Lower Cretaceous magmatic activity in the Timna Valley: Geological setting and $^{40}$Ar/$^{39}$Ar dating

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ABSTRACT


Vents (diatremes) filled with volcaniclastic breccia cut across Lower Cretaceous formations and the underlying Cambrian strata in the northern Timna Valley. The vents are the result of an ascending gabbroic intrusion interacting with groundwater, breaching the surface atop the Avrona Formation. A small plug of microgabbro, which intrudes the Cambrian dolomites near one of the volcaniclastic remnants, belongs to the same event. The volcaniclastic fill consists of heterogeneous fall-back tephra and epiclastic debris of partly altered volcanic and sedimentary clasts of various sizes, and dispersed xenoliths and xenocrysts. $^{40}$Ar/$^{39}$Ar and K/Ar analyses of three biotite crystals and one hornblende crystal from a single vent (Tamar) yield a weighted average age of 108.4 ± 1.7 Ma (late Early Albian). This age also marks the boundary between the Avrona and Samar formations, constraining their ages. Contemporaneous exposures of volcanic rocks, crossing or overlying strata equivalent to the Avrona Formation and terminating below the Samar equivalent, occur also in Makhtesh Ramon 90 km to the north. These volcanic and volcaniclastic occurrences constitute an important marker for correlation of the Lower Cretaceous clastic sequence in the Negev.

INTRODUCTION

Three magmatic episodes took place during the Early Cretaceous in the Negev, Israel (Fig. 1b). The first episode, 138 to 132 Ma (Teutsch et al., 1996; Segev, 2000), is associated with the Jurassic–Lower Cretaceous unconformity and is represented by dikes, sills, and a laccolith of gabbro and dolerite (e.g., Bonen, 1980; Garfunkel, 1989). The second episode, 125 to 123 Ma (Segev, 2000), is represented by quartz-syenite stocks and small trachytic intrusions (Shen Ramon magmatism). Outcrops of these two episodes are confined to the Makhtesh Ramon area. The third episode is known from both Makhtesh Ramon and the Timna Valley (Fig. 1b) where volcanic flows and vents occur at a similar stratigraphic level. In Makhtesh Ramon it is represented by up to 200 m of basanite and tephrite lava flows and by pyroclastics (Ramon Basalt), often containing ultramafic xenoliths. The main volcanic structure (Har Arod) was interpreted as a lava lake and tuff cone intruded by basanitic stocks and dikes (Eyal et al., 1996). Vents and collapse structures were also reported (Garfunkel, 1989). In the Timna Valley (Fig. 1a) volcanic vents (diatremes) filled by volcaniclastic breccia (hydrovolcanic deposits) cut across the Lower Cretaceous and underlying Cambrian strata. Clastic and
Fig. 1. (a) Geological map of the northern Timna Valley. The four exposures of the Early Cretaceous volcanic event are encircled. Numbers in box are samples. (b) Location map. Grey area: Lower Cretaceous volcanic province of the Negev.
chemical crater-lake deposits occur locally (Weissbrod et al., 1989, 1990a; Weissbrod et al., 2001). A small plug of microgabbrro, intruding the Cambrian dolomites near one of the volcaniclastic exposures (Fig. 1a), probably belongs to the same event (Beyth and Segev, 1983; Segev and Beyth, 1983). Due to the anomalous position, exotic composition, and the steep morphology of part of the exposures, they were described as the “crazy wall” and have been credited a formation status (Barak Formation; now obsolete). The volcaniclastic fill was originally interpreted as a fluviatile and limnic deposit (Bartura, 1959), and even as the possible result of a meteoritic impact (Flexer et al., 1988). Weissbrod et al. (1989, 1990a, b) determined, however, its volcanic nature and phreatomagmatic origin. A magnetometric survey in the northern part of the Timna Valley indicated an elongated (15 by 2 km), E–W-trending magnetic anomaly in the Har Mikhrot area, with a second, parallel intrusion north of it (Segev et al., 1995). 3-D magnetic modeling suggests a gabbroic intrusion at a shallow depth (±600 m) emplaced in the upper part of the igneous basement, in places reaching the base of the sedimentary column. Some of its apophyses penetrate the sediments and breached surface at the top of the Avrona Formation as explosion vents (Segev et al., 1995).

