Geol. Mag. **144** (*5*), *2007, pp. 797–810.* © *2007 Cambridge University Press* 797
doi:10.1017/S0016756807003792 First published online 12 July 2007 *Printed in the United Kingdom*

Timing of subduction zone metamorphism during the formation and emplacement of Troodos and Baer–Bassit ophiolites: insights from ^{40}Ar–^{39}Ar geochronology

GAVIN HEUNG-NGAI CHAN*†, JOHN MALPAS*, COSTAS XENOPHONTOS* & CHING-HUA LO‡

*Department of Earth Sciences, The University of Hong Kong, Pokfulam Road, Hong Kong, China
‡Department of Geosciences, National Taiwan University, 245 Choushan Road, Taipei 106, Taiwan

(*Received* 26 July 2006; *accepted* 18 January 2007)

Abstract – The Troodos ophiolite in Cyprus and Baer–Bassit ophiolite in Syria together form part of the Tethyan ophiolite belt. They were generated in a supra-subduction zone setting in Late Cretaceous times. As with many of the ophiolite occurrences in this belt, the sequences are closely associated with tectonic 'coloured mélange' zones, which contain, among a variety of lithologies, metre- to kilometre-size blocks of metamorphic rocks. Precise ^{40}Ar–^{39}Ar laser step-heating experiments performed on four amphibolites from SW Cyprus and six from NW Syria, yield plateau ages ranging from 75.7 ± 0.3 Ma to 88.9 ± 0.8 Ma in Cyprus and 71.7 ± 0.5 to 88.4 ± 0.4 Ma in Syria. The older limits of these time spans are coeval with the age of the formation of the associated ophiolites. Unlike other metamorphic sole rocks which seem to form in relatively short time spans, these metamorphic rocks found in Cyprus and Syria are interpreted to have formed in Late Cretaceous times by accretion below the overriding Troodos and Baer–Bassit crust for a period of 15–18 Ma. The metamorphic complexes were exhumed by extension and crustal thinning associated with subduction roll-back and the rotation of the overriding plate until the cessation of subduction in Maastrichtian times. In Cyprus, the exhumed metamorphic complex was incorporated into an accretionary prism constructed primarily of the collapsed Mamonia passive margin sequence intercalated with rocks of the Troodos ophiolite during plate collision in the Maastrichtian. Concomitantly, in Syria, the Baer–Bassit ophiolite and subcreted metamorphic complex were emplaced onto the Arabian passive margin and fragmented into blocks and knockers, forming the Baer–Bassit mélange.

Keywords: Troodos ophiolite, Baer–Bassit ophiolite, Ayia Varvara, ^{40}Ar–^{39}Ar.

1. Introduction

The Eastern Mediterranean represents a complex orogenic zone which marks the closure of the once extensive Tethyan Ocean (Fig. 1). It is characterized by several discontinuous belts of ophiolitic rocks, associated with slivers of highly deformed amphibolite- to greenschist-facies metamorphic rocks. These metamorphic rocks occur immediately beneath the ophiolites (metamorphic soles) and/or are included in the tectonic 'coloured mélanges' (e.g. Robertson, 2002, 2004; Smith, 2006). In Cyprus and Syria, these metamorphic rocks are preserved within the Mamonia Complex (SW Cyprus) and the Baer–Bassit mélange (NW Syria), respectively.

The objective of the present study is to constrain the timing of development of the metamorphic rocks in Cyprus and Syria using a combination of precise ^{40}Ar–^{39}Ar laser step-heating experiments on amphiboles separated from the metamorphic rocks, in order to gain further insights into the inception and duration of subduction zone metamorphism during the formation and emplacement of the Troodos and Baer–Bassit ophiolites.

^{40}Ar–^{39}Ar and K–Ar geochronologies have been widely used to constrain the ages of metamorphic rocks associated with ophiolites and elucidate their tectonic significance in the Eastern Mediterranean and Oman regions (Fig. 1). Despite the wide range of K–Ar ages in the earlier studies (Thuizat *et al.* 1981; Yilmaz & Maxwell, 1982; Parlak, Delaloye & Bingöl, 1995), precise ^{40}Ar–^{39}Ar ages have only been obtained from the metamorphic rocks associated with the Tauride Belt ophiolites of southern Turkey and the Semail ophiolite of Oman. Çelik, Delaloye & Feraud (2006) documented ^{40}Ar–^{39}Ar amphibole ages from the Lycian ophiolite (90.7 ± 0.5 to 93.0 ± 0.9 Ma), the Antalya ophiolite (93.0 ± 1.0 to 93.8 ± 1.7 Ma) and the Beyşehir ophiolite (90.9 ± 1.3 to 91.5 ± 1.9 Ma). Further east of the Tauride belt, ^{40}Ar–^{39}Ar amphibole ages of the Mersin ophiolite range from 91.6 ± 0.3 to 96.0 ± 0.7 Ma (Parlak & Delaloye, 1999). Dilek *et al.* (1999) presented additional ages for the Mersin ophiolite (91.3 ± 0.4 to

† Author for correspondence: Department of Earth Sciences, Oxford University, Parks Road, Oxford, OX1 3PR, UK; e-mail: gavin.chan@earth.ox.ac.uk

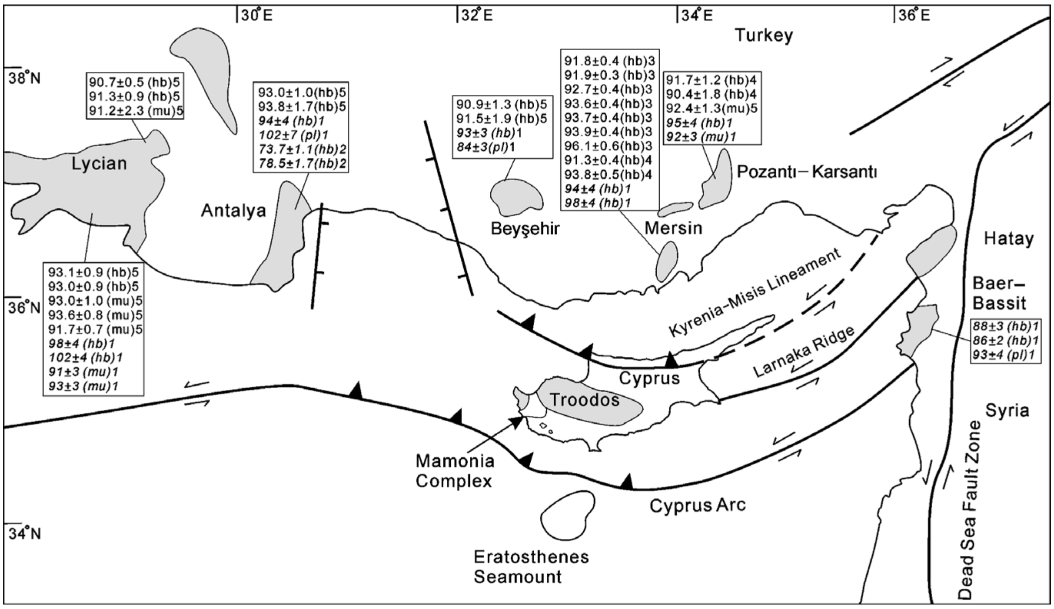

Figure 1. Tectonic map of Eastern Mediterranean, summarizing K–Ar (italic fonts) and ^{40}Ar–^{39}Ar geochronological data from the metamorphic rocks associated with the ophiolites. hb – hornblende; pl – plagioclase; m – mica. Numbers indicate references: 1 – Thuizat *et al.* (1981); 2 – Yilmaz & Maxwell (1982); 3 – Parlak & Delaloye (1999); 4 – Dilek *et al.* (1999) and 5 – Çelik, Delaloye & Feraud (2006).

93.8 ± 0.5 Ma) and a new age for the Alihoca ophiolite (90.6 ± 0.9 Ma). Hornblendes from the amphibolites beneath the Semail ophiolite yielded ^{40}Ar–^{39}Ar ages between 92.6 ± 0.6 and 94.9 ± 0.5 Ma (Hacker, 1994; Hacker, Mosenfelder & Gnos, 1997). The ages of these metamorphic rocks span 4–6 Ma, and show small age differences with the overlying ophiolites. They are therefore interpreted to have formed during the inception of intra-oceanic subduction which ultimately led to the formation of ophiolites in a supra-subduction zone setting.

In SW Cyprus, the high-temperature metamorphic rocks were dated by Spray & Roddick (1981) using ^{40}Ar–^{39}Ar geochronology. In that study, most of the hornblende step-heating analyses yielded irregular plateau ages. The majority of the results do not meet the criteria of Lanphere & Dalrymple (1978) for a meaningful age: (1) a plateau age should comprise more than 50 % of the total ^{39}Ar released from the sample; (2) a well-defined isochron should have an acceptable statistic-fitting parameter (mean square weight deviate: MSWD); (3) the plateau and isochron ages should be concordant and (4) the $^{40}Ar/^{36}Ar$ intercept value for trapped argon should not be significantly different from the atmospheric $^{40}Ar/^{36}Ar$ ratio (295.5). In addition, calculated K/Ca ratios are not consistent with the mineralogical data obtained from microprobe analyses of hornblendes in the separates from the same study, suggesting the dated hornblende separates were contaminated by other minerals. Nonetheless, these authors concluded that the metamorphic rocks range from 86 to 91 Ma in Ayia Varvara and 83 to 90 Ma in Loutra tis Aphroditis, and interpreted the ages as representing timing of metamorphism along an intra-oceanic fracture zone. Swarbrick (1993) emphasized the fact that the metamorphic rocks are in high-angle fault contact with the surrounding ultramafic rocks and envisaged that metamorphism had taken place along a sinistral strike-slip fault prior to the juxtaposition of the Troodos ophiolite and Mamonia Complex. Bailey, Holdsworth & Swarbrick (2000) further elaborated this idea and proposed that localized metamorphism of the Mamonia Complex took place along a transform-related, dextral strike-slip fault. On the other hand, Clube & Robertson (1986) compared the metamorphic rocks in SW Cyprus with metamorphic sole rocks in other ophiolite occurrences and argued that the metamorphic rocks formed along a transpressional oceanic fracture zone and later were involved in regional convergence. However, it is unclear if strike-slip fault movement can provide enough heat for any high-temperature metamorphism. Alternatively, Malpas, Xenophontos & Williams (1992) and Malpas, Calon & Squires (1993) pointed out that the metamorphic rocks are not similar to those expected for a typical metamorphic sole (e.g. Williams & Smyth, 1973; Malpas, 1979; Searle & Malpas, 1980, 1982) as they lack a clear (inverted) metamorphic gradient and are not in contact with an intact overriding ophiolite. Because the metamorphic rocks appeared to be derived from volcanic and sedimentary protoliths akin to those found in the Mamonia Complex, it was concluded that they were formed when the Mamonia Complex was accreted within a subduction zone above which the Troodos ophiolite was forming (Malpas, Xenophontos & Williams, 1992; Malpas, Calon & Squires, 1993). The latter model has now been generally accepted (e.g. Robertson, 2000, 2004; Garfunkel, 2006).

