CAMBRIDGE UNIVERSITY PRESS GeologicalMagazine

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Journal:	*Geological Magazine*
Manuscript ID	GEO-16-1659.R1
Manuscript Type:	Article
Date Submitted by the Author:	n/a
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Keywords:	Ophiolites, geochemistry, radiolarian biostratigraphy, Jurassic, Early Cretaceous, Ankara Mélange, Turkey

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The Jurassic-Early Cretaceous Basalt-Chert association in the Ophiolites of the Ankara Mélange east of Ankara, Turkey: Age and Geochemistry

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Keywords*:* Ophiolites, geochemistry, radiolarian biostratigraphy, Jurassic, Early Cretaceous, Ankara Mélange. Turkey.

Abstract This study is focused on slide blocks including oceanic lavas associated with pelagic sediments within the eastern part of the Ankara Mélange. A detailed petrological characterization of the volcanic rocks and a detailed biochronological investigation of the associated radiolarian cherts in eight sections (east of Ankara) was carried out.

The volcanic rocks are largely represented by basalts and minor ferro-basalts and trachytes. They show different geochemical affinities and overlapping ages including:

a) Late Jurassic-Early Cretaceous garnet-influenced MORB (Section 5, middle late Oxfordian to late Kimmeridgian-early Tithonian and early-early late Tithonian; Section 8, late Valanginian-early Barremian);

b) Early Cretaceous enriched-MORB (Section 4, middle late Barremian-early early Aptian; Section 7, Valanginian to middle Aptian-early Albian);

c) Middle Jurassic plume-type MORB (section 2, early-middle Bajocian to late Bathonian-early Callovian);

d) Late Jurassic-Early Cretaceous alkaline basalts (Section 3, middle-late Oxfordian to late Kimmeridgian-early Tithonian; Section 1, late Valanginian to late Hauterivian).

All rock types show a clear garnet signature, as testified by their high MREE/HREE ratios.

The coexistence of chemically different rock-types from Middle Jurassic to Early Cretaceous suggests that they were formed at a mid-ocean ridge setting from partial melting of a highly heterogeneous mantle characterized by the extensive occurrence of OIB-metasomatized portions, which were likely inherited from a Triassic mantle plume activity associated with the continental rift and opening of the Neotethys branch.

1. Introduction

Despite numerous studies since 1960's in Turkey, the locations, ages and geological evolution of the branches of the Eastern Mesozoic Tethys Ocean or Eastern Neotethys are disputed (see Sengör & Yilmaz, 1981;–Dercourt *et al.*, 1986; Robertson *et al.*, 1996; Dilek *et al.*, 1999; Göncüoglu *et al.*, 1997, 2000; 2006; 2010; Stampfli & Borel, 2002; Bortolotti & Principi, 2005; Schmid *et al.*, 2008; Moix *et al.*, 2008). This is mainly due to two deficiencies. One of them is the fact that next to definite ophiolitic suture belts separating continental blocks with distinct geological history there are also suture-like alignments or peudo-belts of allochthonous ophiolitic bodies. The second shortcoming regards the method of the ophiolite research yet realized, as it was rarely based upon a multidisciplinary approach. Several detailed petrological studies on different units from different ophiolitic bodies lack age data and vice versa. A considerable number of studies were concentrated on the larger and more or less complete ophiolitic bodies and neglected the remarkable amount of basalt-radiolarian chert associations within the mélange complexes. To overcome these problems we applied a multi-disciplinary approach combining petrology and biostratigraphy on

crustal remnants of the Neotethys incorporated in the mélange complexes of the Izmir-Ankara-Erzincan Suture Belt (IAESB).

As previously referred, the location, age and geological evolution of the branche(s) of the Eastern Neotethys are disputed. In fact, most authors favour the hypothesis (presented herein) that implies the existence of two parallel and contemporaneous oceans namely: the Izmir-Ankara Ocean, to the south and the Intra-Pontide Ocean, to the north (see Göncüoglu *et al.*, 2012, for an exhaustive review). In contrast, other authors favour the hypothesis, which implies the existence of a single oceanic basin represented by the Intra-Pontide Ocean (e.g., Bortolotti & Principi, 2005). In this case the Intra Pontide Suture (IPS, see later) would be the eastward continuation of the Vardar Ocean suture whereas the IAESB would represent fragments of the oceanic lithosphere pushed southwards on the continent by orogenic movements (as happened more westwards, in the Hellenides) (see Bortolotti *et al.*, 2013*a*).

The IAESB separates two completely different units of continental crust with different origin: a) the Tauride-Anatolide terrane representing the rifted northern margin of NW Gondwana, in the south and b) the Sakarya Composite Terrane comprising amalgamated oceanic and continental bodies of Variscan and Cimmerian origin and their alpine platform, in the north. To the N of the Sakarya Composite Terrane another suture, the Intra-Pontide Suture, represents the boundary towards the Eurasian Istanbul-Zonguldak terrane (Fig.1).

The IAESB represents remnants of the Vardar-Izmir-Ankara-Erzincan-Lesser Caucasus Ocean in Turkey. This ocean is considered as the main northern branch of Neotethys, whereas the Intra-Pontide oceanic basin to the north of it is a matter of debate (see before and, for a brief discussion, Göncüoglu *et al.* 2012 and Tekin *et al.*, 2012*a*). In NW Turkey, IPS is clearly delineated by the presence of ophiolitic melanges between the Sakarya and the Istanbul-Zonguldak continental plates (e.g., Robertson & Ustaömer, 2004; Göncüoğlu *et al.*, 2008; Akbayram *et al.*, 2012). By wedging out of the Sakarya Composite Terrane in northern Central Anatolia, however, the IPS belt juxtaposes with the IAESB along splays of the North Anatolian Shear Zone (e.g., Ellero *et al.*,

2015*a*) and the Neotectonic stike-slip system generated due to the Tertiary indentation and anticlockwise rotation of the Kırşehir Block (e.g., Cemen *et al.*, 1993; Kaymakci *et al.*, 2003). Towards the east and in NE Anatolia, the IAESB is again in its accustomed position between the Anatolides and the units of the Sakarya Composite Terrane (Topuz *et al.*, 2013*a*, 2013*b*; Parlak *et al.*, 2013; Robertson *et al.*, 2013). The vanishing of the IPS belt in the Central Pontides by the North Anatolian Shear Zone during the Neotectonic Period led some authors to completely ignore the IPS and hence the presence of an oceanic basin (e.g., Elmas & Yiğitbaş, 2001, 2005).

The IAESB is composed of a number south-verging tectonic slices or giant slide blocks representing 1) incomplete sequences of various portions of the Izmir-Ankara-Erzincan oceanic lithosphere (e.g., Floyd *et al.*, 2000; Göncüoglu *et al.*, 2000; Göncüoglu, 2011); 2) an accretionary prism, known as the "Ankara Mélange" (Bailey & McCallien, 1953) including blocks derived from different parts of the oceanic basin; 3) imbricated slices of successions formed in a foredeep basin associated with the emplacement of the oceanic material onto the Tauride-Anatolide passive margin.

This study is focused on slide blocks including oceanic lavas associated with pelagic sediments within the accretionary prism and the foredeep basin successions in the eastern part of the Ankara Mélange (for the preliminary data see Bortolotti *et al.*, 2013*b*). This paper aims to draw a more comprehensive picture of the different basaltic rock-types, erupted in the Neotethys from Middle Jurassic to Early Cretaceous. To this purpose, a detailed petrological and geochemical characterization of the volcanic rocks and a detailed biochronological investigation of the associated radiolarian cherts will be carried out. Similar multidisciplinary studies were applied to other parts of the IAESB between the Aegean coast and the western part of the Ankara Mélange (e.g., Bragin & Tekin., 1996; Yaliniz *et al.*, 2000*a*; Göncüoglu *et al.*, 2001, 2008, 2010, 2015; Rojay *et al.*, 2001; Tekin *et al.*, 2002; Gökten & Floyd, 2007; Tekin & Göncüoglu, 2007, 2009; Tekin et al. 2012a; Moix & Goriçan, 2013; Soycan *et al.*, 2015). These studies reported Middle Triassic to Cretaceous ages for radiolarian cherts stratigraphically associated to basalts showing, in turn, different tectono-

magmatic settings of formation, such as mid-ocean ridge, seamount, forearc and backarc were reported. Our new data from the eastern Ankara Mélange aims to interpret the tectono-magmatic processes and their timing, which will be useful for improving the reconstruction of the geodynamic history of the Neotethys Ocean mainly from the Jurassic to the Early Cretaceous time interval.

2. Geological background

The studied portion of the Izmir-Ankara-Erzincan Suture Belt (IAESB) was characterized by the pre-Eocene development of a huge accretionary prism (for details see Rojay, 2013), which formed between the Sakarya Composite Terrane to the North, and the southerly Kütahya-Bolkardag Belt of the Anatolides, in the western part, and the Central Anatolian Crystalline Complex (CACC), in the eastern part. The first juxtaposition of these oceanic and continental units occurred in the latest Cretaceous-Paleocene. However, compression and related thrusting lasted until the Miocene (Kocyigit *et al*., 1995).

We sampled some ophiolitic outcrops from the IAESB east of Ankara (Fig. 1), where the concave E-W trend of the belt between Izmir and Ankara makes a sharp turn towards NNW, caused by the Tertiary indentation (e.g., Cemen *et al.*, 1993; Kaymakci *et al*., 2003) and anticlockwise rotation of the Kırşehir Block.

The Sakarya Unit marks the active margin of the Izmir-Ankara-Erzican Ocean, and was thrust over the IAESB both to the NNE of Ankara and to the SE of Çorum (Fig. 2). It consists of a composite terrane comprising a Variscan arc complex and its Permian platform, as well as the Paleotethyan subduction-accretion prism (the Triassic Karakaya Complex, Göncüoglu *et al*., 2000; Okay & Göncüoglu, 2004). It has a Jurassic to ?Late Cretaceous cover that belonged to a north-facing passive continental margin but was transformed into an active margin by the northward subduction of the Izmir-Ankara-Erzican oceanic lithosphere.

The Karakaya Complex NNW of Ankara comprises low-grade metamorphic greywackes associated with Permian and Carboniferous limestone blocks and ocean-island-type volcanic rocks with Carnian radiolarian cherts (e.g., Sayit *et al.,* 2011). Unconformably overlying there is a Mesozoic cover that comprises, from bottom to top: late Early Jurassic-Mid Jurassic neritic limestones, Late Jurassic - Early Cretaceous (e.g., Altiner *et al*., 1991) pelagic limestones and Late Cretaceous turbidites. The oldest common overstep sequence on the Izmir-Ankara-Erzincan Suture Belt (and the Sakarya Composite Terrane) comprises Late Paleocene lagoonal sediments, which occur as discontinuous outcrops within the thrust zone between these two units (Göncüoglu *et al*., 2000).

The northern-central part of the sampled area has been recently evaluated as the North Anatolian Shear Zone (Ellero *et al.,* 2015*a*, *b*). The North Anatolian Shear Zone corresponds to a complex deformation zone where the strain is partitioned in a system of faults, folds and thrusts leading to high-angle faults bounding E-W elongated blocks and pull-apart basins. The zone is more than 100 km wide and comprises several km long, lens-shaped tectonic inlayers belonging to the mélanges of the IPS belt (e.g. Göncüoglu *et al*., 2014) the Sakarya Composite Terrane (mainly the Late Jurassic - Early Cretaceous Sogukcam Limestone, e.g. Catanzariti *et al.* 2013), a Late Cretaceous island arc (Berber *et al*., 2014) belonging to the IPS Belt, a Late Cretaceous continental arc (Ellero *et al*., 2015b) and the ophiolitic mélanges of the IAESB. The active main strand of the right-lateral North Anatolian Transform Fault is located in the center of this mega-shear zone, where lateral displacements ranging from 30 to 120 km, have been proposed in the literature (e.g. Hubert-Ferrari *et al*., 2002 and references therein).

The metamorphic rocks of the Sakarya Composite Terrane (the "Tokat Massif", Yilmaz *et al*., 1997), around Çorum, East of the sampled area (Fig. 2), are tectonically overlying the ophiolitic mélange of the IAESB. In this area, both units are in turn unconformably overlain by Middle Eocene rocks. Unfortunately, the primary relations between the Sakarya and IAESB rocks are obscured by intensive Oligocene strike-slip faulting (Fig. 2).

Structurally underlying the IAESB units, the continental crust that was palinspastically located to the south, and west of Ankara, represents the northern rim of the Tauride-Anatolide Platform. It mainly includes high pressure-low temperature metamorphosed tectonic slices (e.g., Okay & Tüysüz, 1999) which lithostratigraphic sequences are similar to the Paleozoic-Mesozoic slope-type successions of the Anatolides (Göncüoglu, 2011). In particular, in the sampled area (Fig. 2), the IAESB units were thrust onto the Central Anatolian Crystalline Complex (Yaliniz *et al.,* 1996; 2000*b*), which comprises high temperature-medium pressure metamorphic successions similar to the Paleozoic-Mesozoic Tauride-Anatolide Platform. In turn, they were overthrust by Turonian supra-subduction ophiolite - the Central Anatolian Ophiolites (Yaliniz *et al*., 2000a), which represent remnants of the Izmir-Ankara-Erzican Ocean. Late Campanian granitoids intrude both the basement rocks and the overlying ophiolite units (Köksal & Göncüoglu, 2008), indicating a Late Cretaceous age of the obduction inception. The oldest overstep sequences in this area are again post-Maastrichtian pre- Early Eocene (Gülyüz *et al.*, 2013) red conglomerates, testifying a Paleocene age for the main juxtaposition of the CACC and IAESB mélanges.

In the central part of the sampled area, the IAESB rocks are covered by the Paleocene-Eocene post-orogenic marine clastic-volcanoclastics, carbonates and volcanics of the Çankırı Basin which, in his turn, is partly covered by Neogene sediments (e.g., Göncüoglu, 1992). Within the basin the anticlockwise rotation of the CACC induced the formation of several NE-SW trending right-lateral faults and, at its western margin, important left-lateral faults (Fig. 2). When restored, the IAESB palinspastically follows also roughly an E-W trend and the present distortion of the main tectonic units is re-established.

To attempt a reconstruction of the thickness of the IAESB rocks that comprise the subducted and accreted remnants of the Izmir-Ankara-Erzican oceanic lithosphere, together with island arc and sedimentary rocks of several Late Cretaceous-Paleocene piggy-back basins (e.g., Cater *et al.*, 1991; Erdogan *et al.*, 1996) geophysical data would be necessary, but at present these date are not available.

3. Description of the sampled sections

All the sampled sequences pertain to the radiolarites-basalts blocks included in the Ankara Mélange. For the numbers of the sections we referred to Bortolotti *et al.* (2013*a*). It is worth of note that in the present paper we don't report the samples of Section 6 of Late Triassic age Bortolotti *et al.* (2013*a*).

Section 1

In a massif of pillow basalts along the road Elmadag - Kırıkkale several metric intercalations of siliceous shales with scattered radiolarian cherts crop out.

We sampled one of these intercalations and the associated basalts (Fig. 3b, N 39°55.023, E 33°21.989). Samples:

TU10.4, radiolarian chert.

TU10.6, TU10.10, basalts below the radiolarian cherts intercalation.

TU 10.9, basalt about 20 metres above the radiolarian cherts intercalation.

Section 2

In a massif of mainly pillowed basalts along the road Sorgun - Çekerek thin layers of radiolarian cherts crop out.

We sampled one of these layers and the associated basalts (N 39°54.889, E 35°18.063), one radiolarian chert sample was collected along the road in uncertain stratigraphic position.

Samples:

TU10.11, radiolarian chert with uncertain stratigraphic position.

TU10.12, radiolarian chert.

TU10.14 basalt at the contact with the radiolarites.

TU10.15, TU10.16, TU10.17, basalts collected several metres from the radiolarites.

Section 3

In a basalt block immediately north of Gökdere village, along the road, a sequence with radiolarian cherts crops out.

Samples:

TU10.19, basalt at the contact with the radiolarian cherts (N 39°59.924, E. 35°24.272).

TU10.22, TU10.23, basalts collected some metres southward (N 39°59.921, E 35°24.274) respectively 3,5 and 2 metres from the contact with the radiolarites.

TU10.28, radiolarian chert collected about 22 metres from the basalts (this sequence is intensely folded)

Section 4

An overturned sequence of basalts and radiolarian cherts with a sheared contact, along the road about 3 km southeast of Bogazkale (N 40°00.377, E 34°38.762).

Samples:

TU10.29, TU10.30, TU10.31 radiolarian cherts collected in about 20 cm above the sheared level.

60 cm of sheared argillites and cherts separates the basalts from the above samples.

TU10.32, basalt at the contact with the sheared level.

TU10.33, basalt collected some metres upstairs.

Section 5

Big quarry cut by small faults which pull up and down the contact basalts-cherts. The sequence could be overturned: the cherts lie under the basalts the contact is very fine with pockets of argillites and cherts in the mainly massif basalts.

The sampled quarry is along the road Çorum to Alaca, south of Küre village (Fig. 3c, N 40°15.861, E 34°48.187).

Samples:

TU10.34, basalt, sample collected about 6 metres for the cherts.

TU10.35, TU10.36, TU10.37, samples collected in a radiolarian cherts-argillites sequence from the base to 40 cm.

Small normal fault shifts of some metres the sequence.

TU10.38, radiolarian chert, collected beyond the fault, about 30 cm from the basalt sample TU10.40.

TU10.40, basalt at the contact with the radiolarian cherts.

TU10.39, basalt nearby the sample TU10.40.

Section 7

Small outcrop of basalts and cherts along the road Iskilip - Tosya, 1,2 km before the junction to Hacihalil village (Fig. 3d, N 40°53.378, E 34°20.756).

Samples:

TU10.45, radiolarian chert nodule in the basalts.

TU10.46, basalt.

Section 8

Large body of breccia(?) with basalts, microgabbros, serpentinites, crystallized limestones in a cherty matrix. We sampled the breccia in two near localities northeast of Yukariöz village. Samples:

First locality (N 40°51.097, E 33°50.723).

TU10.47, TU10.48, radiolarian cherts.

TU10.49a, TU10.49b, basalts.

Second locality (N 40°51.527, E 33°49.577).

TU10.51, M10 radiolarian cherts

Section 9

Pillow basalts enveloped in reddish limestones, road Eldivan - Sabanozu (N 40°31.488, E 33°28.106).

Samples:

TU10.52, TU10.53, basalts.

TU10.54, TU10.55, limestones.

4. Biostratigraphy

The radiolarian samples were etched with hydrochloric and hydrofluoric acid following the method proposed by Dumitrica (1970), Pessagno & Newport (1972), Baumgartner *et al.* (1981), De Wever (1982). The examined samples yielded radiolarians with moderate preservation and the principal markers are illustrated in Figure 4 and Figure 5.

For the taxonomy and ranges of the Late Jurassic-Early Cretaceous principal markers we refer to Aliev (1967), Kozur (1985), Kawabata (1988) Aita & Okada (1986), Goričan (1994), O'Dogherty (1994), Baumgartner *et al.* (1995*a*, 1995*b*), Dumitrica & Dumitrica-Jud (1995), Dumitrica *et al.* (1997), Bak (1996, 1999), Chiari *et al.* (2004), Danelian *et al.* (2004), Smuc & Goričan (2005), Filippov & Kemkin (2005), Chiari *et al.* (2007), Danelian (2008), Dumitrica & Zügel (2008), O'Dogherty *et al.* (2009), Robin *et al.* (2010), Bandini *et al.* (2011), Goričan *et al.* (2012), Chiari *et al.* (2012).

