

Magma generation by slab steepening and breakoff beneath a subduction-accretion complex: An alternative model for collision-related volcanism in Eastern Anatolia, Turkey

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[1] Eastern Anatolia is regarded as one of the best examples of continental collision, represented by a 2 km high plateau. It displays shallow and diffuse seismicity, indicating that the crust is still being actively deformed. Perhaps the most striking aspect of Eastern Anatolia is the volume and compositional variability of collision-related volcanic products erupted during the Neogene and Quaternary time. A number of models have been proposed for the genesis of this volcanism in the region. However, recent geophysical studies have revealed that a mantle lithosphere is almost completely absent beneath a greater portion of the region, which makes us question the validity of the previous models. In this paper, we propose a new model for magma genesis: slab steepening and breakoff beneath a large subduction-accretion complex. This model holds that a northward subducting oceanic lithosphere beneath the Eastern Anatolia Accretionary Prism gets steepened and eventually detached from the continental lithosphere of the Bitlis-Poturge Massif, following the continent-accretionary complex collision. This brings the asthenospheric mantle in contact with the accretionary complex at shallow depths (e.g., around 50 km), resulting in rapid regional uplift and extensive melting which leads to collisional volcanism.

INDEX TERMS: 1025 Geochemistry: Composition of the mantle; 1099 Geochemistry: General or miscellaneous; 3640 Mineralogy and Petrology: Igneous petrology; 8110 Tectonophysics: Continental tectonics—general (0905); 8125 Tectonophysics: Evolution of the Earth.
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1. Introduction

[2] In Eastern Anatolia, over half of the region is covered with young volcanic units, exceeding 1 km in thickness in places and ranging in ages from 11 Ma to present. This volume, in fact, may reflect only a small fraction of the melt generated in the region, because a greater proportion is presumed to have emplaced deep in the crust as plutonic intrusions.

[3] The East Anatolian topographic uplift resembles the Tibetan Plateau and has been thought of a younger version of it in many studies [e.g., *Sengor and Kidd*, 1979; *Dewey et al.*, 1986]. In some of these early studies, lithospheric

mantle beneath Eastern Anatolia was thought to have been doubled in thickness up to ~300 km due to continental collision and thickening.

[4] The *Pearce et al.* [1990] study on collision-related volcanic units (CRVU) across the region provided a new insight into the tectono-magmatic evolution of Eastern Anatolia. They proposed the delamination model that involved the detachment of the thermal boundary layer by delamination. The *Keskin et al.* [1998] study on CRVU on the Erzurum-Kars Plateau (EKP) in the north also supports deep delamination hypothesis of *Pearce et al.* [1990] and demonstrates that the initiation of volcanism has been much earlier in the north (i.e., 11 Ma) than previously thought, almost coincident with rapid uplift of the region.

[5] Results of the Eastern Turkey Seismic Experiment project have provided new insights for the crustal/lithospheric structure of Eastern Turkey. Studies of Pn tomographic imaging of mantle lid velocity and anisotropy by *Al-Lazki et al.* [2003] and regional wave propagation of Sn waves by *Gok et al.* [2000] have revealed that the mantle lithosphere is either very thin or completely absent beneath the region. On the other hand, crustal thicknesses gathered from the studies of receiver functions indicate almost a gradual change from <38 km in the southeast around the southern part of the Bitlis suture zone to 50 km in the north [*Zor et al.*, 2003], averaging to some 45 km. This indicates that an almost normal-thickness crust resides on an extremely thin mantle lithosphere or perhaps almost directly on the asthenosphere! What is even more remarkable is that areas of inferred complete lithospheric detachment almost exactly coincide with the extent of the Eastern Anatolian Accretionary Complex (EAAC) [*Sengor et al.*, 2003].

[6] *Sengor et al.* [2003] argue that the EAAC can be regarded as a remnant of a large accretionary prism located between the Pontides and the Bitlis-Poturge Massif, being formed on a northward subducting oceanic lithosphere. They put forward that the lithospheric detachment occurred when this prism collided with the continent in the south. On the basis of these new results and proposals, it is necessary to reexamine the issue of genesis and evolution of collision-related volcanism in Eastern Anatolia. The aim of this paper is to propose an alternative model for magma genesis that better explains geochemical variations in CRVU across Eastern Anatolia.