This paper describes the Lower Cretaceous magmatic activity in the Timna Valley in its stratigraphic context and presents up-to-date radiometric ages of rocks and minerals of this event. Previous radiometric datings were presented by Segev (2000) and Weissbrod et al. (2001). Of the volcanic and pyroclastic material only the microgabbrro of the plug is relatively fresh, whereas the mafic (gabbroic?) fragments in the volcaniclastic fill are strongly weathered and altered. Nevertheless, large and fresh xenocrysts of biotite are quite abundant, and suitable for dating.

The fact that the volcanics penetrated the Lower Cretaceous Avrona sandstones but did not affect the supposedly Middle to Upper Albian Samar (Weissbrod, 2002) constrains the timing of the event. The radiometric dating, in a sequence lacking indicative fossils, serves to put a time fix on an identifiable Cretaceous horizon. The obtained mineral age (biotite) serves as a reference for the whole rock datings of the same episode.

**STRATIGRAPHIC SETTING**

The Timna Valley (~90 km²) is a structural dome on the western margin of the Dead Sea Rift. It has been half-sheared by the western faults of the rift and breached by erosion. The valley is horseshoe-shaped, surrounding a core of Precambrian igneous basement (Har Timna, ca. 4 × 5 km), and is bounded by steep cliffs (~400 m high) except on the east, where it is open and drained by several ephemeral streams toward the Arava Valley (Fig. 1a). The valley floor consists of gently outward-dipping Cambrian and Lower Cretaceous sediments dissected by dry streams leaving a hilly morphology, whereas the bordering cliffs are built of Lower Cretaceous sandstones in their lower part and are capped by Upper Cretaceous carbonates. In the northern part of the valley several volcanic vents cut across the igneous basement, the overlying Cambrian and Lower Cretaceous sediments, and are filled by volcaniclastic breccia, which, besides pyroclastic fragments, consists mainly of granite, sandstone, siltstone, and dolomite clasts derived from the following formations:

**Precambrian basement**

Consists of mafic to felsic plutonic rocks, which are crossed by four dike systems. The intrusive rocks can be classified into three main groups (Fig. 1a): basic/ultrabasic (norites and peridotites), intermediate (diorite, monzodiorite, monzonites), and acidic (porphyritic calc-alkaline and alkaline granites). All rock types are exposed in the structural core (Har Timna). In the northern part of the valley, where the volcaniclastic sections are found, the crystalline basement is not exposed. The most common subsurface igneous rock type is the Timna Granite.

Overlying it, with a locally prominent relief and talus aprons, are platform Cambrian subarkose with alternating siltstone layers and a carbonate intercalation, reaching a thickness of up to 200 m, in which three units can be differentiated (Fig. 2).

**Amudei Shelomo Formation**

Reddish brown, medium-grained to grit size, poorly sorted pebbly sandstone of large-scale cross-stratified sets arranged in thick tabular sheets of braided streams with bed loads, which were deposited in alluvial fans. It is of Early Cambrian age and attains a thickness of up to 90 m.

**Timna Formation**

Displays three sedimentary suites of siliciclastic, mixed siliciclastic-carbonate and carbonate-shale lithofacies that mark a marine transgression over the platform. The lower suite (Hakhil Member) consists of fine- to grit-size subarkose alternating with laminar mudstone layers and sandy dolomite bands, which...
contain trilobite and brachiopod fragments and a variety of ichnofossils. The overlying sediments (Sasgon Member) consist of three lithofacies types, of which the most prominent is dolomite and dolomitic limestone with stromatolitic (fenestral) laminations and bands and nodules of chert, reflecting a maximum in sea level stand. Less abundant are laminated shales and massive, fine- to coarse-grained sandstones. These sediment types have undergone alteration and dissolution processes (Segev, 1986; Segev and Sass, 1989). The overlying shaly lithofacies is thin, forming a transition to the lower member of the overlying Shehoret Formation. The 45-m-thick Timna Formation was deposited in a shallow sea within the coastal tidal-lagoonal strip. Trilobites and brachiopods indicate its Middle Cambrian age (Parnes, 1971; Rushton and Powell, 1988).

**Shehoret Formation**

Reddish brown, fine- to medium-grained, moderately to well-sorted subarkose alternating with thin siltstone layers. The units display planar and trough cross-beds and less frequent ripple cross-lamination and wavy bedding. *Skolithos* burrows are common locally. The formation consists of alternations of migrating sand shoals and heterolithic facies representing an upper shoreface environment dissected by tidal channels. Its age is Middle Cambrian also. It is up to 40 m thick. In the Timna Valley the section corresponds only to the lower part of the formation elsewhere.