https://doi.org/10.1017/S0016756807003792 Published online by Cambridge University Press

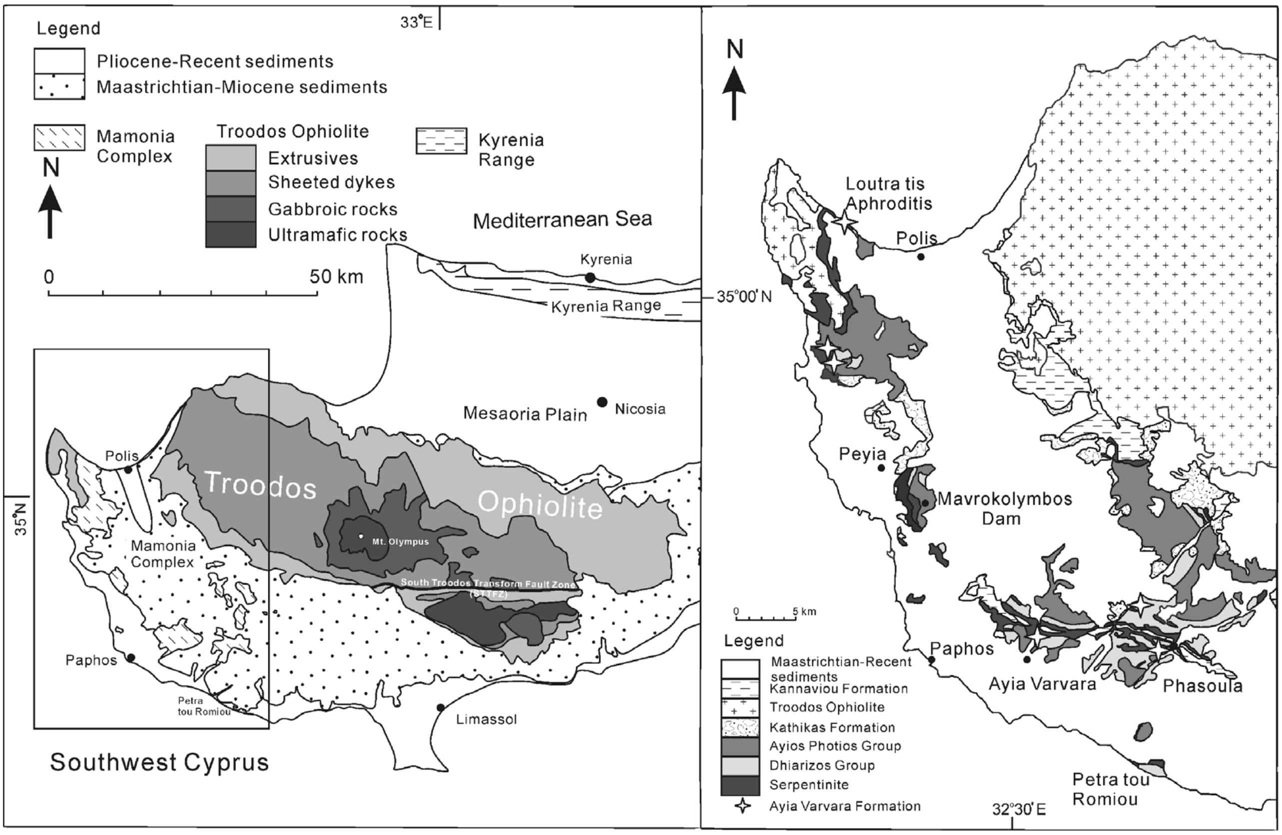

Figure 2. Simplified geological map of Cyprus, after Robertson & Xenophontos (1993) and SW Cyprus, after Swarbrick (1980) & Malpas & Xenophontos (1999).

In NW Syria, K–Ar hornblende ages of the metamorphic rocks range from 85 to 95 Ma (Delaloye & Wagner, 1984). Thuizat *et al.* (1981) reported a wider range of K–Ar ages, including hornblende ages of 84–91 Ma and plagioclase ages of 93 Ma. The huge uncertainties of these published K–Ar hornblende and plagioclase ages (1σ up to 4 Ma) and irregular plateau ages hinder any appropriate interpretation of timing of metamorphism. Nevertheless, two different models have been proposed to explain the origin of metamorphic rocks from NW Syria. Thuizat *et al.* (1981) and Delaloye & Wagner (1984) suggested that they were formed during intra-oceanic thrusting. However, the protoliths of the metamorphic rocks are WPB, similar to those unmetamorphosed seamount-type alkali basalts (Tammima volcanics) in the Baer–Bassit mélange. This led Al-Riyami *et al.* (2002) to suggest that the metamorphic rocks formed when the passive margin sequence was thrust beneath the hot and young Baer–Bassit oceanic lithosphere in a subduction zone.

2. Geological setting

2.a. Cyprus

The Troodos ophiolite of Cyprus occurs as a largely undeformed and coherent massif, forming an ellipsoidal dome-structure (Fig. 2). Ophiolitic rocks are exposed over an area of 2300 km^2 ($\sim$ 90 km in length, $\sim$ 35 km in width). The Troodos ophiolite is cut by the South Troodos Transform Fault Zone in the south and comprises a mantle section, consisting of variably serpentinized peridotites, mainly tectonized harzburgite with dunites and rare lherzolites, overlain by a crustal section that includes cumulate peridotites, layered gabbros, vari-textured gabbros, a sheeted dyke complex and basaltic extrusives (Moores & Vine, 1971; Gass, 1980; Gass *et al.* 1994). The extrusive sequence is covered by the mainly Santonian–Campanian umbers and radiolarites, which are in turn overlain by volcaniclastic and pelagic sediments (Lord *et al.* 2000). The Troodos ophiolite is interpreted to have formed in a supra-subduction zone on the grounds of petrographical and geochemical studies (Robinson *et al.* 1983; Malpas & Langdon, 1984; Rautenschlein *et al.* 1985). Plagiogranites from the Troodos ophiolite have U–Pb zircon ages suggesting crystallization between 90.3 $\pm$ 0.7 Ma and 92.4 $\pm$ 0.7 Ma with a mean age of 91.4 Ma (Mukasa & Ludden, 1987). The extrusive sequence is further covered by umbers and radiolarites of mainly Santonian–Campanian age (Lord *et al.* 2000). Palaeomagnetic studies have inferred that the Troodos microplate underwent anticlockwise rotation after its formation (Moores & Vine, 1971; Clube, Creek & Robertson, 1985; Clube & Robertson, 1986). The $\sim$ 74° of reorientation involved two phases. The first was a regional intraoceanic rotation, associated with the Baer–Bassit and Hatay oceanic lithospheres during the

Campanian–Maastrichtian, and the second, subsequent rotation was completed by Eocene times (Morris *et al.* 2006).

In SW Cyprus, the Mamonia Complex has been tectonically juxtaposed with the Troodos ophiolite (Fig. 2). During the collision, these two terranes were highly deformed and the suture is now essentially represented by a mélange (Robertson & Woodcock, 1979; Clube & Robertson, 1986; Robertson, 1990; Malpas, Xenophontos & Williams, 1992; Malpas, Calon & Squires, 1993). Apart from several erosional windows, the mélange is covered by Maastrichtian debris flow deposits of the Kathikas Formation and the Tertiary chalks of the Lefkara and Pachna formations and subsequent overlying sediments (Swarbrick & Naylor, 1980; Lord *et al.* 2000). The Mamonia Complex represents a collapsed passive margin sequence (Robertson & Woodcock, 1979). It includes Late Triassic to Early Cretaceous MOR- and WPB-volcanic and plutonic rocks and related sediments of the Dhiarizos Group (Lapierre, 1975; Malpas, Xenophontos & Williams, 1992; Malpas, Calon & Squires, 1993) and Late Triassic–Early Cretaceous shallow to deep-water continental margin sediments of the Ayios Photios Group. The latter is now in low-angle thrust contact over the former (Swarbrick & Robertson, 1980). Exposures of the Mamonia Complex also incorporate fragments of Troodos-related serpentinites, pillow lavas and overlying sediments (Malpas, Xenophontos & Williams, 1992; Malpas, Calon & Squires, 1993). While some investigators believed that the Mamonia Complex represents the westward extension of the Arabian passive margin sequence (Moores *et al.* 1984; Malpas, Calon & Squires, 1993; Garfunkel, 1998, 2004), others proposed a northerly origin of the Mamonia Complex (Robertson, 1998, 2000). In the latter model, the tectonostratigraphy of the Mamonia Complex is believed to be comparable with the continental margin rocks of the Anatalya Complex in SW Turkey and interpreted to be part of the northern passive margin of the Neo-Tethys in the easternmost Mediterranean detached and rotated together with the Troodos microplate during Campanian–Eocene times. However, this hypothesis is difficult to evaluate without sufficient palaeomagnetic data from the Mamonia Complex (Clube, Creek & Robertson, 1985; Clube & Robertson, 1986).