2. Geology of Eastern Anatolia

[7] The Eastern Anatolia region can be divided into three tectonic units on the basis of the nature of underlying

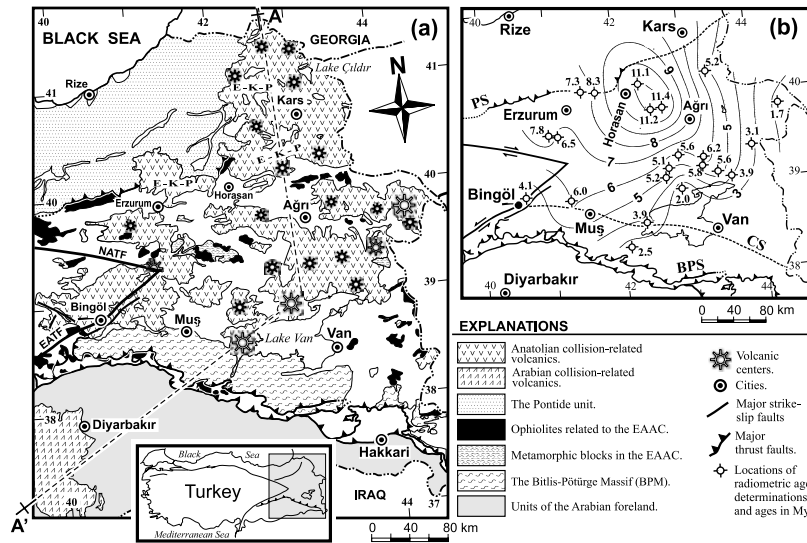


Figure 1. (a) Tectonic units, distribution of collision-related volcanic products and volcanic centers across Eastern Anatolia. A-A': direction of the cross section in Figure 2. E-K-P: the Erzurum-Kars Plateau; NATF and EATF: North and East Anatolian Transform Faults. (b) Distribution of the oldest radiometric ages of the volcanic units. Ages are those given in Pearce et al. [1990], Ercan et al. [1990] and Keskin et al. [1998]. Initiation ages are contoured in 1 My intervals. PS: Pontide suture, BPS: Bitlis-Poturge suture, CS: inferred cryptic suture between the EAAC and BPS.

basements. From the north to the south, these are: (1) The Pontide unit which is represented basically by a magmatic arc, (2) The Eastern Anatolian Accretionary Complex (EAAC) blanketed by young, CRVU of Late Miocene to Quaternary in age, and (3) The Bitlis-Poturge Massif (BPM) (Figures 1 and 2). The EAAC unit is of special importance, because not only has it been accommodating most of the deformation induced by continent-continent collision, but

also it has been subjected to an intensive collision-related magmatic activity.

3. Geochemical Characteristics of Collision-Related Volcanic Units

[8] CRVU across the region span the whole compositional range from basalts to rhyolites. There is a significant

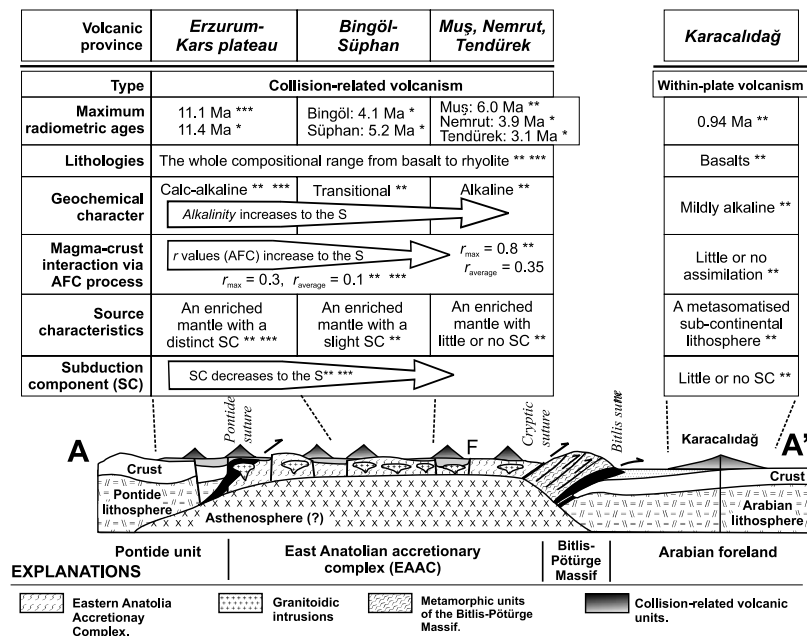


Figure 2. Cross section summarizing the petrologic and geochemical properties of the collision-related volcanic units across the Eastern Anatolia Region. The direction of the cross section (A-A') is shown in Figure 1a. Source of the data: *Ercan et al. [1990], **Pearce et al. [1990], ***Keskin et al. [1998]. SC: subduction component, AFC: Assimilation combined with Fractional Crystallization, F: strike-slip faults.

