

## INTRODUCTION

### Eastern Mediterranean geodynamics

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The present-day geodynamics of the eastern Mediterranean region is controlled by the relative motions of three major plates, Eurasia, Africa, and Arabia. Much of the resulting deformation occurs at these plate boundaries (Figure 1; Le Pichon and Angelier 1979; Jackson and McKenzie 1984; Spakman *et al.* 1988; Westaway 1994; Barka and Reilinger 1997; Jolivet and Faccenna 2000; McClusky *et al.* 2000; Doglioni *et al.* 2002; Piromallo and Morelli 2003; Dilek 2006; Reilinger *et al.* 2006). The Anatolian continental block (Figure 1), which was originally part of Eurasia, has operated as a microplate between these three major plates since the middle Miocene, when Arabia collided with Eurasia (Dewey *et al.* 1986). The modern Anatolian-African plate boundary is represented by a north-dipping subduction zone that has been part of a broad domain of regional convergence between Eurasia and Afro-Arabia since the latest Mesozoic (Faccenna *et al.* 2003; Van Hinsbergen *et al.* 2005; Jolivet and Brun 2008). The convergence rate between Africa and Eurasia is greater than 40 mm/yr across the Hellenic Arc but decreases to <10 mm/yr across the Cyprus Arc. The Arabia-Eurasia convergence across the Bitlis-Zagros suture zone (BZSZ) has been estimated to be ~16 mm/yr based on global positioning system measurements of present-day central movements in this collision zone (Reilinger *et al.* 1997, 2006).

The Anatolian microplate north of these convergent plate boundaries is moving WSW with respect to Eurasia (Figure 1) at ~30 mm/yr along the North (NAF) and East (EAF) Anatolian fault zones (Reilinger *et al.* 1997). It was built up during a series of collisions between Gondwana-derived ribbon continents and trench-rollback systems in the Tethyan realm throughout the late Mesozoic and early Cenozoic (Dewey *et al.* 1986; Dilek and Moores 1990; Yilmaz 1990). These collisional events, which started with ophiolite emplacement and were followed by continental collisions, produced nearly EW-trending, subparallel mountain belts with high elevation and thick orogenic crust in the eastern Mediterranean region. The WSW-moving Anatolian microplate is currently undergoing complex internal deformation via mainly strike-slip and normal faulting (Figure 1). This deformation has resulted in extensional collapse of the young orogenic crust, giving way to the formation of metamorphic core complexes and intracontinental basins (Bozkurt and Park 1994; Dilek and Whitney 2000; Jolivet and Faccenna 2000; Okay and Satir 2000; Doglioni *et al.* 2002; Bozkurt 2003; Ring and Layer 2003). Extensional deformation of the young Anatolian orogenic belts has been accompanied by magmatism with varying geochemical fingerprints and tectonic affinities, commonly following a time-progressive geochemical trend from initially calc-alkaline (high-K calc-alkaline and high-K shoshonitic) to alkaline and ultra-alkaline affinities (Innocenti *et al.* 1982; Pearce *et al.* 1990; Pe-Piper and Piper 1994; Francalanci *et al.* 2000; Alici *et al.* 1998, 2002; Keskin 2003; Köprübasi and Aldanmaz 2004;

