Late Cretaceous subduction-related volcanism in the eastern Sakarya Zone, NE Turkey: petrological and geodynamic constraints

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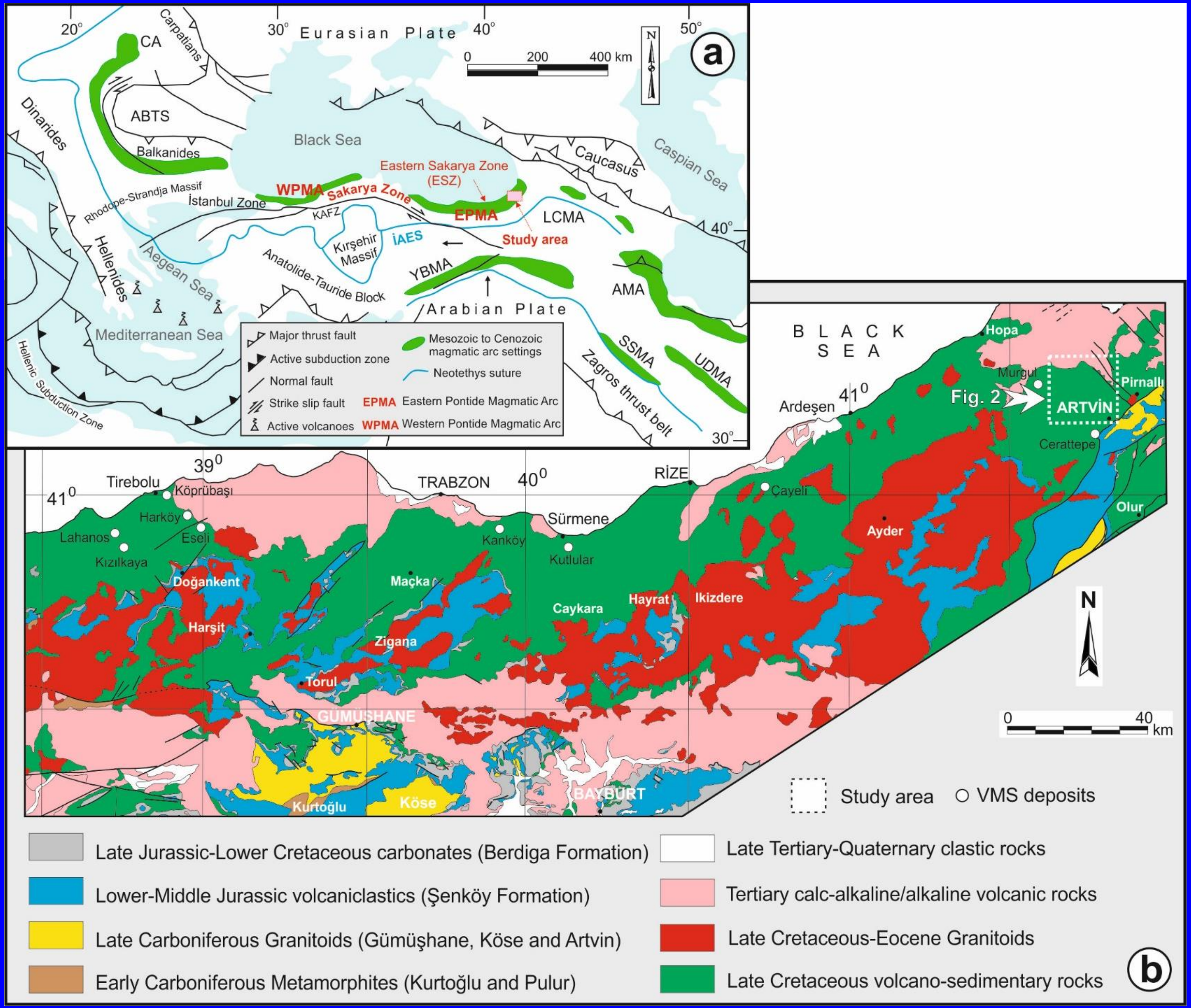
1. Introduction



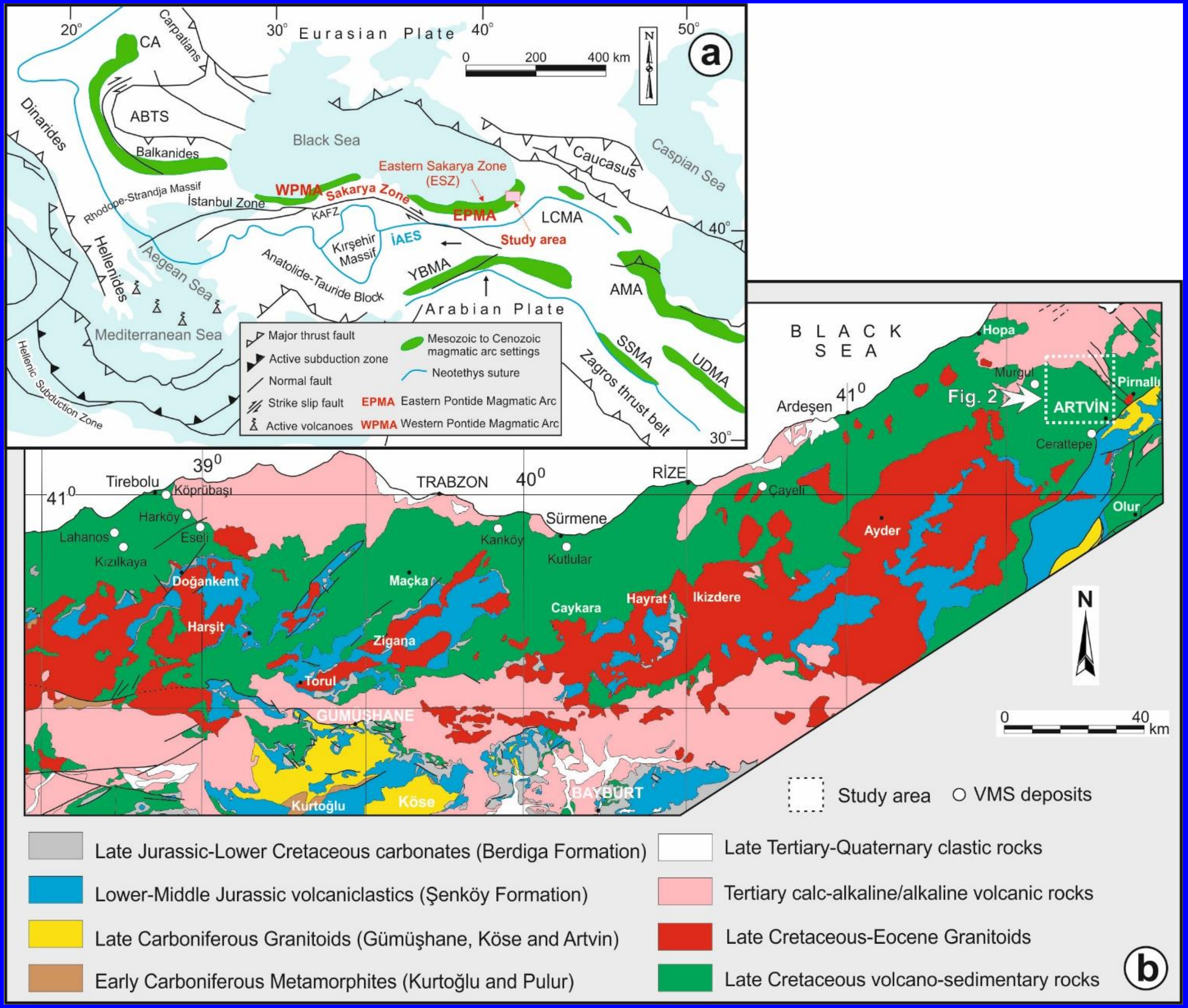
Tectonomagmatic evolution of the Late Cretaceous volcanic rocks (LCVRs) in the eastern Sakarya Zone (ESZ) or eastern Pontides Magmatic Arc (EPMA), which is one of the major tectonic units of Turkey (Fig. 1), is still controversial due to a lack of systematic sampling, from the bottom to the top of the Upper Cretaceous sequence. The systematic lithological, age and geochemical data from the LCVRs will provide significant information about the specific timing of subduction-related magmatism and the stages of the northward closure of the northern Neotethys Ocean (NNO).