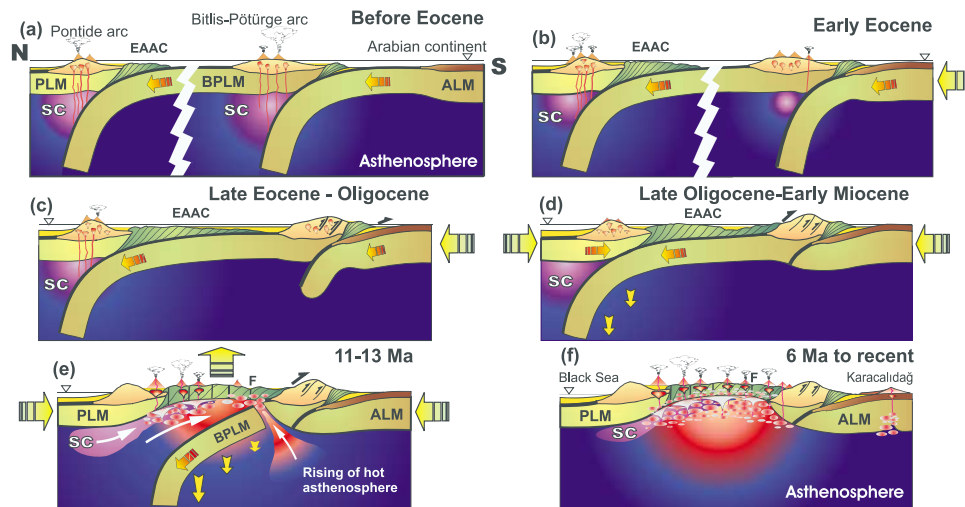


Figure 3. Cross sections displaying regional uplift and magma generation by slab steepening and breakoff in Eastern Anatolia. SC: asthenospheric mantle containing a subduction component, F: strike-slip faults, PLM: lithospheric mantle of the Pontides, BPLM: lithospheric mantle of the Bitlis-Potürge Massif, ALM: Arabian lithospheric mantle.

variation in lava chemistry in the direction of N-S between the EKP in the north and the Mus-Nemrut-Tendurek volcanoes in the south (Figures 1 and 2). Lavas of the Bingöl and Suphan volcanoes display transitional chemical characteristics [Pearce *et al.*, 1990]. Volcanic products in the north around the EKP and Mt. Ararat are calc-alkaline in character and appear to have been derived from an enriched mantle source containing a distinct subduction signature. This signature decreases to the south and diminishes around Mus-Nemrut-Tendurek volcanoes, where the lavas are alkaline and display within-plate signature. Results from AFC modeling show that the degree of magma-crust interaction is more important in the south than in the north (Figure 2). Radiometric dating results indicate that the volcanic activity began earlier in the north than in the south, migrating to the south during the course of time (Figure 1b).

4. Models for Magma Generation and Discrepancies

[9] Seven geodynamic models have been proposed for the Eastern Anatolian collision zone. Note that except for the slab steepening and breakoff model, there appear to be inconsistencies in all the other alternative models: (1) the tectonic escape of micro-plates to the east and west [McKenzie, 1972] does not account entirely for the strain induced by the 2.5 cm/yr convergence of the Arabian plate with respect to Eurasia [Dewey *et al.*, 1986]; (2) the subduction of Arabian plate beneath Eastern Anatolia [Rotstein and Kafka, 1982] is not supported by seismic evidence; (3) the melting of normal asthenosphere by adiabatic decompression of upwelling mantle as a result of extension [McKenzie and Bickle, 1988] is inconsistent with the seismic data; (4) the continental collision and subsequent thickening of the Anatolian lithosphere [Dewey *et al.*, 1986] is not supported by recent tomographic data; (5) the hot spot activity created by a mantle plume is inconsistent with the topographic expression and fault plane solutions; (6) the delamination of mantle lithosphere beneath the region [Pearce *et al.*, 1990;