Metamorphic rocks of the Ayia Varvara Formation also form part of the Mamonia Complex, comprising mainly greenschist- to amphibolite-facies metabasic rocks, interbedded with metasedimentary layers, and appearing as a number of isolated, metre- to kilometre-scale outcrops best seen immediately to the north of Ayia Varvara village (Swarbrick & Robertson, 1980; Spray & Roddick, 1981; Malpas, Xenophontos & Williams, 1992; Malpas, Calon & Squires, 1993). Here, the metamorphic rocks are in steep thrust contact with the Dhiarizos Group volcanics and Troodos-derived boninitic lavas and serpentinites (Malpas, Xenophontos & Williams, 1992; Malpas, Calon & Squires, 1993). Locally, tectonic fabrics in the serpentinized peridotite, which in places are mylonitic, are parallel or subparallel to the dominant foliation in the metamorphic rocks (Malpas, Xenophontos & Williams, 1992; Malpas, Calon & Squires, 1993). Three phases of deformation have been recognized in the metamorphic rocks (Spray & Roddick, 1981; Malpas, Xenophontos & Williams, 1992; Malpas, Calon & Squires, 1993), and metamorphic conditions have been estimated to range up to about 600 °C and ≤ 5 kbar based on petrographical examination of the preserved mineral assemblages (Malpas, Xenophontos & Williams, 1992) and 450–500 °C and 6–8 kbar on the basis of mineral chemistry (Silant'ev, 1993). On the basis of trace element studies, their protoliths are WPB (within-plate basalt)- and MORB (mid-ocean ridge basalt)-type oceanic rocks that are considered to be derived from the Dhiarizos Group (Malpas, Xenophontos & Williams, 1992; Silant'ev, 1993).

2.b. Syria

In contrast to the intact Troodos ophiolite, the dismembered Baer–Bassit ophiolite forms outcrops of about 70 km^2 in two major massifs: the Baer to the northeast and the Bassit to the southwest, with a number of smaller massifs to the southeast (Fig. 3). The ophiolite consists of tectonized peridotite, mainly harzburgites and dunites with minor wehrlites, pyroxenites, layered and massive gabbros, sheeted dykes, and massive and pillowed basaltic rocks. The extrusives are overlain by a sedimentary sequence of ferromanganiferous umbers, followed by radiolarian mudstone and pelagic carbonates (Parrot, 1980; Al-Riyami *et al.* 2002). The ophiolite is thought to have been broken up during its emplacement onto the Arabian platform in middle Maastrichtian times and through subsequent strike-slip deformation associated with the Dead Sea Fault Zone during the Neogene to Present (Parrot, 1980; Al-Riyami *et al.* 2002). The dismembered Baer–Bassit ophiolite is further covered by upper Maastrichtian to Pliocene sediments (Al-Riyami *et al.* 2002). The ophiolite has been ascribed a supra-subduction zone origin, on the basis of its subduction-modified geochemical composition (Al-Riyami *et al.* 2002).

The age of the Baer–Bassit complex is still not accurately constrained. K–Ar whole rock ages from the sheeted dykes have a wide range from 73 to 99 Ma. Low-K secondary amphibole separates from the gabbros yielded ages slightly older than this (Late Jurassic: Delaloye & Wagner, 1984). The age of the ophiolite can probably be further constrained by palaeomagnetic data, in that rocks of both normal and reverse polarities are found, implying that the ophiolite was formed in a magnetic transition period either prior to or after the long Cretaceous C34n interval (83.5–120 Ma: Gradstein *et al.* 1994). The latter of these transition periods coincides with the radiometric ages mentioned above (Morris *et al.* 2002, 2006).

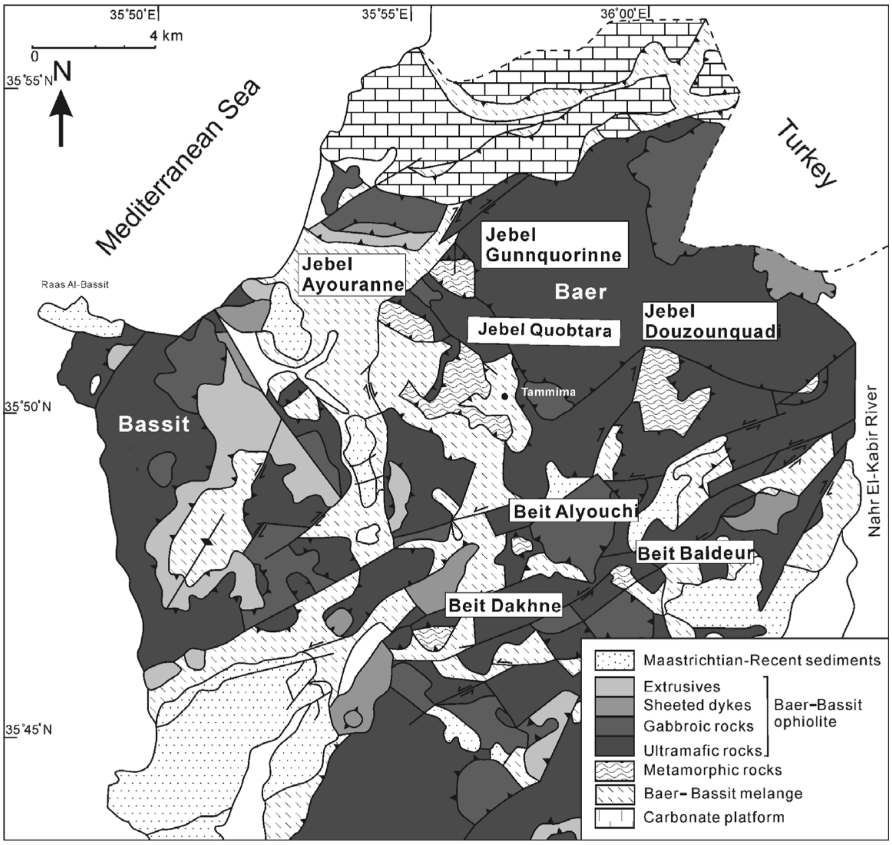

Figure 3. Simplified geological map of the Baer–Bassit region of NW Syria, after Al-Riyami *et al.* (2002).

In these palaeomagnetic studies, the ophiolite blocks are inferred to have undergone anticlockwise rotation varying from 90° to 200°. This extreme rotation is interpreted to have involved two stages. The first was a regional scale, bulk intraoceanic rotation of the Troodos and Hatay oceanic lithosphere before the Baer–Bassit oceanic lithosphere was emplaced onto the Arabian passive margin. Subsequent rotation was probably induced by Late Tertiary deformation along the Dead Sea Fault Zone (Morris *et al.* 2002, 2006).

The Baer–Bassit ophiolite is underlain by the Baer–Bassit mélange (Fig. 3), which comprises a sequence of disrupted thrust sheets, transitional to tectonic mélange, without a contemporaneous sedimentary matrix. The volcanic rocks found in the mélange are represented by alkaline, within-plate mafic extrusives of Late Triassic–Early Cretaceous age. The mélange also includes sedimentary units of Late Triassic to Cenomanian shallow to deep-water continental margin sediments (Delaune-Mayere & Saint-Marc, 1979/80; Delaune-Mayere, 1984; Al-Riyami & Robertson, 2002; Al-Riyami, Danelian & Robertson, 2002). The Baer–Bassit mélange is interpreted as a collapsed volcano-sedimentary sequence representing the Mesozoic Arabian continental margin (Fig. 3) (Parrot, 1980; Delaune-Mayere, 1984; Al-Riyami & Robertson, 2002; Al-Riyami *et al*. 2002). Metamorphic rocks are found in the Baer–Bassit mélange as six major massifs and a number of isolated thrust slices, with variable thicknesses of up to 500 m. They include amphibolite- to greenschist-facies metabasic rocks intercalated with metasedimentary rocks, and are ubiquitously associated with the serpentinites in the region (Whitechurch & Parrot, 1974; Parrot, 1980; Al-Riyami *et al.* 2002). Peak metamorphic conditions have been estimated as 450 °C and 4–8 kbar (Silant'ev, 1993), although Al-Riyami *et al.* (2002) estimated that the metamorphic rocks were formed at a temperature of 600 °C on the basis of preserved mineral assemblages. The metamorphic rocks show WPB- and IAT (island arc tholeiite)-type chemical signatures, and are interpreted to be derived partly from the alkali basalts (Tammima volcanics) now preserved within the underlying Baer–Bassit mélange (Al-Riyami *et al.* 2002).

3. Geochronology of the metamorphic rocks

3.a. Samples and analytical method

In order to constrain better the timing of the metamorphic rock formation, four amphibolite samples from SW Cyprus and six amphibolite samples from NW Syria were analysed by the ^{40}Ar–^{39}Ar laser step-heating method. Coordinates of all sample localities are given in Table 1. The amphibole separates were analysed at National Taiwan University, following the procedures of Lo *et al.* (2002). Ages were calculated relative to LP-6 biotite standard (Odin *et al*. 1982),

https://doi.org/10.1017/S0016756807003792 Published online by Cambridge University Press

Table 1 Summary results of ^{40}Ar–^{39}Ar dating for the amphibolites from SW Cyprus and NW Syria

