg magma that interacted with water. Using the above mass ratios of 0.05–0.3, the optimal volume of water needed for the phreatomagmatic eruptions to occur is 0.2–1.5 × 10⁶ m³, which is equivalent to a level rise of no more than 0.3 m in the ~5 km² Quneitra Lake. This volume could be easily supplied by the Quneitra creek within one rainy season or even within one large rain event.

The phreatomagmatic eruption and the Avital Valley

Depressions up to a few kilometers wide are very common in phreatomagmatic structures (e.g., Schmincke, 2003) and they frequently include some collapse features. In the Golan, large internally drained depressions are rare and are found just in Mount Avital and Birket Ram (Mor, 1986; Heimann, 1993), both in association with phreatomagmatic deposits (Weinstein et al., 2004). Therefore, they should be discussed in the context of the phreatomagmatic eruption. Following the above discussion, it seems that the Avital Valley was formed both by the buildup of the tuff rims (northern lobes) during the phreatomagmatic eruption and by post-eruption collapses of the high structures surrounding the current valley. A good example of the
The fine scoria

Unlike the coarse scoria, the fine scoria does not build cones. It intercalates with the phreatomagmatic deposits, and almost everywhere in the structure (except for the eastern slope of Tel Bental), it is underlain by layers of phreatomagmatic deposits. This indicates that the eruption of the fine scoria commenced after the dry–wet transition took place.

The fine scoria is definitely more fragmented than the cone-building coarse scoria. This indicates that it was formed by more aggressive explosions than those that produced the coarse scoria, which is supported by the frequent presence of very large bombs (up to 3.5 m) in the fine scoria (Fig. 4a). On the other hand, the fine scoria is less fragmented than the phreatomagmatic deposits, implying that the eruption that produced this scoria was less aggressive than the phreatomagmatic explosions. This could be the result of lower water:melt ratios than in the phreatomagmatic explosions, but higher than in the coarse scoria-producing eruptions (Fig. 10). We suggest that after the dry–wet transition occurred, the type of ejecta was site-dependent. When eruption occurred between the cones (FM1 and FM2, Fig. 9), access of water to the magma was relatively free, fragmentation was intense, and phreatomagmatic deposits were produced. On the other hand, when eruption took place in the central cinder cone (FS vent, Fig. 9), the access of water to the magma conduit was inhibited by the coarse scoria and interaction was less intense, thus producing the less fragmented fine scoria. An alternative explanation is that the central cone was the center of magmatic activity at the time. Hence, magmatic pressures in this site were relatively high and water could hardly interact with the magma. On the other hand, the lower magmatic pressure in the surrounding areas allowed water access and better interaction with the magma.

SUMMARY

The volcanic activity in Mount Avital changed from strombolian to phreatomagmatic due to the infiltration of water from the nearby Lake Quneitra into the magma conduit. The infiltration was caused by an increase in the lake level due to the emplacement of the Odem Flow north of Tel Bental and the consequent diversion of the Quneitra creek into the lake. The infiltration of the water into the magmatic system occurred southeast and west of the central cone. The water arrived there through the northeastern rim of the (current) Avital Valley.

The sequence of events in Mount Avital was as follows:

1. Effusion of the ‘En Zivan Basalt centered in the southern part of the complex;
2. Strombolian eruptions in the south and center of the complex and buildup of Tel Avital and the central cone;
3. Effusion of lavas (Avital Basalt) from the flanks of Tel Avital and the central cone;
4. Buildup of Tel Bental;
5. Phreatomagmatic eruptions commence in the center of the complex;
6. Alternating activity of phreatomagmatic and fine scoria-producing eruptions;
7. Terminal effusion of lavas (Benton Basalt and A vital Flow).
8. Collapses and landslides destroy Tel Avital and the central cone and shape the current morphology of the Avital Valley.

Events 3–6, and probably also 7, occurred within a relatively short time interval.

The tuff erupted from two vents, located at the western lobe and south of the central cone, while the fine scoria erupted from another vent, located on the central cone. The different eruption styles probably reflect differences in the accessibility of water to the vents and/or variability in magma pressure. Accessibility was inhibited or magma pressure was higher in the central cone area, thus water/melt ratios were lower and explosions were less aggressive in this vent.

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