Keskin *et al.*, 1998] well explains magma genesis across the region, provided that a sub-continental lithospheric mantle is or was present beneath the region. However, as discussed above, new seismic data reveal that there appears to be no lithospheric mantle over a great area beneath the region. This raises the question of whether a shallow delamination in which the whole lithospheric mantle and even the lower crust are involved could be an alternative model. However, the shallow delamination could not be a viable alternative model, since it requires the presence of a lithospheric mantle to be delaminated, attached to the base of the crust. This is obviously not the case for the area underlain by the EAAC in Eastern Anatolia, because, in contrast to continents, large subduction-accretion complexes are devoid of their own lithospheric roots; (7) as can be seen in the next section, the slab steepening followed by breakoff beneath a subduction-accretion complex appears to be the most viable model, consistent with the geology of the region as well as variations in magma age and chemistry across the region (Figures 1 and 2).

5. Proposed Model for Magma Generation: Slab Steepening and Breakoff

[10] Sengor *et al.* [2003] argue that oceanic realm in the region was closed in a period between Late Eocene and Oligocene when the EAAC made its initial contact with the BPM (Figure 3c). During the period between Late Oligocene and 13–15 Ma, the EAAC was shortened and thickened over the oceanic lithospheric slab (Figure 3d), until the slab was possibly steepened and eventually detached from the EAAC around 10–11 Ma, due to the buoyancy contrast between the slab and the BPM. The detached slab should have completely disappeared in a 10 Myr time-span by sinking into the asthenosphere. The absence of deep earthquakes seems to support this view. New geophysical data indicate that the breakoff may have occurred as shallow as 45–50 km. The release of this huge load followed by the emplacement of less denser astheno-

spheric material beneath the EAAC appears to have been the driving force of the rapid block uplift and volcanism in the region around 10–11 Ma (Figure 3e). The model proposed here differs from the original slab breakoff model of *Davies and von Blanckenburg* [1995] in that it involves a large accretionary prism precluding the opposition of two converging continents, under which a slab gradually gets steepened until it is finally detached. In this model, melting occurs in the asthenospheric mantle and resultant volcanic activity spreads over a large area away from the suture zone. In contrast, in the original model, what melts is the lithospheric mantle and this is generally confined to the suture zone.

[11] *Orgulu et al.* [2003] and *Koçyigit et al.* [2001] suggest that the crustal stress field has changed dramatically in the past 5 to 10 Myr. This change also corresponds with the initiation of wide spread volcanism throughout the eastern Anatolian plateau. Both of these observations are potentially linked to the NeoTethys slab breakoff beneath the region.

[12] The slab steepening and breakoff model appears to better explain geochemical variations in volcanic products across the region than any other proposed models. First of all, it is much easier to generate large volumes of melts by upwelling a relatively hot asthenosphere to shallower depths (~50 km) than having the colder lithospheric mantle heated and melted (e.g., by the delamination model). *McKenzie and Bickle* [1988] demonstrated that upwelling of asthenosphere with a potential temperature of 1280°C generates extensive adiabatic decompression melting at around 50 km. Existence of a subduction component in the mantle promotes melting by decreasing the melting temperature. This might explain why volcanic units erupted in greater volumes in the north around the EKP compared to those in the south. Possible interaction of hot asthenosphere with the EAAC that contains retained water even further decreases the melting temperatures at a given depth, generating extensive melting in the crust. This may account for the great variability in lava chemistry and degree of magma-crust interaction across the region. It may also explain the presence of low velocity zones in the crust detected by seismic studies [*Zor et al.*, 2003] and the lack of earthquakes deeper than ~30 km during the Eastern Turkey Seismic Experiment.

[13] Prior to having been detached around 10–11 Ma, the slab beneath the EAAC was possibly gradually steepened, opening out an asthenospheric mantle wedge gradually widening to the south (Figure 3e). This not only exposed the base of the EAAC to the asthenospheric temperatures, but also created a sucking effect on the asthenosphere, possibly creating a mantle flow to the south. This might account for why the volcanism tended to initiate earlier in the north and then migrated to the south, because the lithosphere in the north was exposed to asthenosphere much earlier. Similarly, this may also provide an answer to why lavas in the north contain a distinct subduction signature that diminishes to the south: the inferred asthenospheric flow possibly pulled a portion of asthenosphere that once had resided beneath the Pontide arc and hence contained a distinct subduction component (Figure 3e). However, as most of the EKP overlies the Pontide basement, the delam-

ination of lithospheric mantle may still account for magma generation in the north beneath the EKP.

