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A Simple Model for Plate Motion and Topography

Tektonik Levha Hareketiyle Oluşan Topoğrafyanın Fiziksel Modeli

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Abstract: The traditional explanation of slow dynamic subsidence and uplift of tectonic plates solely depends on the vertical motion of mantle density anomalies. This has been challenged by observations of rapid and short-lived elevation changes exceeding 100 meters per-million-year in numerous sedimentary basins. Bodur et al., (2023) have shown that relative tectonic plate motion and associated basal shear stress can explain those rapid and short-lived elevation changes. In this paper, I suggest a basic approach to quantify elevation changes resulting from basal shear stress by employing torque-balance calculations. The results confirm the existing flow model solution and offer a more robust formula for estimating the impact of plate motion on changes in Earth's topography. Such functionality may prove invaluable in various applications including interpretation of stratigraphic records.

Keywords: Basal shear stress, dynamic topography, Earth's topography, stratigraphy, tectonic plate motion, torque balance.

Öz: *Kıtaların dinamik olarak yavaşça alçalması ve yükselmesi, Dünya'nın mantosundaki yoğunluk anomalilerinin (alçalan yitmiş levha ya da manto yükselmesi) hareketine dayandırılır. Ancak, birçok sedimanter havzada milyon yıl başına 100 metreyi aşan hızlı ve kısa ömürlü yükseklik değişikliklerinin gözlemleri, sadece bu mekanizmanın dinamik dikey kıta hareketlerini tetiklediği görüşünü sorgulatmıştır. Bodur vd. (2023) tektonik yatay levha hareketinin ve bununla ilintili taban kayma gerilmesinin, gözlemlenen hızlı ve kısa ömürlü kıta yükselme ve alçalmalarını açıklayabileceğini göstermiştir. Bu makalede, taban kayma gerilmesinden kaynaklanan kıtasal yükseklik değişikliklerini nicelendirmek için tork-denge hesaplamalarını kullanarak temel fiziksel bir yaklaşım öneriyorum. Elde ettiğim sonuçlar, mevcut akış modeli çözümünü doğrulamakta ve Dünya'nın topoğrafyasındaki levha hareketinin etkisini tahmin etmek için daha kolay kullanılabilir bir formül sunmaktadır. Bu tür işlevsellik, stratigrafik kayıtların yorumlanması dahil olmak üzere birçok uygulamada faydalı olabilir.*

Anahtar Kelimeler: *Dünya'nın topoğrafyası, dinamik topoğrafya, kayma gerilimi, stratigrafi, tektonik levha hareketi, tork dengesi.*

INTRODUCTION

Cold and dense slabs sink into the Earth's mantle, pulling down the base of tectonic plates. Simultaneously, the upward movement of the Earth's hot mantle pushes against the plates, causing them to rise in response. Basins and plateaus can be formed by these processes extending across thousands of kilometres (Morgan, 1965; Pysklywec and Mitrovica, 1997;

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Gurnis et al., 1998). The amplitudes of topography predicted by dynamic topography models vary significantly; reaching 2,000 m (e.g., Flament et al., 2013; Steinberger, 2007) or lower than 300 m (Molnar et al., 2015). The viscosity of the mantle limits the rate at which internal mantle flow fields change and nonlinear rheology tends to decrease dynamic topography amplitudes (Bodur and Rey, 2019). Although complex viscosities in the upper mantle can result in higher vertical surface motions, dynamic topography models typically predict vertical motions less than 100 metres per million years (Myr) over a duration of a few tens of Myr (Gurnis et al., 1998; Moucha et al., 2008; Flament et al., 2013). During periods of relative sea-level and tectonic stability, there is direct geological evidence that phases of uplift and subsidence have occurred at rates exceeding 100 m Myr^{-1} in less than a few Myr (e.g., Gurnis et al., 2020; Pedoja et al., 2011).

These rates and periods are inconsistent with eustasy (e.g., Miller et al., 2020), and typical estimates of dynamic topography based on mantle convection models (Petersen et al., 2010; Gurnis et al., 2020). That does not rule out the fact that dynamic topography models can predict higher vertical motion rates; however, they have not been shown to explain the brief (lasting for a few Myr) and rapid (>100 m Myr^{1}) subsidence of sedimentary basins during tectonic and eustatic stability. Bodur et al. (2023) have shown that variation in basal shear stress of a few MPa due to change in relative horizontal plate motion can induce brief elevation changes equivalent in magnitude to those induced by sea-level changes, and at rates of elevation change comparable to those measured in sedimentary basins. This mechanism can be considered as another type of dynamic topography, although it is driven by shear stress rather than normal stress at the base of tectonic plates.

In this paper, a similar approach is considered but a simpler solution is derived by using torque-balance calculations for a plate-asthenosphere system to quantify elevation changes driven by basal shear stress. The results confirm the existing flow model solution and offer a simple formula for estimating the impact of plate motions on changes in Earth's topography.

TILTING of PLATES by BASAL SHEAR STRESS

A plate which is in horizontal motion relative to the underlying asthenosphere will be subject to a basal stress. Figure 1 depicts a rigid lithosphere of length L experiencing a rotation (i.e., torque) due to applied basal stress from underneath.