Unconformably overlying the Cambrian sequence are Lower Cretaceous strata consisting of mature quartz arenites (Fig. 2). The gap between the two depositional cycles represents two major uplift and erosion events that resulted in the truncation of 3000-m-thick Paleozoic and Lower Mesozoic sections (Weissbrod and Gvirtzman, 1988; Gvirtzman and Garfunkel, 1998).

**Amir Formation**

White, fine- to medium-grained quartz arenites alternating with thin lenticular laminated siltstone. The sandy units display medium- to large-scale sets of planar tabular and occasionally recumbent and convolute cross-beds. Laminae of granules occur in many of the lower sets. Fining-upward sequences are discerned. Colony-like clusters of tubular and U-shaped burrows of the *Skolithos*-facies are abundant in the upper part, whereas the top of the formation is locally incised by a system of subparallel channels (Weissbrod and Sneh, 1997; Weissbrod and Barthel, 1998). It appears to represent deposition in a shallow marine littoral or tidal environment and is probably of Barremian to Early Aptian age. The Amir Formation is up to 55 m thick.

**Avrona Formation**

Grey-white, medium- to coarse-grained quartz arenite with some lenticular layers of grey sandy siltstone. Bands and stringers of well-rounded pebbles and granules are quite abundant. Medium- to large-scale planar tabular cross-beds are the dominant structures. Frag-
ments of ferns (*Paradoxopteris*, *Alstaeitia*) and trunks of conifers (*Dadoxylon*) are found mostly in the lower part. The Avrona Formation sediments were deposited in low-sinuosity bed-load-dominated braided streams. Its age is Early Aptian to Early Albian. The vents cross the above-described local rock units and breach the surface at the top of the Avrona Formation. The upper age limit of this formation is constrained by the radiometric age of the volcaniclastics, which are cut by the unconformity at the base of the overlying Samar Formation.

**Samar Formation**

Grey, white, pink, purple, and yellowish white, fine- to medium-grained sandstone with random quartz pebbles, alternating with red and ochre, occasionally mottled, siltstone layers, some of which are paleosols. Planar cross-beds are common and several upward-fining sequences are distinguished. The Samar Formation displays mostly a fluvial braided stream pattern and lacustrine environments. Its age is most likely Middle to Late Albian as it is intercalated between the Lower Aptian to Lower Albian Avrona Formation and the Upper Albian–Cenomanian Hazera Formation. It is up to 110 m thick.

**Judea Group**

350–400 m of shallow marine platform carbonates and some shale, comprising the Hazera (its previous members have been amended to formation status (Sneh et al., 1998)), Ora, Gerofit, and Zihor formations, ranging from Late Albian to Coniacian age. These hard carbonates form the upper part of the escarpment surrounding the Timna Valley.

Large areas of the valley floor are covered by Neogene and Quaternary conglomerates, river terraces, and talus aprons.

**THE VOLCANICLASTIC ROCKS**

**Occurrence and composition**

Vent-filling volcaniclastic sediments are exposed in the northern part of the Timna Valley, to the north, west, and east of Har Mikhrot (Fig. 1a). The main vents are named Tamar, Sivan, and Nathan. East of the Tamar vent and in Nahal Mangan, east of the Nathan vent, other volcaniclastics are exposed on the banks of present-day creeks. Similar volcaniclastics are reported by Bartura (1959) from a drillhole (FG-8) some 4 km southwest of the exposed vents. The outline of the main vents is roughly circular, but in others it is elongated or irregular, which may indicate fissure fill or linear offshoots of nearby unexposed vents. Some 2.5 km east of the Tamar vent a small gabbroic plug is exposed over 100 m², cutting through dolomite of the Timna Formation (Fig. 1a). This plug belongs to the same volcanic event, as is indicated by its radiometric age. The volcaniclastic fill consists of mixed volcanic breccia and country rock of various sizes, including
intensely weathered and largely altered mafic ingredients and all types of transversed sediment (quartz arenite, subarkose, mudstone, shale, and dolomite) and the local Precambrian basement (Timna Granite). The mafic fragments are mostly bombs (or blocks) and lapilli, whereas clasts of the country rock range in size from blocks to boulders, some over 1.5 m in diameter. An upward-fining-upward trend together with decreasing amounts of volcanic material is observed. The matrix consists of quartz grains derived mainly from the Amir and Avrona formations, which at the time of eruption were unconsolidated, and a lot of clay (mostly montmorillonite) originating from the alteration of the mafic fragments. The volcaniclastic sequence is overlain by lacustrine mudstone, dolostone, chert, and iron crusts.