				Age spectra					Isochron analysis		
	Unit	Latitude	Longitude	Integrated age (Ma)	Increments used (watt)	$^{39}Ar_K$(%) in plateau	Plateau age (Ma)	No. of steps	Intercept age (Ma)	$(^{40}Ar/^{36}Ar)i$	MSWD
Cyprus											
LT1-07	Loutra tis Aproditis	35°03.56′N	32°20.85′E	88.9 ± 0.8	0.1–1.9	100	88.9 ± 0.8	19 of 19	90.5 ± 1.6	290.5 ± 4.9	0.658
LT2-01	Loutra tis Aproditis	35°03.59′N	32°20.63′E	80.1 ± 0.3	0.4–2.0	85.5	80.5 ± 0.3	17 of 20	80.1 ± 0.3	299.2 ± 3.0	0.471
AV2-25	Ayia Varvara	34°46.12′N	32°31.39′E	76.5 ± 0.4	0.1–2.0	100	76.5 ± 0.4	20 of 20	76.0 ± 0.5	297.8 ± 2.5	0.383
AV2-03	Ayia Varvara	34°45.89′N	32°31.20′E	75.7 ± 0.3	0.1–2.2	100	75.7 ± 0.3	21 of 21	75.8 ± 0.4	294.8 ± 1.4	0.412
Syria											
SY-48	Beit Dakhne	35°55.93′N	35°46.66′E	88.1 ± 0.1	0.2–2.1	88.1	88.4 ± 0.4	20 of 21	88.1 ± 0.3	298.8 ± 4.2	0.307
SY-34	Jebel Douzounquadi	35°59.85′N	35°50.85′E	81.6 ± 0.3	0.1–2.1	100	81.6 ± 0.3	21 of 21	81.6 ± 0.6	295.8 ± 8.7	0.688
SY-14	Jebel Gunnquorinne	35°55.88′N	35°52.21′E	81.6 ± 0.3	0.2–2.0	100	81.6 ± 0.3	17 of 17	81.6 ± 0.6	296.9 ± 0.1	0.489
SY-50	Beit Baldeur	35°59.38′N	35°47.88′E	78.7 ± 0.3	0.2–2.1	100	78.7 ± 0.3	14 of 14	80.7 ± 0.6	273.1 ± 7.0	0.502
SY-31	Jebel Quobtara	35°55.74′N	35°50.14′E	75.3 ± 0.7	0.3–2.0	88.5	75.9 ± 0.7	18 of 20	76.5 ± 0.5	294.2 ± 0.9	0.263
SY-24	Jebel Ayouranne	35°55.54′N	35°51.24′E	72.2 ± 0.5	0.3–2.0	79.4	71.7 ± 0.5	18 of 20	71.3 ± 1.0	298.2 ± 4.7	0.872

with the results plotted as age spectrum and isotope correlation diagrams in Figure 4. The ^{40}Ar–^{39}Ar dating results for the amphibole separates for the amphibolites from SW Cyprus and NW Syria are summarized in Table 1. Detailed analytical data for ^{40}Ar–^{39}Ar laser step-heating experiments are available online at http://earthref.org.

3.b. Results

Sample LT1–07 yielded a fairly flat plateau, covering all 19 steps, suggesting a plateau age of 88.9 ± 0.8 Ma. The intercept age calculated from the 19 plateau steps is 90.5 ± 1.6 Ma and an ^{40}Ar–^{36}Ar intercept of 290.5 ± 4.9 is therefore obtained from the isotope correlation plot (Fig. 4a). Sample LT2–01 shows some unusually low ages in the low-temperature steps (probably caused by degassing of secondary hydrous phases and/or contamination during step-heating). Nevertheless, the rest of the temperature steps, comprising 17 of the 20 increments and 95.6 % of the total $^{39}Ar_K$ released during the analysis, still show concordant ages to form a good plateau, with age of 80.5 ± 0.3 Ma. A well-constrained intercept age of 80.1 ± 0.3 Ma and an $^{40}Ar/^{36}Ar$ initial value of 299.2 ± 3.0 are successfully obtained from the isotope correlation plot (Fig. 4b). AV2–25 amphibole exhibits a perfect flat plateau with an age of 76.5 ± 0.4 Ma. Regression of the data of the plateau step on the isotope correlation diagram suggests an intercept age of 76.0 ± 0.5 Ma with an ^{40}Ar–^{36}Ar intercept value of 297.8 ± 2.5, which are all perfectly in agreement with its respective plateau age and the atmospheric composition (295.5) (Fig. 4c). Similarly, sample AV2–03 also yielded an undisturbed age spectrum, in which all 21 steps define a plateau age of 75.7 ± 0.3 Ma. Using an $^{36}Ar/^{40}Ar$ v. $^{39}Ar/^{40}Ar$ isotope correlation diagram, the intercept age calculated from the 21 plateau steps is 75.8 ± 0.4 Ma with an ^{40}Ar–^{36}Ar intercept of 294.8 ± 1.4 (Fig. 4d).

An amphibole separate from SY-48 shows a flat age spectrum with 88.1 % of $^{39}Ar_K$ released and yields a plateau age of 88.4 ± 0.4 Ma. The intercept age and the initial $^{40}Ar/^{36}Ar$ values are 88.1 ± 0.3 Ma and 298.8 ± 4.2 Ma, respectively (Fig. 4e). Amphibole from sample SY-34 also yields a flat plateau, comprising all 21 steps, with a perfect flat plateau age of 81.6 ± 0.3 Ma (Fig. 4f). Likewise, SY-14 amphibole yields a perfect flat plateau covering all 17 steps, and gives an identical plateau age of 81.6 ± 0.3 Ma to that of sample SY-34, which is in good agreement with its respective intercept age (81.6 ± 0.6 Ma) (Fig. 4g). Sample SY-50 yields a plateau that consists of all 14 steps, with an age of 78.7 ± 0.3 Ma. In the isotope correlation plot, 14 steps yields a ^{40}Ar–^{36}Ar intercept age of 80.7 ± 0.6 Ma with an $^{40}Ar/^{36}Ar$ intercept value of 273.1 ± 7.0 (Fig. 4h). This $^{40}Ar/^{36}Ar$ intercept value appears to be slightly less than the atmospheric $^{40}Ar/^{36}Ar$ ratio (295.5),

https://doi.org/10.1017/S0016756807003792 Published online by Cambridge University Press

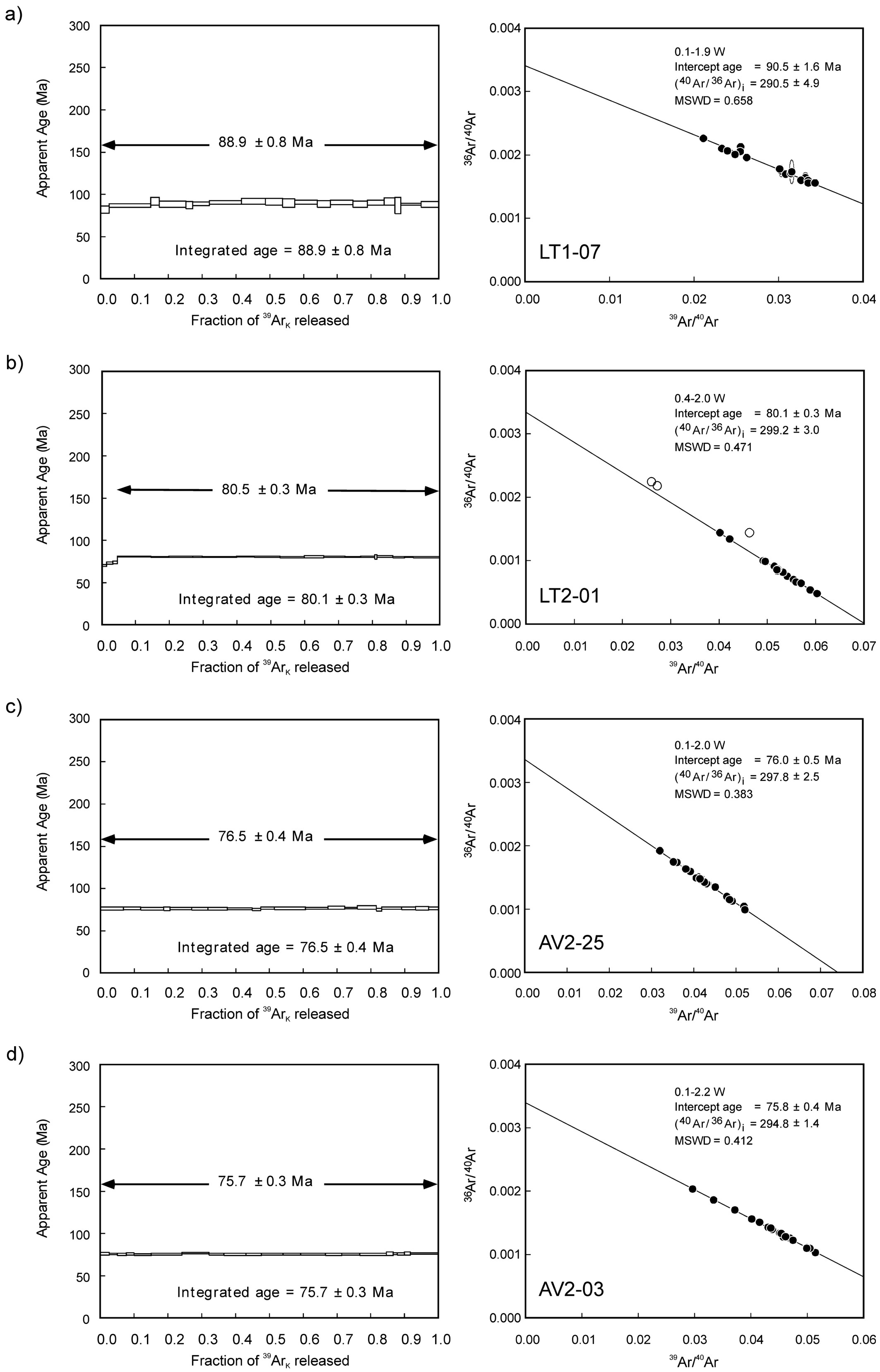

Figure 4. For legend see page no. 9.

suggesting the trapped argon may not solely be derived from atmospheric contamination. Instead, the sample may have been thermally disturbed. However, the obtained intercept age (80.7 ± 0.6 Ma) still appears to be consistent with its respective plateau age because of its high radiogenic argon content, and agrees generally

https://doi.org/10.1017/S0016756807003792 Published online by Cambridge University Press