From the analyzed cherts the following radiolarian assemblages and ages were obtained:

Section 1 *TU10.4: Angulobracchia portmanni* Baumgartner, *Archaeodictyomitra mitra* Dumitrica, *Archaeodictyomitra* sp. cf. *A. lacrimula* (Foreman) (Fig. 4a), *Archaeodictyomitra* sp. cf. *A. mitra* Dumitrica, *Archaeodictyomitra* sp., *Archaeodictyomitra* (?) sp., *Aurisaturnalis variabilis variabilis*

(Squinabol) (Fig. 4b), *Hemicryptocapsa* sp. cf. *H. capita* Tan (Fig. 4c), *Neorelumbra* (?) sp., *Pseudodictyomitra* sp., *Pseudodictyomitra* (?) sp., *Pyramispongia* (?) sp., *Tethysetta* (?) sp, *Thanarla brouweri* (Tan) (Fig. 4d), *Thanarla* sp., *Torculum* (?) sp., *Xitus* sp. cf. *X. robustus* Wu, *Xitus* sp.

AGE: late Valanginian to late Hauterivian (UAZ. 17- 20; UAZones after Baumgartner *et al.*, 1995*b*) for the presence of *Aurisaturnalis variabilis variabilis* (Squinabol). ~~with *Hemicryptocapsa capita* Tan.~~ Ranges after Baumgartner *et al.* (1995*a*). ~~and Robin *et al.* (2010).~~

Section 2

TU10.11: Eoxitus (?) sp. (Fig. 4e), *Praewilliriedellum* sp. cf. *P. japonicum* (Yao), *Stichomitra* (?) *takanoensis* Aita (Fig. 4f), *Striatojaponocapsa* (?) sp.

AGE: early-middle Bajocian to late Bathonian-early Callovian (UAZ. 3-7; UAZones after Baumgartner *et al.*, 1995*b*) for the presence of *Stichomitra* (?) *takanoensis* Aita. Range after Baumgartner *et al.* (1995*a*).

TU10.12: Hiscocaspsa sp. (Fig. 4g), *Mirifusus* sp. cf. *M. guadalupensis* Pessagno (Fig. 4h), *Parahsuum* sp., *Parahsuum* (?) sp., *Praewilliriedellum* sp. cf. *P. japonicum* (Yao), ~~*Praewilliriedellum* sp. cf. *P. convexum* (Yao),~~ *Praewilliriedellum* (?) sp., *Pseudodictyomitra* (?) sp., *Stichomitra* (?) *takanoensis* Aita (Fig. 4i), *Transhsuum* sp., *Transhsuum* (?) sp., *Tritrabs* (?) sp.

AGE: early-middle Bajocian to late Bathonian-early Callovian (UAZ. 3-7; UAZones after Baumgartner *et al.*, 1995*b*) for the presence of *Stichomitra* (?) *takanoensis* Aita. Range after Baumgartner *et al.* (1995*a*).

Section 3

TU.10.28: Acaeniotylopsis sp., *Crolanium* (?) sp., *Emiluvia* sp. cf. *E. ordinaria* Ozvoldova (Fig. 4j), *Eoxitus* (?) sp., *Fultacapsa sphaerica* (Ozvoldova) (Fig. 4k), *Mirifusus* sp. cf. *M. guadalupensis*

Pessagno, *Mirifusus* sp., *Podocapsa amphitreptera* Foreman (Fig. 4l), *Spinosicapsa* sp. cf. *S. triacantha* (Fischli), *Spinosicapsa* (?) sp. (Fig. 4m), *Spongocapsula* sp., *Svinitzium* sp., *Svinitzium* (?) sp., *Triactoma* (?) sp.

AGE: middle-late Oxfordian to late Kimmeridgian-early Tithonian (UAZ. 9-11; UAZones after Baumgartner *et al.*, 1995*b*) for the occurrence of *Podocapsa amphitreptera* Foreman with *Fultacapsa sphaerica* (Ozvoldova). Ranges after Baumgartner *et al.* (1995*a*).

Section 4

TU10.29: Archaeodictyomitra lacrimula (Foreman) (Fig. 4n), *Archaeodictyomitra mitra* Dumitrica (Fig. 4o), *Archaeodictyomitra* sp., *Dicerosaturnalis trizonalis* (Rüst) (Fig. 4p), *Holocryptocanium* sp. cf. *H. barbui* Dumitrica, *Orbiculiformella* (?) sp., *Pantanellium* sp. cf. *P. squinaboli* (Tan) (Fig. 4q), *Praeconosphaera* (?) sp. cf. *P.* (?) *multiconus* Yang, *Praeconosphaera* (?) sp., *Praewilliriedellum* sp. cf. *P. japonicum* (Yao), *Pseudoeucyrtis* sp., *Thanarla brouweri* (Tan) sensu O'Dogherty (1994), *Thanarla* sp. cf. *T. gutta* Jud (Fig. 4r), *Thanarla* sp.

AGE: early-early late Berriasian to middle Aptian-early Albian (UAZ. 14 - Costata subzone of Turbocapsula Zone, Zone after O'Dogherty, 1994; UAZone after Baumgartner *et al.*, 1995*b*) for the occurrence of *Archaeodictyomitra lacrimula* (Foreman) and *Archaeodictyomitra mitra* Dumitrica. Ranges after Baumgartner *et al.* (1995*a*), O'Dogherty (1994), Dumitrica *et al.* (1997) and Bandini *et al.* (2011).

TU10.30: Archaeodictyomitra sp. cf. *A. communis* (Squinabol), *Archaeodictyomitra* sp. cf. *A. lacrimula* (Foreman), *Archaeodictyomitra* sp. (Fig. 4s), *Archaeodictyomitra* (?) sp., *Emiluvia* (?) sp., *Eoxitus* sp., *Hiscocapsa* (?) sp., *Holocryptocanium barbui* Dumitrica (Fig. 4t), *Holocryptocanium* sp. cf. *H. barbui* Dumitrica, *Pantanellium* sp., *Praeconosphaera* (?) sp., *Pseudodictyomitra lanceloti* Schaaf (Fig. 4u), *Pseudodictyomitra* sp. cf. *P. lanceloti* Schaaf, ~~*Thanarla pulchra* (Squinabol),~~ *Thanarla* sp. aff. *T. brouweri* (Tan), *Thanarla* sp. cf *T. pacifica*

Nakaseko & Nishimura (Fig. 4v), *Thanarla* sp. cf. *T. praeveneta* Pessagno, ~~*Thanarla* sp. cf. *T. pulchra* (Squinabol),~~ *Thanarla* sp., *Thanarla* (?) sp.

AGE: late Hauterivian to middle Aptian-early Albian (UAZ. 20 - Costata subzone of Turbocapsula Zone, Zone after O'Dogherty, 1994; UAZone after Baumgartner *et al.*, 1995*b*) for the presence of *Pseudodictyomitra lanceloti* Schaaf. Range after Baumgartner *et al.* (1995*a*) and Bandini *et al.* (2011).

TU10.31: Angulobracchia (?) sp., *Archaeodictyomitra lacrimula* (Foreman) (Fig. 5a), *Archaeodictyomitra mitra* Dumitrica, *Archaeodictyomitra* sp. cf. *A. lacrimula* (Foreman), *Archaeodictyomitra* sp., *Aurisaturnalis carinatus perforatus* Dumitrica & Dumitrica Jud (Fig. 5b), *Dicerosaturnalis trizonalis* (Rüst), *Halesium* (?) sp., *Pantanellium* sp., *Praeconosphaera* (?) sp. cf. *P.* (?) *multiconus* Yang, *Praeconosphaera* (?) sp., *Praexitus* sp., *Pseudodictyomitra lanceloti* Schaaf, *Pseudodictyomitra* sp. cf. *P. lanceloti* Schaaf, *Pseudodictyomitra* sp., *Pseudodictyomitra* (?) sp., *Spinosicapsa* (?) sp., *Thanarla brouweri* (Tan) (Fig. 5c), *Thanarla* sp. cf. *T. brouweri* (Tan), *Thanarla* sp. cf. *T. pacifica* Nakaseko & Nishimura, *Thanarla* sp. cf. *T. pulchra* (Squinabol), *Thanarla* sp., *Xitus* sp., *Xitus* (?) sp.

AGE: middle late Barremian-early early Aptian for the occurrence of *Aurisaturnalis carinatus perforatus* Dumitrica & Dumitrica Jud. Range after Dumitrica and Dumitrica-Jud (1995).

Section 5

TU10.35: Archaeodictyomitra (?) sp., *Dicerosaturnalis trizonalis* (Rüst), ~~*Dicerosaturnalis* sp. cf. *D. trizonalis* (Rüst),~~ *Dicerosaturnalis* sp. cf. *D. trizonalis* (Rüst), *Emiluvia* sp. cf. *E. ultima* Baumgartner, *Emiluvia* sp., *Eucyrtidiellum pyramis* (Aita) (Fig. 5d), *Mirifusus* sp. cf. *M. dianae* (Karrer) s.l., *Mirifusus* sp., *Napora* sp., *Podocapsa amphitreptera* Foreman (Fig. 5e), ~~*Podocapsa amphitreptera* Foreman,~~ *Praeconosphaera* (?) sp., *Pseudodictyomitra* (?) sp., *Spinosicapsa* (?) sp.,

Svinitzium (?) sp., *Syringocapsa* (?) sp., *Triactoma* sp. cf. *T. jonesi* (Pessagno), *Triactoma* (?) sp., *Zhamoidellum* (?) sp.

AGE: early-early late Tithonian to latest Tithonian-earliest Berriasian (UAZ. 12-13; UAZones after Baumgartner *et al.*, 1995*b*) for the presence of *Eucyrtidiellum pyramis* (Aita). Range after Baumgartner *et al.* (1995*a*).

TU10.36: Archaeodictyomitra apiarium (Rüst), *Archaeodictyomitra* sp. aff. *A. excellens* (Tan), *Archaeodictyomitra* sp. aff. *A. rigida* Pessagno, *Archaeodictyomitra* sp. cf. *A. apiarium* (Rüst), *Archaeodictyomitra* sp. 1, *Archaeodictyomitra* sp., *Cinguloturris cylindra* Kemkin & Rudenko (Fig. 5f), *Emiluvia* sp. cf. *E. ordinaria* Ozvoldova (Fig. 5g), *Emiluvia* sp. cf. *E. orea* Baumgartner, *Emiluvia* (?) sp., *Eucyrtidiellum pyramis* (Aita) (Fig. 5h), *Eucyrtidiellum* (?) sp. cf. *E.* (?) *quinatum* Takemura, *Loopus primitivus* (Matsuoka & Yao) (Fig. 5i), *Loopus* sp. cf. *L. doliolum* Dumitrica, *Mirifusus dianae* s.l. (Karrer), *Mirifusus* sp., *Olanda* sp., *Podocapsa amphitreptera* Foreman, *Praeconosphaera* (?) *sphaeroconus* (Rüst), *Praeconosphaera* (?) sp. cf. *P.* (?) *sphaeroconus* (Rüst), *Praeconosphaera* (?) sp., *Pseudodictyomitra* sp. cf. *P. carpatica* (Lozyniak), *Pseudodictyomitra* (?) sp., *Ristola cretacea* (Baumgartner) (Fig. 5j), *Ristola* (?) sp., *Sethocapsa horokanaiensis* Kawabata, *Syringocapsa* (?) sp., *Zhamoidellum* sp. cf. *Z.* sp. A sensu Goričan (1994), *Zhamoidellum* sp.

AGE: early-early late Tithonian (UAZ. 12; UAZone after Baumgartner *et al.*, 1995*b*) for the occurrence of *Cinguloturris cylindra* Kemkin & Rudenko, *Eucyrtidiellum pyramis* (Aita), *Ristola cretacea* (Baumgartner) with *Loopus primitivus* (Matsuoka & Yao). Ranges after Baumgartner *et al.* (1995*a*).

TU10.37: Archaeodictyomitra (?) sp., *Podocapsa amphitreptera* Foreman (Fig. 5k), ~~*Podocapsa amphitreptera* Foreman,~~ *Praeconosphaera* (?) *sphaeroconus* (Rüst) (Fig. 5l), *Pseudodictyomitra* (?) sp., *Spinosicapsa* (?) sp.

AGE: late Oxfordian-early Kimmeridgian to latest Valanginian-earliest Hauterivian (UAZ. 10-18; UAZones after Baumgartner *et al.*, 1995*b*) for the occurrence of *Praeconosphaera* (?) *sphaeroconus* (Rüst) with *Podocapsa amphitreptera* Foreman. Ranges after Baumgartner *et al.* (1995*a*), Chiari *et al.* (2007) and Bandini *et al.* (2011).

TU10.38: Archaeodictyomitra sp. aff. *A. chalilovi* (Aliev), *Archaeodictyomitra* sp. aff. *A. excellens* (Tan), *Archaeodictyomitra* sp. aff. *A. ioniana* Danelian, *Archaeodictyomitra* sp. cf. *A. apiarium* (Rüst), *Archaeodictyomitra* sp. cf. *A. excellens* (Tan) (Fig. 5m), *Archaeodictyomitra* sp. cf. *A. minoensis* (Mizutani), *Archaeodictyomitra* sp., *Archaeodictyomitra* (?) sp., *Becus* (?) sp., *Cinguloturris* sp. cf. *C. carpatica* Dumitrica, *Dicerosaturnalis trizonalis* (Rüst), *Dicerosaturnalis* sp. cf. *D. trizonalis* (Rüst), *Emiluvia* sp., *Pantanellium* sp., *Podocapsa amphitreptera* Foreman (Fig. 5n), *Praeconosphaera* (?) sp., *Pseudodictyomitra* sp. cf. *P. thurowi* Dumitrica, *Pseudodictyomitra* sp., *Saitoum* sp. cf. *S. elegans* De Wever (Fig. 5o), *Saitoum* (?) sp., *Spinosicapsa* (?) sp., *Syringocapsa* (?) sp., *Zhamoidellum ovum* Dumitrica (Fig. 5p), *Zhamoidellum* sp.

AGE: middle-late Oxfordian to late Kimmeridgian-early Tithonian (UAZ. 9-11; UAZones after Baumgartner *et al.*, 1995*b*) for the presence of *Podocapsa amphitreptera* Foreman and *Zhamoidellum ovum* Dumitrica. Ranges after Baumgartner *et al.* (1995*a*) and Smuc and Goričan (2005).

Section 7

TU10.45: Archaeodictyomitra sp. cf. *A. communis* (Squinabol), *Archaeodictyomitra* sp. cf. *A. coniforma* Dumitrica (Fig. 5q), *Archaeodictyomitra* sp., *Archaeodictyomitra* (?) sp., *Cryptamphorella clivosa* (Aliev) (Fig. 5r), ~~*Dictyomitra* sp.,~~ *Godia* sp. cf. *G. decora* (Li & Wu), *Godia* (?) sp., *Holocryptocanium* sp. cf. *H. barbui* Dumitrica, *Praeconosphaera* (?) *sphaeroconus* (Rüst) (Fig. 5s), *Praeconosphaera* (?) sp., ~~*Pseudodictyomitra* sp.,~~ *Pseudodictyomitra* (?) sp.,

Tethysetta sp. cf. *T. usotanensis* (Tumanda), *Thanarla brouweri* (Tan), *Thanarla* sp. cf. *T. pulchra* (Squinabol), *Thanarla* sp., *Thanarla* (?) sp.

AGE: Valanginian to middle Aptian-early Albian (Valanginian to Costata subzone of Turbocapsula Zone; Zone after O'Dogherty, 1994) for the presence of *Cryptamphorella clivosa* (Aliev) with *Praeconosphaera* (?) *sphaeroconus* (Rüst). Ranges after Aliev (1967), O'Dogherty (1994), Filippov and Kemkin (2005), Chiari *et al.* (2007) and Bandini *et al.* (2011).

Section 8

TU10.47: Archaeodictyomitra excellens (Tan) (Fig. 5t), *Archaeodictyomitra lacrimula* (Foreman), *Archaeodictyomitra* sp. cf. *A. communis* (Squinabol), *Archaeodictyomitra* sp. cf. *A. ioniana* Danelian, *Archaeodictyomitra* sp. cf. *A. vulgaris* Pessagno, *Archaeodictyomitra* sp., *Archaeodictyomitra* (?) sp., ~~*Cecrops*~~ *Cana septemporatus* (Parona) (Fig. 5u), ~~*Dictyomitra* sp.,~~ *Halesium* sp. cf. *H. palmatum* Dumitrica (Fig. 5v), *Hiscocapsa* sp. cf. *H. grutterinki* (Tan), *Hiscocapsa* sp., *Holocryptocanium barbui* Dumitrica, *Holocryptocanium* sp. cf. *H. barbui* Dumitrica, ~~*Mictyoditra* sp. cf. *M. thiensis* (Tan),~~ *Pantanellium* sp., *Praeconosphaera* (?) sp. cf. *P.* (?) *sphaeroconus* (Rüst), *Praeconosphaera* (?) sp., *Pseudodictyomitra* sp. cf. *P.* sp. 5 in Dumitrica *et al.* (1997), *Pseudodictyomitra* sp., *Pseudodictyomitra* (?) sp., *Pseudoxitus* (?) sp., *Syringocapsa* (?) sp., *Thanarla* sp. cf. *T. brouweri* (Tan), *Thanarla* sp., *Thanarla* (?) sp., *Williriedellum* (?) sp., *Xitus* sp. cf. *X. normalis* (Wu & Li), *Xitus* sp., *Xitus* (?) sp.

AGE: late Valanginian-early Barremian (UAZ. 17-21; UAZones after Baumgartner *et al.*, 1995*b*) for the presence of ~~*Cecrops*~~ *Cana septemporatus* (Parona). Ranges after Baumgartner *et al.* (1995*a*).

TU10.48: Age not determinable for the very low preservation of radiolarians.

TU10.51: Acaeniotyle sp. cf. *A. umbilicata* (Rüst), *Archaeodictyomitra lacrimula* (Foreman) (Fig. 5w), *Archaeodictyomitra* sp. cf. *A. communis* (Squinabol), *Archaeodictyomitra* sp.,

Archaeodictyomitra (?) sp., *Crucella* (?) sp., *Praeconosphaera* (?) sp., *Pseudodictyomitra* (?) sp., *Pseudoeucyrtis* sp. cf. *P. hanni* (Tan) sensu O'Dogherty (1994) (Fig. 5x), *Spinosicapsa* (?) sp., *Thanarla* sp. cf. *T. pulchra* (Squinabol), *Thanarla* sp.

AGE: early-early late Berriasian to middle Aptian-early Albian (UAZ. 14 - Costata subzone of Turbocapsula Zone, Zone after O'Dogherty, 1994; UAZone after Baumgartner *et al.*, 1995*b*) for the presence of *Archaeodictyomitra lacrimula* (Foreman). Range after Baumgartner *et al.* (1995*a*) and O'Dogherty (1994).

TU10.M1O: Archaeodictyomitra sp., *Archaeodictyomitra* (?) sp., *Kilinora* (?) sp., *Triversus* (?) sp.

AGE: Age not determinable for the low preservation of radiolarians.

5. Petrography and Geochemistry of the basaltic rocks

5.a Petrography

All the studied rocks are affected by low-temperature, ocean-floor alteration, which resulted in the replacement of primary minerals, though primary igneous textures are well preserved. Plagioclase is usually replaced by albite or calcite and rarely by clay mineral assemblages. Clinopyroxene is normally pseudomorphosed either by chlorite or actinolitic amphibole. In samples TU10-22 and TU10-23 (Section 3) clinopyroxene is replaced by brown hornblende, though fresh clinopyroxene relics are locally observed. The groundmass secondary phases mainly consist of chlorite, and clay minerals. Regardless of the secondary mineralogical transformation, the following petrographic description of the various rock-types has been made on the bases of the primary igneous phases. Moreover, for a better understanding, it has been made according to the geochemical groups described in the next section.