Fig. 1. (a) Regional tectonic setting of Anatolia with main blocks in relation to the Afro-Arabian and Eurasian plates (Okay&Tüysüz, 1999). **(b)** Simplified geological map of the ESZ, NE Turkey, showing the main lithological units with study area.

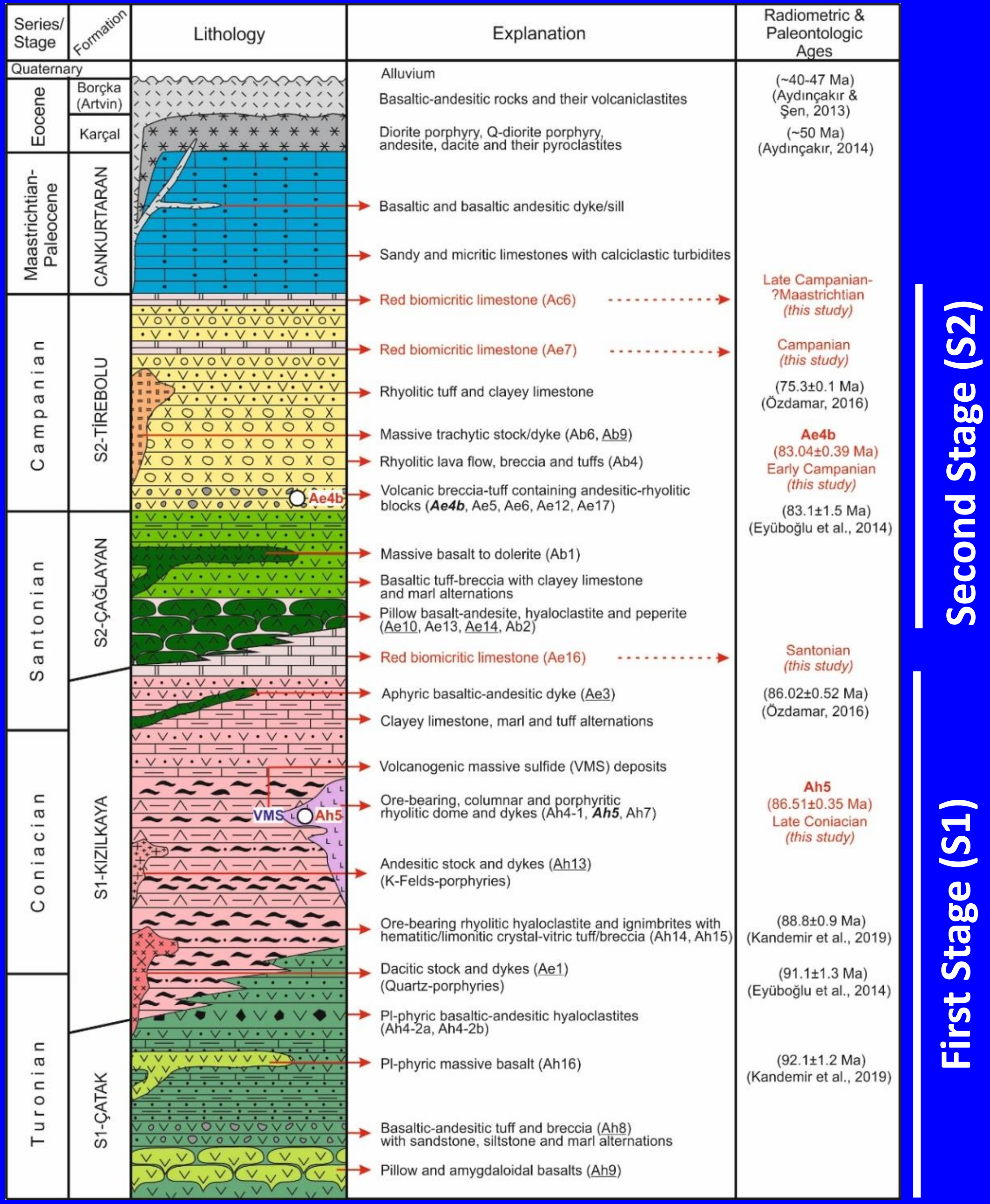
2. General Geology

During the Late Cretaceous, the ESZ is a magmatic arc due to the ongoing convergence between the East European Platform (Laurasia) in the north and Arabian (Gondwana) Platform in the south, resulting in a northward subduction of Neotethys along the southern border of Sakarya Zone (Fig. 1a).

The ESZ is lithologically divided into two subzones; the northern (outer) zone and southern (inner) zone. The northern zone, where the study area (i.e., Artvin) is included, is dominated by volcanic and plutonic rocks, whereas the southern zone is generally represented by carbonates and clastic sedimentary rocks (Fig. 1b).



