Mantle lithosphere delamination driving plateau uplift and synconvergent extension in eastern Anatolia

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ABSTRACT

Eastern Anatolia is the site of lithospheric thinning, plateau uplift, heating, and synconvergent extension. Using numerical geodynamic experiments, we test the hypothesis that these tectonic anomalies are all related and the consequence of delamination of the mantle lithosphere. Our findings indicate that delamination during plate convergence results in ~2-km-high plateau uplift. The removal of mantle lithosphere induces distinct regions of contraction and thickening, as well as extension and thinning of the crust. The latter occurs even within a regime of plate shortening, although it is muted with increasing plate convergence. Detachment of the delaminating slab results in minor surface topographic perturbation, but only above the delamination hinge. The plateau uplift and pattern of surface contraction and/or extension are consistent with a topographic profile at 42°E and geologically interpreted zone of synconvergent extension at eastern Anatolia.

Keywords: Eastern Anatolian plateau, delamination, lithospheric thinning, synconvergent extension.

INTRODUCTION

The Eastern Anatolian plateau has formed as part of a Himalayan-type orogenic system through the collision of the Arabian and Eurasian plates (Fig. 1A). Based on receiver function studies, the crust beneath the plateau is only 38–50 km thick (Zor et al., 2003); hence it has been suggested that the high topography is not isostatically supported by a thick crustal root (Şengör et al., 2003; Keskin, 2003). Furthermore, seismic data for eastern Anatolia are interpreted as evidence for the complete absence of the mantle lithosphere beneath the plateau (Gok et al., 2007) (Fig. 1B) and are consistent with high heat flow and volcanic activity (e.g., Nemrut, Suphan, and Agri-Ararat volcanoes) across eastern Anatolia.

Large-scale plate deformation in the region is dominated by plate convergence with shortening and contraction, but normal fault–controlled extensional basins such as the Kagizman-Tuzluca, Hinis, Karliova, and Mus basins are well documented (Dhont and Chorowicz, 2006) within the plateau. Such extensional features, as well as the presence of the young volcanics, are notable because their stress orientations are inconsistent with E-W extensional deformation. Rather, the inferred extension seems to be oriented ~N25°E. Global positioning system measurements slightly to the west of this region also indicate local extension, but directed N-NW (Reilinger et al., 2006). Although there is some discrepancy in the precise orientations, the geology and geodesy both suggest extension in the same general direction and contemporaneous with the dominant plate convergence.

Anderson (2005) suggested that topographic uplift with widespread volcanism in eastern Anatolia may be related to lithospheric delamination in the manner defined by Bird (1979). That is, mantle lithosphere is removed as a coherent slice by peeling away along the crust-mantle boundary or at the upper margin of the anomalously dense lower crust (Anderson, 2007). In the light of the observations given above, a slab break-off model was proposed by Şengör et al. (2003) and Keskin (2003). These studies suggest that break-off of the northward-subducting oceanic Arabian plate in the past 7–8 m.y. has caused domal uplift and volcanic activity in eastern Anatolia through rising mantle. We note that although Şengör et al. (2003) and Keskin (2003) did not use the term delamination, they implicitly assumed a delamination-style separation of the mantle lithosphere from the crust prior to its detachment beneath the entire plateau.

Alternatively, Ershov and Nikishin (2004) proposed a mantle plume scenario for eastern Anatolia. However, petrological and geophysical evidence, e.g., the migration of the volcanism from north to south within the plateau and its change in the chemistry (calc-alkaline to alkaline) (Keskin, 2003) and seismic tomographic interpretations of the detached slab beneath the plateau (Lei and Zhao, 2007), does not favor the viability of a plume model.

Here we propose that all the primary tectonic anomalies for Eastern Anatolia plateau uplift and heating, but also the notable presence of synconvergent crustal extension, may be related as the coupled response of the crust to active underlying mantle dynamics during plate collision. Using computational geodynamic models, we test whether the geological and geophysical observables are consistent with delamination of the mantle lithosphere. Any mantle lithosphere removal in eastern Anatolia progresses within a convergent plate regime, so we conduct a series of experiments with variable rates of the imposed convergence of the delaminated slab and with higher yield strength of the mantle lithosphere. The mantle lithosphere is permitted to detach and we consider how slab break-off modifies the surface tectonic expression.