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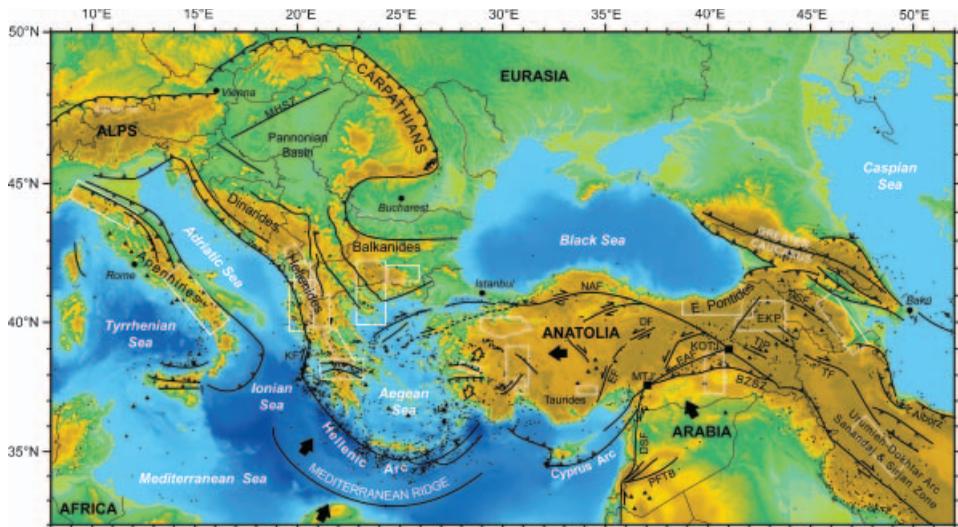


Figure 1. Digital relief image of the eastern Mediterranean region, depicting the major plates (Africa, Arabia, Eurasia, and Anatolia) and their boundaries, important fault systems, and orogenic belts. Tick marks (black triangles) are on the upper plates along fault boundaries. Thick black arrows show the plate convergence directions. White boxes outline the study areas covered in the papers of this special issue. Circles = earthquakes, triangles = volcanoes. Key to lettering: BZSZ – Bitlis-Zagros suture zone; DF – Deliler fault; DSF – Dead Sea fault; EAF – East Anatolian fault; EF – Ecemis fault; EKP – Erzurum-Kars Plateau; KF – Kefalonia fault; KOTJ – Karlova triple junction; MHSZ – Mid-Hungarian shear zone; MTJ – Maras triple junction; NAF – North Anatolian fault; PFTB – Palmyra fold and thrust belt; PSF – Pampak-Sevan fault; TF – Tebriz fault; TIP – Turkish-Iranian plateau.

Innocenti *et al.* 2005; Aldanmaz *et al.* 2006; Çoban and Flower 2006; Keskin *et al.* 2006; Agostini *et al.* 2007; Altunkaynak 2007; Dilek and Altunkaynak 2007).

Similarly, discrete collisional events between some Gondwana-derived continental fragments, including Adria, Pelagonia, and Arabia, with Eurasia throughout the late Mesozoic-Cenozoic controlled the geodynamic evolution of the Mediterranean region, and caused the formation of some major orogenic belts (Sengör and Yilmaz 1981; Robertson and Dixon 1984). For example, the diachronous collision of Adria with Europe along its irregular margins created the Alps, Apennines, and Dinaride-Albanide-Hellenide mountain belt at different times (Figure 1; Dilek 2006 and references therein). The collision of the Arabian promontory with Eurasia at ~13 Ma caused intense deformation taken up by crustal shortening and conjugate strike-slip fault systems in a zone of ~1000 km length stretching from the Bitlis-Zagros suture zone in the south to the Greater Caucasus in the north (Figure 1; Al-Lazki *et al.* 2003; Sengör *et al.* 2003; Sandvol *et al.* 2003; Angus *et al.* 2006; Tan and Taymaz 2006). In due course, the East Anatolian, Greater and Lesser Caucasus, Zagros, and Sanandaj-Sirjan orogenic belts formed around the periphery of the Arabian plate.

While the convergence between these continental blocks and the Eurasian mainland obliterated a series of interconnected Tethyan ocean basins, some new and small oceanic domains were created in the Mediterranean region (i.e. Tyrrhenian Sea, Aegean Sea, Black Sea; Figure 1). These new embryonic oceans developed as a result of the opening of back-arc basins behind active subduction zones (i.e. Black Sea) and/or slab rollback processes (i.e. Aegean Sea, Tyrrhenian Sea; Spakman *et al.*

1993; Allesandrini *et al.* 1997). Magmatism associated with the opening of these embryonic basins produced within-plate, alkaline volcanic and plutonic rock suites, mid-ocean ridge basalts, and calc-alkaline island arc extrusives, and even new oceanic crust. Some of these most recent, embryonic oceans are currently in the process of being closed, leading to the formation of new orogenic belts. Scrapes and flakes of all these magmatic rocks that formed during the short Wilson cycle evolution of these infant basins will be preserved in mélanges and ophiolites of the evolving, future mountains in the region.