Group 1. Pillow and massive lavas have aphyric, micro-crystalline sub-ophitic textures in which only small laths of plagioclase can be recognized. Pillow breccias are generally monogenetic and show corse-grained, intergranular texture with euhedral plagioclase and interstitial clinopyroxene.

Group 2. Massive lavas show both aphyric and porphyritic (PI = ~40) textures. In both varieties, the groundmass texture is hyalopilitic. Phenocrysts are represented by large crystals of plagioclase.

Groups 3 and 4. Pillow and massive lavas most commonly display aphyric, ophitic or sub-ophitic textures with crystal size ranging from micro-crystalline to coarse-grained. Nonetheless, a few samples display slightly porphyritic textures with plagioclase microphenocrysts. In addition, hyalopilitic texture is locally observed. The groundmass mineral assemblage includes plagioclase, clinopyroxene, and variable amount of opaque phases. Pillow breccias are generally monogenetic and the individual fragments are texturally and compositionally similar to the pillow lavas. Most of these rocks are characterized by variable abundance of varioles filled by calcite. In all the studied rock groups, the crystallization order is: plagioclase + clinopyroxene ± Fe-Ti-oxides.

5.b Analytical methods

Whole-rock major and some trace element analyses were obtained by X-ray fluorescence (XRF) on pressed-powder pellets, using an ARL Advant-XP automated X-ray spectrometer. The matrix correction methods proposed by Lachance & Trail (1966) were applied. Volatile contents were determined as loss on ignition (L.O.I.) at 1000°C. In addition, Rb, Sr, Nb, Hf, Ta, Th, U, and the rare earth elements (REE) were determined on twelve representative samples by inductively coupled plasma-mass spectrometry (ICP-MS) using a Thermo Series X-I spectrometer.

The CO_2 content was determined by simple volumetric technique (Jackson, 1958) only on the samples affected by calcite veins and amygdales. This technique was calibrated using standard amounts of reagent grade $CaCO_3$. In addition, for the discussion of the geochemical characteristics and for a better comparison of chemical data, the major element composition of these samples was recalculated on calcite-free bases. In detail, CaO content in secondary calcite has been calculated

according to stoikiometric proportions with CO_2 contents, given that the secondary carbonates are exclusively composed of calcite. Major element composition has then been re-calculated to 100 wt% without considering L.O.I. and CaO in calcite.

The accuracy of the data for XRF and ICP-MS analyses were evaluated using results for international standard rocks run as unknown. The detection limits for XRF and ICP-MS analyses were evaluated using results from several runs of about twenty-nine international standards. Accuracy and detection limits for the CO_2, analyses were determined using different amounts of reagent grade $CaCO_3$ run as unknown. Results are given in Appendix A. All whole-rock analyses were performed at the Dipartimento di Science della Terra, Università di Ferrara. The results are shown in Table 1.

5.c Geochemistry

The following geochemical description is made mainly using those major and trace elements that are virtually immobile during low-temperature alteration and metamorphism (e.g., Pearce & Norry, 1979). These elements include many incompatible element, such as: Ti, P, Zr, Y, Sc, Nb, Ta, Hf, Th, middle (M-) and heavy (H-) REE, as well as some transition metals (e.g., Ni, Co, Cr, V). Light REE (LREE) may be affected by some mobilization during alteration. However, the good correlations between these elements and many immobile elements (not shown) indicate that LREE have not been mobilized by the alteration. For example, the correlation coefficients (r^2) for the linear correlation Zr – La and Zr – Ce are 0.96 and 0.90, respectively. Rb, Ba, K, and Sr are commonly mobilized during alteration. In fact, these elements plotted against Zr generally show low or very low r^2. However, the fairly good correlation with Zr and Rb in Group 4 samples ($r^2 = 0.91$), as well as Ba in Group 4 ($r^2 = 0.87$) and in Group 2 samples ($r^2 = 0.85$), suggest that these elements were only slightly mobilized during alteration in these rock-types.

According to Bortolotti *et al.* (2013*b*), four groups of volcanic rocks can be recognised in the studied sections. Group 1 is represented by basalts cropping out in the Sections 5 and 8. These rocks

have a clear sub-alkaline nature with low Nb/Y ratios (Fig. 6) and show relatively high TiO_2, P_2O_5, Zr, and Y contents. Ni is generally low, whereas Cr is relatively high, with the only exception of sample TU10-49b. V content is also generally high (Table 1). The values of these elements are similar to those of Group 2 basalts (see below). By contrast, Hf, Ta, Th, and U contents are low. These rocks show a sharp increase of FO_t and Y and a sharp decrease of Mg# and Ni with increasing Zr, as well as very low Th/Tb ratios (Fig. 7). *Group 1* basalts are characterized by flat normalized incompatible element patterns (Fig. 8a). The REE abundance (Fig. 8b) varies from ~10 to ~20 times that of chondrite and displays LREE/MREE smoothly depleted patterns with $(La/Sm)_N$ ratios ranging from 0.78 to 0.82. The overall geochemical features of these rocks, as well as both incompatible elements and REE patterns resemble those of typical N-MORB (Sun & McDonough, 1989). Nonetheless, HREE are slightly depleted with respect to both LREE and MREE (Fig. 8b) with $(La/Yb)_N$ ratios = 1.06 – 1.30 and $(Sm/Yb)_N$ ratios = 1.31 – 1.58. In particular, the $(Sm/Yb)_N$ ratios are higher than that of typical N-MORB (Sm_N/Yb_N = 0.96, Sun & McDonough, 1989). These values are comparable to those of garnet-influenced MORBs (G-MORB) from the External Ligurides of Northern Apennine (Sm_N/Yb_N = 1.25-1.50, Montanini *et al.*, 2008), Corsica (Sm_N/Yb_N = 1.30-1.81, Saccani *et al.*, 2008), and Elba Island (Sm_N/Yb_N = 1.49-2.10, Saccani & Principi, 2016), as well as to those of the Paleozoic Misho mafic complex in north Iran (Saccani *et al.*, 2013*a*) and the Mesozoic Kermanshah ophiolites in south Iran (Saccani *et al.*, 2013*b*). The G-MORB affinity of Group 1 rocks is also suggested by Th-Nb co-variation and by their $(Ce/Yb)_N$ and $(Dy/Yb)_N$ ratios (Fig. 9), although in the most common tectonic discrimination diagrams these basalts plot in the field for N-MORBs (e.g., Fig. 10).

Group 2 is represented by basalts cropping out in the Sections 4 and 7. These rocks have a sub-alkaline nature with low Nb/Y ratios ranging from 0.27 to 0.40 (Fig. 6) and show relatively high TiO_2, P_2O_5, Zr, and Y contents (Table 1). Ni, though variable, is generally low, whereas Cr and V are rather high. As exemplified in the variation diagrams in Figure 7, these rocks have major element contents and compositions of many trace elements largely overlapping those of Group 1 basalts.

Nonetheless, as a distinctive feature, Group 2 basalts are characterized by LILE/HFSE smoothly enriched patterns (Figs. 8c). Likewise, REE patterns show a slight enrichment in LREE compared to HREE (Figs. 8d), with $(La/Sm)_N$ and $(La/Yb)_N$ ratios ranging from 1.12 to 1.51 and from 1.27 to 2.19, respectively. These patterns are similar to that of the typical enriched-type MORB (E-MORB) of Sun & McDonough, 1989. The Th-Nb values are also similar to those of the typical E-MORB (Fig. 9a). In the most common tectonic discrimination diagrams these basalts plot across the boundary between the fields for N-MORB and E-MORB (e.g., Fig. 10).

Group 3 is represented by pillow basalts and ferrobasalts from Section 2, as well as by massive lava basalts from Section 9. These rocks have a transitional nature, as testified by their high Nb/Y ratios (Fig. 6). Basalt TU10-15 (Section 2) displays a rather primitive composition with relatively high Mg# and low TiO_2 and P_2O_5 contents (Table 1). In contrast, ferrobasalts from Section 2 and basalts from Section 9 have rather evolved compositions with relatively low Mg# and very high TiO_2 and P_2O_5 contents (Table 1). Accordingly, Ni and Cr contents are generally high in basalts, whereas they are relatively low in the differentiated rocks. Except for Mg#, the variation of many elements with respect to Zr display roughly common evolutionary trends towards high contents of the incompatible elements and FeO_t and low contents of the compatible elements for all Group 3 samples (Fig. 7). In contrast, Mg# for samples from Sections 2 and 9 show distinct evolutionary trends with respect to Zr. All these trends are compatible with a magmatic evolution by fractional crystallization. The Th/Tb ratios of these rocks are significantly higher than those of Groups 1 and 2 rocks and significantly lower than those of Group 4 rocks (Fig. 7). Group 3 rocks show high abundance in LFSE with respect to N-MORB and display regularly decreasing N-MORB normalized patterns from Rb to Y (Fig. 8e). The REE abundance (Fig. 8f) varies from ~30 to ~100 and from ~10 to ~12 times that of chondrite for LREE and HREE, respectively. These rocks displays LREE/MREE and LREE/HREE enriched patterns, with $(La/Sm)_N$ ratios = 2.61 - 4.15 and $(La/Yb)_N$ ratios = 4.65 - 9.17. These incompatible elements and REE patterns are comparable with those of P-MORB (plume-type MORB). This conclusion is also supported by the co-variation of the

Th and Nb concentrations (Fig. 9a). In the most common tectonic discrimination diagrams (e.g., Fig. 10) these rocks generally plot in the fields for E-MORBs and alkaline ocean island basalts (OIB).

Group 4 is represented mainly by alkaline basalts and subordinate trachytes from Sections 1 and 3. These rocks have a clear alkaline nature, as testified by their very high Nb/Y ratios (Fig. 6). Alkaline basalts from Section 3 mainly display relatively primitive compositions, whereas alkaline basalts from Section 1 represent rather evolved compositions. Generally, all samples have high contents of TiO_2, P_2O_5, Zr, Nb, Hf, Th and low contents of compatible elements (Table 1, Fig. 7). In the variation diagrams in Figure 7, rocks from the different sections show different evolutionary trends, most likely reflecting the distinct evolutions of magmas of different initial compositions. This is particularly evident in the FeO_t, Mg#, Ni, and Y vs. Zr diagrams. Nonetheless, the well-defined trends observed for samples from each single section suggest that each section consist of rocks belonging to a comagmatic suite. Group 4 rocks show high abundance in LFSE with respect to N-MORB and display regularly decreasing N-MORB normalized patterns from Rb to Y (Fig. 8g). The REE abundance (Fig. 8h) varies from ~60 to ~400 and from ~9 to ~10 times that of chondrite for LREE and HREE, respectively. These rocks displays LREE/MREE and LREE/HREE strongly enriched patterns, with $(La/Sm)_N$ ratios = 4.15 - 5.25 and $(La/Yb)_N$ ratios = 18.75 - 23.13. Group 4 rocks can readily be distinguished from Group 3 rocks, as they show higher Zr, incompatible element, and LREE concentrations, as well as Th/Tb ratios at comparable Mg# (Figs. 7, 7g, h). The overall geochemistry of these basalts resembles that of alkaline basalts generated at within-plate ocean island settings (OIB), as also exemplified by the generally high Ti/V ratios (Table 1). This conclusion is also supported by the co-variation of the Th and Nb values (Fig. 9), as well as by the most common tectonic discrimination diagrams (e.g., Fig. 10).

6. Discussion

6.a Mantle melting processes and magma generation

One of the main goals of this study is to assess the nature and tectonic significance of the magmatic events that occurred in the Turkish sector of the Neotethys during the Middle Jurassic – Early Cretaceous time span. According to many authors (e.g., Pearce, 1982), the compositional differences between magma types are related to different source characteristics that are associated, in turn, to distinct tectono-magmatic settings of formation. We will therefore focus our petrogenetic discussion to the identification of the possible mantle sources and related tectonic setting of formation of the four distinct lava groups identified in the previous chapter, which are: (1) G-MORBs (Group 1); (2) E-MORBs (Group 2); (2) P-MORBs (Group 3); (4) OIB-type alkaline volcanic rocks (Group 4). Unfortunately, the chemical variation due to fractional crystallization cannot be defined in detail, as the mélange nature of the sampled rocks prevents us to establish definite genetic relationships between rocks within each single chemical group. Nonetheless, some trace element ratios (e.g., Zr/Nb, Ce/Y, Th/Ta, Th/Tb) are little affected by fractional crystallization of predominantly olivine + clinopyroxene + plagioclase. Therefore, even in presence of significant amounts of fractionation, they are believed to represent the elemental ratios in the source (e.g., Allègre & Minster, 1978; Beker *et al.*, 1997). Ratios of incompatible elements (Ce/Y, Nb/Yb), ratios of hygromagmatophile element ratios ((Th/Ta)/(Th/Tb)) (Table 1), as well as distinct normalized multi-element and REE patterns (Fig. 8) suggest that the different magmatic rocks from the Ankara Mélange units have been most likely originated from chemically distinct mantle sources. In order to constrain the possible mantle sources of the different rock series of the Ankara Mélange, non-modal, batch partial melting models are presented in Figure 11. A rigorous quantification of the melting processes is not possible as the composition of the mantle sources are difficult to constrain. However, a semi-quantitative modelling of the REE can place some solid constraints. The melt modelling uses plots of LREE/HREE (i.e., La/Yb) vs. MREE/HREE (i.e., Dy/Yb) ratios, which are particularly useful for distinguishing between melting in the spinel and garnet stability fields (Thirlwall *et al.*, 1994). Partial melting of a mantle source in the spinel-facies produces little change

in Dy/Yb ratios in melts with respect to melt fraction. In contrast, mantle partial melting in the garnet-facies produces large changes in Dy/Yb ratios with melt fraction. In both cases, La/Yb ratios are particularly responsive to melt fraction change (Fig. 11). Another important feature of these plots is that mixing between different melt fractions will generate linear mixing arrays (e.g., Beker *et al.*, 1997).

Group 1 basalts. As observed in the previous chapter, the Group 1 rocks (G-MORBs) show unusually high MREE/HREE ratios (Dy_N/Yb_N = 1.20 – 1.34) compared to the typical N-MORB (Dy_N/Yb_N = 1, Sun & McDonough, 1989). REE modelling for Group 1 basalts (Fig. 11a) shows that these rocks cannot have been simply derived from partial melting of a typical depleted MORB mantle (DMM) source (Workman & Hart, 2005) in the spinel-facies. Rather, their significant HREE/MREE fractionation can be interpreted as a garnet signature, which can be related either to a deep initiation of melting in the garnet peridotite stability field, or to the melting of an heterogeneous mantle source characterized by garnet-bearing mafic/ultramafic layers (e.g., Montanini *et al.*, 2008; Saccani *et al.*, 2008; Saccani, 2015). However, melting of a DMM source bearing garnet mafic/ultramafic layers would generate primary melts characterized by high MREE/HREE ratios coupled with low (<0.8) LREE/HREE ratios (not shown). By consequence, the high (1.06 - 1.30) LREE/HREE ratios observed in the Group 1 basalts are inconsistent with this hypothesis. Therefore, in Figure 11a the partial melting model of DMM source that starts in the garnet-facies and continues to larger degrees in the spinel-facies (with various combinations of melting fractions in the garnet- and spinel-facies) is shown. It can be observed that the REE composition of the Group 1 basalts is compatible with the calculated compositions for 2.5% melting in the garnet-facies and 10% melting in the spinel-facies, assuming mixing of ~70-80% of melt derived from spinel-facies mantle with ~30-20% melt from garnet-facies mantle.

Group 2 basalts. Group 2 basalts (E-MORBs) show variable LREE/HREE enrichments (Fig. 8d), which can be considered as a result from variable mixing between depleted and enriched asthenospheric sources or, alternatively, from lower degree of partial melting of a DMM source,

compared to N-MORBs. In fact, basalt TU10-32 is generally compatible with low degree (~2.5%) of partial melting of a DMM source in the spinel-facies (Fig. 11b). However, basalt TU10-46 shows HREE values lower than those of the N-MORBs of Group 1, which cannot be generated by lower degrees of partial melting of a common mantle source (Figs. 8b, d). In addition, lower degrees of partial melting of a DMM source in the spinel-facies cannot generate the $(La/Yb)_N$ and $(Dy/Yb)_N$ ratios of this sample. The most appropriate solution for the genesis of this E-MORB sample is not straightforward. The LREE/HREE and MREE/HREE ratios are compatible with mixing of melt derived from very low degree (~1%) partial melting of a DMM source in the garnet-facies with melt derived from much larger degree (~10%) of partial melting in the spinel-facies mantle (Fig. 11a). The REE composition of these basalts is compatible with mixing of <10% of melts generated in the garnet-facies with >90% of melts generated in the spinel-facies. Nonetheless, a possible alternative solution is to invoke a more enriched source than DMM. Figure 11b shows that the melting curve of a hypothetical DMM source slightly enriched LREE with $(La/Yb)_N = 1.09$ and $(Dy/Yb)_N = 1.49$, and has a Yb concentration equal to that of DMM ($Yb_N = 2.08$). The model shows that the REE composition of E-MORB TU10-46 is compatible with the calculated composition for ~8% partial melting of this theoretical source in the spinel facies.

Group 3 and Group 4 rocks. The high LREE/HREE ratios displayed by the transitional basalts of Group 3 rocks (P-MORBs) and by the alkaline basalts of Group 4 (Figs. 8f, h) suggest an involvement of a garnet peridotite source. Moreover, the high La/Yb ratio observed in these basalts implies a source more enriched in LREE than DMM. In fact, variable degrees of partial melting of a DMM source in the spinel-facies cannot generate the observed La/Yb ratios and variable degrees of partial melting of a DMM source in the garnet-facies cannot generate the observed La/Yb and Dy/Yb ratios (Fig. 11a). Therefore, the most appropriate solution is to invoke a more enriched source than DMM, although it is impossible to assess the exact composition of this source. The model in Figure 11c illustrates melting curves for a hypothetical LREE-enriched source (Beker *et al.*, 1997) with $(La/Yb)_N = 1.32$ and $(Dy/Yb)_N = 1.49$, and has a Yb concentration equal to that of DMM ($Yb_N =$

2.08). Higher Yb concentrations (e.g., PM values) in the source would generate concentrations of HREE in the melts that are too high compared with the Group 3 and Group 4 volcanic rocks.

The co-variation in La/Yb-Dy/Yb systematics of Group 3 and Group 4 samples (Fig. 11c) cannot however be explained by variable degrees of partial melting of this enriched source in either the spinel- or garnet-facies. Melting in the garnet-facies produces melts with much higher Dy/Yb ratios than those of both Group 3 and Group 4 samples at reasonable degrees of melting (i.e., <20%). Alternatively, the mantle source would require an unusually low Dy/Yb ratio if the samples were to be simply the product of garnet-facies mantle melting. By contrast, melting in the spinel-facies produces melts with both La/Yb and Dy/Yb ratios lower than those of both Group 3 and Group 4 samples. Therefore, the simplest model to account for the REE systematics of these rocks involves mixing of small melt fractions from garnet-facies enriched mantle with relatively larger melt fractions from spinel-facies (Fig. 11c). This figure shows that the La/Yb-Dy/Yb systematics of Group 3 basalts can be explained by mixing of small degree melts (~0.5-1%) and larger degree melts (~5%) from garnet- and spinel-facies mantle, respectively. ~~In contrast~~ Likewise, the observed REE data for Group 4 basalts can be accounted for by mixing of ~~small degree melts (~0.5%) and larger degree melts (~5%) from garnet- and spinel-facies mantle, respectively~~ melts from ~0.5% and ~5% partial melting from garnet- and spinel-facies mantle, respectively. Alternatively, the La/Yb-Dy/Yb systematics of Group 4 basalts can be explained by comparatively higher degree of melting (~1%) in the garnet-facies mantle and comparatively lower degree of melting (~2.5%) in the spinel-facies mantle. In any case, the different La/Yb-Dy/Yb ratios shown by Group 3 and Group 4 basalts can be accounted for by mixing of different proportions of melts generated in the garnet- and spinel facies mantle. In detail, Group 4 basalts may have resulted from mixing of ~60% of melt derived from spinel-facies mantle with ~40% melt from garnet-facies mantle, whereas Group 3 basalts may have resulted from mixing of ~90% of melt derived from spinel-facies mantle with ~10% melt from garnet-facies mantle (Fig. 11c).