3. Volcanostratigraphy



Upper Cretaceous units in the study area, with no direct contact relationship with the pre-Cretaceous basement rocks, are conformably overlain by the Maastrichtian–Paleocene Cankurtaran Formation, consisting of sandy-micritic limestone and calciclastic turbidites and the Eocene Karçal and Kabaköy formations, comprising plutonic and volcanic rocks (Fig. 2).

Based on the volcanostratigraphic and paleontologic studies, zircon U-Pb dating and geochemical data, the LCVRs from the Artvin region in the eastern Sakarya zone (NE Turkey) consist of mafic/basaltic (**S1-Çatak** and **S2-Çağlayan**) and felsic/acidic (**S1-Kızılkaya** and **S2-Tirebolu**) rock types that occurred in two successive stages: **(i)** first stage (S1: Turonian to Early Santonian) and **(ii)** second stage (S2: Late Santonian to Campanian).

Fig. 2. General stratigraphic column section of the Late Cretaceous volcano-sedimentary series from the study area.

4. Petrography and Mineralogy

In both stages, the S1-Çatak (Fig. 3a, b) and S2-Çağlayan (Fig 3e, f) basaltic rocks contain generally calcic plagioclase and lesser augite crystals, whereas the S1-Kızılkaya (Fig. 3c, d) and S2-Tirebolu (Fig. 3 e, f) felsic (dacitic-rhyolitic) samples commonly contain quartz, sodic plagioclase and K-sanidine phenocrysts.

Data from clinopyroexene thermobarometry point to the S2-Çağlayan basaltic rocks having crystallised at higher temperatures and under deeper crustal conditions (T = 1128 ± 15 ^{o}C, P = 6.5 ± 0.7 kbar and D = 19.5 ± 2.1 km) than those of the S1-Çatak basaltic rocks (T = 1073 ± 11 ^{o}C, P = 2.2 ± 1.0 kbar, D = 6.6 ± 3.0 km).

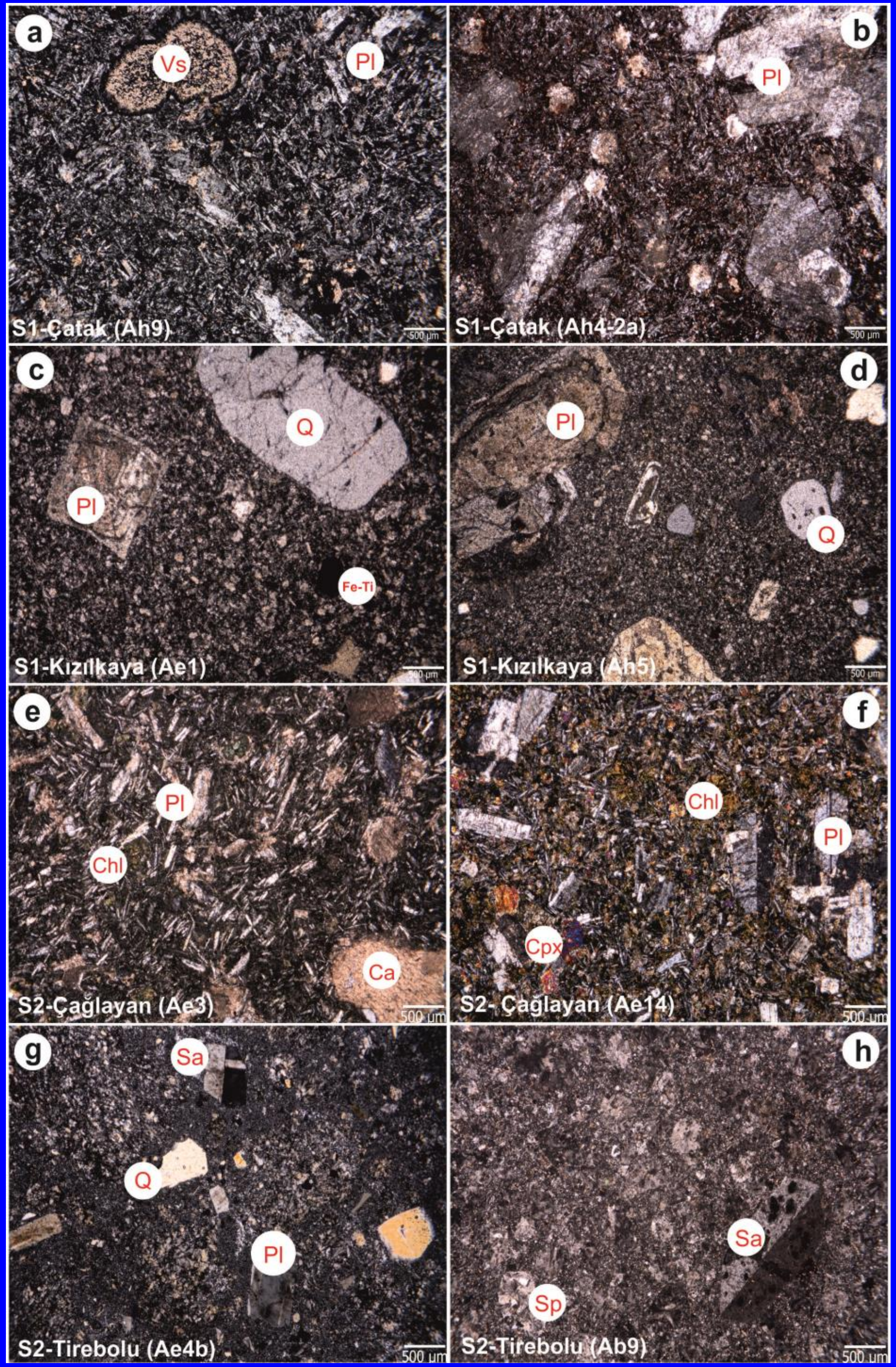
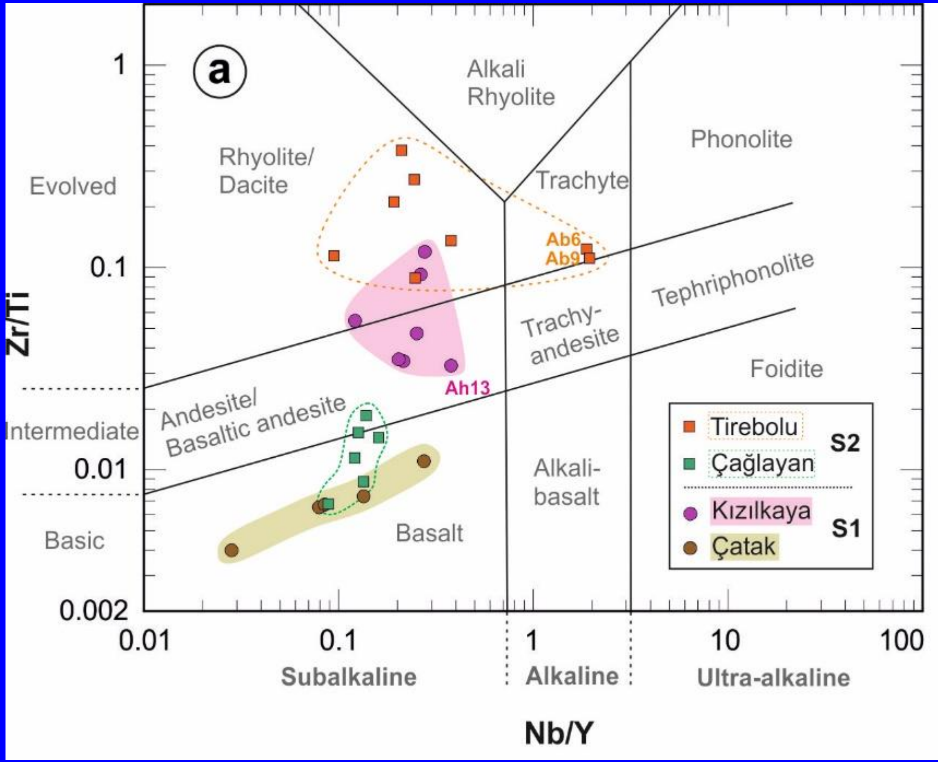