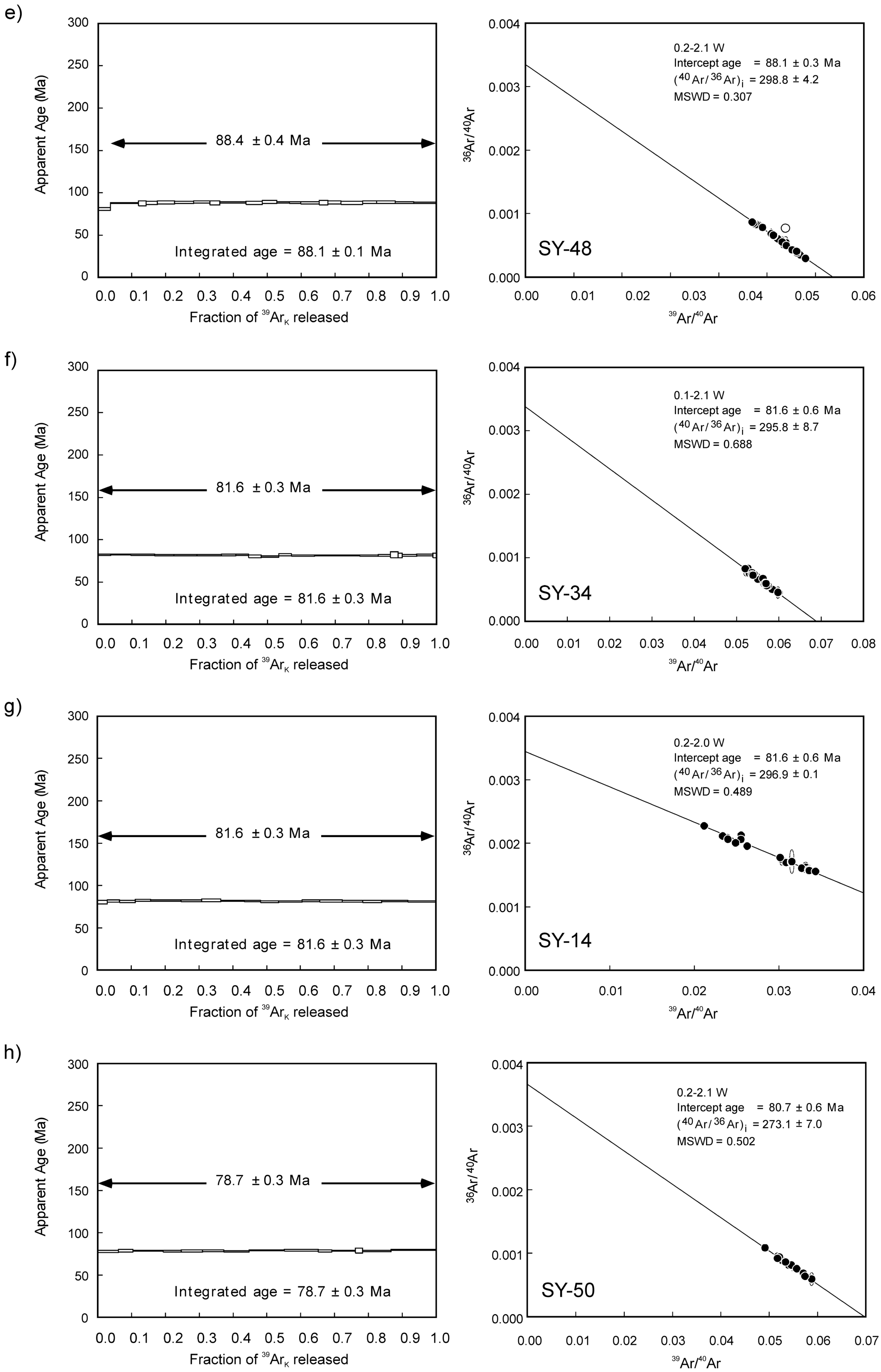

Figure 4. For legend see facing page.

with the plateau ages obtained from the samples in the same belt. Similar to LT2–01, SY-31 amphibole also exhibits relatively young ages in the first two steps, and the remaining steps show concordant ages to form a plateau over 88.5 % of total $^{39}Ar_K$ released, with an age of 75.9 ± 0.7 Ma. An intercept age of 76.5 ± 0.5 Ma

https://doi.org/10.1017/S0016756807003792 Published online by Cambridge University Press

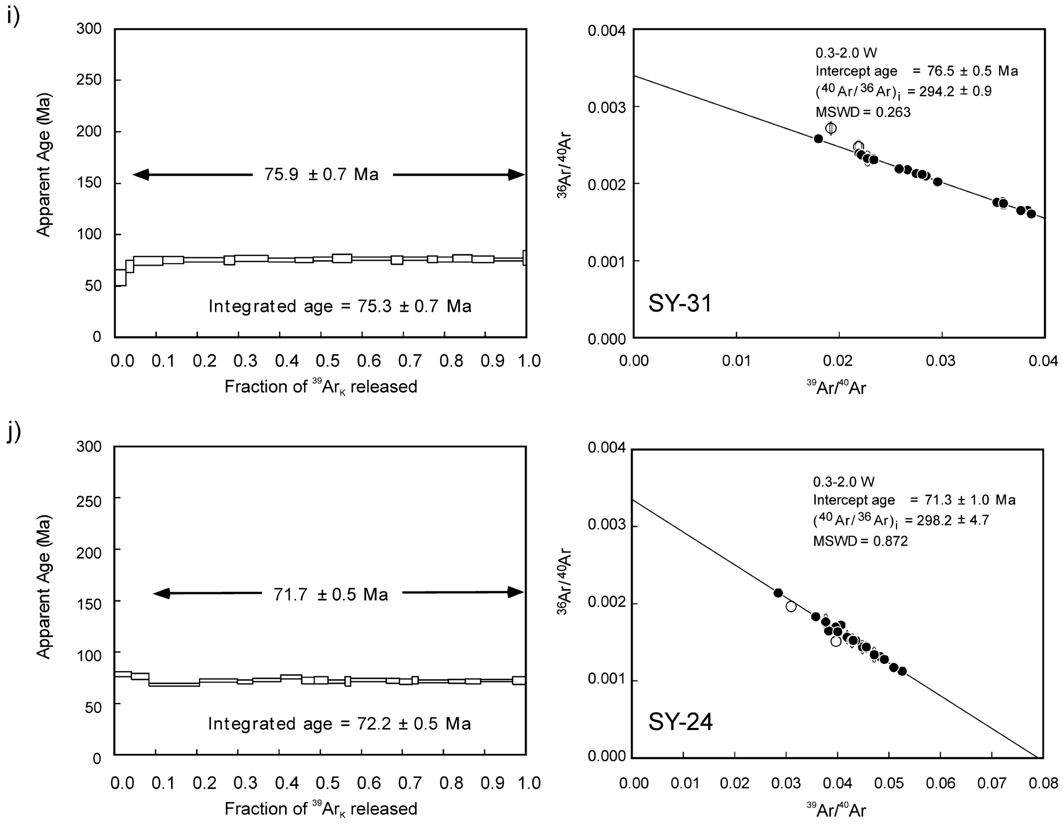

Figure 4. Apparent age spectrum and $^{36}Ar/^{40}Ar–^{39}Ar/^{40}Ar$ isotope correlation diagrams for amphibolites from SW Cyprus and NW Syria.

and an $^{40}Ar–^{36}Ar$ initial value of 294.2 ± 0.9 were obtained from the data regression for these plateau steps (Fig. 4i). The amphibole separated from SY-24 presents an age spectrum with some abnormally older ages in the low-temperature steps, followed by concordant ages in higher-temperature steps. The gas compositions of these concordant steps over 79.4 % of total $^{39}Ar_K$ released, define a plateau age of 71.7 ± 0.5 Ma. Regression of the data for these plateau steps suggests an intercept age of 71.3 ± 1.0 Ma and an $^{40}Ar/^{36}Ar$ initial value of 298.2 ± 4.7 (Fig. 4j).

4. Discussion

$^{40}Ar–^{39}Ar$ thermochronology has been widely used for different mineral phases based on the assumption of the argon closure temperature, and amphibole has a closure temperature of about 550 °C (Harrison, 1981). The amphiboles which formed in the amphibolites may have reached a maximum temperature of about 800 °C (Cosca, Sutter & Essene, 1991; Gnos & Peters, 1993). The generally flat release patterns of dated samples suggest that there were no thermal disturbances after cooling below the closure temperature. Thus, the obtained ages from SW Cyprus and NW Syria are interpreted to represent the timing of formation and/or the timing of the earliest stage of exhumation of the metamorphic rocks.

The $^{40}Ar–^{39}Ar$ thermochronological data obtained from the present study show a wide spread of amphibole ages in both SW Cyprus and NW Syria. In SW Cyprus, the $^{40}Ar–^{39}Ar$ amphiboles ages vary between 75.7 ± 0.3 to 76.5 ± 0.4 Ma in the south (Ayia Varvara) and 80.1 ± 0.3 to 88.9 ± 0.8 Ma in the north (Loutra tis Aphroditis), that is, the ages are older in the north than in the south, with a difference of 5–10 Ma. These results do not concur with the results of Spray & Roddick (1981), showing similar ages in both Ayia Varvara and Loutra tis Aphroditis. Amphiboles from NW Syria also display a wide range of ages, spanning 71.5 ± 0.5 to 88.4 ± 0.4 Ma. However, these ages do not show any systematic change in any particular direction. It is notable that the metamorphic rocks from both SW Cyprus and NW Syria exhibit broad ranges of age (15–18 Ma) which are significantly greater than those recorded in the Tauride belt ophoilites (4 Ma) or the Semail ophiolite (6 Ma) (Hacker, 1994; Hacker, Mosenfelder & Gnos, 1997; Dilek *et al.* 1999; Parlak & Delaloye, 1999; Çelik, Delaloye & Feraud, 2006).