Figure 11b shows that the La/Yb and Dy/Yb ratios of Group 3 basalts can also be compatible with very low degree (<0.8%) of partial melting in the spinel-facies of the slightly metasomatized mantle source hypothesized for the genesis of Group 2 rocks. Such very low degree of partial melting is however unreasonable. In fact, experimental studies on melt mobility in peridotites showed that very small melt fractions are not readily mobile and therefore they remain within the host peridotite rather than migrating to form volcanic rocks melt (see Warren, 2016 for a more detailed discussion). Finally, it should be noted that variations in the degree of partial melting in the spinel field are difficult to constrain due to the small range in La/Yb ratios generated by spinel-facies melting. Some scatter in the La/Yb-Dy/Yb systematics (Fig. 11c) might be accounted for by small fluctuations in the degree of melting of garnet-facies mantle. In any case, from a semi-quantitative point of view, melt fractions in the garnet field are restricted to <1% whereas those in the spinel field are probably several percent (~5%).

The possible influence of crustal contamination can be excluded as the Th-Nb compositions of all rock-types plot within the MORB-OIB array (Fig. 9). Other geochemical indicators further support this conclusion. For example, high Th/Ta and low Nb/U ratios are effective indicators of crustal contamination. All Groups of Middle Jurassic–Early Cretaceous basalts from the Ankara mélange show very low Th/Ta ratios (<1.74), as well as Nb/U ratios averaging 44 in N-MORBs, 50 in E-MORBs, 40 in P-MORBs, and 43 in OIBs. These Nb/U ratios are comparable to those of the typical N-MORB (49.6), E-MORB (46,1), and OIB (47.1) of Sun & McDonough (1989).

Bortolotti *et al.* (2013*b*) have noted that the association of depleted basalts (N-MORBs), moderately enriched basalts (E-MORBs), and variably enriched rocks (P-MORBs and OIBs) occurring in the Ankara Mélange is also observed in many peri-Mediterranean ophiolitic complexes (e.g., Saccani & Photiades, 2005, Saccani *et al.*, 2011, and references therein), as well as from several Middle East ophiolites (Allahyari *et al.*, 2010; Saccani *et al.*, 2010, 2013*a*, 2013*b*), where it is interpreted as the result of partial melting of a MORB-type asthenospheric source enriched in HFSE and LREE by an ocean island basalt (OIB) type chemical component (plume-type

component). Bortolotti *et al.* (2013*b*) have used the co-variation of Zr/Y and Zr/Nb to qualitatively depict the influence of a plume-type component on MORB compositions in the Middle Jurassic – Early Cretaceous basalts from the Ankara Mélange (Fig. 12). From Figure 12it is evident that the data conform extremely well to the mixing curve calculated using the OIB and N-MORB end-members. Such mixing relationships are consistent with either magma mixing or source region mixing (or eventually, a combination of these).

6.b Tectono-magmatic significance

The melting models carried out for the different groups of volcanic rocks, which are presented in the previous section, allow to draw the following conclusions: 1) the geochemically distinct Groups of Middle Jurassic – Early Cretaceous volcanic rocks in the Ankara Mélange are related to different mantle source compositions and partial melting degrees; 2) regardless of their geochemical affinities, all the studied volcanic rocks were generated by partial melting starting in the garnet-facies mantle and continuing to larger degrees in the spinel-facies mantle. Perhaps, Group 2 basalts from Section 7 may represent the only exception to this conclusion. In fact, their chemistry is compatible either with partial melting starting in the garnet-facies mantle and continuing to larger degrees in the spinel-facies mantle, or partial melting in the spinel facies from a slightly enriched source. As shown before, the formation of enriched alkaline and P-MORB type rocks imply the occurrence of mantle sources strongly metasomatized by OIB-type ~~(i.e., plume-type)~~ components. Two alternative hypotheses can account for such OIB-type metasomatism of depleted mantle sources: 1) the existence of plume activity in the region during Middle Jurassic – Early Cretaceous times and 2) the existence of deep mantle heterogeneously modified by previous mantle plume activity that occurred in the same area in association with the opening of the Neo-Tethys. However, the extant geological evidence suggests that the first hypothesis can be disregarded. In fact, the lack of magmatic evolution from more depleted to more enriched rocks that is commonly observed in plume-related magmatism, the absence of basaltic plateaus, and a relatively small volume of plume-

related volcanic rocks collectively argue against the existence of a well established, long-lasting mantle plume in the region. Therefore, we favour the hypothesis that the different Middle Jurassic – Early Cretaceous volcanic rock types from the Ankara mélange were formed from partial melting of a strongly heterogeneous mantle, with OIB-type components inherited from a previous mantle plume activity associated with the opening of the Neo-Tethys. In fact, the Anisian alkaline volcanics intruding the Kütahya-Bolkardag have been interpreted as the early products of the rifting of the Neotethys Ocean with the involvement of a plume (Göncüoglu *et al*., 2003; Göncüoglu 2010; Akal *et al*., 2012). Recent studies on modern oceanic basins further support our favoured hypothesis. In fact, these studies have demonstrated the upper mantle is much more heterogeneous than previously thought (e.g., Brunelli *et al*., 2006; Warren, 2016). The mantle heterogeneities can be either the result of earlier tectonic events or ancient episodes of melting, melt extraction, and melt entrapment and they can occur at local or at regional scale (e.g., Liu *et al*., 2008; Warren *et al*., 2009).

A possible tectono-magmatic model that can explain the formation of the different volcanic rock from the Ankara mélange during the Middle Jurassic – Early Cretaceous is shown in Figure 13. In this model, the OIB-type metasomatized portions are likely to be prominent in the asthenospheric mantle. The uprising asthenospheric mantle underwent polybaric partial melting, which started in the garnet-facies and continued in the spinel-facies. The strongly enriched alkaline and P-MORB rocks were generated from various, but limited degrees of polybaric partial melting of OIB-type metasomatized portions. G-MORB and E-MORB were generated from various degrees of polybaric partial melting of depleted asthenosphere portions. Alternatively, E-MORB (particularly, that of Section 7) may have been generated from partial melting of a slightly enriched mantle source in the spinel stability field. The tectono-magmatic model presented in Figure 13 implies that the different rocks were formed by partial melting of chemically different portions of the sub-oceanic mantle in different times. In consequence, this model does not necessarily imply the existence of genetic relationship between different rock-groups or within a single rock-group.

6.c Geodynamic implications

The ages obtained for the studied radiolarian assemblages coupled with the geochemistry of the associated basalts indicate that a composite oceanic crust including G-MORB, E-MORB, P-MORB and alkaline basalts was forming during the Middle Jurassic- Early Cretaceous times. These ages are in agreement with the radiolarians (Bragin & Tekin, 1996; Tekin, 1999; Celik, 2010; Uner, 2010; Tekin *et al.*, 2012*b*; Göncüoğlu *et al.*, 2015) and foraminifera (Boccaletti *et al.*, 1966; Bortolotti & Sagri, 1968; Yaliniz *et al.*, 2000*b*; Rojay *et al.*, 2001) data obtained from different parts of the IAESB. The age ranges from the published biostratigraphical data indicate gaps in Early Jurassic and late Early Cretaceous (see Göncüoglu *et al.* 2010). Moreover, Middle Jurassic findings were restricted to a limited number of samples. Our new findings partially fill the gap during late Early Cretaceous (see Göncüoglu *et al.*, 2010). In fact, the radiolarian cherts associated to the G-MORB of Section 8 indicated a late Valanginian-early Barremian age.

The Middle Jurassic-Early Cretaceous rock assemblage found in the mélange complexes of the IAESB, as well as the tectono-magmatic model presented in the previous section can be framed within the geodynamic model presented by Göncüoglu (2010) (Fig. 14). According to this model, the rifting of the Neotethys Ocean started in Late Triassic with the involvement of a mantle plume (Fig. 14a). Anisian and Norian volcanic rocks showing alkaline affinity were erupted at this stage (Göncüoglu *et al.*, 2003; Göncüoglu 2010, Akal *et al.*, 2012; Bortolotti *et al.*, 2013*b*). The Early Jurassic history of this oceanic basin cannot be straightforwardly constrained due to the lack of data. In fact, Early Jurassic (Hettanginian-Sinemurian) radiolarian chert blocks were found as single blocks in the Ankara Mélange, but they are not associated with volcanic rocks (Çelik, 2010; Göncüoglu *et al.*, 2015). Nonetheless, it is reasonable to postulate that during this time the Neotethys Ocean experienced an oceanic spreading phase. During the Middle Jurassic-Early Cretaceous time span the formation of a composite oceanic crust including G-MORB, E-MORB, P-

MORB and alkaline basalts suggest that the volcanic rocks of IAESB formed at a mid-ocean ridge setting by tapping different portions of a deep, highly heterogeneous mantle (Fig. 14b). Mantle heterogeneities consisted in portions variably enriched by OIB-type components, which were inherited from the Triassic mantle plume activity associated with the opening of this Neotethys oceanic branch (Fig. 14a). Our findings show that P-MORBs have Middle Jurassic age, G-MORBs have Late Jurassic age, E-MORBs were erupted during the Early Cretaceous, and alkaline basalts were erupted from Late Jurassic to Early Cretaceous. Partial melting of different portions of a heterogeneous sub-oceanic mantle (Figs. 13, 14b) can explain the formation of different and genetically unrelated magmatic rocks in the same time span.

The intra-oceanic subduction likely started from late Early Cretaceous on the northern side of the Neotethys branch, leading to the production of SSZ-type rocks during the late Early Cretaceous (Fig. 14c). Previous data on the earliest ages related to supra-subduction type volcanism and formation of metamorphic sole indicated early Late Cretaceous (e.g., Üner, 2010), therefore the intra-oceanic decoupling within the ocean was considered as pre-Late Cretaceous. This age could not be verified in this study, since in contrast to the western part of the IAESB, none of the basalt samples collected from the eastern part yielded supra-subduction characteristics. The different rock-types formed in the ocean were then incorporated into the accretionary prism during the Late Cretaceous closure.

7. Conclusion

This study is focused on slide blocks including oceanic lavas associated with pelagic sediments within the eastern part of the Ankara Mélange. A detailed petrological characterization of the volcanic rocks and a detailed biochronological investigation of the associated radiolarites was carried out. The main conclusions can be summarized as follows.

1) The radiolarian cherts associated with volcanic rocks show the following ages: late Valanginian to late Hauterivian (Section 1, OIB); early-middle Bajocian to late Bathonian-early Callovian (Section 2, P-MORB); middle-late Oxfordian to late Kimmeridgian-early Tithonian (Section 3, OIB); middle late Barremian-early early Aptian (Section 4, E-MORB); middle late Oxfordian to late Kimmeridgian-early Tithonian and early-early late Tithonian (Section 5, G-MORB); Valanginian to middle Aptian-early Albian (Section 7, E-MORB); late Valanginian-early Barremian (Section 8, G-MORB).

2) Volcanic rocks are largely represented by basalts and minor ferro-basalts and trachytes. They show different geochemical affinities and overlapping ages including: a) Late Jurassic-Early Cretaceous garnet-influenced MORB; b) Early Cretaceous enriched-MORB; c) Middle Jurassic plume-type MORB; d) Late Jurassic-Early Cretaceous alkaline basalts. All rock types show a clear garnet signature, as testified by their high MREE/HREE ratios.

3) REE modelling shows that their garnet signature is related to polybaric partial melting starting in the garnet peridotite stability field and continuing to larger degrees in the spinel-facies mantle. However, the different geochemical affinities displayed by the studied rocks are related to different mantle source compositions. G-MORBs were generated from 2.5% melting in the garnet-facies and 10% melting in the spinel-facies of a depleted MORB mantle source. E-MORBs composition is compatible with mixing of melts derived from very low degree (~1%) partial melting of a DMM source in the garnet-facies with melts derived from much larger degree (~10%) of partial melting in the spinel-facies mantle. Alternatively, these rocks may have derived from for ~8% partial melting of a theoretical slightly enriched source in the spinel facies. P-MORBs and alkaline basalts have REE composition that can accounted for by mixing of different proportions of melts generated in the garnet- and spinel facies from an enriched mantle source metasomatized by OIB-type (plume-type) components.

4) The coexistence of chemically different rock-types from Middle Jurassic to Early Cretaceous suggests that they were formed at a mid-ocean ridge setting from partial melting of a highly

heterogeneous mantle characterized by the extensive occurrence of OIB-metasomatized portions, which were likely inherited from a Triassic mantle plume activity associated with the continental rift and opening of the Neotethys branch.

Aknowledgments

The Italian Ministry of Education, University and Research (MIUR) is acknowledged for the financial support (Prin 2010-2011). This research has also been funded by the Ferrara University (FIR-2016 Project). Many thanks go to Mirella Bonora (Ferrara University) for her support with analytical techniques. Radiolarian micrographs were taken with a Philips XL20 of the Ivalsa Institute (CNR) by Simona Lazzeri and with a Zeiss EVO MA15 of the MEMA (University of Florence) by Maurizio Ulivi. Special thanks go to Špela Goričan and anonymous reviewer for their constructive reviews of this paper.

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CAPTIONS

Figure 1. The main tectonic zones of Turkey (modified after Sengör & Yılmaz, 1981; Göncüoğlu *et al.* 2012, modified).

Figure 2. Sketch geological map of the study area, with the location of the sampled sections (after Bortolotti *et al.* 2013*a*, modified and Yolsal-Çevikbilen *et al.*, 2012) EFZ: Eldivan Fault Zone; ODFZ: Orta–Devrez Fault Zone, KFZ, Kızılırmak Fault Zone; ESFZ: Ezine Pazarı–Sungurlu Fault Zone, AFZ: Alaca Fault Zone, CF: Çekerek Fault.

Figure 3. a) Serpentinite mélange near Beynam; b) Pillow basalts along the road from Elmadag to Kırıkkale (Section 1); c) Overturned sequence of basalts and radiolarian cherts along the road from Çorum to Alaca (Section 5); d) Outcrop of basalts and radiolarian cherts along the road from Iskilip to Tosya (Section 7). Modified from Bortolotti *et al.* (2013*a*).

Figure 4. (scale bar = 50 μm), a) *Archaeodictyomitra* sp. cf. *A. lacrimula* (Foreman), Section 1, TU10.4; b) *Aurisaturnalis variabilis variabilis* (Squinabol), Section 1, TU10.4; c) *Hemicryptocapsa* sp. cf. *H. capita* Tan, Section 1, TU10.4; d) *Thanarla brouweri* (Tan), Section 1, TU10.4; e) *Eoxitus* (?) sp., Section 2, TU10.11; f) *Stichomitra* (?) *takanoensis* Aita, Section 2, TU10.11; g) *Hiscocapsa* sp. ~~*Praewilliriedellum* sp. cf. *P. convexum* (Yao)~~, Section 2, TU10.12; h) *Mirifusus* sp. cf. *M. guadalupensis* Pessagno, Section 2, TU10.12; i) *Stichomitra* (?) *takanoensis* Aita, Section 2, TU10.12; j) *Emiluvia* sp. cf. *E. ordinaria* Ozvoldova, Section 3, TU10.28; k) *Fultacapsa sphaerica* (Ozvoldova), Section 3, TU10.28; l) *Podocapsa amphitreptera* Foreman, Section 3, TU10.28; m) *Spinosicapsa* (?) sp., Section 3, TU10.28; n) *Archaeodictyomitra lacrimula* (Foreman), Section 4, TU10.29; o) *Archaeodictyomitra mitra* Dumitrica, Section 4, TU10.29; p) *Dicerosaturnalis trizonalis* (Rüst), Section 4, TU10.29; q) *Pantanellium* sp. cf. *P. squinaboli* (Tan), Section 4, TU10.29; r) *Thanarla* sp. cf. *T. gutta* Jud, Section 4, TU10.29; s) *Archaeodictyomitra* sp., Section 4, TU10.30; t) *Holocryptocanium barbui* Dumitrica, Section 4, TU10.30; u) *Pseudodictyomitra lanceloti* Schaaf, Section 4, TU10.30; v) ~~*Thanarla pulchra* (Squinabol)~~ *Thanarla* sp. cf *T. pacifica* Nakaseko & Nishimura, Section 4, TU10.30.

Figure 5. (scale bar = 50 µm), a) *Archaeodictyomitra lacrimula* (Foreman), Section 4, TU10.31; b) *Aurisaturnalis carinatus perforatus* Dumitrica & Dumitrica Jud, Section 4, TU10.31; c) *Thanarla brouweri* (Tan), Section 4, TU10.31; d) *Eucyrtidiellum pyramis* (Aita), Section 5, TU10.35; e) *Podocapsa amphitreptera* Foreman, Section 5, TU10.35; f) *Cinguloturris cylindra* Kemkin & Rudenko, Section 5, TU10.36; g) *Emiluvia* sp. cf. *E. ordinaria* Ozvoldova, Section 5, TU10.36; h) *Eucyrtidiellum pyramis* (Aita), Section 5, TU10.36; i) *Loopus primitivus* (Matsuoka & Yao), Section 5, TU10.36; j) *Ristola cretacea* (Baumgartner), Section 5, TU10.36; k) *Podocapsa amphitreptera* Foreman, Section 5, TU10.37; l) *Praeconosphaera* (?) *sphaeroconus* (Rüst), Section 5, TU10.37; m) *Archaeodictyomitra* sp. cf. *A. excellens* (Tan), Section 5, TU10.38; n) *Podocapsa amphitreptera* Foreman, Section 5, TU10.38; o) *Saitoum* sp. cf. *S. elegans* De Wever, Section 5, TU10.38; p) *Zhamoidellum ovum* Dumitrica, Section 5, TU10.38; q) ~~*Pseudodictyomitra* sp.,~~ *Archaeodictyomitra* sp. cf. *A. coniforma* Dumitrica, Section 7, TU10.45; r) *Cryptamphorella clivosa* (Aliev), Section 7, TU10.45; s) *Praeconosphaera* (?) *sphaeroconus* (Rüst), Section 7, TU10.45; t) *Archaeodictyomitra excellens* (Tan), Section 8, TU10.47; u) ~~*Cecrops*~~ *Cana septemporatus* (Parona), Section 8, TU10.47; v) *Halesium* sp. cf. *H. palmatum* Dumitrica, Section 8, TU10.47; w) *Archaeodictyomitra lacrimula* (Foreman), Section 8, TU10.51; x) *Pseudoeucyrtis* sp. cf. *P. hanni* (Tan) sensu O'Dogherty (1994), Section 8, TU10.51.

Figure 6. Ti/Y vs. Nb/Y discrimination diagram (Pearce, 1982) for Middle Jurassic – Early Cretaceous volcanic rocks from the Ankara Mélange. Modified from Bortolotti *et al.* (2013*a*).

Figure 7. Variation diagrams for some representative major and trace elements vs. Zr for Middle Jurassic – Early Cretaceous volcanic rocks from the Ankara Mélange. Major elements are re-calculated on volatiles-free and calcite-free bases. Abbreviations, pl: plagioclase; ol: olivine; cpx: clinopyroxene; opx: orthopyroxene; mt: magnetite. Mg# = 100xMg/(Mg + Fe^{2+}). Lines represent the inferred fractionation trends for the different rock-groups.