Fig. 3. Representative photomicrographs illustrating mineral assemblages and textural characteristics of the basaltic (**a-b** for Çatak; **e-f** for Çağlayan) and felsic (**c-d** for Kızılkaya; **g-h** for Tirebolu) volcanic rocks. Pl: Plagioclase: Sa: Sanidine, Q: Quartz: Cpx: Clinopyroxene, Fe-Ti: Fe–Ti oxides, Sp: Spherulite, Vs: Vesicular, Chl: Chlorite, Ca: Calcite. The scale bar length is 500 µm.

5. Whole-rock Geochemistry & Classification



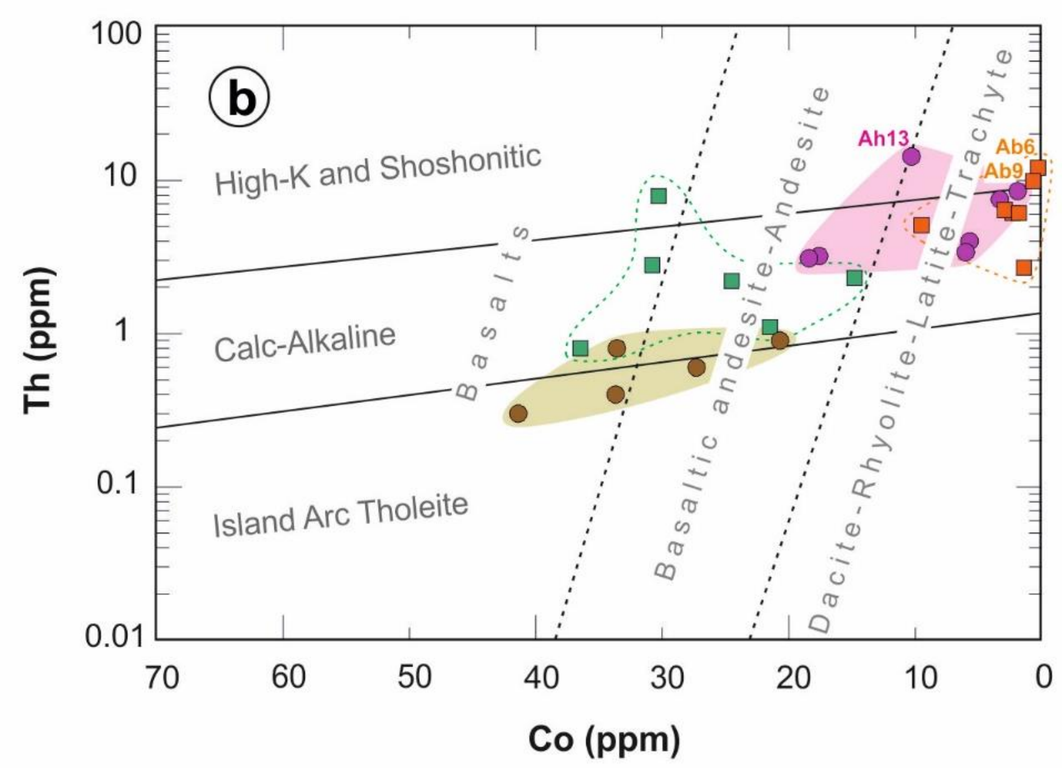
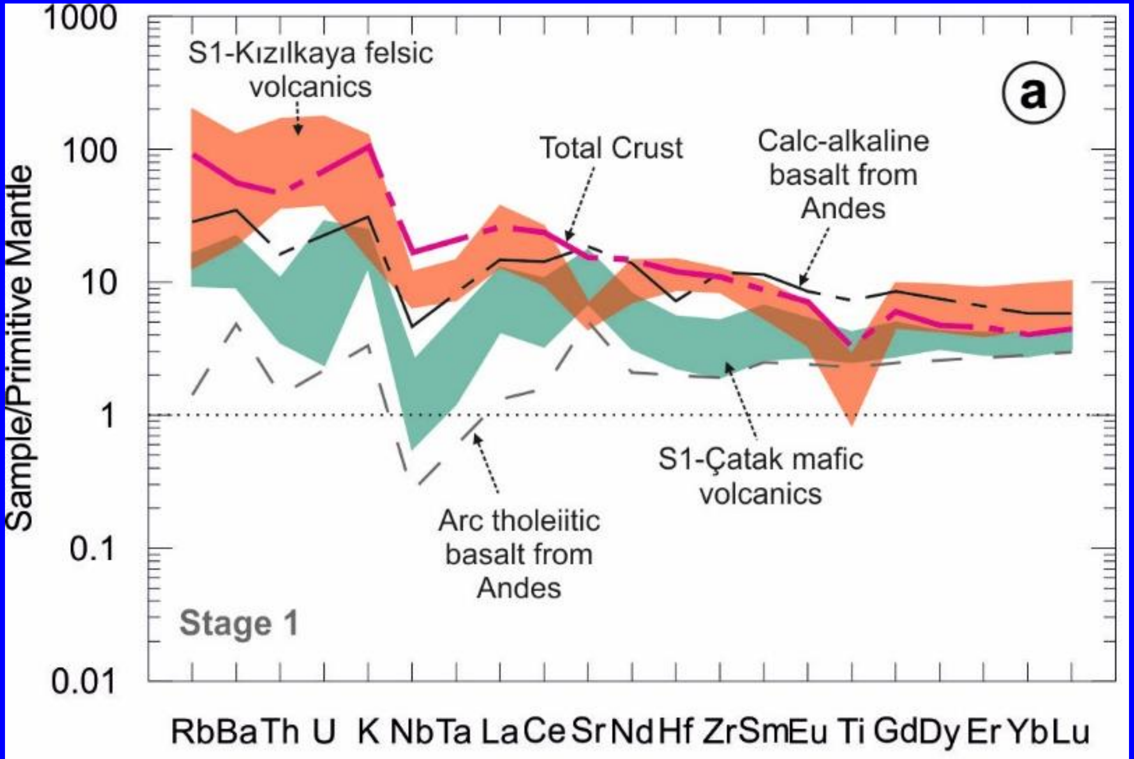