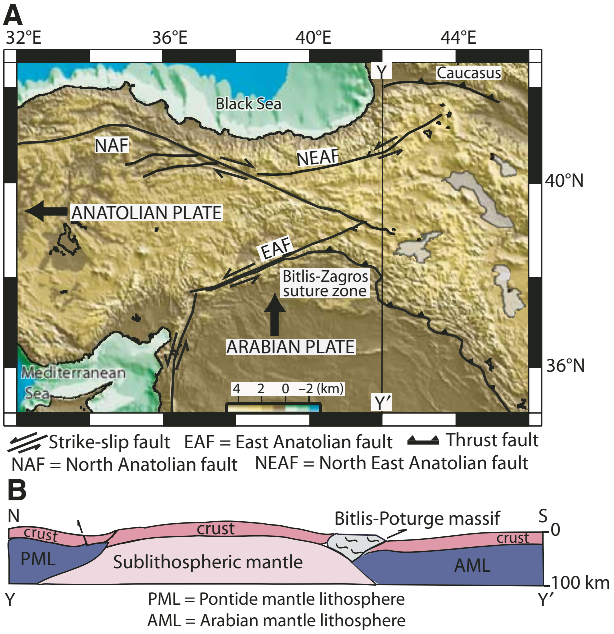

Figure 1. A: Topographic map of eastern Anatolia created with generic mapping tools (GMT) showing the major tectonic boundaries. B: Lithospheric structure beneath eastern Anatolia modified from Şengör et al. (2003), Dhont and Chorowicz (2006), Gok et al. (2007), and Keskin (2003).

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MODELING DELAMINATION

In our numerical experiments, we used a plane strain viscous-plastic finite element code, SOPALE (Fullsack, 1995; Pysklywec et al., 2002). The configuration of the model (Fig. 2A) is designed as an idealized representation of the continent-continent plate boundary at eastern Anatolia. We impose a convergence velocity V_{AR} to the northern edge of the Arabian lithosphere and pin the southern edge of Eurasian lithosphere at $V_{EU} = 0$ (Fig. 2A). The top of the box is a free surface. A viscous flow law of $\dot{\varepsilon} = A\sigma^n \exp\left(\frac{-Q}{RT}\right)$ is used for viscous material response, where $\dot{\varepsilon}$ is the strain rate, T is temperature, and σ is differential stress. A, n, Q, and R are the viscosity parameter, power law exponent, activation energy, and ideal gas constant, respectively. For mantle $A = 4.89 \times 10^{-17}$ Pa$^{-3.5}$/s, $n = 3.5$, $Q = 535$ kJ/mol (Hirth and Kohlstedt, 1996), and a Coulomb yield stress of 120 MPa are used. For continental crust $A = 1.1 \times 10^{-28}$ Pa^{-4}/s, $n = 4$, and $Q = 223$ kJ/mol are used based on wet quartzite (Gleason and Tullis, 1995). In addition, the upper crust has a brittle Coulomb behavior with an internal angle of friction $\phi = 15°$. Density, ρ, is a function of composition and temperature (using $\alpha = 2 \times 10^{-5}$ 1/K).

A low viscosity (5×10^{19} Pa s) weak zone is inserted between a portion of the crust and mantle lithosphere to initiate the delamination process (e.g., Morency and Doin, 2004). We recognize that anomalously dense (e.g., eclogitized) lower crust may also participate in the removal. However, the model setup is simplified by assuming that such crust is already descending with the mantle lithosphere.

Figure 2A shows the evolution of our reference model that may correspond to the evolution of the mantle lithosphere in eastern Anatolia, where $V_{AR} = 3.0$ cm/yr. At time, $t = 1.2$ m.y. the mantle lithosphere is delaminating from the crust, exposing a Moho width of ~300 km to the mantle. Subsequently, hot and buoyant sublithospheric mantle flows into the region vacated by the peeling mantle lithosphere. The rapid nature of the delamination means that the high mantle temperatures are efficiently advected upward, heating the lower crust (Gogus and Pysklywec, 2008). The delaminated mantle lithosphere is bent steeply into the mantle but remains intact as a coherent plate, i.e., as opposed to a viscous dripping-type removal. Between 2.9 and 7.0 m.y., there is detachment and/or break-off of this mantle lithosphere slab. At the latest stage shown ($t = 7.0$ m.y.), the Eurasian mantle lithosphere on the left side undergoes a much more subdued delamination as it is eroded by the mantle flow.