Figure 8. N-MORB normalized incompatible element patterns (a, c, e, g) and chondrite-normalized REE patterns (b, d, f, h) for Middle Jurassic – Early Cretaceous volcanic rocks from the Ankara Mélange. Normalizing values and the compositions of normal mid-ocean ridge basalt (N-MORB), enriched mid-ocean ridge basalt (E-MORB), and ocean-island basalt (OIB) are from Sun & McDonough (1989).

Figure 9. a) Th_N vs. Nb_N and b) $(Dy/Yb)_N$ vs. $(Ce/Yb)_N$ discrimination diagrams for Middle Jurassic – Early Cretaceous volcanic rocks from the Ankara Mélange. Modified after Saccani (2015). N-MORB and Chondrite normalization values for panels a) and b), respectively are from Sun & McDonough (1989).

Figure 10. Th-Ta-Hf/3 (Wood, 1980) discrimination diagrams for Middle Jurassic – Early Cretaceous volcanic rocks from the Ankara Mélange.

Figure 11. Melt curve models based on Dy/Yb vs. La/Yb. Melt curves are calculated using non-modal, batch melts of garnet and spinel lherzolites. a) melt curves for DMM mantle (Workman & Hart, 2005); b) melt curves for a theoretical DMM mantle (Workman & Hart, 2005) enriched in LREE by OIB-type) components; c) melt curves for a theoretical enriched (OIB-type) mantle. Garnet lherzolite mode is: 0.598 ol, 0.211 opx; 0.076 cpx, 0.115 gt that melts in the proportions 0.05 ol, 0.20 opx, 0.30 cpx, 0.45 gt. Spinel lherzolite mode is: 0.578 ol, 0.270 opx, 0.119 cpx, 0.033 spl that melts in the proportions 0.10 ol, 0.27 opx, 0.50 cpx, 0.13 spl. Mantle mode and melting proportions are from Thirlwall *et al.* (1994). Arrays representing the mixing between various proportions of melt fractions from the garnet-facies mantle and melt fractions from spinel-facies mantle are also shown. Distribution coefficients are from Irving & Frey (1984) with the exception

of those for spinel, which are from McKenzie & O'Nions (1991). Normalizing values are from Sun & McDonough (1989).

Figure 12. Zr/Y vs. Zr/Nb diagram for volcanic rocks from the Middle Jurassic – Early Cretaceous volcanic rocks from the Izmir-Ankara Mélange (modified from Bortolotti *et al.*, 2013*a*). The compositions of modern normal mid-ocean ridge basalt (N-MORB) and ocean-island basalt (OIB) are from Sun & McDonough (1989). The compositional variation for ocean-floor basalts erupted in the North Atlantic Ocean is shown for comparison (data from Hanan *et al.*, 2000). The dashed line represents the mixing curve calculated using the OIB and N-MORB end members.

Figure 13. 2-D cartoon showing the tectono-magmatic mechanisms responsible for the formation of garnet-influenced (G-) enriched (E-), and plume-type (P-) mid-ocean ridge basalts (MORB), as well as alkaline ocean island-type (OIB) basalts from the Ankara Mélange during the Late Jurassic-Early Cretaceous. Other abbreviations, sp: spinel; gt: garnet.

Figure 14. 2-D cartoon showing the geodynamic evolution the Izmir-Ankara Neotethys branch from Late Triassic to late Early Cretaceous (modified from Göncüoglu, 2010). Abbreviations, MORB: mid-ocean ridge basalts; G-: garnet-influenced MORB; E-: enriched-MORB; P-: plume-type MORB; alk: alkaline basalts; SSZ: supra-subduction zone.

Table 1. Representative major and trace element analyses of Middle Jurassic – Early Cretaceous volcanic rocks from the Ankara Mélange. Abbreviations, bas: basalt; tra: trachyte; Fe-bas: ferrobasalt; trans: transional-type; sub-alk: sub-alkaline-type; OIB: ocean island basalt; P-MORB: plume-type mid-ocean ridge basalt; E-MORB: enriched-type mid-ocean ridge basalt; G-MORB: garnet-influenced mid-ocean ridge basalt; E: Early; M: Middle; L: Late; Jr: Jurassic; Cr: Cretaceous;

mlf: massive lava flow; n.d.: not detected. Mg# = 100xMg/(Mg+Fe^{2+}). Fe_2O_3 = 0.15xFeO. Normalizing values for REE ratios are from Sun & McDonough (1989).

Table 1.

Section	1			2				3		
Sample	TU10-6	TU10-9	TU10-10	TU10-14	TU10-15	TU10-16	TU10-17	TU10-19	TU10-22	TU10-23
Rock	bas	tra	bas	bas	bas	Fe-bas	Fe-bas	bas	bas	bas
Group	4	4	4	3	3	3	3	4	4	4
Type	alkaline OIB	alkaline OIB	alkaline OIB	trans P-MORB	trans P-MORB	trans P-MORB	trans P-MORB	alkaline OIB	alkaline OIB	alkaline OIB
Age	E Cr			M Jr	M Jr	M Jr	M Jr		L Jr	L Jr
Note	pillow	breccia	pillow	pillow	pillow	pillow	pillow	mlf	pillow	pillow
	(XRF)	*(XRF)*	*(XRF)*	*(XRF)*	*(XRF)*	*(XRF)*	*(XRF)*	*(XRF)*	*(XRF)*	*(XRF)*
SiO_2	41.40	56.12	39.61	44.12	40.20	42.40	44.87	44.36	46.03	44.81
TiO_2	1.91	2.35	1.96	2.28	1.65	3.27	2.55	2.97	2.32	2.21
Al_2O_3	11.76	15.96	11.81	14.48	11.92	13.81	13.82	13.41	17.06	16.49
Fe_2O_3	0.93	1.33	1.00	1.74	1.00	2.08	1.96	1.45	1.42	1.40
FeO	6.18	8.90	6.67	11.60	6.66	13.89	13.06	9.63	9.47	9.31
MnO	0.15	0.11	0.12	0.23	0.22	0.19	0.19	0.40	0.20	0.20
MgO	4.24	1.68	3.86	9.25	6.32	7.42	9.98	9.14	7.31	9.05
CaO	16.69	3.61	17.84	8.16	18.02	8.04	6.23	6.96	6.48	7.45
Na_2O	3.73	7.37	2.93	2.39	2.11	3.07	1.74	3.24	2.07	1.84
K_2O	1.72	0.65	2.06	0.82	1.89	0.69	1.26	1.13	3.54	2.95
P_2O_5	0.48	0.59	0.60	0.33	0.21	0.54	0.62	0.52	0.96	0.86
L.O.I.	10.94	1.16	11.56	4.65	9.89	4.65	3.73	6.94	3.15	3.50
Total	100.13	99.84	100.03	100.05	100.08	100.05	100.01	100.15	100.01	100.06
CO_2	6.23		6.13		7.05					
Mg#	55.0	25.2	50.8	58.7	62.9	48.8	57.7	62.8	57.9	63.4
Zn	73	104	57	72	63	110	101	109	75	72
Cu	25	35	44	77	71	59	57	69	40	40
Sc	23	9	18	36	40	43	35	36	8	10
Ga	15	14	16	21	15	24	20	16	17	19
Ni	70	26	54	78	53	8	11	100	25	42
Co	27	16	23	37	33	37	30	36	23	25
Cr	227	56	115	135	81	26	21	271	16	29
V	204	180	206	334	275	403	329	474	188	210
Ba	289	186	340	246	717	199	177	193	1980	1380
Pb	4	7	5	7	4	7	6	16	8	7
Zr	217	320	225	165	128	239	196	265	330	287
	(ICP-MS)		*(ICP-MS)*	*(ICP-MS)*	*(ICP-MS)*			*(ICP-MS)*		*(ICP-MS)*
Rb	30.8	12	36.7	8.41	17.6	8	16	27.2	75	58.5
Sr	575	441	478	292	280	391	371	197	740	760
Y	28.5	40	29.3	22	27.6	58	48	29	39	36.1
La	40.3	64	39	20.7	24.6	50	45	49.7	65	58.9
Ce	70.3	192	70.9	43	46.7	129	82	85.3	160	109
Pr	8.01		8.14	4.91	5.35			9.25		11.3
Nd	27.2	45	28.1	18.1	19.1	33	30	30.4	60	39.7
Sm	5.84		6.07	4.63	4.54			6.11		9.08
Eu	1.77		1.84	1.53	1.53			1.69		2.77
Gd	4.50		4.69	4.6	4.45			4.62		7.11
Tb	0.702		0.722	0.718	0.657			0.697		1.03
Dy	3.71		3.76	4.28	3.82			3.67		5.33
Ho	0.704		0.711	0.896	0.793			0.707		0.992
Er	1.78		1.78	2.38	2.11			1.81		2.58
Tm	0.239		0.236	0.339	0.295			0.242		0.35
Yb	1.49		1.49	2.21	1.92			1.54		2.19
Lu	0.214		0.213	0.335	0.291			0.221		0.324
Nb	61.5	83	65.9	30.6	40.4	50	45	88	142	88
Hf	5.11	5	5.34	4.56	3.69	4	3	4.82	5	7
Ta	2.93		3.71	1.76	3.34			4.77		7.13
Th	5.09	9	5.49	2.77	3.48	7	5	7.49	9	11.6
U	1.48		1.34	0.793	1.04			1.75		2.99
$(La/Sm)_N$	4.46		4.15	2.88	3.49			5.25		4.19
$(Sm/Yb)_N$	4.36		4.52	2.33	2.63			4.40		4.62
$(La/Yb)_N$	19.43		18.75	6.72	9.17			23.13		19.33
Ti/V	69	79	71	43	44	51	48	40	76	65
Ce/Y	2.40	4.80	2.69	1.87	1.64	2.20	1.60	3.16	4.10	4.01
Nb/Yb	41.32		44.13	13.86	21.03			57.02		40.25
(Th/Ta)/(Th/Tb)	0.24		0.19	0.41	0.20			0.15		1.14

Table 1 (cont.)

Section	4		5			7	8		9	
Sample	TU10-32	TU10-33	TU10-34	TU10-39	TU10-40	TU10-46	TU10-49a	TU10-49b	TU10-52	TU10-53
Rock	bas	bas	bas	bas	bas	bas	bas	bas	bas	bas
Group	2	2	1	1	1	2	1	1	3	3
Type	sub-alk E-MORB	sub-alk E-MORB	sub-alk G-MORB	sub-alk G-MORB	sub-alk G-MORB	sub-alk E-MORB	sub-alk G-MORB	sub-alk G-MORB	trans P-MORB	trans P-MORB
Age	E Cr	E Cr	L Jr	L Jr	L Jr	E Cr	E Cr	E Cr		
Note	mlf	mlf	mlf	breccia	mlf	mlf	pillow	pillow	mlf	mlf
	(XRF)	*(XRF)*	*(XRF)*	*(XRF)*	*(XRF)*	*(XRF)*	*(XRF)*	*(XRF)*	*(XRF)*	*(XRF)*
SiO_2	45.98	46.18	47.04	48.28	46.35	48.35	53.76	48.67	48.72	39.89
TiO_2	1.51	1.46	1.48	1.46	1.74	1.20	1.51	1.46	1.89	1.37
Al_2O_3	13.44	13.30	13.50	14.84	15.70	17.65	13.26	13.83	17.70	11.71
Fe_2O_3	1.44	1.26	1.28	1.42	1.59	0.77	1.28	1.65	1.42	1.05
FeO	9.61	8.43	8.51	9.49	10.60	5.14	8.52	11.01	9.49	6.97
MnO	0.29	0.27	0.26	0.19	0.11	0.11	0.13	0.16	0.05	0.17
MgO	5.69	5.14	5.24	5.48	2.40	4.69	5.80	7.48	3.77	4.26
CaO	14.15	15.60	15.85	9.28	12.16	9.55	8.03	6.18	4.16	21.76
Na_2O	2.82	3.21	3.27	3.39	3.77	5.71	3.88	2.49	2.04	1.88
K_2O	0.46	0.40	0.41	1.49	1.31	0.29	0.36	0.88	4.64	0.53
P_2O_5	0.14	0.13	0.14	0.17	0.28	0.12	0.17	0.11	0.32	0.14
L.O.I.	4.58	4.66	3.02	4.56	3.94	6.45	3.2	6.02	5.83	10.28
Total	100.11	100.06	100.00	100.05	99.95	100.03	99.89	99.94	100.04	100.01
CO_2	1.80	2.27	0.95		0.93					7
Mg#	51.4	52.1	52.3	50.7	28.8	61.9	54.8	54.8	41.4	52.2
Zn	84	87	87	115	124	63	79	97	115	63
Cu	77	94	92	62	27	95	55	12	35	27
Sc	42	39	44	55	48	26	19	40	28	32
Ga	16	14	16	18	17	14	21	18	16	19
Ni	139	139	139	106	69	40	32	15	140	213
Co	39	41	41	33	32	33	26	24	35	36
Cr	389	371	372	197	273	266	67	18	392	305
V	390	377	370	300	368	194	176	380	317	333
Ba	83	75	73	69	130	132	116	173	274	85
Pb	4	3	3	5	n.d.	3	5	6	6	6
Zr	74	73	73	97	98	75	84	88	135	84
	(ICP-MS)		*(ICP-MS)*	*(ICP-MS)*		*(ICP-MS)*		*(ICP-MS)*	*(ICP-MS)*	
Rb	6.35	5	25.2	28.4	17	3.15	2	14.8	68.8	2
Sr	130	136	129	385	201	429	120	129	160	96
Y	31.8	27	14.8	19.9	40	12.5	29	26.3	28.1	26
La	5.63	5	2.76	3.15	3	5.16	3	3.77	14.5	13
Ce	14.0	12	7.84	9.59	n.d.	11.8	9	10.1	26.2	31
Pr	2.18		1.32	1.59		1.63		1.67	3.38	
Nd	10.1	9	6.49	7.88	13	7.59	10	8.91	14.0	10
Sm	3.24		2.16	2.61		2.20		2.99	3.59	
Eu	1.13		0.778	0.907		0.811		1.10	1.06	
Gd	4.21		2.68	3.21		2.72		3.99	4.13	
Tb	0.752		0.47	0.560		0.463		0.714	0.698	
Dy	5.04		3.03	3.63		2.95		4.70	4.42	
Ho	1.15		0.638	0.791		0.626		1.01	0.869	
Er	3.23		1.70	2.15		1.75		2.78	2.43	
Tm	0.478		0.247	0.32		0.258		0.401	0.354	
Yb	3.18		1.52	2.03		1.69		2.54	2.24	
Lu	0.492		0.224	0.304		0.258		0.362	0.322	
Nb	7.81	9	2.88	3.36	5	5.25	4	2.74	25.7	19
Hf	2.78	3	1.61	2.24	n.d.	2.45	3	1.81	3.51	n.d.
Ta	0.404		0.161	0.188		0.277		0.159	1.48	
Th	0.619	n.d.	0.112	0.211	1	0.342	n.d.	0.195	2.51	3
U	0.151		0.071	0.008		0.102		0.052	0.573	
$(La/Sm)_N$	1.12		0.82	0.78		1.51		0.81	2.61	
$(Sm/Yb)_N$	1.13		1.58	1.43		1.45		1.31	1.78	
$(La/Yb)_N$	1.27		1.30	1.12		2.19		1.06	4.65	
Ti/V	25	25	25	31	30	40	53	25	38	31
Nb/Y	0.27	0.30	0.14	0.12	0.20	0.25	0.20	0.09	0.86	0.70
Nb/Yb	2.46		1.90	1.66		3.12		1.08	11.46	
(Th/Ta)/(Th/Tb)	1.86		2.91	2.98		1.67	4.50	0.88		

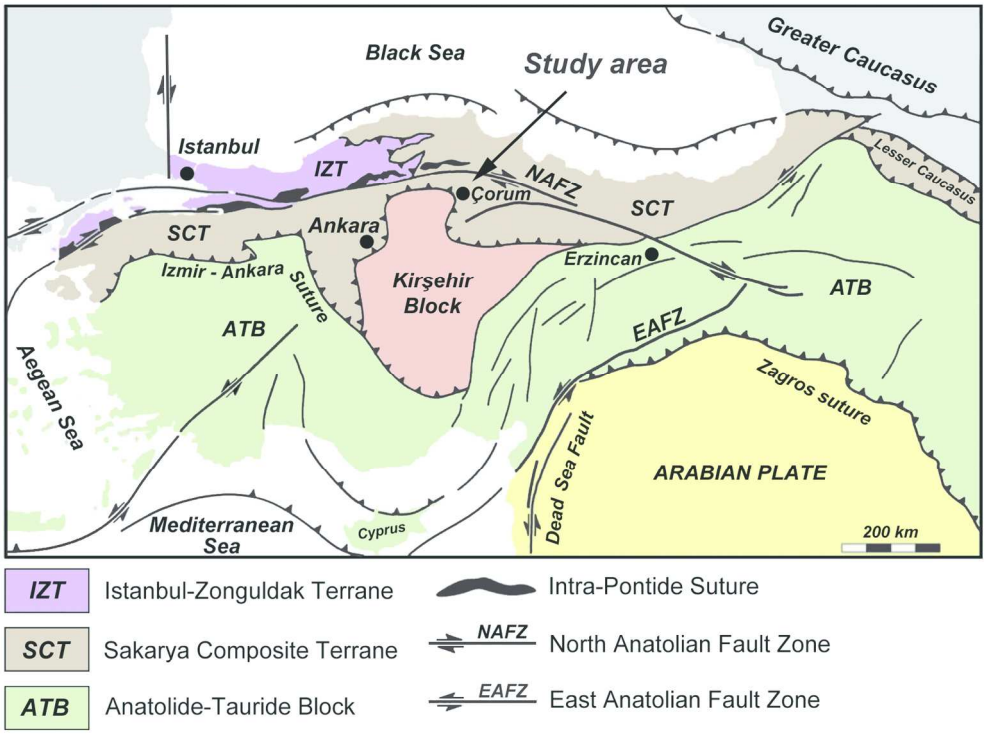

FIGURE 1

168x128mm (300 x 300 DPI)

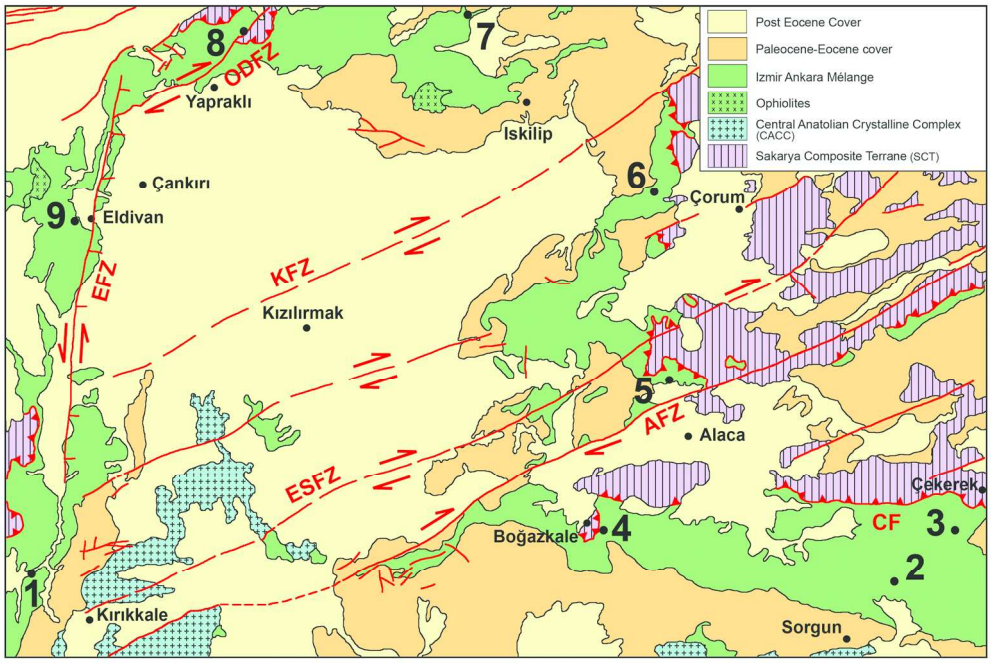

FIGURE 2

168x112mm (300 x 300 DPI)