Fig. 4. Classification diagrams of the studied volcanic 1129 rocks. **(a)** Nb/Y versus Zr/Ti (Pearce, 1996), **(b)** Co (ppm) versus Th (ppm) (Hastie et al., 2007).

The Late Cretaceous Artvin volcanic rocks consist of basaltic (S1-Çatak & S2-Çağlayan) and dacitic-rhyolitic (S1-Kızılkaya & S2-Tirebolu) rock types and show a wide compositional spectrum, ranging from tholeiite to calc-alkaline/shoshonite character (Fig. 4).

5. Trace Element Geochemistry



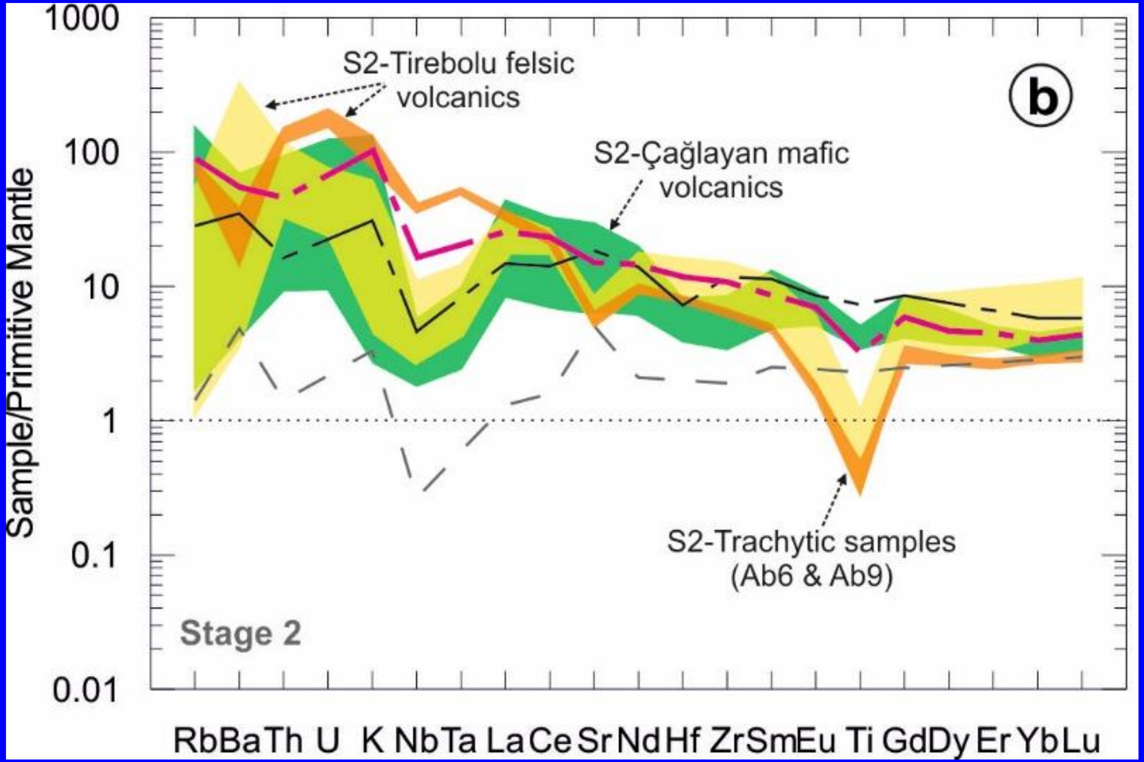


Fig. 5. Primitive mantle-normalized multi-element variation patterns. **(c)** S1-stage and **(c)** S2-stage volcanic rock series.

Mafic and felsic samples from both stages (S1 and S2) show enrichment of large ion lithophile (LIL) elements (Rb, Ba, Th, U, K) and high field strenght (HFS) elements (Nb, Ta, Hf, Zr) compared to the primitive mantle although the enrichment of LILE is more pronounced (Figs. 5a, b). All samples are also characterized by negative Nb and, Ta anomalies, which indicate subduction-related metasomatised mantle source.