SURFACE TOPOGRAPHY AND CRUSTAL DEFORMATION

At $t = 1.2$ m.y., negative surface topography (~−2.8 km) develops as the crust is pulled down by the dense delaminating mantle lithosphere (Fig. 2B). Flanking uplift features arise as a consequence of upward return flow and replacement of less dense mantle in the mantle lithosphere gap (Fig. 2A). Crustal contraction, driven by entrainment toward the downgoing mantle lithosphere and the imposed convergence, is subtly visible within the Lagrangian mesh (Fig. 2A). Note that the negative surface topography is observed at the surface, even though the crust has thickened by ~5 km.

At $t = 2.9$ m.y., positive surface topography dominates with a peak near the delaminating gap where upwelling flow is most vigorous. Inspection of the Lagrangian mesh elements also shows that there is localized crustal contraction, with ~12.5 km crustal thickening and as much as 30% shortening near the hinge (Figs. 2A and 2B). At the center of the lithospheric gap, crustal extension of ~30% and thinning of as much as several kilometers are observed (Fig. 2A). This extension and thinning are notable as internally driven tectonic processes within the overall convergent plate regime.

By $t = 7.0$ m.y., the surface topography is characterized by plateau-type uplift with

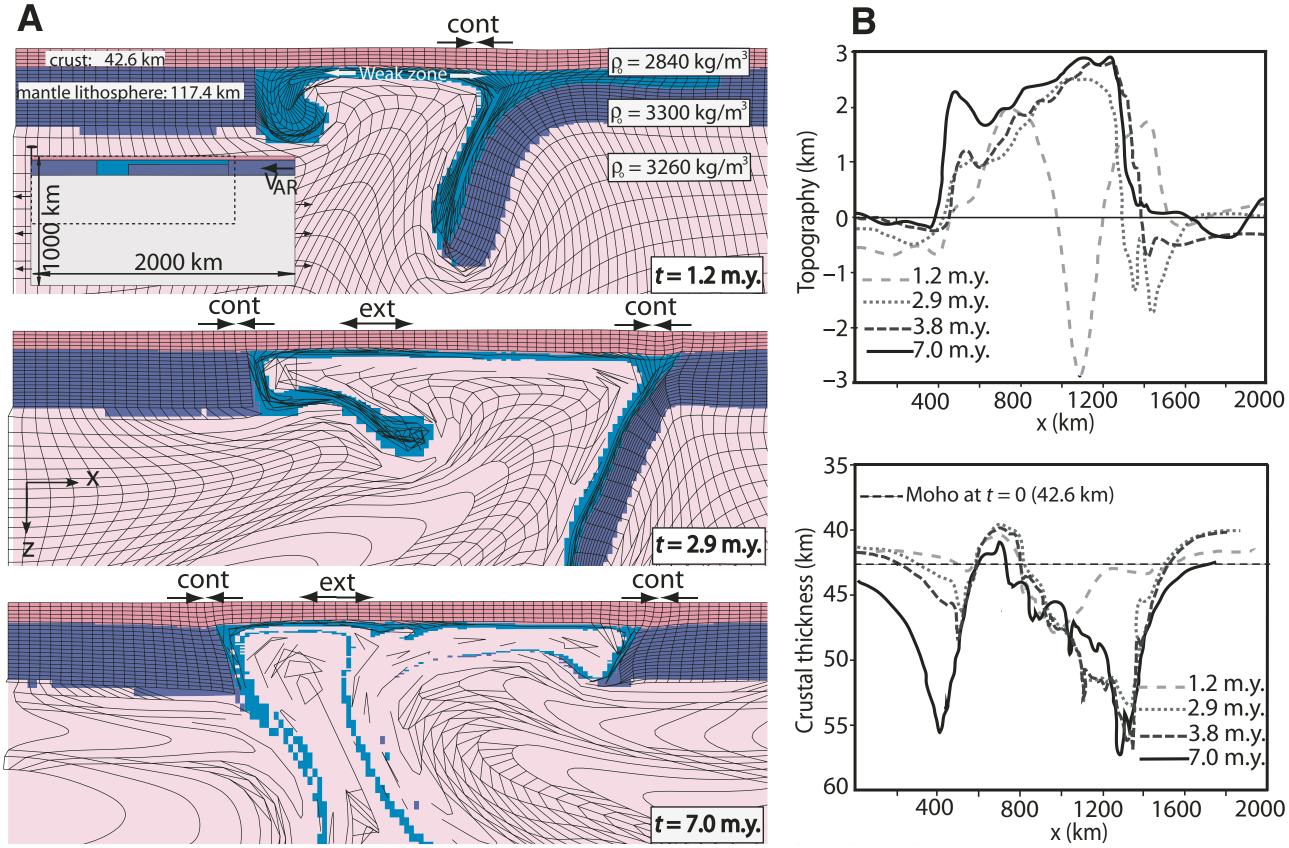

Figure 2. A: Progressive evolution of mantle lithosphere delamination for modeled eastern Anatolia. B: Plots of surface topography and crustal thickness; ext—extension, cont—contraction. Dashed line at 42.6 km represents initial crustal thickness.

average values of >2 km (Fig. 2B). The subsidence has disappeared since the delaminated slab has detached (Figs. 2A and 2B). A zone of much thinner crust persists above the gap, although the extensional forcing from the delamination is being overtaken by the continued lithospheric convergence.