Two groups of clasts can be distinguished:

i. **Pyroclastic group**—originating from explosive eruptions through volcanic vents and consisting of heterogeneously-sized tephra and sedimentary country rock fragments that were deposited within the vents and on their rims (airfall) as scoria and cinder cones, up to a few kilometers from the center of the eruption sites (Figs. 1–3). The latter subsequently infiltrated the sandstones of the underlying formation (Figs. 2, 3). The red encrustation of sandstone grains in the upper part of the Avrona Formation may be remnants of this process.

ii. **Epiclastic group**—reredeposited pyroclastic material and collapse breccia which were washed or slid from the rims and filled the vents (Figs. 2, 3).

The most outstanding and best preserved is the Tamar vent (coords. 1473/9136), a funnel-shaped maar-type crater with steep walls (Fig. 4) and approximately circular, some 300 m across (Fig. 5). In this vent the thickest and most heterogeneous section of the fill is exposed for a distance of about 1100 m along its perimeter, except for its western unexposed side. Only the upper 40 m of the
Fig. 5. Geology of the Tamar vent, showing distribution of the volcaniclastic lithofacies types at the vent’s margins.

Fig. 6. Lateral variations in thickness of the volcaniclastic lithofacies along the eastern and southern margins of the Tamar vent. Datum: base lithofacies 4. For lithofacies descriptions see text.
fill is exposed, overlying or lying against sandstones of the Amir and Avrona formations (Figs. 3, 5). The volcaniclastic fill does not cross the intra-Cretaceous unconformity associated with the base of the Samar Formation.

The thickness of the volcaniclastic section or the depth of the crater is not known. However, at Nahal Mangan, the fill lies against the Shehoret or Timna formations at a level that is at least 150 m lower than the vent’s shoulders. Here the Neogene erosion removed the Amir and Avrona formations and most of the volcaniclastic section, leaving only the material that was deposited deeper in the vents, within the Cambrian formations. According to the magnetometric model, the depth of the fill is about 600 m and part of it is located in the underlying Timna Granite (Segev et al., 1995).

Lithofacies

Four lithofacies types are distinguished in the fill of the Tamar vent and can be followed around its perimeter (Fig. 6a). They are best exposed along the eastern and southern faces where lateral and vertical variations in bed thickness are demonstrated (Fig. 7). They are, from bottom to top:

1. Polymict, matrix-supported, brown volcano-sedimentary breccia, consisting of angular to sub-rounded fragments, including sandstone, siltstone, shale, and dolomite, as well as granite and mafic clasts in a sandy-silty matrix (Fig. 6b). The rock is generally massive, rarely stratified, and the fragments are not oriented. In this lithofacies there are many sandstone boulders, 10 to 80 cm in diameter, but some reach 1.5 m. The volcanic and granitic clasts do not exceed 20%. The maximal thickness of this lithofacies is 13 m. Occasionally this breccia is overlain by sandstone with dispersed clasts, up to 4 m thick (lithofacies 1a).

2. Polymict, clast-supported, dark green to black volcanic breccia, with up to 60% angular to sub-angular mafic fragments (microgabbro?) and some granite, ranging between 1 and 8 cm, in a brown sandy matrix (Fig. 7c). These fragments are strongly weathered, and include ghosts of olivine, augite, biotite, and plagioclase laths, as well as amygdals of calcite and zeolites. The chemical composition (range and average) of 18 mafic fragments (Table 1), indicates a basic composition, though the Loss on Ignition (L.O.I.) points to alteration.

Next in abundance are fragments of the Timna Granite (up to 10%), whereas sandstone clasts are minor. Peculiar to this lithofacies are dispersed, exotic mixtures of lithospheric-lower crust and mantle-derived xenoliths such as hornblendites, graphic slate, and many large xenocrysts of titaniferous biotite. This type of breccia is generally massive (Fig. 7a), but displays breccia in its upper half, which may actually be due to secondary solutions and cementation at certain horizons. The maximum thickness exposed is 20 m.

3. Non-stratified fine- to medium-grained sandstone with granule- to gravel-size fragments or splinters of altered mafic clasts and devitrified glass. In the lower part the color is green due to the many mafic clasts. In the upper part the mafic fragments are smaller, less abundant, and totally altered, and the color changes to yellow. Occasionally, granitic fragments are present. Maximal thickness of the sandy lithofacies (up to 25 m) is found in the eastern margins of the crater (Fig. 7, section 8). Elsewhere this facies is not more than several meters thick.