5. REE Geochemistry

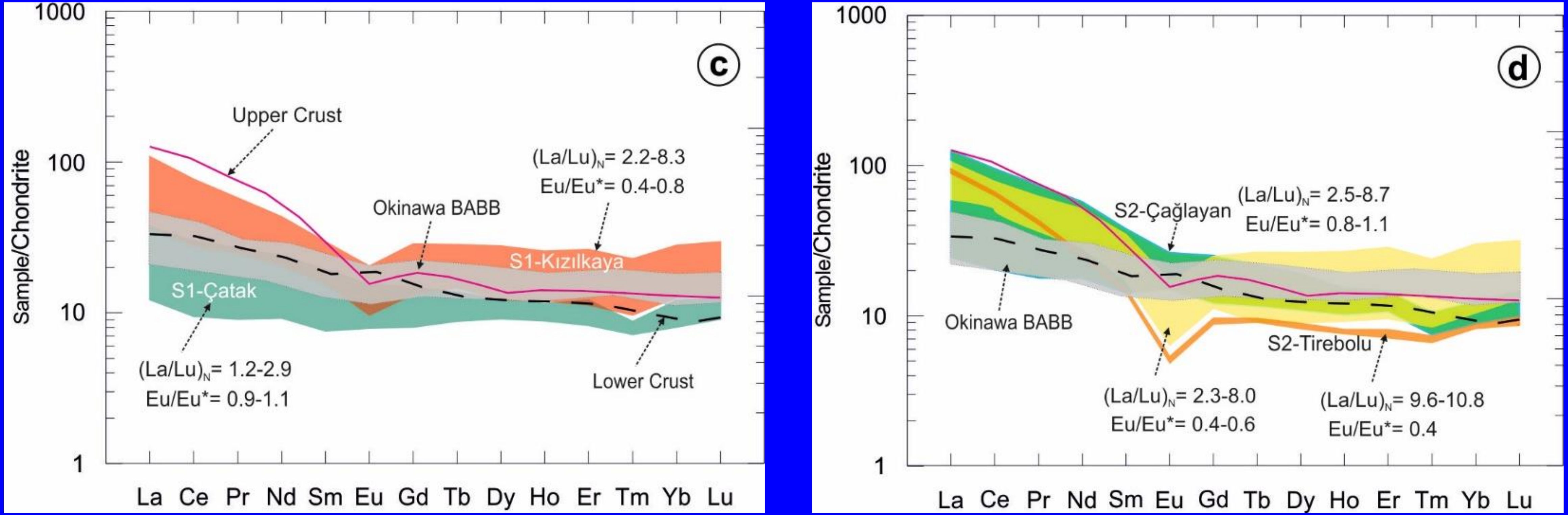


Fig. 5. Chondrite-normalized rare earth element patterns. **(c)** S1-stage and **(c)** S2-stage volcanic rock series.

In chondrite-normalised rare earth element (REE) diagrams, the felsic samples (**S1-Kızılkaya;** Fig. 5c and **S2-Tirebolu;** Fig. 5d) are more enriched in total REE concentrations and are represented by higher La_N/Lu_N ratios compared to basaltic samples (**S1-Çatak;** Fig. 5c and **S2-Çağlayan;** Fig. 5d). The basaltic samples are characterized by lack of Eu anomaly whilst the felsic samples show slight positive Eu anomaly (Figs. 5c, d), supporting the plagioclase fractionation.

6. Sr-Nd-Pb Isotope Compositions

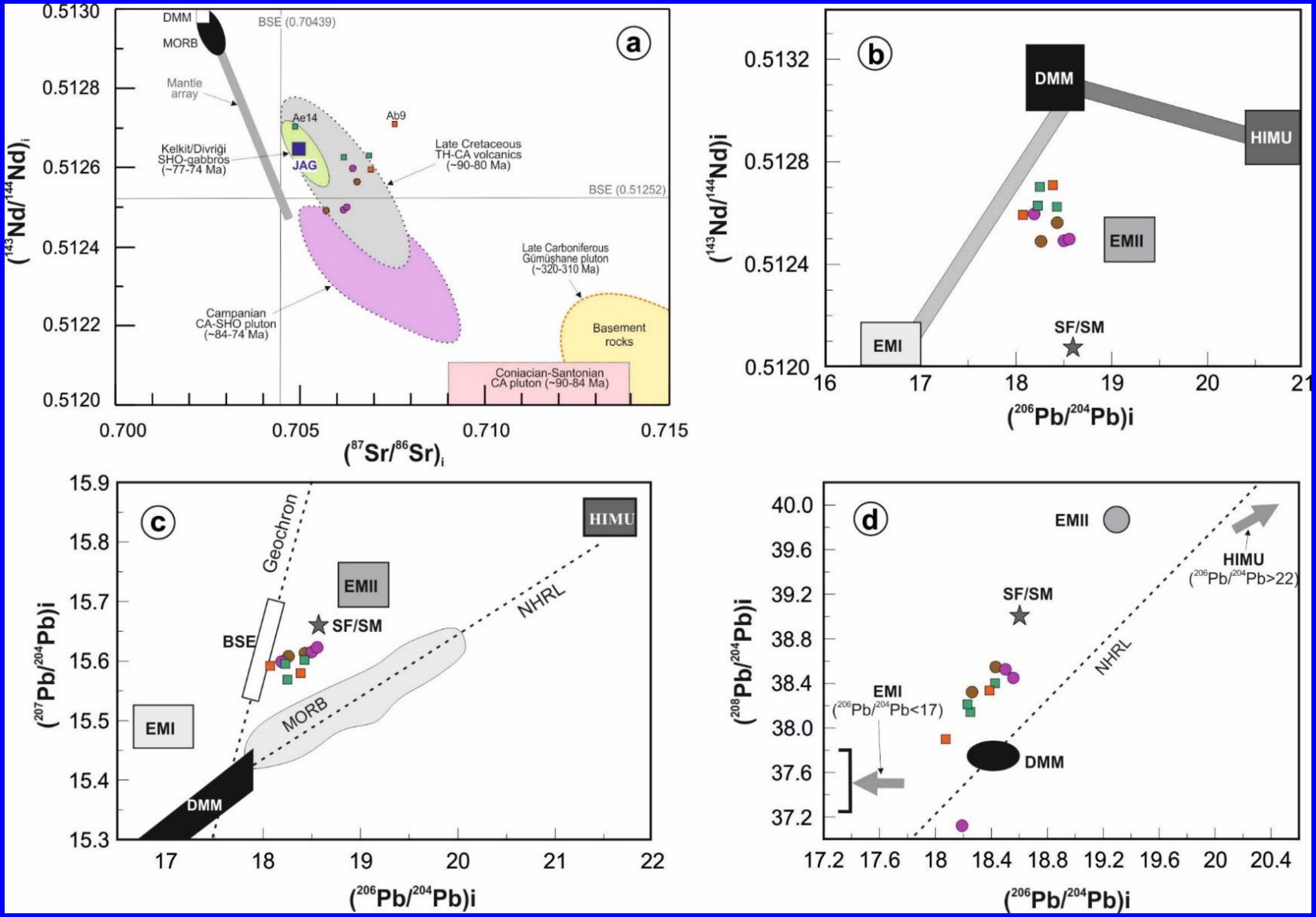


Fig. 6. Sr-Nd-Pb isotopic diagrams of the studied volcanic rocks.

The initial Sr-Nd-Pb ratios of the LCVRs show very limited variation and are grouped in a place between the isotopic compositions of depleted MORB (Mid-Ocean Ridge Basalt) mantle (DMM) and subduction fluid/melt (Figs. 6a-d), pointing out a contribution of subduction components. In addition, the Nd isotopic compositions of our basaltic and felsic samples resemble neither pure continental crust nor pure mantle (Fig. 6a) and thus, melting of pure mantle or crustal rocks cannot explain the isotopic composition of our samples. Therefore, we believe that our samples were produced mainly from the mantle melt but the isotopic compositions of the samples require that some crustal melts also incorporated in the generation of our samples.