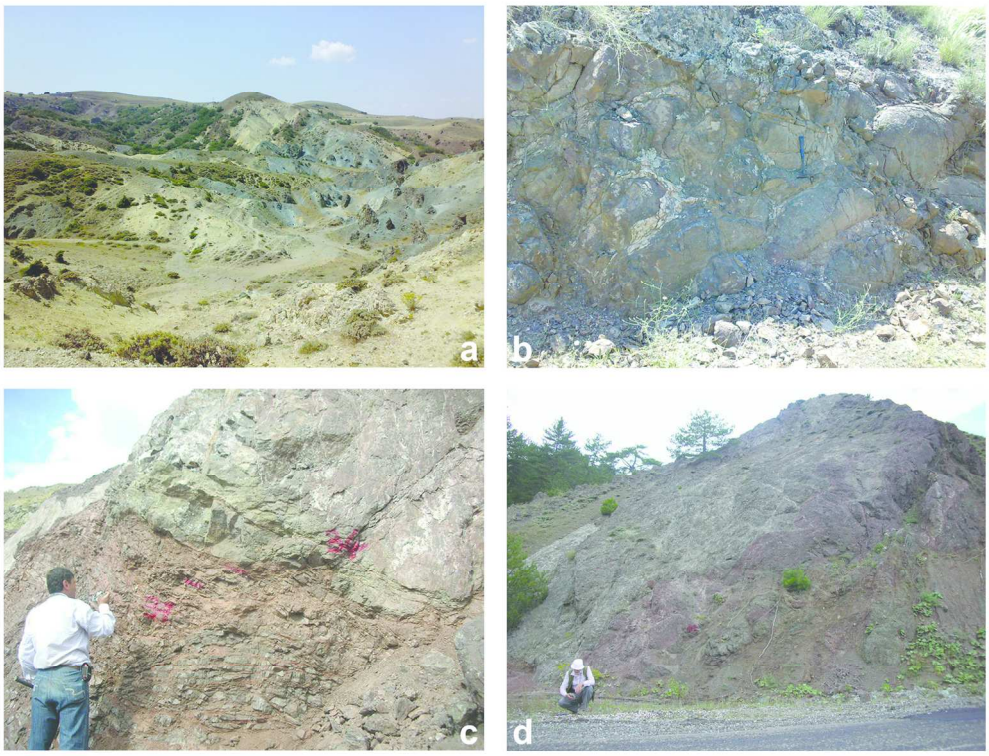

FIGURE 3

168x129mm (300 x 300 DPI)

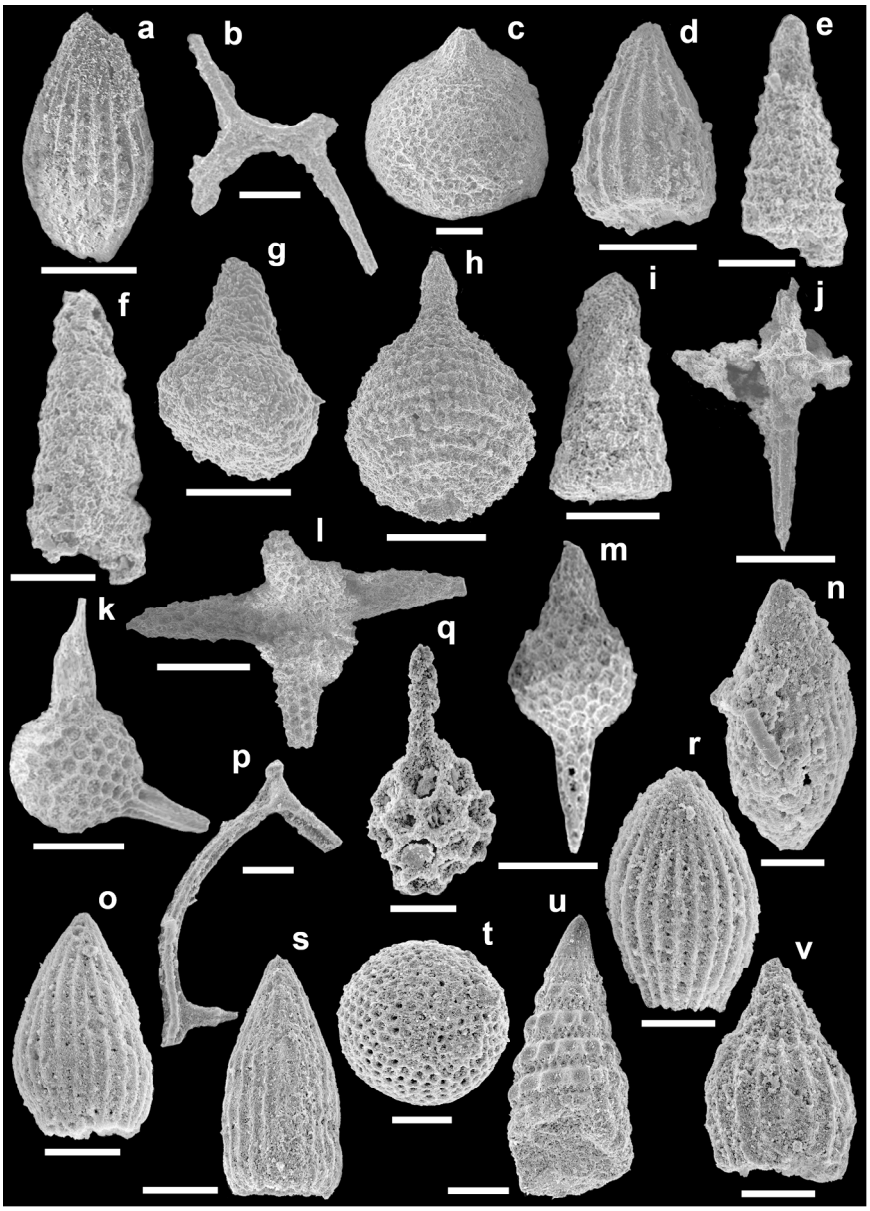

FIGURE 4

168x235mm (300 x 300 DPI)

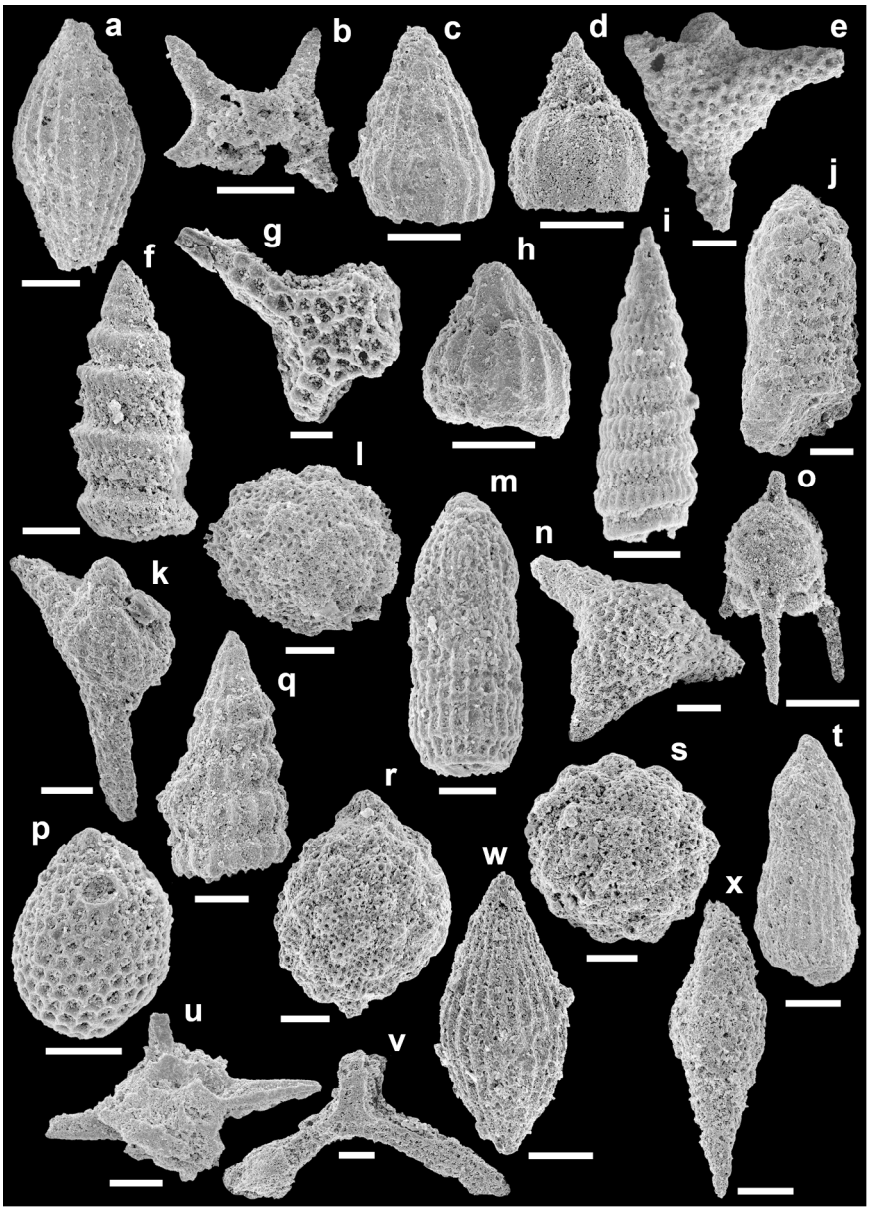

FIGURE 5

168x235mm (300 x 300 DPI)

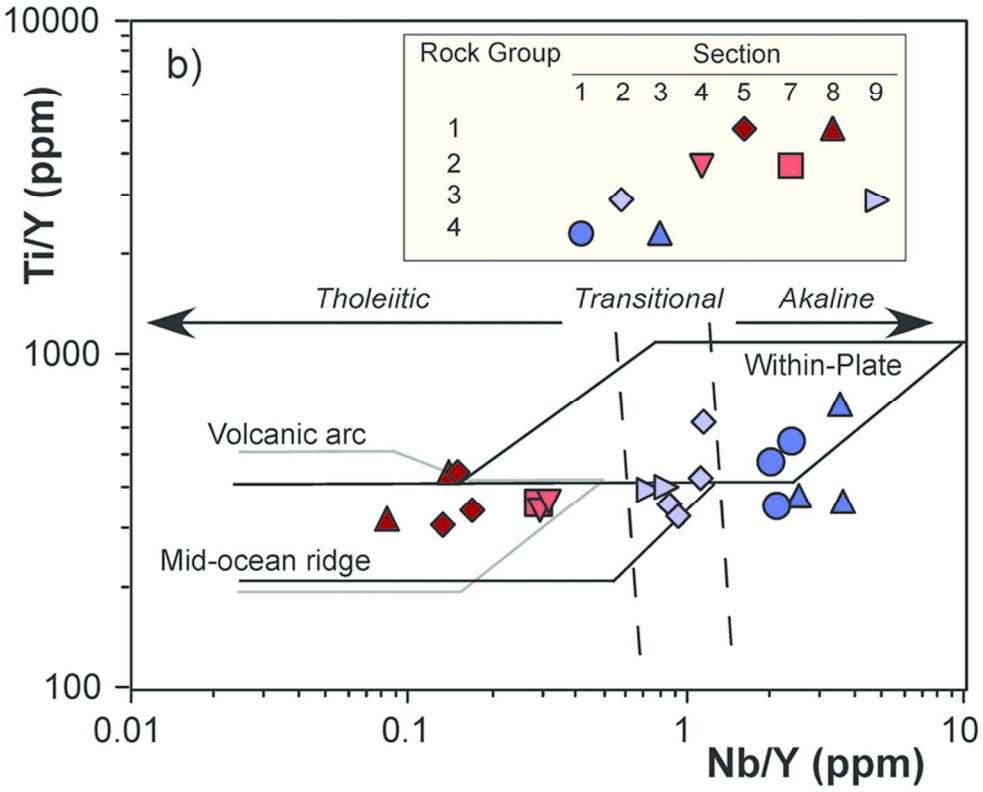

FIGURE 6

80x65mm (300 x 300 DPI)

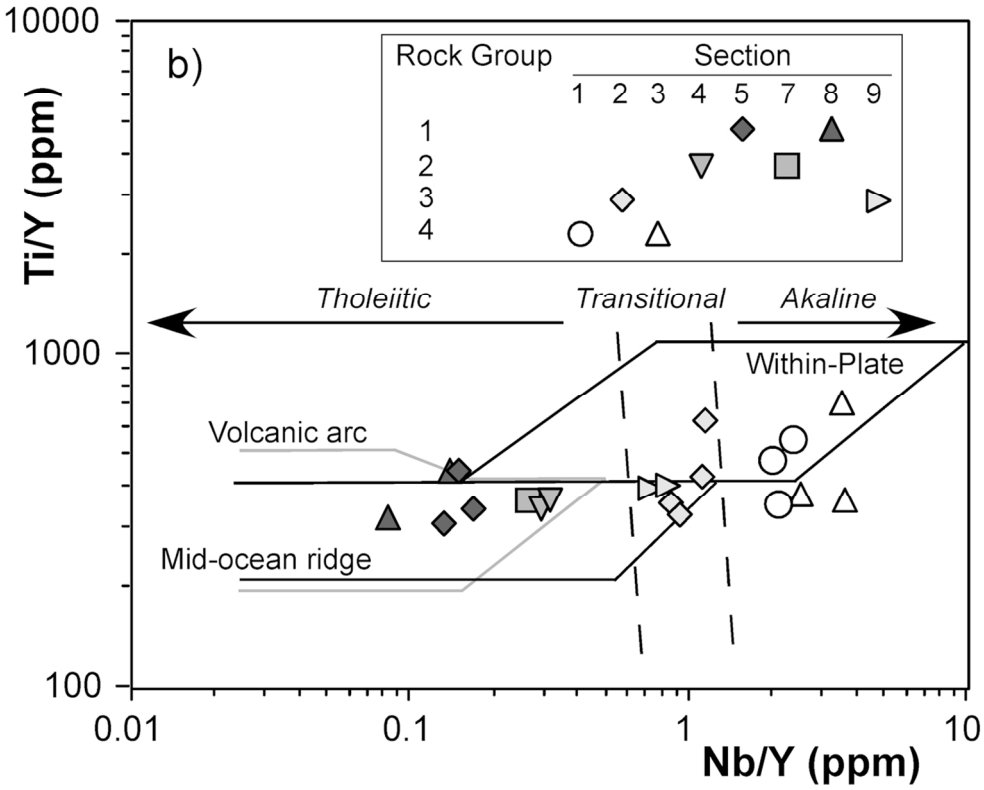

FIGURE 6 black and white

117x94mm (300 x 300 DPI)

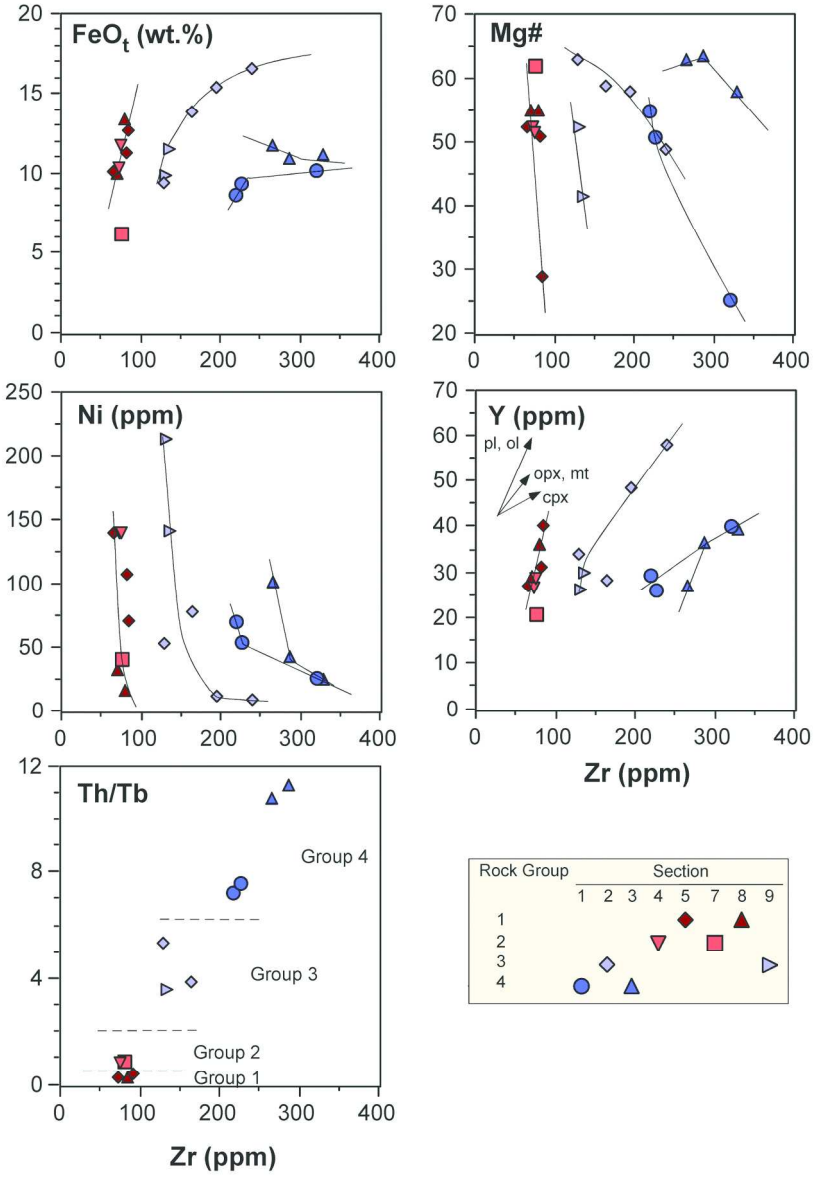

FIGURE 7

168x246mm (300 x 300 DPI)