In Cyprus, the U–Pb zircon ages of plagiogranites of the Troodos ophiolite range from 90.3 ± 0.7 Ma to 92.4 ± 0.7 Ma with a mean age of 91.4 Ma (Mukasa & Ludden, 1987). The closeness in age between the U–Pb zircon ages in the plagiogranites and the oldest metamorphic $^{40}Ar–^{39}Ar$ amphibole ages (88.9 ± 0.8 Ma) is palpable, suggesting the supra-subduction

https://doi.org/10.1017/S0016756807003792 Published online by Cambridge University Press

zone-type Troodos oceanic lithosphere was young and hot when the metamorphic rocks were formed. Heat needed for metamorphism could therefore have been provided by the residual heat of the oceanic lithosphere. In addition, geochemistry shows that the metabasites formed from Neo-Tethyan tholeiitic MOR-oceanic crust and tholeiitic and alkali WP-seamounts equivalent to the Late Triassic–Middle Jurassic Dhiarizos Group volcanic rocks that are now seen in SW Cyprus (Malpas, Xenophontos & Williams, 1992). The similarities in age and chemistry suggests that the metamorphic rocks result from the accretion of Dhiarizos Group rocks beneath the ophiolite mantle sequence synchronous with the formation of the ophiolite crustal sequence.

Palaeomagnetic studies show that the Troodos microplate underwent anticlockwise rotation soon after its formation (Moores & Vine, 1971; Clube, Creek & Robertson, 1985; Clube & Robertson, 1986; Morris *et al.* 2006). Approximately 60° of this rotation took place during the Late Campanian–Early Maastrichtian interval and the reorientation was completed by Early Eocene times. The inferred formation and/or exhumation ages of the amphibolites are synchronous with the early part of the rotation. These ages also pre-date the deposition of the Maastrichtian Kathikas Formation, which represents the sealing of the suture between the Troodos and Mamonia terranes (Swarbrick & Naylor, 1980; Swarbrick & Robertson, 1980; Lord *et al.* 2000).

The metamorphic rocks from NW Syria formed in a similar time frame, although the age of the Baer–Bassit ophiolite is still not well constrained. K–Ar whole rock ages from the sheeted dykes show a wide range of 73–99 Ma (Delaloye & Wagner, 1984). Further age constraints can be provided by palaeomagnetics, which indicate that the Baer–Bassit ophiolite formed in a magnetic transition period, most likely around 82.5 Ma (Morris *et al.* 2002, 2006). Given these constraints, the oldest ^{40}Ar–^{39}Ar amphibole age of the metamorphic rocks overlaps with the range of available radiometric ages for the ophiolite. Both Baer–Bassit and Troodos oceanic crust together probably experienced a regional anticlockwise rotation soon after their formation in the Maastrichtian (Morris *et al.* 2002, 2006). The inferred timing of Baer–Bassit microplate reorientation is almost the same as the formation and exhumation ages of the metamorphic rocks (Morris *et al.* 2002, 2006). Geochemical data from NW Syria suggests that the metamorphic rocks represent metamorphosed alkali WP-seamount basalts and IAT (Al-Riyami *et al.* 2002). They correlate closely with the Baer–Bassit mélange alkalic seamount lavas (Tammima volcanics) in their immobile element and REE geochemistry. These lines of evidence lead to a conclusion that the metamorphic rocks were formed as the result of underplating of Baer–Bassit mélange ocean basin below the ophiolite mantle sequence at a subduction zone at approximately the same time as the Baer–Bassit lithosphere was forming above (Al-Riyami *et al.* 2002), which is similar to the case in Cyprus as discussed above.

Following the metamorphism, the metamorphic sequence was exhumed relative to its overlying ophiolite prior to the deposition of the Maastrichtian Kathikas Formation, which sealed the contacts between the Troodos and Mamonia terranes (Clube & Robertson, 1986; Robertson, 1990, 1998; Lord *et al.* 2000). Malpas, Calon & Squires (1993) argued on the basis of structural evidence that this exhumation event should have occurred during the earliest stages of plate juxtaposition in Cyprus, because the metamorphic rocks are entrained in highly sheared serpentines although the schistosity of the metamorphic rocks is oblique to the deformation fabrics of the surrounding serpentinites. This suggests the metamorphic rocks were exhumed soon after their formation and further wrapped by serpentinites. Subsequently, the serpentinites were sheared during plate collision processes.

The exhumation of the metamorphic rocks may have resulted from a combination of buoyancy of the subducted slab, subduction roll-back, thinning of the overriding plate, rotation of the Troodos and Baer–Bassit microplates and slab break-off. The first mechanism involves the detachment of the upper crust from its basement, followed by incorporation into the hanging wall of the subduction zone and subsequent buoyancy. Carmichael (1989) showed that mafic eclogites have a mean density of 3.45 g cm^{-3}, while the mean bulk density of amphibolites is only 3.15 g cm^{-3}. The density of ecologites is higher and amphibolite is lower than the upper mantle (3.30 g cm^{-3}). The density difference between the amphibolite and eclogite would induce the dense eclogite to tear away from the amphibolitic portion of the slab. The detached amphibolitized oceanic crust may then return to shallow depths as a result of its positive buoyancy against the denser surrounding mantle. The buoyant ascent of the detached upper crustal slice along the subduction zone does not, however, lead to a removal of the mantle wedge above the descending slab. Palaeomagnetic studies show that the Troodos microplate and Baer–Bassit microplate (Clube, Creek & Robertson, 1985; Clube & Robertson, 1986; Morris *et al.* 2002, 2006) have similarly undergone anticlockwise intra-oceanic rotation during Late Campanian–Maastrichtian times. The tensional pull of these microplate edges away from the subduction zone would stretch the forearc region, creating a progressive thinning of the crust towards the subduction zone. The thinning of the overriding plate would have been further accelerated by subduction roll-back. As the old and dense Mamonia and Baer–Bassit passive continental margin sequence was consumed at the subduction zone, southward migration of the trench resulted in consequent extension of the overriding plate. This extension coupled with the rotation of Troodos and Baer–Bassit microplates could have given rise to the thinning and possible removal of mantle wedge material

https://doi.org/10.1017/S0016756807003792 Published online by Cambridge University Press

overlying the metamorphic rocks. In addition, exhumation may have been accelerated by continuing subduction and progressive formation of thrust planes at deeper levels, thus uplifting the stacks of metamorphic rock to the surface. Another possible exhumation mechanism is related to the break-off of the subducted slab. Recent tomographic images of the upper mantle stretching from the Nile Cone, northward across the present active Cyprus Arc, through Cyprus to Turkey, reveal several high-velocity anomalies (Koulakov *et al.* 2002). To the south of Cyprus, a sinking slab dipping steeply towards the north is interpreted as subduction at the presently active Cyprus Arc. To the north of this subducting slab, another possible slab rests at a depth of about 500 km, the positive anomaly representing a detached piece of former oceanic lithosphere. This detached slab might be associated with the subducted remnants of the Mamonia passive margin and attached oceanic lithosphere. The rupture of the subducted slab would have induced the rapid ascent of the amphibolites as well as shallowing of the remaining portion of the still-attached portion of the slab. The exhumed metamorphic rocks are fragmented and preserved at a structurally high level. This can be achieved if the metamorphic rocks are exhumed from the site of formation during continuous subduction and the thinning of overriding plate by rotation of Troodos and Baer–Bassit microplate and subduction roll-back. Continuous subduction also leads to off-scraping of the metamorphic blocks under low-temperature conditions. Other models of exhumation of the metamorphic rocks in SW Cyprus have also been discussed by Robertson & Xenophontos (1993) and Robertson (1998, 2000).

5. Regional tectonic model

Based on the present geochronological data and the available geological constraints, a tectonic model is proposed here. Accretion of Late Triassic to Early Cretaceous Dhiarizos Group oceanic crust and the associated seamount sequence subsequently occurred along the subduction zone (Malpas, Xenophontos & Williams, 1992; Malpas, Calon & Squires, 1993) between 75 and 90 Ma for a period of *c.* 15 Ma, causing the greenschist- to amphibolite-facies metamorphism of these rocks (Fig. 5a). As the subduction continued, the metamorphic complex now preserved at a structurally high level was uplifted and incorporated into an accretionary wedge (Fig. 5b). This took place coincident with the anticlockwise rotation of Troodos microplate mainly in Campanian to Maastrichtian times (Clube & Robertson, 1986; Morris *et al.* 2006). The tensional pull of the margin of Troodos microplate away from the subduction zone stretched the leading edge of Troodos microplate and produced a progressive thinning of the crust towards the subduction zone. Eventually, the accretionary prism, constructed dominantly of the collapsed Mamonia passive margin sequence coupled with

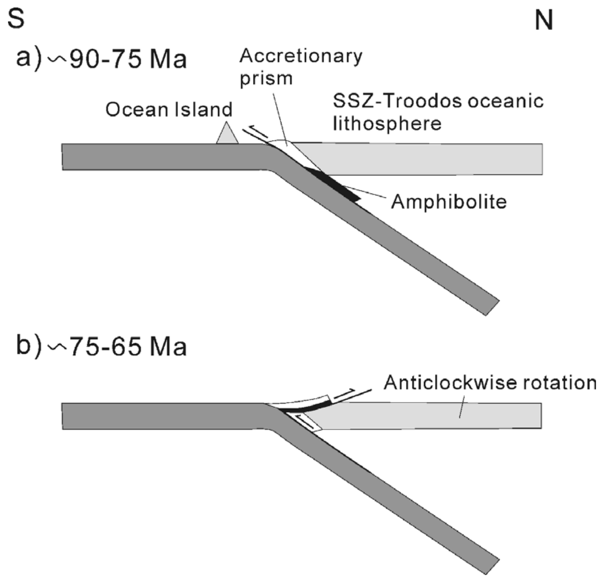

Figure 5. Schematic tectonic diagrams illustrating the formation of the metamorphic rocks in SW Cyprus. (a) Accretion of Late Triassic to Early Cretaceous Dhiarizos Group oceanic crust and associated seamount sequence subsequently occurred at the subduction zone where the Troodos ophiolite formed above. (b) The metamorphic rocks were exhumed from their site of formation during the rotation of the Troodos microplate and incorporated into an accretionary prism, subsequently juxtaposed with the Troodos ophiolite in the Maastrichtian.

exhumed metamorphic rocks complex began to collide with the Troodos ophiolite. The final amalgamation of the Mamonia and the Troodos microplates took place during Maastrichtian times and was marked by the deposition of the Kathikas Formation which sealed the suture zone (Lord *et al.* 2000).