6. Oxygen Isotope Compositions

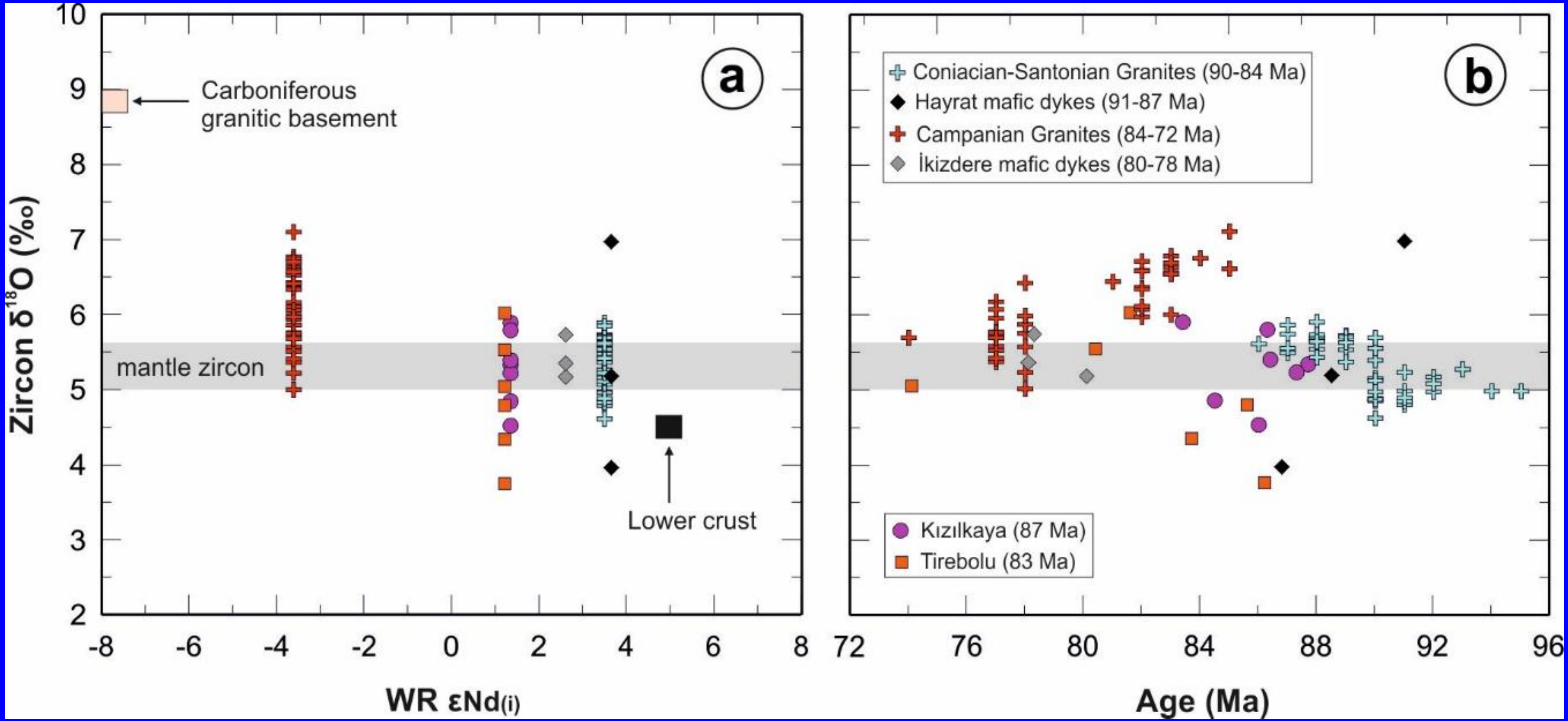


Fig. 7. $\delta^{18}O$ isotope diagrams of the studied volcanic rocks.
(a) WR $_{\varepsilon}Nd_{(i)}$ vs zircon $\delta^{18}O$ (‰) **(b)** Age (Ma) vs zircon $\delta^{18}O$ (‰)

The average $\delta^{18}O$ isotope values of the **S1-Kızılkaya** (5.3 ± 0.5‰) and **S2-Tirebolu** (4.9 ± 0.8‰) zircons are quite consistent with average mantle values (5.3 ± 0.3‰) (Fig. 7a). The similar $\delta^{18}O$ isotopic compositions of the studied mafic and felsic volcanic rocks, like plutons in the region (Fig. 7b), and the relatively high Mg# values (up to 0.4–0.51) of the felsic samples indicate a cogenetic (i.e., mixed) origin.