4. Laminated green siltstone and mudstone alternating with yellow to reddish platy micritic dolostone, locally replaced by lenses of chert with stromatolitic to spotted texture. This lithofacies is up to 6 m thick. The contact with the underlying sandy lithofacies is generally sharp, but sometimes it displays low structures. The top of the section displays pedogenic features, such as iron crusts and mottled clays, and it terminates at the intra-Cretaceous unconformity, overlain by sandstones of the Samar Formation.

The two lowermost lithofacies types are debris flows from pyroclastic talus surrounding the vent, and as peripheral wall-rock breccia. The uppermost lithofacies was deposited in a lake or playa within the crater. At the other volcaniclastic exposures the outline of the vent is not distinct and only a few meters of the volcaniclastic fill is exposed. At these localities most of the above-described lithofacies types are absent, and the most abundant type resembles the sandstone unit with dispersed clasts of lithofacies 1a, though more weathered and ferruginous, displaying dark red colors. This lithofacies dominates small exposures of the Sivan vent. Apparently they are not connected to any specific vent and they seem to fill depressions or pockets on the sandstone surface. However, each of these pockets displays bleaching at its contact with the sandstones, which by themselves
Fig. 7. (a) The volcaniclastic fill at the southern margin of the Tamar vent, showing a succession of four lithofacies types (numbered). The measuring yard is 4 m long. The rock at the bottom left (AV) is a remnant of the vent’s wall in the Avrona Formation. (b) Close-up view of lithofacies 1: coarse, clast-supported, polymict, volcaniclastic breccia with angular to sub-rounded blocks and fragments of sandstone, siltstone, dolomite, and some granite and mafic rock components. Scale in decimeters. *Figure continues next page.*
show some liquefaction contortions. These features probably point to flushing of hydrothermal fluids along the periphery of the pockets at a late stage of the volcanic activity. Such bleaching phenomena are also known along the contact of the distinct vents with the surrounding rocks (Fig. 4), and as already mentioned, by the apparent stratification of the fill in them.

**Origin**

The geometry of the Tamar vent and the character of the fill material resemble maar-type craters, which are formed by groundwater–magma interaction. Such a process occurs when runoff or underground water penetrates down along joints or faults to the contact of ascending magma. The groundwater converts to steam, which causes rapid increase of pressure and phreatomagmatic explosions that may breach the surface. It is postulated that the causative body for the phreatomagmatic activity in the Timna Valley is probably the elongate (15 by 2 km), shallow (±600 m depth), E–W-trending Lower Cretaceous gabbronor gabbro intrusion, sensed by magnetometry underneath the Har Mikhrot and the volcaniclastic exposures (Segev et al., 1995). Its ascending apophyses formed the circular vents or craters and the elongate or irregular vents (pockets), which were subsequently filled with a heterogeneous volcaniclastic fall-back ejecta from the rims and epiclastic debris from nearby vents and country rocks, together with shattered sandy blocks from the wall. The evolutionary stages of the fill of the vents or craters are illustrated in Fig. 3.

The two lowermost lithofacies were deposited on pyroclastic talus surrounding the vents and, together with peripheral wall-rock breccia, were washed as lobes of debris flows to the craters. This is expressed by the variable thickness of the lithofacies types (Fig. 7). Most of the material that was deposited in the crater following the explosion was very coarse breccia from nearby, followed by finer material from further afield. Finally, the crater was filled almost up to its shoulders, and a lake or a playa developed within the remaining shallow depression, which collected clay and micritic carbonate that underwent dolomitization and silicification and became encrusted with iron crusts. Shortly after, subsidence of the base level took place and renewed sedimentation of fluviatle clastics (Samar Formation) covered and buried the volcaniclastics. The phreatomagmatic activity in the Timna Valley could have occurred repeatedly, however, the

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<th>Chemical composition of 18 mafic rock fragments from the volcaniclastic breccia (lithofacies 2) in the Tamar vent</th>
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<tr>
<td>SiO₂</td>
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Fig. 7 continued. (c). Close-up view of lithofacies 2: clast-supported, polymict, volcaniclastic mixed breccia with angular to subangular fragments of altered mafic rock (microgabbro?) and granite.
overall duration of the volcanic activity was brief since all occurrences are restricted to the transition from the Avrona Formation to the overlying Samar Formation. The explosions took place when the landscape almost reached maturity, and materials that were ejected from the vents were subsequently transported back and swept into them. Fine material that fell further away was altered and disaggregated and has left no trace in the stratigraphic column.