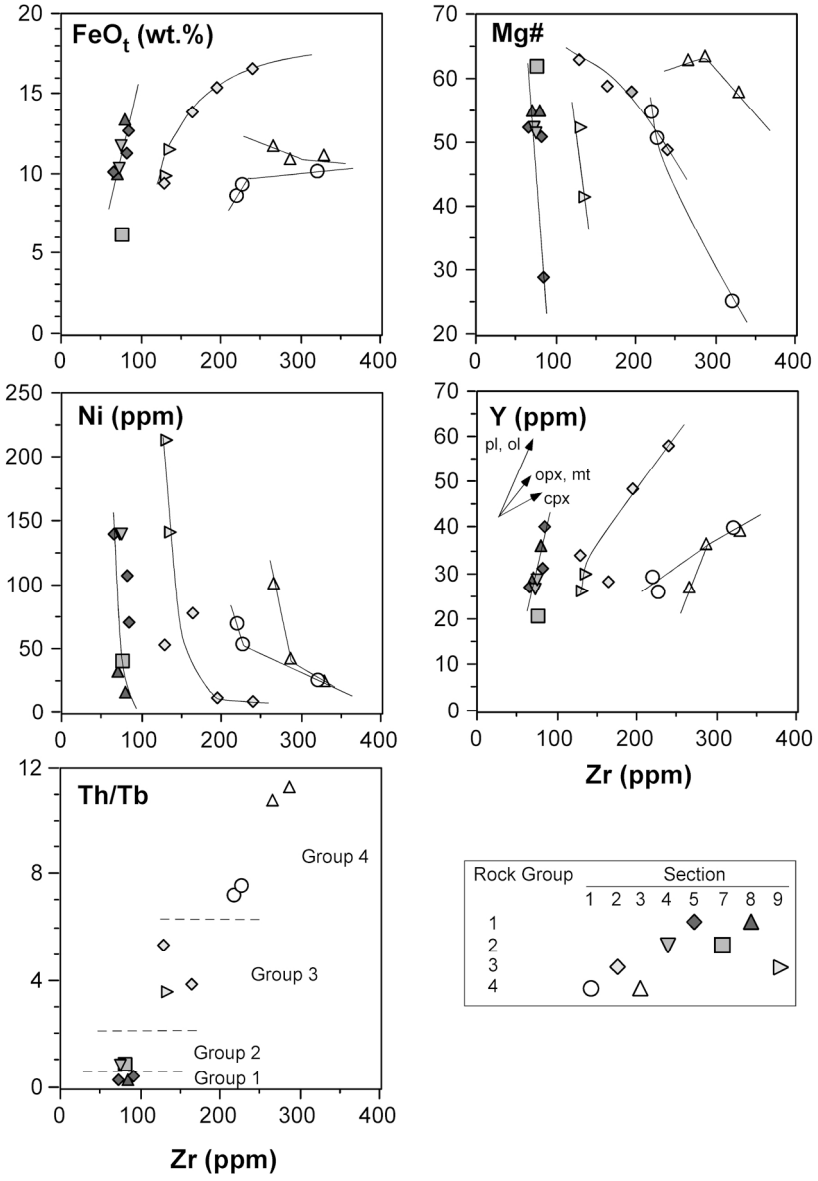

FIGURE 7 black and white

151x220mm (300 x 300 DPI)

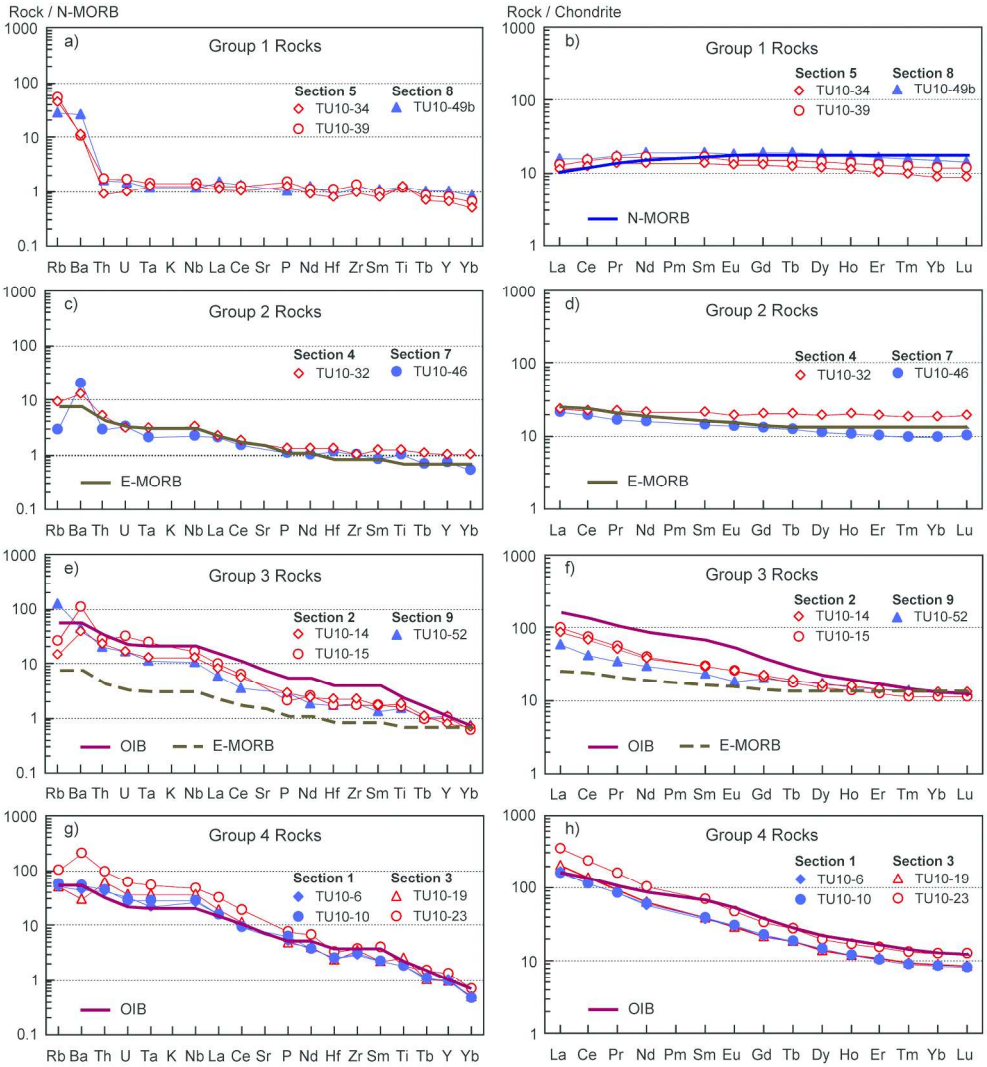

FIGURE 8

224x242mm (300 x 300 DPI)

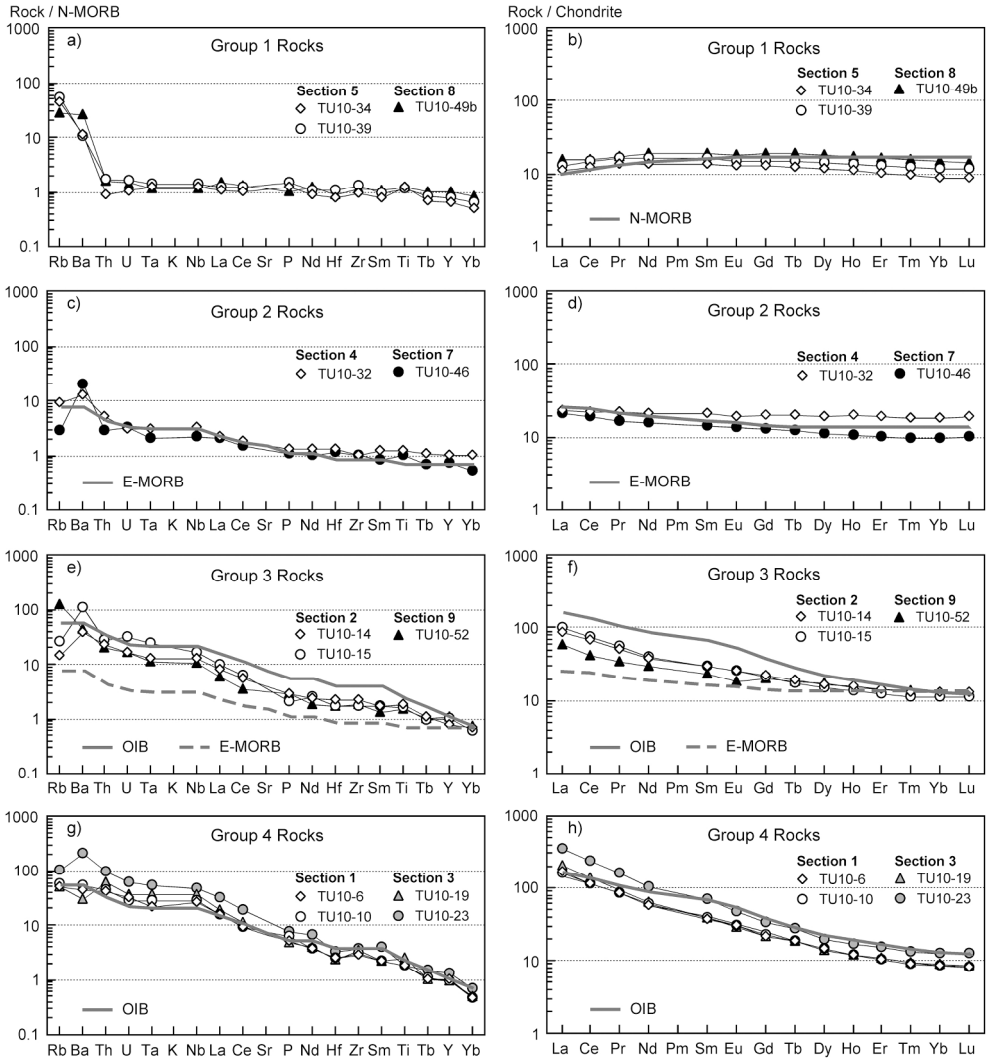

FIGURE 8 black and white

224x241mm (300 x 300 DPI)

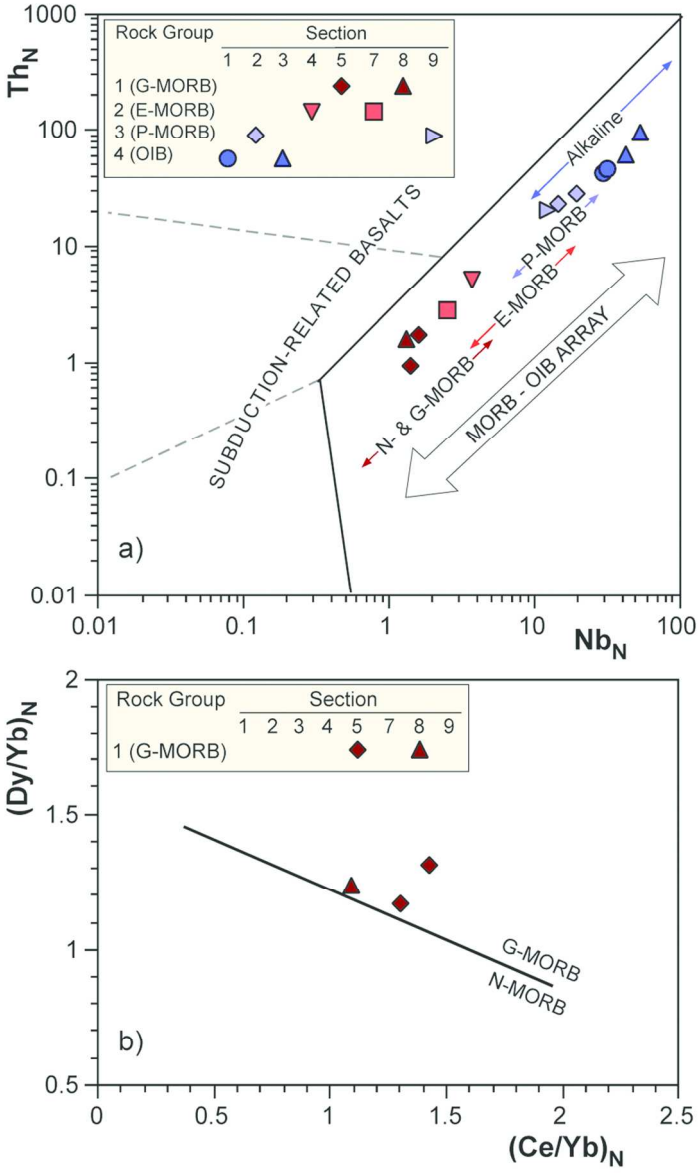

FIGURE 9

80x134mm (300 x 300 DPI)

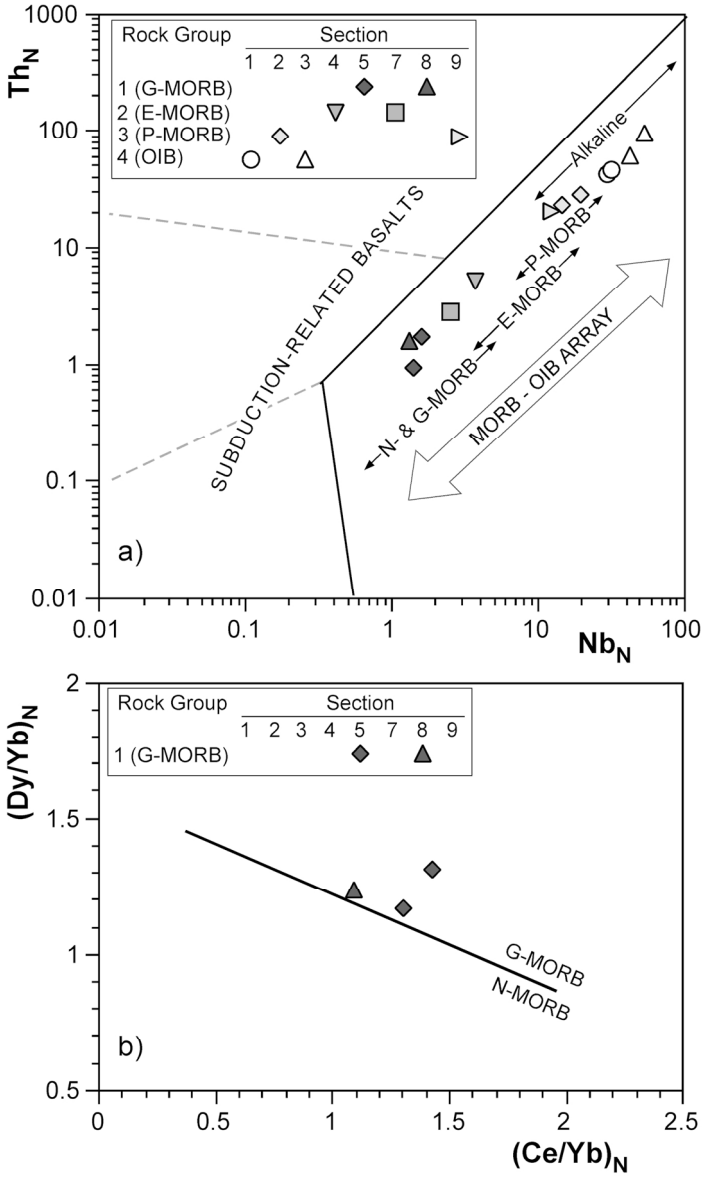

FIGURE 9 black and white

119x201mm (300 x 300 DPI)

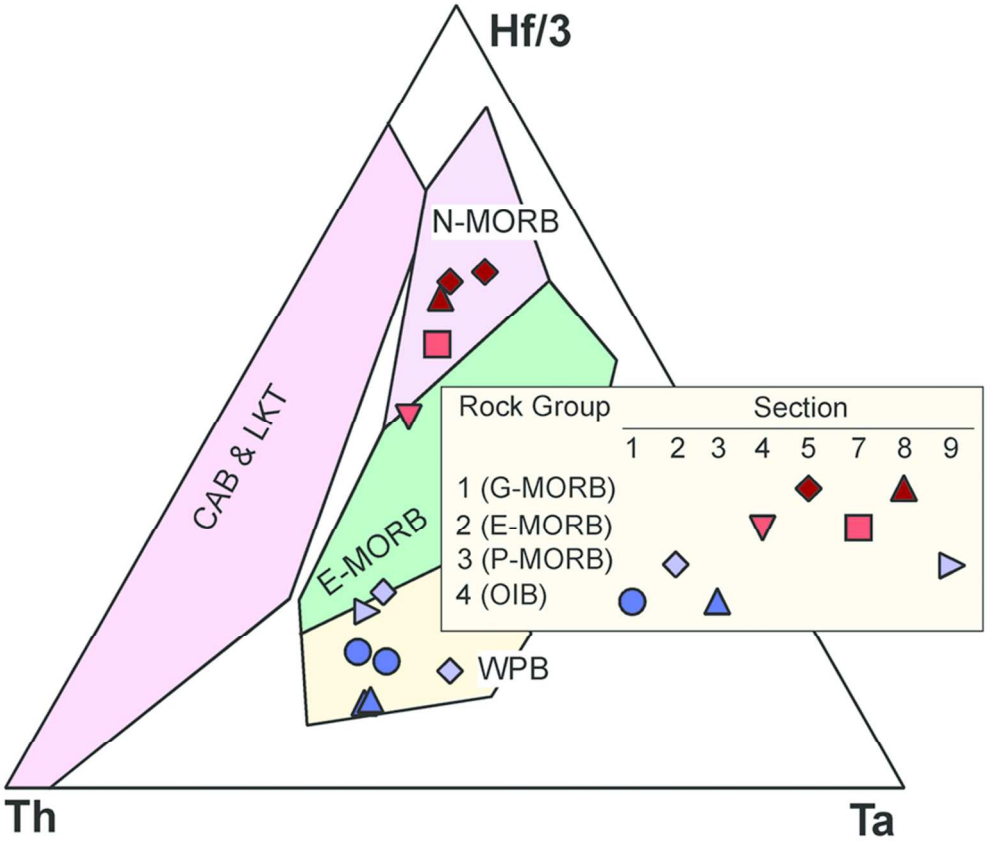

FIGURE 10

80x68mm (300 x 300 DPI)

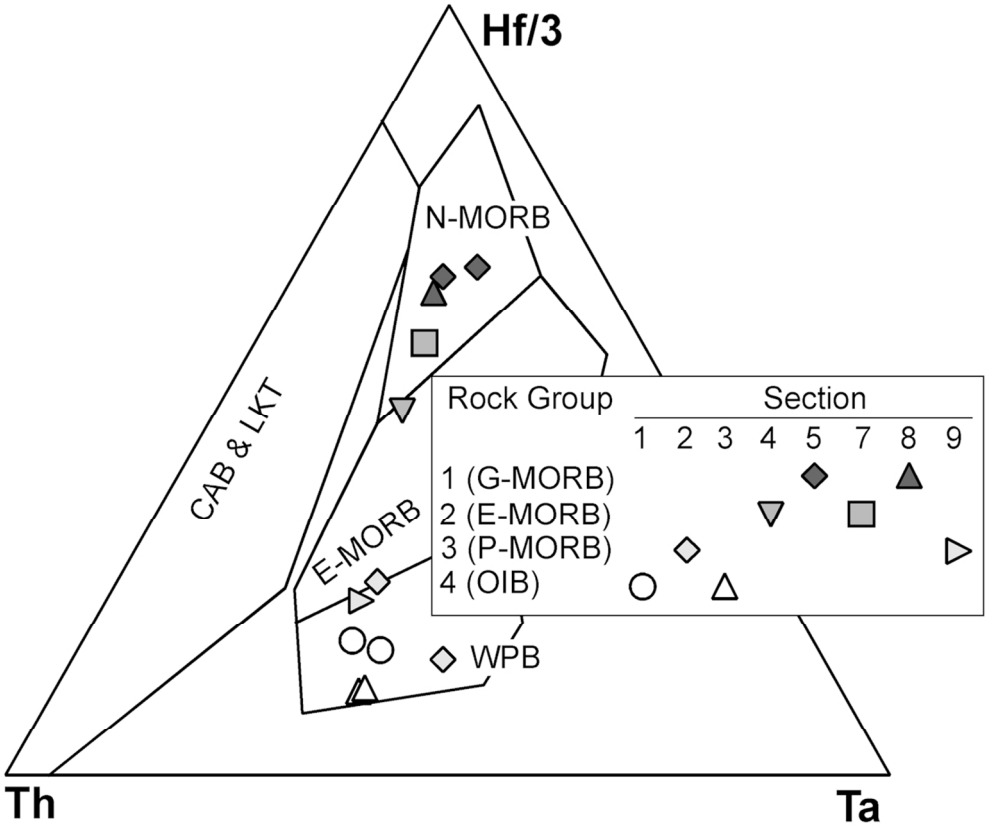

FIGURE 10 black and white

110x92mm (300 x 300 DPI)