The evolution of orogenic belts in the eastern Mediterranean region appears to have followed a common pathway with some minor deviations, mostly due to the changes in types and sizes of colliding lithospheric plates/blocks and their convergence rates (Dilek and Altunkaynak 2007). This pathway may include: ophiolite formation in subduction rollback systems; ophiolite emplacement due to collision between continents and arc-trench rollback systems; continent-continent collision followed by continental subduction; slab breakoff and high-K magmatism; strike-slip faulting and tectonic escape; crustal thickening, topographic build-up and orogenic root formation; lithospheric delamination-tearing, asthenospheric upwelling, and magmatism (ultimately leading to alkaline-ultra-alkaline in nature); and lithospheric-scale extension, core complex formation, and extensional sedimentary basin evolution.

The eastern Mediterranean region is an excellent natural laboratory to investigate the nature of this pathway, and the mechanisms of and the spatial and temporal relationships between these events during the evolution of orogenic belts. The papers in this special issue are original, process-oriented contributions dealing with various aspects of the development of orogenic belts in key localities in this region, and examining through case studies some of the important events and processes outlined above. The coverage of these contributions extend from the Apennines in Italy and the Albanides-Hellenides in the western Balkan Peninsula, to the Rhodopes and Serbo-Macedonia in Bulgaria and eastern Greece, western Anatolia, south-central Taurides, eastern Pontides, and Bitlis-Zagros suture zone in Turkey, Lesser Caucasus in Azerbaijan, and Sanandaj-Sirjan and Urumieh-Dokhtar zones in NW Iran (Figure 1). The observations and findings reported in these papers should help us to better understand the tectonic, magmatic, metamorphic, seismic, and sedimentary processes, the interactions between the crust and mantle, and the causes and distribution of seismic and volcanic events involved in other active collision zones.

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## References

- Agostini, S., Doglioni, C., Innocenti, F., Manetti, P., Tonarini, S., and Savasçin, M.Y., 2007, The transition from subduction-related to intraplate Neogene magmatism in the Western Anatolia and Aegean area, *in* Beccaluva, L., Bianchini, G., and Wilson, M., eds., *Cenozoic Volcanism in the Mediterranean Area: Geological Society of America Special Paper 418*, p. 1–16.
- Aldanmaz, E., Köprübasi, N., Gürer, Ö.F., Kaymakçi, N., and Gourgaud, A., 2006, Geochemical constraints on the Cenozoic, OIB-type alkaline volcanic rocks of NW Turkey: Implications for mantle sources and melting processes: *Lithos*, v. 86, p. 50–76.