MINERAL AND WHOLE ROCK DATING

Samples and methods

Three biotite xenocrysts and a hornblendite xenolith were sampled from the volcaniclastic breccia (lithofacies 2) at the Tamar vent (coords. 1473/9136). The biotite samples (AST-11, 12, 13) are single crystals up to 3 cm in size, whereas the hornblende sample (AST-10) was obtained from a hornblendeite, which is composed mainly of coarse (~1 cm) prismatic hornblende crystals that were separated under the binocular. The crystals appeared quite fresh and suitable for dating. This fact was examined under the microscope and validated by the age determination isotopic analysis of argon, in which flat, undisturbed spectra were obtained. In addition, a microgabbro whole rock (WR) sample (no. 6588) was obtained from the plug in the northeast Timna Valley (coords. 1497/9131; Fig. 1a). All samples were cleaned and crushed, and the 1–3 mm (minerals) and 40–60 mesh (0.42–0.25 mm) WR fractions were separated for analysis. The samples were bathed for about 15 minutes in dilute hydrochloric acid to remove impurities and then thoroughly flushed.

The $^{40}\text{Ar}/^{39}\text{Ar}$ measurements were conducted at the Geological Survey of Israel (GSI) geochronological laboratory using procedures as described by Heimann et al. (1992). Samples were irradiated at the IRR-1 reactor at the Soreq Nuclear Center. The samples were heated in an inductive furnace and analyzed by an MM-1200B mass-spectrometer. Neutron fluence was calibrated using K–Ar measurements; potassium was determined after fusing with Li$_2$B$_2$O$_4$ by ICP-AES (Perkin Elmer Optima 3000). Argon isotopic measurements were done at the GSI using standard isotope dilution and an MM-1200B mass spectrometer (Steinitz et al., 1982; Kotlarsky et al., 1992). Plateau ages were calculated using the standard criteria. A plateau is defined by three or more contiguous steps whose apparent ages are not significantly different at 2σ and which contain at least 50% of the released $^{39}\text{Ar}$ (McDougall and Harrison, 1999).

Normal isochron ($^{40}\text{Ar}/^{36}\text{Ar}$ vs. $^{39}\text{Ar}/^{36}\text{Ar}$) isotope correlation diagrams (isochrons) were generated using the Isoplot 2.3 (Ludwig, 2000). The isochrons constructed by a Model 1 fit based on York’s (1969) algorithm. On the assumption that the assigned uncertainties are the only reason the data diverge from a straight line, the points are weighted proportionally to the inverse square of their uncertainty (allowing for correlated uncertainties). The Mean Square of Weighted Deviates (MSWD) expresses the goodness of fit, using these assumptions. The uncertainties are quoted at the 2σ level, assigning a 1.5% estimated error to J. If the assigned uncertainties are the only cause of scatter, the MSWD tends towards 1, while MSWD values much higher than 1 suggest either underestimated analytical error or the presence of a non-analytical scatter (Ludwig, 2000).

The plateau and isochron ages for all the mineral samples are generally concordant. We use only isochron ages for comparison, as they are not influenced by the choice of the $^{40}\text{Ar}/^{36}\text{Ar}$ ratio of the trapped nonradiogenic $^{40}\text{Ar}$.

In the present study the samples were calculated using a slightly different way of correcting the air argon discrimination in the mass spectrometer (Harlavan, pers. comm.), thus yielding a difference of ~1% from the previous results in Segev (2000) and Weissbrod et al. (2001).

RESULTS

The $^{40}\text{Ar}/^{39}\text{Ar}$ results are presented in Appendix 1, and illustrated (age spectra and isochron diagrams) in Figs. 8 and 9. The K/Ar ages of all the samples are given in Table 2 and a summary of all age calculations is given in Table 3.