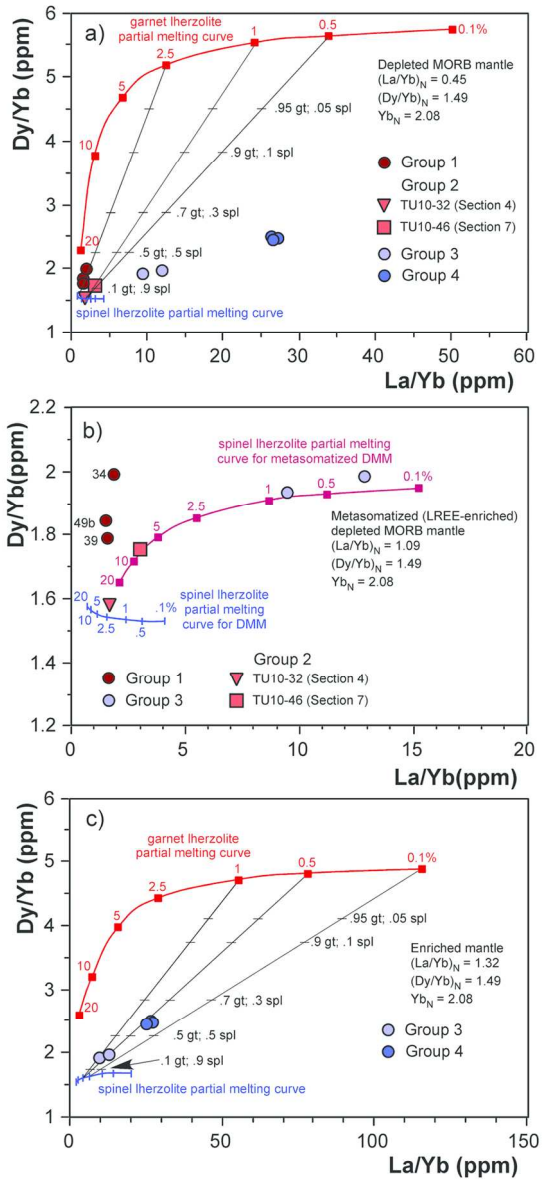

FIGURE 11

80x172mm (300 x 300 DPI)

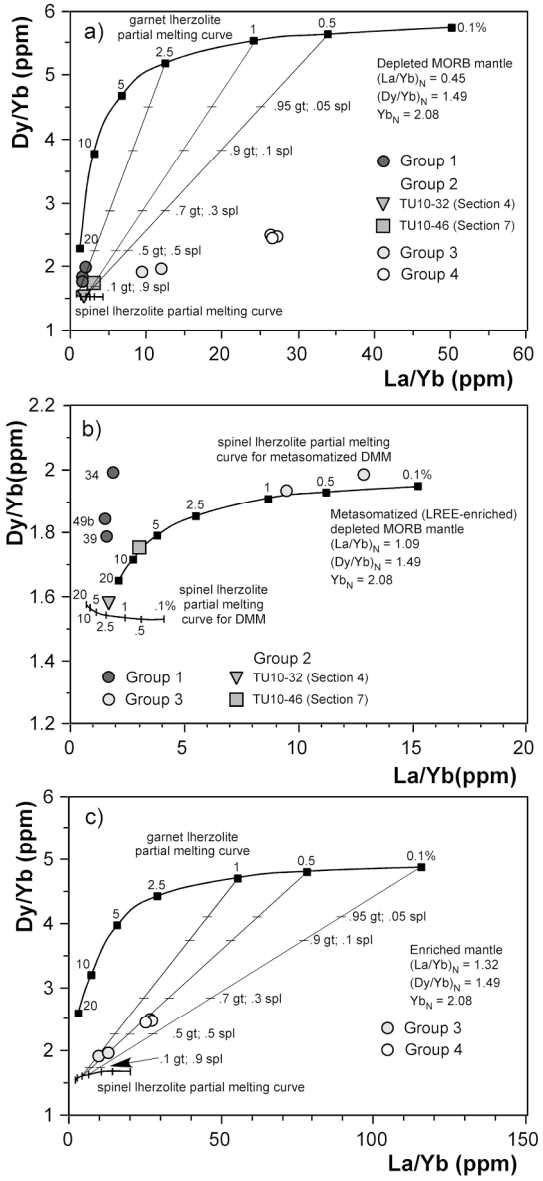

FIGURE 11 black and white

119x257mm (300 x 300 DPI)

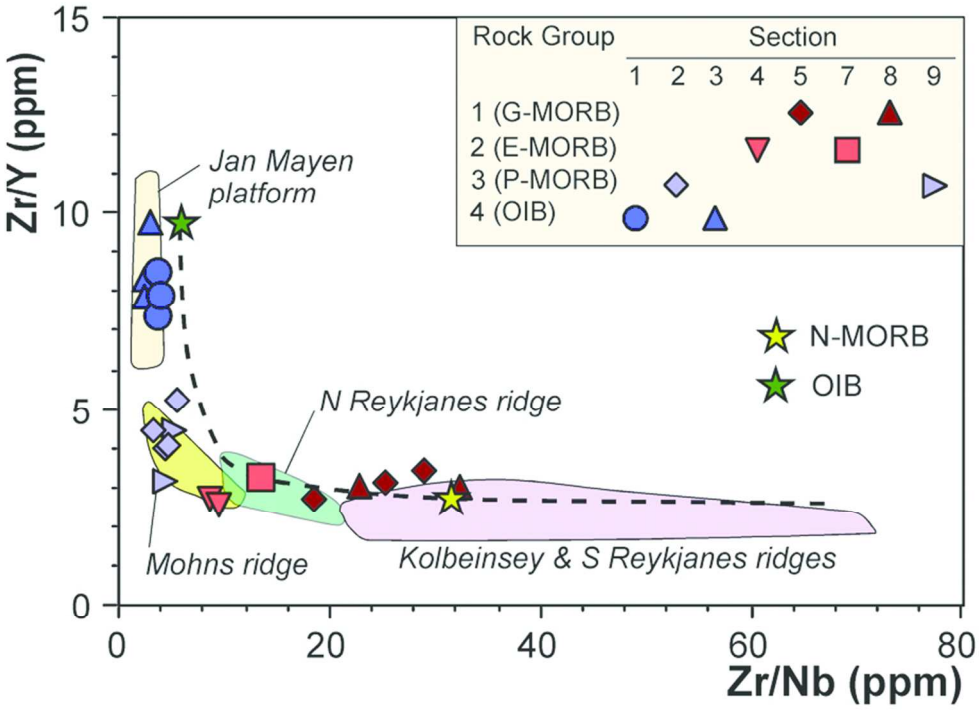

FIGURE 12

80x58mm (300 x 300 DPI)

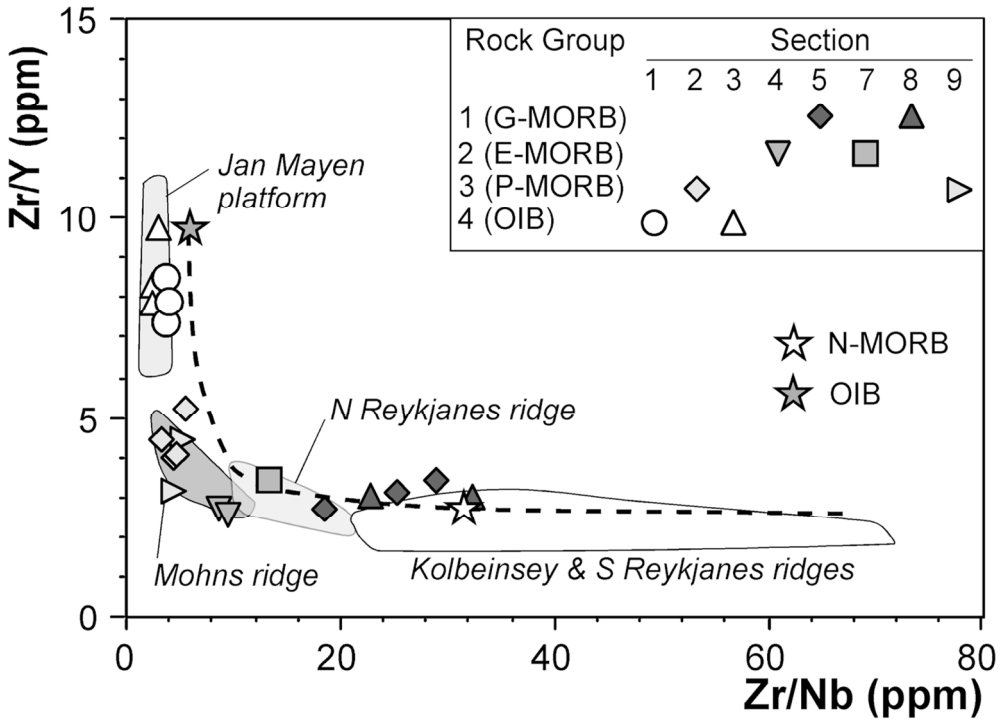

FIGURE 12 black and white

116x84mm (300 x 300 DPI)

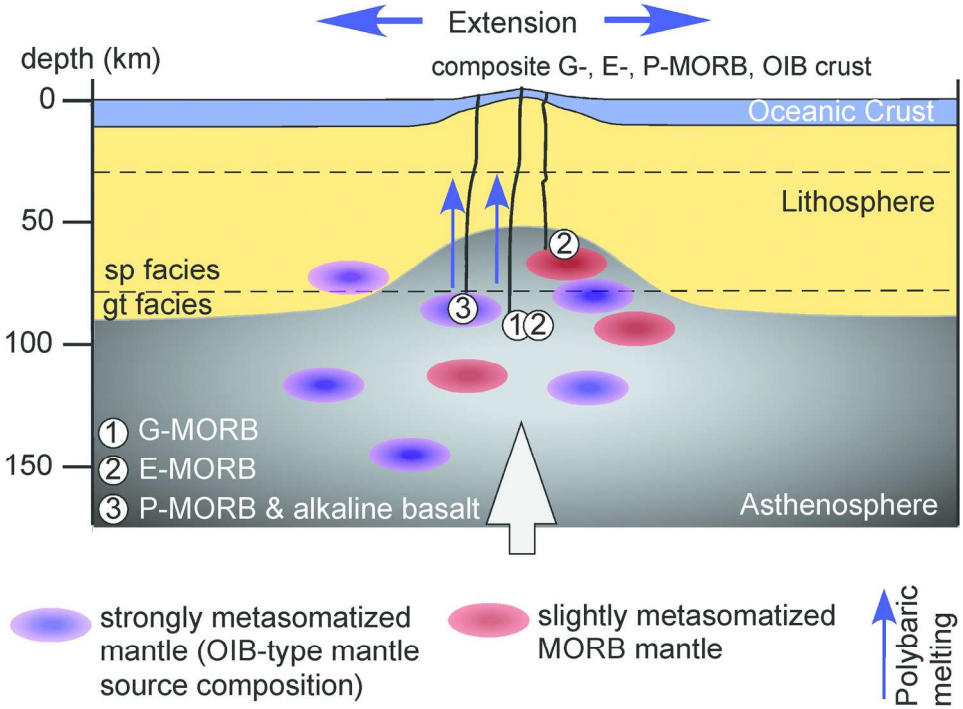

FIGURE 13

168x127mm (300 x 300 DPI)

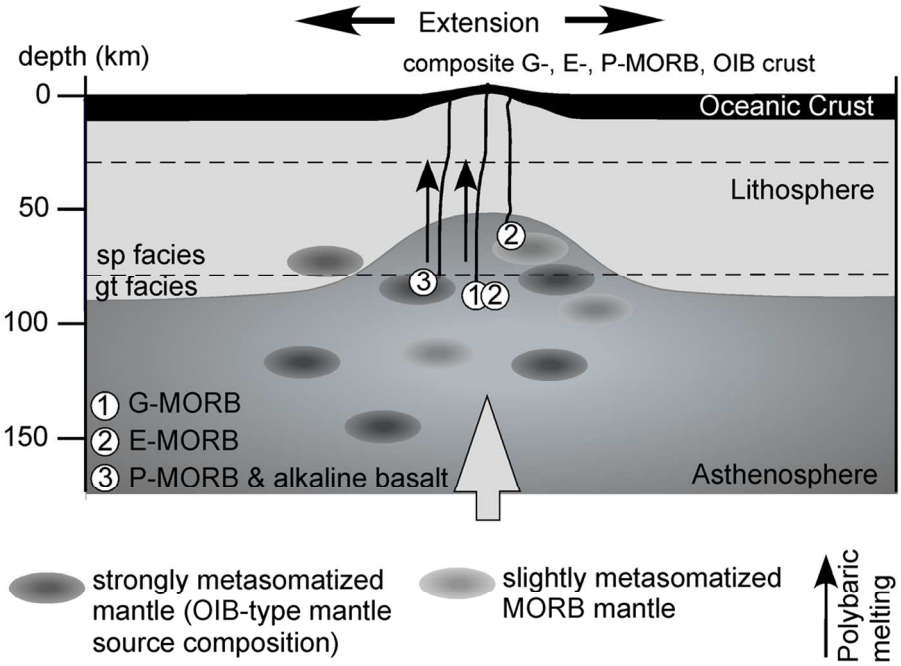

FIGURE 13 black and white

114x84mm (300 x 300 DPI)

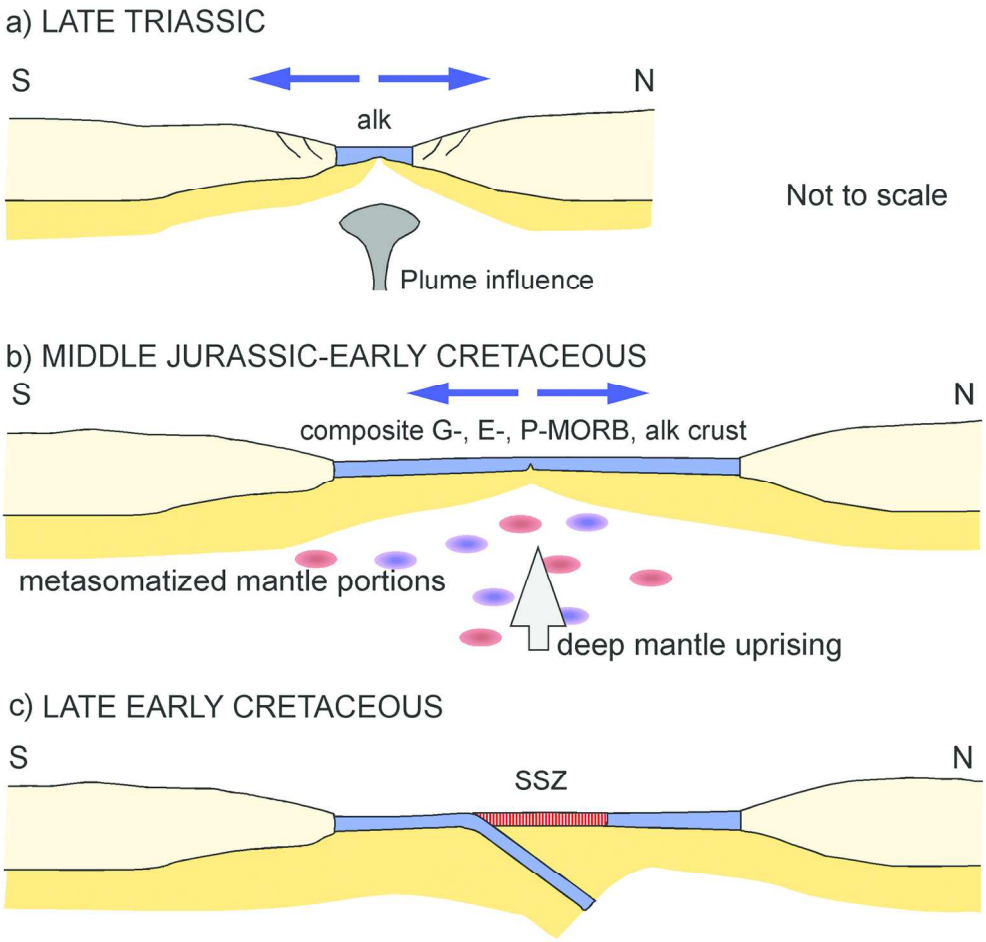

FIGURE 14

168x164mm (300 x 300 DPI)

Appendix A. Comparison of major (wt%) and trace element (ppm) concentrations in reference samples analyzed using X-Ray Fluorescence spectrometry (XRF) and Inductively Coupled Plasma-Mass Spectrometry (ICP-MS), as well as simple volumetric technique for CO_2.

	BE-N			BHVO-1			
	Recomm.	Measured	Relative error (%)	Recomm.	Measured	Relative error (%)	Detection limit
XRF:							
SiO_2	38.48	38.59	-0.3	49.94	49.57	0.74	0.05
TiO_2	2.63	2.62	0.3	2.71	2.75	-1.48	0.01
AL_2O_3	10.14	9.79	3.4	13.80	14.02	-1.59	0.05
Fe_2O_3	12.93	12.77	1.3	12.23	12.52	-2.37	0.10
MnO	0.20	0.19	7.4	0.17	0.17	0.00	0.05
MgO	13.25	13.61	-2.8	7.23	6.90	4.56	0.01
CaO	13.97	13.71	1.9	11.40	11.52	-1.05	0.04
Na_2O	3.20	3.29	-2.7	2.26	2.36	-4.42	0.01
K_2O	1.40	1.35	3.6	0.52	0.50	3.85	0.01
P_2O_5	1.06	0.99	6.4	0.27	0.25	7.41	0.01
Zn	120	116	3.3	105	98	6.67	2
Cu	72	73	-0.8	136	140	-2.94	3
Sc	22	21	4.6	31.8	32	-0.63	3
Ga	17	16	4.4	21	22	-4.76	4
Ni	267	261	2.2	121	124	-2.48	2
Co	60	63	-5.0	45	46	-2.22	2
Cr	360	352	2.2	289	298	-3.11	2
V	235	231	1.7	317	312	1.58	2
Ba	1025	991	3.3	139	145	-4.32	3
Rb	47	47	0.2	11	10	9.09	1
Sr	1370	1362	0.6	403	408	-1.24	2
Y	30	28	5.3	27.6	28	-1.45	2
Zr	260	269	-3.6	179	172	3.91	2
La	82	81	1.6	15.8	17	-7.59	5
Ce	152	161	-6.0	39	42	-7.69	8
Nd	67	65	3.7	25.2	24	4.76	3
Nb	105	105	-0.1	19	18	5.26	1
Th	10.4	11	-2.7	1.08	1	7.41	1
ICP-MS:							
Rb				11	10.8	2.09	0.02
Sr				403	389	3.47	0.02
Y				27.6	28.6	-3.55	0.003
Zr				179	184	-2.79	0.02
La				15.8	16.0	-1.20	0.051
Ce				39	37.7	3.44	0.051
Pr				5.7	5.54	2.81	0.009
Nd				25.2	26.2	-3.89	0.023
Sm				6.2	6.38	-2.90	0.004
Eu				2.06	2.12	-2.91	0.05
Gd				6.4	6.29	1.72	0.007
Tb				0.96	0.93	3.12	0.057
Dy				5.2	5.47	-5.19	0.002
Ho				0.99	1.05	-6.06	0.046
Er				2.4	2.52	-5.00	0.005
Tm				0.33	0.31	6.06	0.017
Yb				2.02	2.12	-4.95	0.01
Lu				0.291	0.31	-6.53	0.012
Nb				19	18.3	3.79	0.01
Hf				4.38	4.31	1.60	0.007
Ta				1.23	1.28	-4.07	0.026
Th				1.08	1.10	-1.85	0.007
U				0.42	0.41	2.38	0.027
CO_2						0.35	0.25

Recommended (Recomm.) values for international reference materials BE-N and BHVO-1 are from K. Govindaraju (1994) Geostandard Newsletter, Special Issue, v. 118, 158 p. Detection limits for XRF and ICP-MS analyses were determined using 29 international reference standards run as unknowns. Accuracy and detection limits for CO_2 analyses were determined using standard amounts of reagent grade $CaCO_3$.