- Alessandrini, B., Beranzoli, L., Drakatos, G., Falcone, C., Karantonis, G., Mele, F.M., and Stavrakakis, G., 1997, Back arc basins and P-wave crustal velocity in the Ionian and Aegean regions: *Geophysical Research Letters*, v. 24, p. 527–530.
- Alici, P., Temel, A., Gourgaud, A., Kieffer, G., and Gündođdu, M.N., 1998, Petrology and geochemistry of potassic rocks in the Gölcük area (Isparta, SW Turkey): genesis of enriched alkaline magmas: *Journal of Volcanology and Geothermal Research*, v. 85, p. 423–446.
- Alici, P., Temel, A., and Gourgaud, A., 2002, Pb–Nd–Sr isotope and trace element geochemistry of Quaternary extension-related alkaline volcanism: a case study of Kula region (western Anatolia, Turkey): *Journal of Volcanology & Geothermal Research*, v. 115, p. 487–510.
- Al-Lazki, A.I., Seber, D., Sandvol, E., Turkelli, N., Mohamad, R., and Barazangi, M., 2003, Tomographic Pn velocity and anisotropy structure beneath the Anatolian plateau (eastern Turkey) and the surrounding regions: *Geophysical Research Letters*, v. 30, no. 24, p. 8043, doi: 10.1029/2003GL017391.
- Altunkaynak, Ş., 2007, Collision-driven slab breakoff magmatism in northwestern Anatolia, Turkey: *Journal of Geology*, v. 115, p. 63–82.
- Angus, D.A., Wilson, D.C., Sandvol, E., and Ni, J.F., 2006, Lithospheric structure of the Arabian and Eurasian collision zone in eastern Turkey from S-wave receiver functions: *Geophysical Journal International*, v. 166, p. 1335–1346.
- Barka, A., and Reilinger, R., 1997, Active tectonics of the Eastern Mediterranean region: deduced from GPS, neotectonic and seismicity data: *Annali Di Geofisica*, v. XL, p. 587–610.
- Bozkurt, E., 2003, Origin of NE-trending basins in western Turkey: *Geodinamica Acta*, v. 14, p. 61–81.
- Bozkurt, E., and Park, R.G., 1994, Southern Menderes Massif: an incipient metamorphic core complex in western Anatolia, Turkey: *Journal of the Geological Society London*, v. 151, p. 213–216.
- Çoban, H., and Flower, M.F.J., 2006, Mineral phase compositions in silica-undersaturated ‘leucite’ lamproites from the Bucak area, Isparta, SW Turkey: *Lithos*, v. 89, p. 275–299.
- Dewey, J.F., Hempton, M.R., Kidd, W.S.F., Saroglu, F., and Sengör, A.M.C., 1986, Shortening of continental lithosphere: the neotectonics of Eastern Anatolia – a young collision zone, *in* Coward, M.P., and Ries, A.C., eds., *Collision Zone Tectonics: Geological Society of London Special Publication 19*, p. 3–36.
- Dilek, Y., 2006, Collision tectonics of the Mediterranean region: causes and consequences, *in* Dilek, Y., and Pavlides, S., eds., *Postcollisional tectonics and magmatism in the Mediterranean region and Asia: Geological Society of America Special Paper 409*, p. 1–13.
- Dilek, Y., and Moores, E.M., 1990, Regional Tectonics of the Eastern Mediterranean ophiolites, *in* Malpas, J., Moores, E.M., Panayiotou, A., and Xenophontos, C., eds., *Ophiolites, Oceanic Crustal Analogues, Proceedings, Symposium ‘Troodos 1987’: Nicosia, Cyprus, The Geological Survey Department*, p. 295–309.
- Dilek, Y., and Whitney, D.L., 2000, Cenozoic crustal evolution in central Anatolia: Extension, magmatism and landscape development, *in* Panayides, I., Xenophontos, C., and Malpas, J., eds., *Proceedings, Third International Conference on the Geology of the Eastern Mediterranean: Nicosia, Cyprus, Geological Survey Department*, p. 183–192.
- Dilek, Y., and Altunkaynak, S., 2007, Cenozoic crustal evolution and mantle dynamics of post-collisional magmatism in western Anatolia: *International Geology Review*, v. 49, p. 431–453.
- Doglionni, C., Agostini, S., Crespi, M., Innocenti, F., Manetti, P., Riguzzi, F., and Savasçin, Y., 2002, On the extension in western Anatolia and the Aegean Sea, *in* Rosenbaum, G., and Lister, G.S., eds., *Reconstruction of the evolution of the Alpine-Himalayan Orogen: Journal of the Virtual Explorer*, v. 8, p. 169–183.