In Syria, the Baer–Bassit mélange oceanic crust and associated seamounts were consumed in the subduction zone dipping beneath the leading edge of the supra-subduction zone Baer–Bassit ophiolite (Al-Riyami *et al.* 2002). During the period 71–89 Ma, accretion of the oceanic crust and seamounts and associated sediments under the leading edge of the Baer–Bassit ophiolite resulted in the formation of greenschist- to amphibolite-facies metamorphism (Al-Riyami *et al.* 2002) (Fig. 6a). During the anticlockwise rotation of the Baer–Bassit microplate in Campanian to Maastrichtian times (Morris *et al.* 2002, 2006), the metamorphic rocks were exhumed and subsequently subcreted beneath the ophiolite. In the Maastrichtian, the N-dipping subduction ceased when the Arabian passive margin sequence jammed the system as it was partly subducted, and the Baer–Bassit ophiolite together with the metamorphic rocks were emplaced over it (Fig. 6b). During emplacement, the passive margin sequence was deformed and disrupted to form a tectonic mélange. As emplacement continued, an imbricated tectonic unit incorporating the Baer–Bassit ophiolite, metamorphic rocks and the Baer–Bassit mélange developed (Al-Riyami *et al.* 2002).

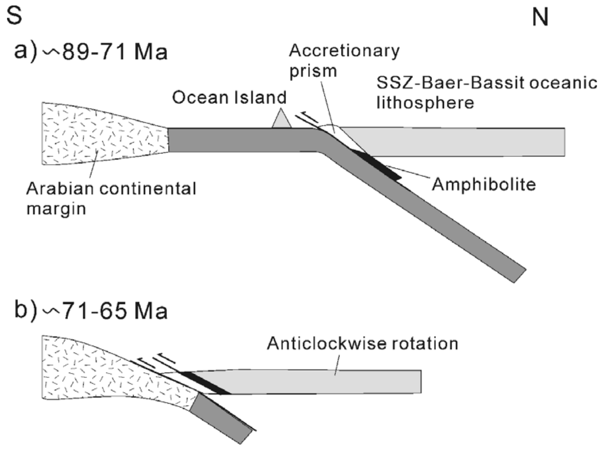

Figure 6. Schematic tectonic diagrams illustrating the formation of the metamorphic rocks. (a) Accretion of the Neo-Tethyan oceanic crust and seamounts under the leading edge of the Baer–Bassit ophiolite caused the formation of the metamorphic rocks. (b) The metamorphic rocks were exhumed during the ophiolite rotation. In the Maastrichtian, the Baer–Bassit ophiolite together with the subcreted metamorphic rocks were emplaced over the Arabian continental margin.

6. Conclusion

The best time constraints on the formation and/or exhumation of the metamorphic rocks from SW Cyprus are 75.7 ± 0.3 to 76.5 ± 0.4 Ma in the south (Ayia Varvara), to 80.1 ± 0.3 to 88.9 ± 0.8 Ma in the north (Loutra tis Aphroditis), and are obtained from ^{40}Ar–^{39}Ar dating of hornblendes. Thus, the oldest ages of metamorphism are almost contemporaneous with the age of formation of the Troodos ophiolite crustal sequence. In NW Syria, the age constraints on the metamorphism which produced the metamorphic rocks associated with the Baer–Bassit ophiolite are 71.5 ± 0.5 to 88.4 ± 0.4 Ma. These metamorphic rocks were formed during the accretion of oceanic crust and seamount rocks beneath the ophiolites in a period of 15–18 Ma. This is in contrast to those metamorphic sole rocks which formed in short time spans.

Acknowledgements. We are grateful to the Director of the Geological Establishment of Syria, Dr Talal Ballani, and his successor for authorizing the fieldwork to Baer–Bassit and providing accommodation in Qastal Maaf. This work was supported by the Block Grant Earmarked for Research, The University of Hong Kong, to J. Malpas. The manuscript has benefited from insightful comments of Alastair Robertson and an anonymous referee.

References

AL-RIYAMI, K., DANELIAN, T. & ROBERTSON, A. H. F. 2002. Radiolarian biochronology of Mesozoic deep-water successions in NW Syria and Cyprus: implications for south-Tethyan evolution. *Terra Nova* **14**, 271–80.

AL-RIYAMI, K. & ROBERTSON, A. 2002. Mesozoic sedimentary and magmatic evolution of the Arabian continental margin, northern Syria: evidence from the Baer–Bassit Mélange. *Geological Magazine* **139**, 395–420.

AL-RIYAMI, K., ROBERTSON, A. H. F., DIXON, J. E. & XENOPHONTOS, C. 2002. Origin and emplacement of the Late Cretaceous Baer–Bassit ophiolite and its metamorphic sole in NW Syria. *Lithos* **65**, 225–60.

BAILEY, S. W., HOLDSWORTH, R. E. & SWARBRICK, R. E. 2000. Kinematic history of a reactivated oceanic suture: the Mamonia Complex Suture Zone, SW Cyprus. *Journal of the Geological Society, London* **157**, 1107–126.

CARMICHAEL, R. S. 1989. *Practical handbook of physical properties of rocks and minerals*. CRC Press, 741 pp.

ÇELIK, O. F., DELALOYE, M. & FERAUD, G. 2006. Precise ^{40}Ar–^{39}Ar ages from the metamorphic sole rocks of the Tauride Belt Ophiolites, Southern Turkey: implications for the rapid cooling history. *Geological Magazine* **143**, 213–27.

CLUBE, T. M., CREEK, K. M. & ROBERTSON, A. H. F. 1985. Palaeorotation of the Troodos microplate, Cyprus. *Nature* **317**, 522–5.

CLUBE, T. M. & ROBERTSON, A. H. F. 1986. The palaeorotation of the Troodos microplate, Cyprus, in the Late Mesozoic–Early Cenozoic plate tectonic framework of the Eastern Mediterranean. *Surveys in Geophysics* **8**, 375–434.

COSCA, M. A., SUTTER, J. F. & ESSENE, E. J. 1991. Cooling and inferred uplift/erosion history of the Grenville orogen, Ontario: constraints from $^{40}Ar/^{39}Ar$ thermochronology. *Tectonics* **10**, 959–77.

DELALOYE, M. & WAGNER, J. J. 1984. Ophiolites and volcanic activity near the western edge of the Arabian plate. In *The Geological Evolution of the Eastern Mediterranean* (eds J. E. Dixon & and A. H. F. Robertson), pp. 225–33. Geological Society of London, Special Publication no. 17.

DELAUNE-MAYERE, M. 1984. Evolution of a Mesozoic passive continental margin: Baer–Bassit (NW Syria). In *The Geological Evolution of the Eastern Mediterranean* (eds J. E. Dixon & A. H. F. Robertson), pp. 151–9. Geological Society of London, Special Publication no. 17.

DELAUNE-MAYERE, M. & SAINT-MARC, P. 1979/80. Donnees stratigraphiques nouvelles sur les sediments oceaniques Mesozoiques associees aux nappes ophiolitiques du Baer–Bassit (N. W. Syrien). *Cahier–ORSTOM, Serie Geologie* **11**, 151–64.

DILEK, Y., THY, P., HACKER, B. & GRUNDVIG, S. 1999. Structure and petrology of Tauride ophiolites and mafic dike intrusions (Turkey): implications for the Neotethyan ocean. *Geological Society of America Bulletin* **111**, 1192–1216.

GARFUNKEL, Z. 1998. Constraints on the origin and history of the Eastern Mediterranean basin. *Tectonophysics* **298**, 5–35.

GARFUNKEL, Z. 2004. Origin of the Eastern Mediterranean basin: a reevaluation. *Tectonophysics* **391**, 11–34.

GARFUNKEL, Z. 2006. Neotethyan ophiolites: formation and obduction within the life cycle of the host basins. In *Tectonic Development of the Eastern Mediterranean Region* (eds A. H. F. Robertson & D. Mountrakis), pp. 301–26. Geological Society of London, Special Publication no. 260.

GASS, I. 1980. The Troodos massif: its role in the unraveling of the ophiolite problem and its significance in the understanding of constructive margin processes. In

Ophiolites: Proceedings of the International Ophiolite Symposium 1979 (ed. A. Panayiotou), pp. 23–35. Cyprus Geological Survey.

GASS, I., MACLEOD, C. J., MURTON, B. J., PANAYIOTOU, A., SIMONIAN, K. O. & XENOPHONTOS, C. 1994. The geology of the Southern Troodos Transform Zone. *Geological Survey of Cyprus Memoirs* **9**, 218 pp.

GNOS, E. & PETERS, T. 1993. K–Ar ages of the metamorphic and deformational history of the Semail ophiolite: implications for cooling history. *Contributions to Mineralogy and Petrology* **113**, 325–32.

GRADSTEIN, F. M., AGTERBERG, F. P., OGG, J. G., HARDENBOL, J., VAN-VEEN, P., THIERRY, J. & HUANG, Z. 1994. A Mesozoic time scale. *Journal of Geophysical Research* **99**, 24051–74.

HACKER, B. R. 1994. Rapid emplacement of young oceanic lithosphere: argon geochronology of the Oman ophiolite. *Science* **265**, 1563–5.

HACKER, B. R., MOSENFELDER, J. L. & GNOS, E. 1997. Rapid ophiolite emplacement constrained by geochronology and thermal considerations. *Tectonics* **15**, 1230–47.

HARRISON, T. M. 1981. Diffusion of ^{40}Ar in hornblende. *Contributions to Mineralogy and Petrology* **78**, 324–31.

KOULAKOV, I., TYCHKOV, S., BUSHENKOVA, N. & VASILEVSKY, A. 2002. Structure and dynamics of the upper mantle beneath the Alpine–Himalayan orogenic belt, from teleseismic tomography. *Tectonophysics* **358**, 77–96.

LANPHERE, M. A. & DALRYMPLE, G. B. 1978. The use of ^{40}Ar/^{39}Ar data in evaluation of disturbed K–Ar systems. *U. S. Geological Survey Open-file Report* **78–701**, 241–3.