We illustrate how variable rates of plate shortening from $V_{AR} = 0$ and $V_{AR} = 6$ cm/yr modify the results (Figs. 3A and 3B). In the former case at $t = 2.9$ m.y., delamination causes an uplift and subsidence pattern above the lithospheric gap and delaminating lithosphere. Zones of crustal extension and thinning, as well as contraction and thickening, develop; again, paradoxically to the patterns of uplift and subsidence. However, the extension and thinning are much more pronounced with ~15 km crustal thinning in this model since there is no imposed plate convergence. Clearly, the delamination process alone is effective for stretching the crust. A broad topographic uplift develops by $t = 7.0$ m.y. (Fig. 3A), although it is not as regular and plateau-like as in the reference model (Fig. 2B). With an increased convergence velocity of $V_{AR} = 6.0$ cm/yr there is accelerated contraction and thickening of the crust during the delamination event (Fig. 3B). The surface topography is significantly elevated by $t = 2.9$ m.y. and most of the crust has thickened from its initial value. Any subsidence due to loading from the delaminated slab is overwhelmed by uplift from the widespread crustal thickening. By $t = 7.0$ m.y., a broad plateau of thickened crust has developed.

In Figure 3C, we show a model in which the yield stress of the mantle lithosphere is doubled to $\sigma_Y = 240$ MPa compared to the reference model. The stronger mantle lithosphere is less prone to detachment. This does not cause much difference in the evolution of surface topography and crustal thickness (cf. Figs. 3C and 2B), except at the hinge zone where the delaminating slab is hanging. At $t = 3.8$ m.y., the stronger mantle lithosphere is still attached and consequently there is a narrow zone of ~1.3 km surface subsidence at x = 1200 km (Fig. 3C). At the same time, with the weaker mantle lithosphere that has detached, this subsidence has diminished to ~500 m (Fig. 2B).