- Faccenna, C., Jolivet, L., Piromelli, C., and Morallo, A., 2003, Subduction and the depth of convection in the Mediterranean mantle: *Journal of Geophysical Research*, v. 108, p. 2099, doi: 10.1029/2001JB001690.
- Francalanci, L., Innocenti, F., Manetti, P., and Savasçin, M.Y., 2000, Neogene alkaline volcanism of the Afyon-Isparta area, Turkey: petrogenesis and geodynamic implications: *Mineralogy and Petrology*, v. 70, p. 285–312.
- Innocenti, F., Agostini, S., Di Vincenzo, G., Doglioni, C., Manetti, P., Savasçin, M.Y., and Tonarini, S., 2005, Neogene and Quaternary volcanism in Western Anatolia: Magma sources and geodynamic evolution: *Marine Geology*, v. 221, p. 397–421.
- Innocenti, F., Mazzouli, G., Pasquare, F., Radicati Di Brozola, F., and Villari, L., 1982, Tertiary and Quaternary volcanism of the Erzurum-Kars area (Eastern Turkey): geochronological data and geodynamic evolution: *Journal of Volcanological and Geothermal Research*, v. 13, p. 223–240.
- Jackson, J., and McKenzie, D., 1984, Active tectonics of the Alpine-Himalayan belt between western Turkey and Pakistan: *Geophysical Journal International*, v. 77, p. 185–264.
- Jolivet, L., and Faccenna, C., 2000, Mediterranean extension and the Africa-Eurasia collision: *Tectonics*, v. 19, p. 1095–1106.
- Jolivet, L., and Brun, J.-P., 2008, Cenozoic geodynamic evolution of the Aegean: *International Journal of Earth Sciences*: doi: 10.1007/s00531-008-0366-4.
- Keskin, M., 2003, Magma generation by slab steepening and breakoff beneath a subduction-accretion complex: an alternative model for collision-related volcanism in Eastern Anatolia, Turkey: *Geophysical Research Letters*, v. 30, p. 8046, doi: 10.1029/2003GL018019.
- Keskin, M., Pearce, J.A., Kempton, P.D., and Greenwood, P., 2006, Magma-crust interactions and magma plumbing in a postcollisional setting: Geochemical evidence from the Erzurum-Kars volcanic plateau, eastern Turkey, *in* Dilek, Y., and Pavlides, S., eds., *Postcollisional tectonics and magmatism in the Mediterranean region and Asia*: Geological Society of America Special Paper 409, p. 475–505.
- Köprübasi, N., and Aldanmaz, E., 2004, Geochemical constraints on the petrogenesis of Cenozoic I-type granitoids in Northwest Anatolia, Turkey: evidence for magma generation by lithospheric delamination in a post-collisional setting: *International Geology Review*, v. 46, p. 705–729.
- Le Pichon, X., and Angelier, J., 1979, The Hellenic arc and trench system: a key to the evolution of the Eastern Mediterranean area: *Tectonophysics*, v. 60, p. 1–42.
- McClusky, S., Balassanian, S., Barka, A., Demir, C., Ergintav, S., Georgiev, I., Gürkan, O., Hamburger, M., Hurst, K., Kahle, H., Kastens, K., Kekilidze, G., King, R., Kotzev, V., Lenk, O., Mahmoud, S., Mishin, A., Nadariya, M., Ozounis, A., Paradissis, D., Peter, Y., Prelipin, M., Reilinger, R., Sanli, I., Seeger, H., Tealeb, A., Toksöz, M.N., and Veis, G., 2000, Global Positioning System constraints on plate kinematics and dynamics in the eastern Mediterranean and Caucasus: *Journal of Geophysical Research*, v. 105, p. 5695–5719.
- Okay, A.I., and Satir, M., 2000, Coeval plutonism and metamorphism in a latest Oligocene metamorphic core complex in northwest Turkey: *Geological Magazine*, v. 137, p. 495–516.
- Pearce, J.A., Bender, J.F., Delong, S.E., Kidd, W.S.F., Low, P.J., Guner, Y., Saroglu, F., Yilmaz, Y., Moorbath, S., and Mitchell, J.J., 1990, Genesis of collision volcanism in eastern Anatolia, Turkey: *Journal of Volcanology and Geothermal Research*, v. 44, p. 189–229.
- Pe-Piper, G., and Piper, D.J.W., 1994, Miocene magnesian andesites and dacites, Evia, Greece: adakites associated with subducted slab detachment and extension: *Lithos*, v. 31, p. 125–140.
- Piromallo, C., and Morelli, A., 2003, P wave tomography of the mantle under the Alpine-Mediterranean area: *Journal of Geophysical Research*, v. 108, p. 2065, doi: 10.1029/2002JB001757.