6. Conclusion

[14] In the light of these results, perhaps it is fair to say that Eastern Anatolia is, in fact, not like Tibet or any other collision setting; rather it has its own identity both in terms of its crustal/lithospheric structure and plate tectonic history. Slab steepening and breakoff beneath the EAAC appears to be the major controlling mechanism for the collision-related magma genesis in the region although other mechanisms such as delamination and localized extension related to strike slip faulting might also contribute to magma generation.

References

- Al-Lazki, A., D. Seber, E. Sandvol, N. Turkelli, R. Mohamad, and M. Barazangi, Tomographic Pn velocity and anisotropy structure beneath the Anatolian plateau (eastern Turkey) and the surrounding regions, *Geophys. Res. Lett.*, 30(24), doi:10.1029/2003GL017391, 2003.
- Davies, J. H., and F. von Blanckenburg, Slab breakoff: A model of lithosphere detachment and its test in the magmatism and deformation of collisional orogens, *Earth Planet. Sci. Lett.*, 129, 85–102, 1995.
- Dewey, J. F., M. R. Hempton, W. S. F. Kidd, F. Saroglu, and A. M. C. Sengor, Shortening of continental lithosphere: The neotectonics of Eastern Anatolia—a young collision zone, in *Collision Tectonics*, Geological Society special publications no: 19, edited by M. P. Coward and A. C. Ries, 3–36, 1986.
- Ercan, T., T. Fujitani, J.-I. Madsuda, K. Notsu, S. Tokel, and U. I. Tadahide, Dogu ve guneydogu Anadolu Neojen-Kuvaterner volkanitlerine ilişkin yeni jeokimyasal, radyometrik ve izotopik verilerin yorumu, *M.T.A. Dergisi*, 110, 143–164, 1990.
- Gok, R., N. Turkelli, E. Sandvol, D. Seber, and M. Barazangi, Regional wave propagation in Turkey and surrounding regions, *Geophys. Res. Lett.*, 27(3), 429–432, 2000.
- Keskin, M., J. A. Pearce, and J. G. Mitchell, Volcano-stratigraphy and geochemistry of collision-related volcanism on the Erzurum-Kars Plateau, North Eastern Turkey, *J. Volcanol. Geothermal Res.*, 85(1–4), 355–404, 1998.
- Koçyigit, A., A. Yilmaz, S. Adamia, and S. Kuloshvili, Neotectonics of East Anatolian Plateau (Turkey) and Lesser Caucasus: implication for transition from thrusting to strike-slip faulting, *Geodinamica Acta*, 14(1–3), 177–195, 2001.
- McKenzie, D. P., Active tectonics of the Mediterranean, *Geophys. J. R. Astr. Soc.*, 30(2), 109–185, 1972.
- McKenzie, D. P., and M. J. Bickle, The volume and composition of melt generated by extension of the lithosphere, *J. Petrol.*, 29, 625–679, 1988.
- Orgulu, G., M. Aktar, N. Turkelli, E. Sandvol, and M. Barazangi, Contribution to the Seismotectonics of the Eastern Anatolian Plateau from Moderate and Small Size Events, *Geophys. Res. Lett.*, 30(24), doi:10.1029/2003GL018258, 2003.
- Pearce, J. A., J. F. Bender, S. E. De Long, W. S. F. Kidd, P. J. Low, Y. Guner, F. Saroglu, Y. Yilmaz, S. Moorbath, and J. G. Mitchell, Genesis of collision volcanism in Eastern Anatolia, Turkey, *J. Volcanol. Geothermal Res.*, 44, 189–229, 1990.
- Rotstein, Y., and A. L. Kafka, Seismotectonics of the southern boundary of Anatolia, eastern Mediterranean region, subduction, collision and arc jumping, *J. Geophys. Res.*, 87, 7694–7706, 1982.
- Sengor, A. M. C., and W. S. F. Kidd, Post-collisional tectonics of the Turkish-Iranian Plateau and a comparison with Tibet, *Tectonophysics*, 55, 361–376, 1979.
- Sengor, A. M. C., S. Ozeren, E. Zor, and T. Genc, East Anatolian high plateau as a mantle-supported, N-S shortened domal structure, *Geophys. Res. Lett.*, 30(24), doi:10.1029/2003GL017858, 2003.
- Zor, E., C. Gurbuz, N. Turkelli, E. Sandvol, D. Seber, and M. Barazangi, The crustal structure of the East Anatolian Plateau from receiver functions, *Geophys. Res. Lett.*, 30(24), doi:10.1029/2003GL018192, 2003.