7. Petrogenesis

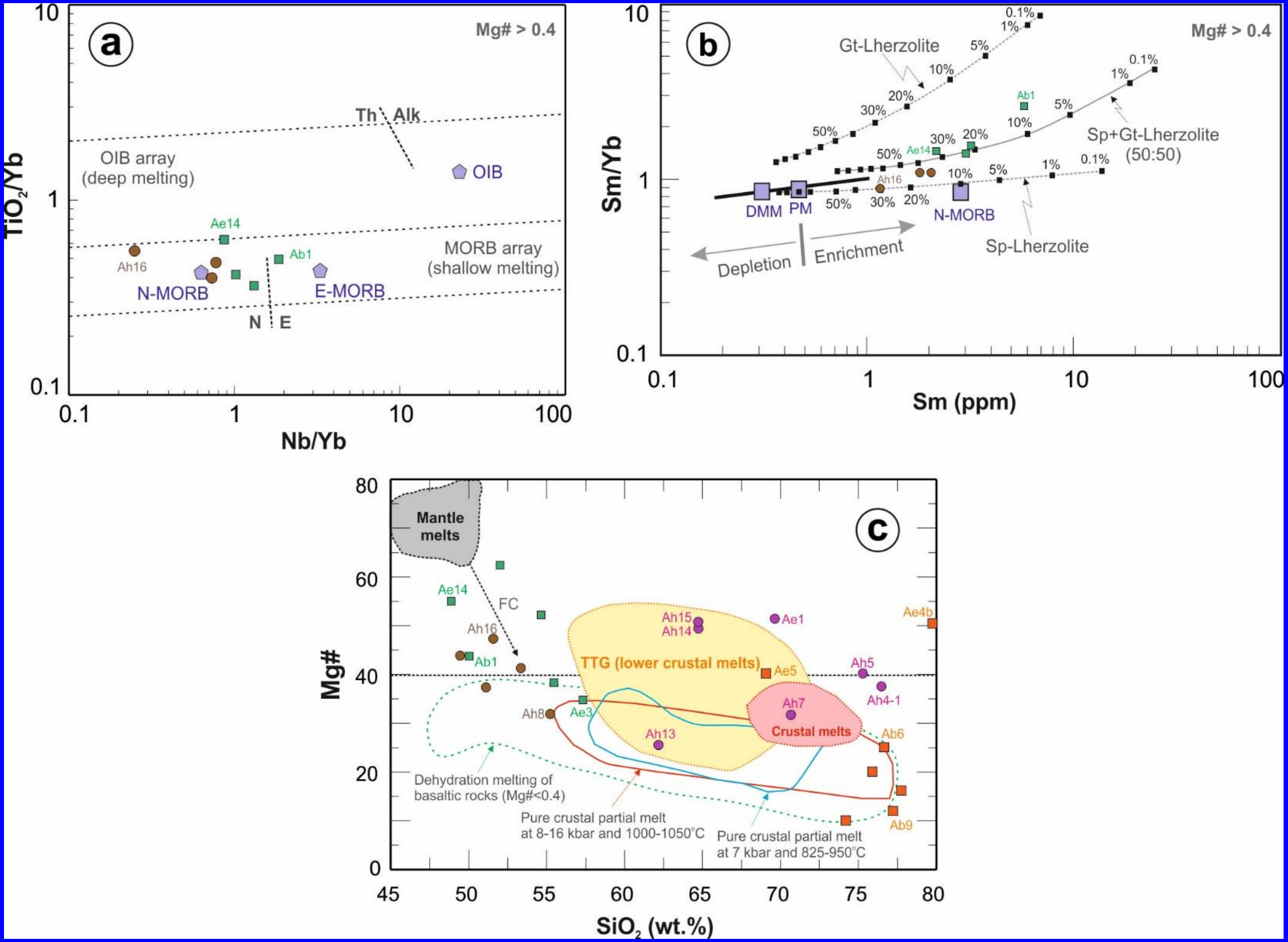


Fig. 8. (a) Nb/Yb versus TiO2/Yb (Pearce, 2008) and **(b)** Sm versus Sm/Yb plots. Mantle array (heavy line) defined by depleted MORB mantle (DMM, McKenzie and O'Nions, 1991) and primitive mantle (PM, Sun and McDonough, 1989). **(c)** SiO2 (wt%) versus Mg# diagram.

Low TiO_2/Yb (<0.6) and Nb/Yb ratios (<1.8) of the S1-Çatak and S2-Çağlayan basaltic rocks imply that the melt responsible for the formation of these basalts originated from the shallow mantle source (Fig. 8a). The parent magmas of the **S1-Çatak** and **S2-Çağlayan** mafic volcanic rocks were derived from underplated basaltic melts that originated by partial melting of metasomatised spinel lherzolite and spinel-garnet lherzolite, respectively (Fig. 8b). It is also proposed that the compositions of the **S1-Kızılkaya** (mainly dacitic) and **S2-Tirebolu** (rhyolitic to trachytic) felsic rocks were particularly controlled by metasomatised mantle–crust interaction and MASH zone plus shallow crustal fractionation processes (Fig. 8c).

8. Conclusions

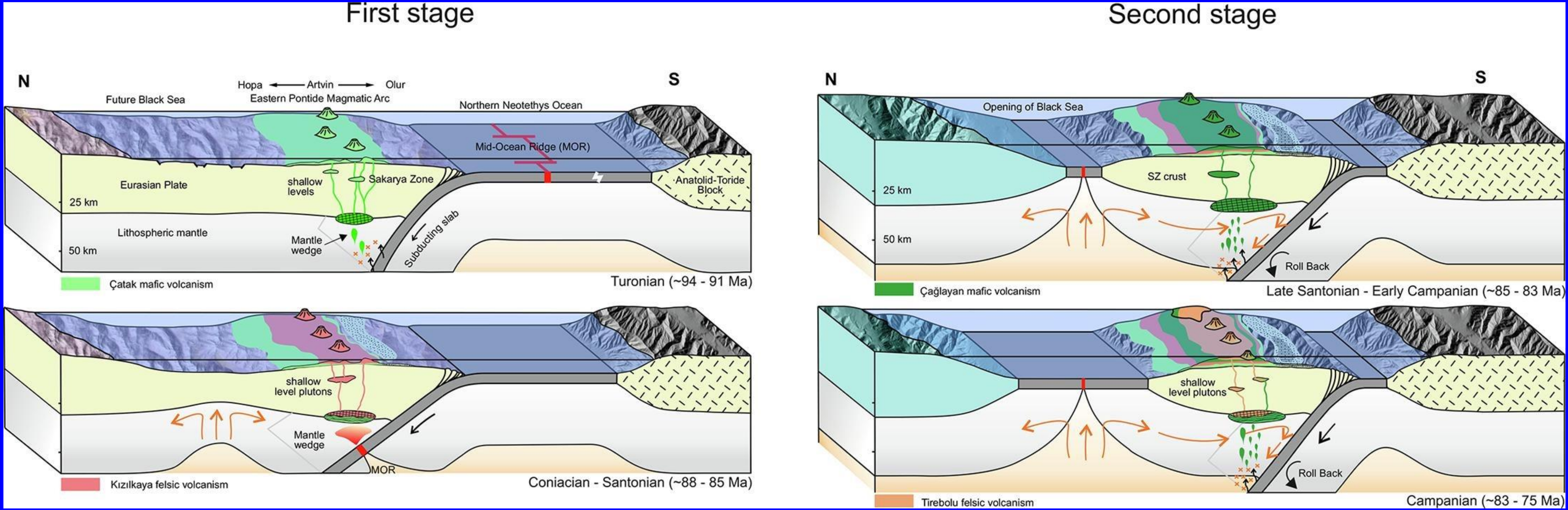


Fig. 9. Schematic illustrations for the Late Cretaceous geodynamic evolution of the S1- and S2-stage volcanic rocks in NE Turkey.

- Late Cretaceous volcanism of the ESZ erupted in two successive stages (~95–75 Ma) .
- The successive stages are characterized by mafic (**S1**) and felsic (**S2**) volcanic rocks.
- Mafic rocks of both stages were derived from underplated basaltic melts.
- Composition of the felsic rocks was controlled by MASH and crustal processes.
- Volcanism took place during northward subduction of the northern Neotethys Ocean.

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