The three biotites yielded similar, well-defined plateau ages, as follows:

Biotite sample AST-11 yielded a somewhat disturbed flat plateau age of 106.2 ± 0.8 Ma (Fig. 8c) defined by 99% of cumulative released $^{39}\text{Ar}$ (9 contiguous steps). The isochron age (107 ± 4 Ma, MSWD = 0.3, with an initial $^{40}\text{Ar}/^{36}\text{Ar}$ ratio of 273 ± 230; Fig. 8d) is similar to the plateau age. The K/Ar age of this sample is slightly older (111.2 ± 2.2 Ma, Table 2), probably because it contains an older component at the low temperature step, but remains in the range of the analytical error. Biotite sample AST-12 yielded a flat plateau age of 107.9 ± 0.4 Ma (Fig. 8e) defined by
Fig. 8. Curves of \(^{40}\text{Ar}/^{39}\text{Ar}\) spectra and isochron diagrams of biotite and hornblende samples from the Tamar vent.
99% of cumulative released $^{39}$Ar (14 contiguous steps) and a similar isochron age of $109.3 \pm 1.8$ Ma, $\text{MSWD} = 0.3$, with an initial $^{40}$Ar/$^{36}$Ar ratio of $267 \pm 19$ (Fig. 8f). The K/Ar age of this sample is similar ($108.6 \pm 2.2$ Ma, Table 2). Biotite sample AST-13 yielded a flat plateau age of $106.0 \pm 1.0$ Ma (Fig. 9a) defined by $79\%$ of cumulative released $^{39}$Ar (5 contiguous steps) and an isochron age of $107.3 \pm 9.7$ Ma (MSWD = 0.007, with initial $^{40}$Ar/$^{36}$Ar ratio of $197 \pm 1300$; Fig. 9b). The K/Ar age of this sample is $107.8 \pm 2.2$ Ma (Table 2).

The hornblende sample AST-10 yielded a slightly disturbed plateau age of $102.8 \pm 1.7$ Ma (Fig. 8a) defined by $95\%$ of cumulative released $^{39}$Ar (6 contiguous steps). The isochron age of $104.4 \pm 4.8$ Ma with a high MSWD = 3.7 and a $^{40}$Ar/$^{36}$Ar intercept of $262 \pm 140$ (Fig. 8b) shows considerable scatter of data-points from this straight line.

The WR microgabbro (6588) yielded a disordered spectrum (Fig. 9c) with a total gas age of $110 \pm 8$ Ma and a meaningless regression-line date of $118 \pm 5$ Ma with a very high MSWD = 25 and a not-valid negative $^{40}$Ar/$^{36}$Ar initial ratio ($-87$; Fig. 9d). All the Ar/Ar age calculations for this sample are therefore meaningless. The K/Ar age of the microgabbro is $97 \pm 2$ Ma. These non-valid results are partly due to alteration processes that include the replacement of olivine by serpentine and chlorite, veins of ferruginous minerals, void-filling dolomite, and the L.O.I. content (6%, of which 4.3% is CO$_2$).

Since the three biotites are from the same site and represent the same eruption, we have calculated the weighted average age for the isochrons and K/Ar ages.
of the biotites (excluding the K/Ar age of sample AST-11, see above) together with one K/Ar age of the hornblende). The weighted average age (Tukey’s Biweight Mean (Ludwig, 2000) for the six valid age calculations from the Tamar vent is 108.4 ± 1.7 Ma.

**DISCUSSION**

Apart from the volcanic exposures in the Timna Valley and Makhtesh Ramon, Lower Cretaceous magmatic activity is evident elsewhere in the Negev: igneous rocks were penetrated in several boreholes, and three aeromagnetic anomalies encountered in the Har Govay (1) and Hameishar (2) in the central Negev have been interpreted to be magmatic occurrences (Gvirtzman, 1992). The inferred subsurface igneous bodies, which are larger than the exposed occurrences, display high susceptibility values and apparently intruded the roof of the Precambrian and pre-Cretaceous section, reaching the sub-Cretaceous unconformity surface, or are emplaced several hundred meters below it. Gvirtzman (1992) postulated that the Har Govay body penetrated Triassic rocks, whereas the Hameishar bodies seem to be emplaced in older rocks. These igneous occurrences are similar in composition and stratigraphy to the inferred Har Mikhrot intrusion in the northern Timna Valley (Segev et al., 1995) and they all may represent the same episode, though Baer (1989) argued that the Har Govay anomaly reflects a body that formed the radial system of dikes in east Makhtesh Ramon and hence belong to the earliest Early Cretaceous episode (138 to 132 Ma), which did not cross the sub-Cretaceous unconformity. On the other hand, the Hameishar intrusions like that of Har Mikhrot are mostly emplaced in the upper part of the igneous basement and, again like the latter, may in places cross the igneous-sedimentary unconformity and serve as a feeder of the explosive surface volcanism (vents) at the intra-Cretaceous Avrona–Samar boundary.