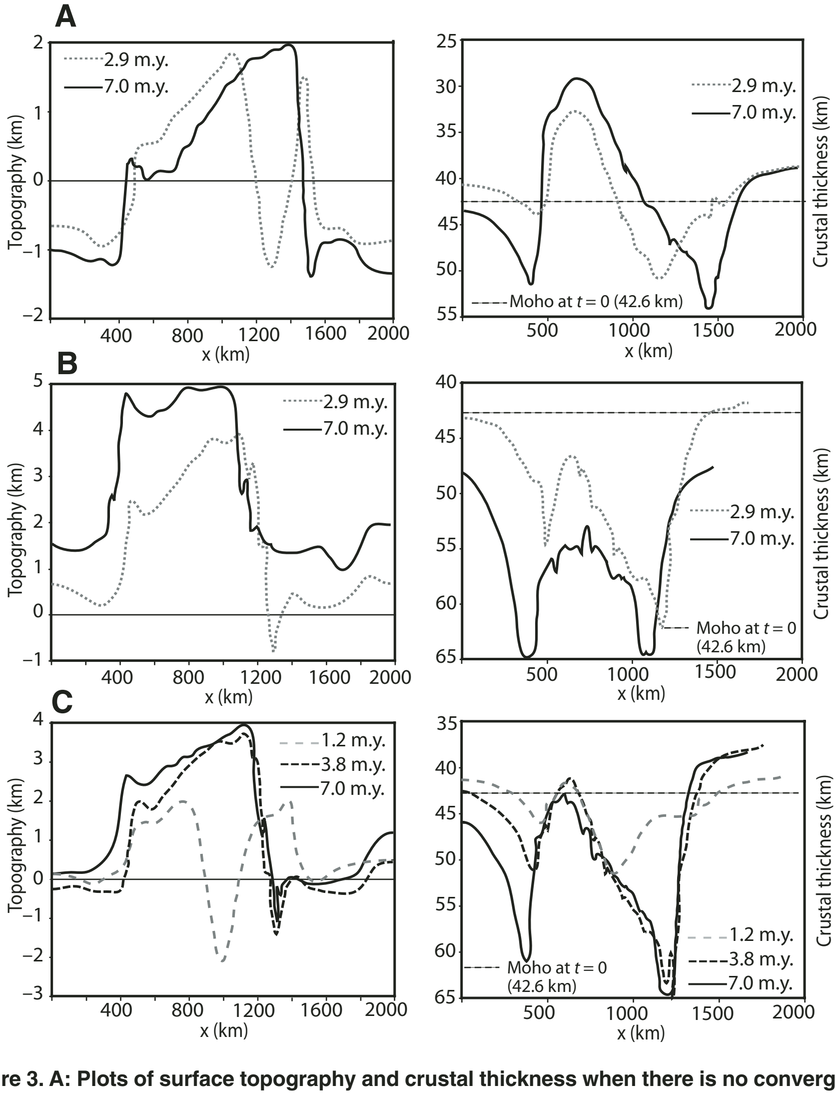

Figure 3. A: Plots of surface topography and crustal thickness when there is no convergence velocity imposed ($V_{AR} = 0$). B: Plots of surface topography and crustal thickness of model when convergence velocity is increased to $V_{AR} = 6.0$ cm/yr. C: Plots of surface topography and crustal thicknesses when yield stress of mantle lithosphere is doubled to $\sigma_Y = 240$ Mpa.

DELAMINATION BENEATH EASTERN ANATOLIA

A comparison of model surface topography at 7.0 m.y. and present-day surface topography across eastern Anatolia (at 42°E) demonstrates a similar plateau uplift (Fig. 4A). It has been suggested that eastern Anatolia emerged from sea level ~11 m.y. ago, a time scale similar to that of modeled delamination events. The short-wavelength topographic features in the observed profile are related to geomorphologic processes not included in our models. The long-wavelength plateau uplift of eastern Anatolia is consistent with delamination removal of mantle lithosphere across an ~500-km-wide zone.

Figure 4B demonstrates that both eastern Anatolian and modeled crust are relatively thin across the middle of the plateau; however, only in the latter case is the crust thickened at the plateau flanks. Several factors may account for this. The models do not include material transformations that could result in removal of the lower parts of the thickened crust (Jull and Kelemen, 2001). It is possible that anomalously thinner crust in the northern part of the Bitlis suture zone may be due to post-delamination removal of eclogitic lower crust. Perhaps most significantly, our two-dimensional models present an upper bound on the amount of crustal thickening since they do not permit extrusion of material out of the plane. For eastern Anatolia, recent geodetic measurements suggest that as much as ~70% of the Arabian-Eurasian plate convergence is accommodated by lateral extrusion of the Anatolian plate (Reilinger et al., 2006). It may be that if this extrusion is permitted in the models, predicted anomalous topography from delamination may be reduced.

Most interesting is a comparison of horizontal surface strain rate ($\dot{\varepsilon}_{xx}$) in the model and primary structural features across eastern Anatolia (Figs. 4C and 4D). Within the model there is a zone of surface extension that corresponds with observed anomalous extensional features, such as E-W–trending normal fault-controlled structures (Mus, Hinis, and Karliova basins and the Nemrut and Agri volcanic calderas). The northern and southern ends of the extensional zone are associated with contractional deformation. In the south, this zone may be represented with the large-scale Bitlis-Zagros suture zone, and in the north, such contractional deformation may correspond to development of the thrust fault–controlled Pasinler and Erzurum basins.