LAPIERRE, H. 1975. Les formations sedimentaires et eruptives des nappes de Mamonia et leurs relations avec le massif du Troodos (Chypre occidentale). *Memoires de la Société Géologique de France* **54**, 123.

LO, C.-H., CHUNG, S.-L., LEE, T.-Y. & WU, G.-Y. 2002. Age of the Emeishan flood magmatism and relations to Permian–Triassic boundary events. *Earth and Planetary Science Letters* **198**, 449–58.

LORD, A. R., PANAYIDES, I., URQUHART, E. & XENOPHONTOS, C. 2000. A biochronostratigraphical framework for the Late Cretaceous–Recent circum-Troodos sedimentary sequence, Cyprus. In *Proceedings of the Third International Conference on the Geology of the Eastern Mediterranean* (eds I. Panayides, C. Xenophontos & J. Malpas), pp. 289–97. Cyprus Geological Survey Department.

MALPAS, J. 1979. The dynamothermal aureole of the Bay of Island ophiolite suite. *Canadian Journal of Earth Sciences* **16**, 2086–101.

MALPAS, J., CALON, T. & SQUIRES, G. 1993. The development of a late Cretaceous microplate suture zone in SW Cyprus. In *Magmatic Processes and Plate Tectonics* (eds H. M. Prichard, T. Alabaster, N. B. W. Harris & C. R. Neary), pp. 177–95. Geological Society of London, Special Publication no. 76.

MALPAS, J. & LANGDON, G. 1984. Petrology of the Upper pillow lava suite, Troodos ophiolite, Cyprus. In *Ophiolites and Oceanic Lithosphere* (eds I. G. Gass, S. J. Lippard & A. W. Shelton), pp. 155–67. Geological Society of London, Special Publication no. 13.

MALPAS, J. & XENOPHONTOS, C. 1999. *Geological Map of the Ayia Varvara–Pentalia area. Scale 1:25000*. The Geological Survey Department, Nicosia, Cyprus.

MALPAS, J., XENOPHONTOS, C. & WILLIAMS, D. 1992. The Ayia Varavara Formation of S. W. Cyprus, a product of complex collisonal tectonics. *Tectonophysics* **212**, 193–211.

MOORES, E. M., ROBINSON, P. T., MALPAS, J. & XENOPHONTOS, C. 1984. Model for the origin of the Troodos massif, Cyprus, and other mideast ophiolites. *Geology* **12**, 500–3.

MOORES, E. M. & VINE, F. 1971. The Troodos Massif, Cyprus and other ophiolites as oceanic crust evaluation and implications. *Philosophical Transactions of Royal Society of London* **268**, 443–66.

MORRIS, A., ANDERSON, M. W., INWOOD, J. & ROBERTSON, A. H. F. 2006. Palaeomagnetic insights into the evolution of Neotethyan oceanic crust in the eastern Mediterranean. In *Tectonic Development of the Eastern Mediterranean Region* (eds A. H. F. Robertson and D. Mountrakis), pp. 351–72. Geological Society of London, Special Publication no. 260.

MORRIS, A., ANDERSON, M. W., ROBERTSON, A. H. F. & AL-RIYAMI, K. 2002. Extreme tectonic rotations within an eastern Mediterranean ophiolite (Baer–Bassit, Syria). *Earth and Planetary Science Letters* **202**, 247–61.

MUKASA, S. B. & LUDDEN, J. N. 1987. Uranium–lead isotopic ages of plagiogranites from the Troodos ophiolite, Cyprus, and their tectonic significance. *Geology* **15**, 825–8.

ODIN, G. S. *et al.* 1982. Interlaboratory standards for dating purposes. In *Numerical Dating in Stratigraphy* (ed. G. S. Odin), pp. 123–49. Chichester: Wiley & Sons.

PARLAK, O. & DELALOYE, M. 1999. Precise ^{40}Ar/^{39}Ar ages from the metamorphic sole of the Mersin ophiolite (Southern Turkey). *Tectonophysics* **301**, 145–58.

PARLAK, O., DELALOYE, M. & BINGÖL, E. 1995. Origin of sub-ophiolitic metamorphic rocks beneath the Mersin ophiolite, Southern Turkey. *Ofioliti* **20**, 97–110.

PARROT, J. F. 1980. The Baer–Bassit (Northwestern Syria) ophiolitic area. *Ofioliti* **2**, 279–95.

RAUTENSCHLEIN, M., JENNER, G. A., HERTOGEN, J., HOFMANN, A., KERRICH, R., SCHMINCKE, H. U. & WHITE, W. M. 1985. Isotopic and trace element compositions of volcanic glasses from the Akaki Canyon, Cyprus: implication for the origin of the Troodos ophiolite, Cyprus. *Earth and Planetary Science Letters* **75**, 369–83.

ROBERTSON, A. H. F. 1990. Tectonic evolution of Cyprus. In *Ophiolites and oceanic crustal analogues. Proceeding of Symposium 'Troodos 1987'* (eds J. Malpas, E. M. Moores, A. Pannayiotou & C. Xenophontos), pp. 235–52. Geological Survey of Cyprus.

ROBERTSON, A. H. F. 1998. Mesozoic–Tertiary tectonic evolution of the Easternmost Mediterranean area: integration of marine and land evidence. *Proceedings of the Ocean Drilling Program, Scientific Results* **160**, 723–82.

ROBERTSON, A. H. F. 2000. Mesozoic–Tertiary tectonic–sedimentary evolution of a South Tethyan oceanic basin and its margins in southern Turkey. In *Tectonics and magmatism in Turkey and the surrounding area* (eds E. Bozkurt, J. A. Winchester & J. D. A. Piper), pp. 97–138. Geological Society of London, Special Publication no. 173.

ROBERTSON, A. H. F. 2002. Overview of the genesis and emplacement of Mesozoic ophiolites in the Eastern Mediterranean Tethyan region. *Lithos* **65**, 1–67.

ROBERTSON, A. H. F. 2004. Development of concepts concerning the genesis and emplacement of Tethyan ophiolites in the Eastern Mediterranean and Oman regions. *Earth-Science Reviews* **66**, 331–87.

ROBERTSON, A. H. F. & WOODCOCK, N. H. 1979. The Mamonia Complex, S. W. Cyprus: the evolution and emplacement of a Mesozoic continental margin. *Geological Society of America Bulletin* **90**, 651–65.

ROBERTSON, A. H. F. & XENOPHONTOS, C. 1993. Development of concepts concerning the Troodos ophiolite and adjacent units in Cyprus. In *Magmatic Processes and Plate Tectonics* (eds H. M. Prichard, T. Alabaster, N. B. W. Harris & C. R. Neary), pp. 85–120. Geological Society of London, Special Publication no. 76.

ROBINSON, P. T., MELSON, W. G., O'HEARN, T. & SCHMINCKE, H. U. 1983. Volcanic glass compositions of the Troodos ophiolite, Cyprus. *Geology* **11**, 400–4.

SEARLE, M. P. & MALPAS, J. 1980. Structure and metamorphism of rocks beneath the Semail ophiolite of Oman and their significance in ophiolite obduction. *Transaction of the Royal Society of Edinburgh, Earth Sciences* **71**, 247–62.

SEARLE, M. P. & MALPAS, J. 1982. Petrochemistry and origin of sub ophiolitic metamorphic rocks in the Oman mountains. *Journal of the Geological Society, London* **139**, 235–48.

SILANT'EV, S. A. 1993. Metamorphic complexes of the Eastern Mediterranean: metamorphic conditions, protoliths, and geodynamic environment. *Petrology* **1**, 450–73.

SMITH, A. G. 2006. Tethyan ophiolite emplacement, Africa to Europe motions, and Atlantic spreading. In *Tectonic Development of the Eastern Mediterranean Region* (eds A. H. F. Robertson & D. Mountrakis), pp. 11–34. Geological Society of London, Special Publication no. 260.

SPRAY, J. G. & RODDICK, J. C. 1981. Evidence for Upper Cretaceous transform fault metamorphism in West Cyprus. *Earth and Planetary Science Letters* **55**, 273–91.

SWARBRICK, R. E. 1980. The Mamonia Complex of SW Cyprus and its relationship with the Troodos complex. In *Ophiolites: Proceedings of the International Ophiolite Symposium, 1979* (ed. A. Panayiotou), pp. 86–92. Geological Survey of Cyprus.

SWARBRICK, R. E. 1993. Sinistral strike-slip and transpressional tectonics in an ancient ocean setting: the Mamonia Complex, southwest Cyprus. *Journal of the Geological Society, London* **150**, 381–92.

SWARBRICK, R. E. & NAYLOR, M. A. 1980. The Kathikas Melange, South-west Cyprus: Late Cretaceous, submarine debris-flows. *Sedimentology* **27**, 63–78.

SWARBRICK, R. E. & ROBERTSON, A. H. F. 1980. Revised stratigraphy of the Mesozoic rocks of southern Cyprus. *Geological Magazine* **117**, 547–63.

THUIZAT, R., WHITECHURCH, H., MONTIGNY, R. & JUTEAU, T. 1981. K–Ar dating of some infra-ophiolitic metamorphic soles from the Eastern Mediterranean: new evidence for oceanic thrusting before obduction. *Earth and Planetary Science Letters* **52**, 302–10.

WHITECHURCH, H. & PARROT, J. F. 1974. Les ecailles metamorphiques infra-peridotitiques du Baer–Bassit (nord-ouest de la Syrie). *Cahier–ORSTOM, Serie Geologie* **6**, 173–84.

WILLIAMS, H. R. & SMYTH, W. R. 1973. Metamorphic aureoles beneath ophiolite suites and Alpine peridotites: Tectonic implications with west Newfoundland examples. *American Journal of Science* **273**, 594–621.

YILMAZ, P. O. & MAXWELL, J. C. 1982. K–Ar investigations from the Antalya complex ophiolites, SW Turkey. *Ofioliti* **2**, 527–38.

https://doi.org/10.1017/S0016756807003792 Published online by Cambridge University Press