Four vents filled by blocky breccia to coarse lapilli tuff in a matrix of sand are exposed in the northern Timna Valley above the inferred buried intrusion, and the ratio of juvenile material to country rock fragments varies considerably. Among the igneous fragments, hornblende xenoliths and large biotite crystals, which were transported rapidly to the surface along conduits from their source regions in the lower crust or uppermost mantle, are found locally.

Three of these biotite xenocrysts yielded uniform 40Ar/39Ar plateau ages between 106.0 ± 1.0 and 107.9 ± 0.4 Ma and isochron ages between 107 ± 4 and 109.3 ± 1.8 Ma, and K/Ar ages between 107.8 ± 2.2 and 111.2 ± 2.2 Ma.

The hornblende sample yielded a slightly younger, disturbed 40Ar/39Ar age of 104.4 ± 4.8 Ma, still within the
analytical error, though with a valid K/Ar age of 110.8 ± 2.2 Ma. The ^{40}Ar/^{39}Ar measurements of the WR microgabbro yielded disordered, meaningless results and a young K/Ar age of 97 ± 2 Ma, caused by loss of argon during alteration. The weighted average age for the five biotite ages, together with the valid K/Ar age of the hornblende, yielded an age of 108.4 ± 1.78 Ma (late Early Albian; Gradstein et al., 1995), which reliably represents the resetted age of the biotites from the volcanic eruption in the northern Timna Valley and the emplacement of the microgabbro plug.

This age also marks the transition between the Avrona and Samar formations because the measured minerals, together with the volcaniclastic material, were derived from a vent that burst to the surface on the top of the Avrona Formation and were subsequently washed back into the vent/crater, which eventually was covered by the basal Samar sandstones. The length of this time interval and how long the third Lower Cretaceous magmatic episode lasted is not evident in the Timna Valley, since all minerals were obtained from a single vent and yielded practically the same cooling or resetted ages. Nevertheless, volcanic rocks of similar age (Ramon Basalt) that invade or overlie a rock unit equivalent to the Avrona Formation and are terminate below the Samar Formation-equivalent (Weissbrod and Sneh, 1997) suggest several volcanic pulses throughout the Late Aptian and Early Albian stages, as attested from the thick volcanic flows and intermittent paleosol horizons and the range of ages (116.4 to 109 Ma = Middle Aptian to Early Albian, Gradstein et al., 1995) obtained at different locations and stratigraphic levels (Segev et al., in prep.).

Petrographic-mineralogic and physical characteristics have been found to be useful criteria for correlating the Lower Cretaceous clastic sequence (which lacks diagnostic fossils) across the Negev and Sinai (Weissbrod and Sneh, 1997), beside a Lower Aptian
marine fossiliferous horizon at the top of the Amir Formation and the base of the Upper Albian to Cenomanian carbonates of the Hazera Formation, which are conspicuous markers that retain their characteristics and stratigraphic level over large distances. In this regard the dated volcanic occurrences constitute another important marker for correlation and age assignment to the Avrona and Samar formations. Thus, the age of the Avrona Formation is constrained between the Early Aptian and late Early Albian, whereas the time interval of the Samar Formation is delimited between the late Early and Late Albian. Volcanic age determinations may be extended to equivalent rock units in Sinai and the SW Desert of Egypt (Weissbrod and Sneh, 1997) and in Jordan (Weissbrod, 2002), even though no volcanism has been found there in a similar stratigraphic setting (Fig. 10).

ACKNOWLEDGMENTS

Discussions with Dr. J.N. Theron and Dr. M. Beyth during the field survey are greatly appreciated. Many thanks go to Dr. J. Kapusta for radiometric measurements in the early stage of this study, to Dr. Y. Harlavan for initial geochronological data processing and calculations, to Dr. B. Lang, Dr. S. Peltz, and I. Perath for their useful comments and suggestions, and to C. Dallal for performing the $^{40}$Ar/$^{39}$Ar measurements. We are indebted to D. Stieber, O. Yoffe, and S. Ehrlich for the potassium analyses. Thanks are also due to B. Katz for editing assistance.

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Segev, A., Beyth, M. 1983. Preliminary report on the geol-

see Appendix next page
APPENDIX 1

$^{40}\text{Ar}/^{39}\text{Ar}$ analytical data and apparent ages of minerals and WR samples from the volcaniclastic fill and the plug in the Timna Valley

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