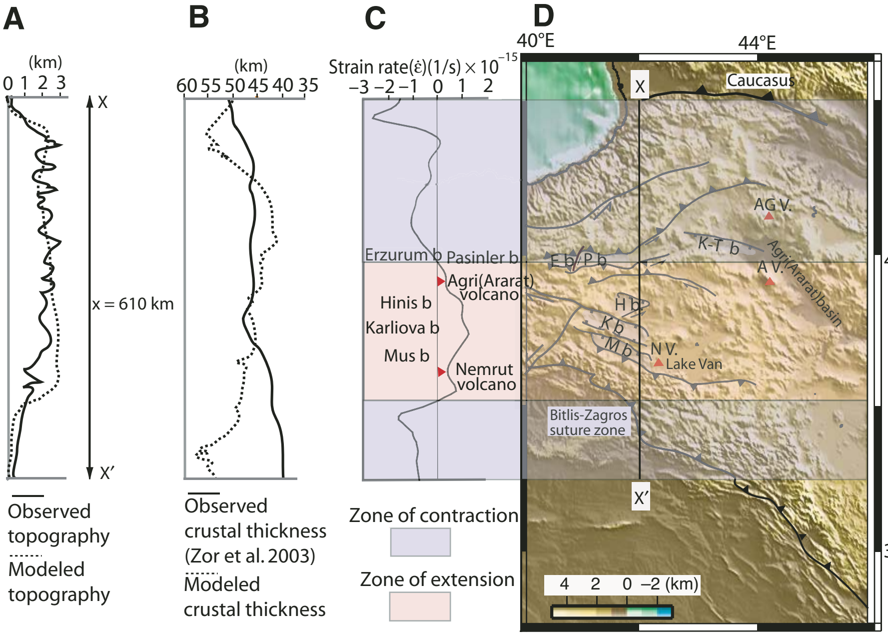

Figure 4. A: Modeled (reference model; 7 m.y.) and observed surface topography at 42°E. B: Modeled and observed (Zor et al., 2003) crustal thickness both were taken along 42°E. C: Modeled horizontal surface strain rate ($\dot{\varepsilon}_{xx}$), where in our convention, positive strain rate is extensional; b—basin. D: Structural map of eastern Anatolia. All modeled plots are scaled into zone of 610 km within plateau.

CONCLUSIONS AND DISCUSSION

The geodynamic experiments demonstrate that delamination causes surface uplift as a result of the isostatic and dynamic effect of lithospheric removal. The uplift is enhanced and evened into a plateau by plate shortening. A pulse of (migrating) subsidence can develop as the delaminating lithosphere loads the lithosphere at the hinge zone.

Lithospheric delamination causes distinct zones of contraction and thickening (at the plateau flanks) and extension and thinning (within the plateau, to the far side of the delaminating hinge) within the crust. The crustal extension and thinning can occur within an overall plate convergent regime, but it becomes more muted with higher rates of plate shortening.

Such synconvergent extension is a common, yet largely enigmatic phenomena at many collisional environments. For example, it has been observed at the Apennines-Tyrrhenian, Himalayas, and Alboran Sea–Rif–Betics. The Alboran Sea is currently undergoing subsidence rather than plateau uplift, but as our experiments show, surface subsidence is the early-stage response to mantle lithosphere delamination before the inversion to uplift (Fig. 2B).

Detachment (or break-off) of the delaminated slab modifies the surface topography. However, the effect is confined largely to a narrow region close to the delamination hinge (i.e., within ~100 km). We suggest that the surface effects of detachment (sensu stricto) do not span a large, well-developed continental collision like eastern Anatolia.

The upwelling mantle flow with delamination also has significant thermal and metamorphic consequences for the crust. We do not focus on the thermal consequences of delamination in this contribution, but a different study demonstrates that delamination removal of the mantle lithosphere results in rapid heating of the base of the crust and likely a migrating pulse of high-temperature, low-pressure metamorphism (Gogus and Pysklywec, 2008). Thus, delamination of mantle lithosphere would possibly reconcile the high heat flow and volcanism that occur across eastern Anatolia (Keskin, 2003).

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