- Reilinger, R.E., McClusky, S.C., and Oral, M.B., 1997, Global positioning system measurements of present-day crustal movements in the Arabia-Africa-Eurasia plate collision zone: *Journal of Geophysical Research*, v. 102, p. 9983–9999.
- Reilinger, R.E., McClusky, S.C., Vernant, P., Lawrence, S., Ergintav, S., Çakmak, R., Nadariya, M., Hahubia, G., Mahmoud, S., Sakr, K., Arrajehi, A., Paradissis, D., Al-Aydrus, A., Prilepin, M., Guseva, T., Evren, E., Dmitritsa, A., Filikov, S.V., Gomes, F., Al-Ghazzi, R., and Karam, G., 2006, GPS constraints on continental deformation in the Africa-Arabia-Eurasia continental collision zone and implications for the dynamics of plate interactions: *Journal of Geophysical Research*, v. 111, p. V05411, doi: 10.1029/2005JB004051.
- Ring, U., and Layer, P.W., 2003, High-pressure metamorphism in the Aegean, eastern Mediterranean: Underplating and exhumation from the Late Cretaceous until the Miocene to Recent above the retreating Hellenic subduction zone: *Tectonics*, v. 22, p. 6–1–6–23, doi: 10.1029/2001TC001350.
- Robertson, A.H.F., and Dixon, J.E., 1984, Introduction: aspects of the geological evolution of the eastern Mediterranean, *in* Dixon, J.E., and Robertson, A.H.F., eds., *The Geological Evolution of the Eastern Mediterranean*: Geological Society of London Special Publications, v. 17, p. 1–74.
- Sandvol, E., Türkelli, N., Zor, E., Gök, R., Bekler, T., Gürbüz, C., Seber, D., and Barazangi, M., 2003, Shear wave splitting in a young continent-continent collision: an example from eastern Turkey: *Geophysical Research Letters*, v. 30, no. 24, p. 8041, doi: 10.1029/2003GL017390.
- Sengör, A.M.C., and Yılmaz, Y., 1981, Tethyan evolution of Turkey, a plate tectonic approach: *Tectonophysics*, v. 75, p. 181–241.
- Sengör, A.M.C., Özeren, S., Genç, T., and Zor, E., 2003, East Anatolian high plateau as a mantle-supported, north-south shortened domal structure: *Geophysical Research Letters*, v. 30, p. 8045, doi: 10.1029/2003GL017858.
- Spakman, W., Van Der Lee, S., and Van Der Hilst, R., 1993, Travel-time tomography of the European-Mediterranean mantle down to 1400 km: *Physics of the Earth and Planetary Interiors*, v. 79, p. 3–74.
- Spakman, W., Wortel, M.J.R., and Vlaar, N.J., 1988, The Hellenic subduction zone: a tomographic image and its geodynamic implications: *Geophysical Research Letters*, v. 15, p. 60–63.
- Tan, O., and Taymaz, T., 2006, Active tectonics of the Caucasus: Earthquake source mechanisms and rupture histories obtained from inversion of teleseismic body waveforms, *in* Dilek, Y., and Pavlides, S., eds., *Postcollisional tectonics and magmatism in the Mediterranean region and Asia*: Geological Society of America Special Paper 409, p. 531–578.
- Van Hinsbergen, D.J.J., Hafkenscheid, E., Spakman, W., Meulenkamp, J.E., and Wortel, R., 2005, Nappe stacking resulting from subduction of oceanic and continental lithosphere below Greece: *Geology*, v. 33, p. 325–328.
- Westaway, B., 1994, Present-day kinematics of the Middle East and eastern Mediterranean: *Journal of Geophysical Research*, v. 99, p. 12071–12090.
- Yılmaz, Y., 1990, Comparison of young volcanic associations of western and eastern Anatolia under compressional regime; a review: *Journal of Volcanology and Geothermal Research*, v. 44, p. 69–87.