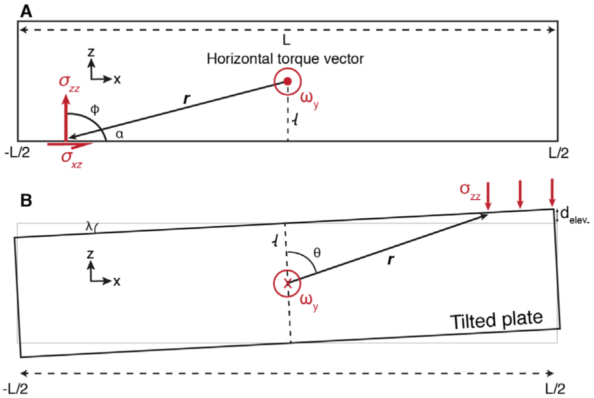

Figure 1. Free body diagrams for calculating the torque arising from **A)** applied basal shear and normal stress, and **B)** gravitational load of the tilted plate.

Şekil 1. A) *Levha tabanına etki eden yatay taban kayma gerilimi ve düşey gerilimin meydana getirdiği torkun hesaplanmasında kullanılan serbest cisim diyagramı.* ***B)*** *Tork sonucu eğilen levhanın yerçekimsel yükünün oluşturduğu dengeleyici torkun hesaplanmasında kullanılan serbest cisim diyagramı.*

The torque $\omega(\hat{y})$ applied by basal stresses on the lithosphere is calculated by taking the surface integral of the vector product of the distance vector (r) and the total stress vector (shear and normal stresses):

$$\omega(\hat{y}) = \int r \times [\tau_{xz}\hat{\imath} + \sigma_{zz}\hat{z}]da \quad (1)$$

where (i) and ($\hat{z}$) are unit normal vectors in x and z directions, respectively. The torque per unit width is:

$$\omega_w(\hat{y}) = \int r \times [\tau_{xz}\hat{\imath} + \sigma_{zz}\hat{z}]dx = \int r \times (\tau_{xz}\hat{\imath})dx + \int r \times (\sigma_{zz}\hat{z})dx \quad (2)$$

$$\omega_w = \int r\tau_{xz}\sin(\alpha)dx + \int r\sigma_{zz}\sin(\phi)dx \quad (3)$$

where α and ϕ are the angles indicated in Figure 1B. The plate extends from -L/2 to L/2. If I rewrite the harmonic terms, it becomes:

$$\omega_w = \int_{-L/2}^{L/2} \tau_{xz} l dx + \int_{-L/2}^{L/2} \sigma_{zz} x dx \quad (4)$$

where l is the distance between the base of the plate and its centre of mass. For simplicity, I assume that the lithosphere is homogenous, and the centre of mass lies at the geometrical centre of the plate, therefore l indicates half of the plate thickness.

I consider a constant basal shear stress, whereas the normal stress varies linearly along the plate, such that $\sigma_{zz} = \Omega x$ where Ω is constant.The horizontal torque per unit width is:

$$\omega_w = l\tau_a L + \Omega\frac{L^3}{12} \quad (5)$$

Once the plate is tilted, there will be counter-balancing torque due to gravitational load of the tilted plate. The amount of tilt will be determined by the arrangement where the net torque will be zero.

I assume the plate is tilted with a slope of λ in radians upward to the right and downward to the left. The increased lithostatic stress applies a torque in -*y* direction (Figure1B). The counter-balancing torque per unit width of the plate becomes:

$$\omega tilt_w = -\int r \times (\sigma_{zz}\hat{z})dx \quad (6)$$

$$\omega tilt_w = -\int_{-L/2}^{L/2} rgh(x)\rho_{lith}\sin(\theta)dx \quad (7)$$

where *h(x)* is the topography varying with the x coordinate, ρ_{lith} is the average density of the lithosphere, and g is the gravitational acceleration. According to Figure1B *h(x)*=sin(λ)≈λx and sin*(θ)*=x/r.

Therefore:

$$\omega tilt_w = -\lambda\rho_{lith}g\frac{L^3}{12} \quad (8)$$

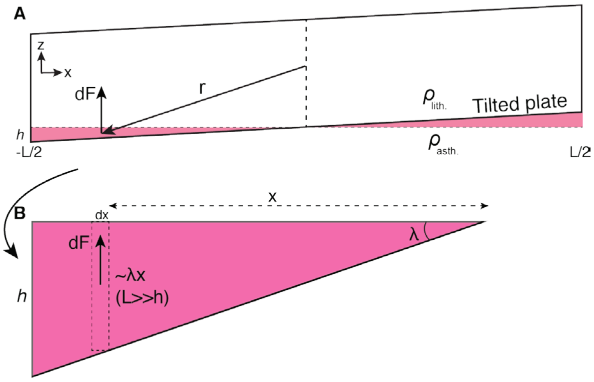

Figure 2. Free body diagrams for calculating the counter-balancing torque applied to a tilted plate due to the buoyancy of the asthenosphere.

Şekil 2. *Astenosferin kaldırma kuvvetinin eğik bir levha üzerinde oluşturduğu dengeleyici torkun hesaplanmasında kullanılan serbest cisim diyagramı.*

According to Archimedes' principle, the tilt of the plate induces a buoyant force applied at the centre of the displaced volume of the asthenosphere, due to the density difference between the average lithospheric density and asthenospheric density (Figure 2). This also contributes to counter-balancing the torque induced by the basal shear stress. The buoyancy torque per unit width around the centre of mass of the plate can be calculated by the integral below:

$$\omega buoy_w = -\int_{-L/2}^{L/2} -\rho_{asth}\, g\lambda x^2 dx \tag{9}$$

$$\omega buoy_w = -\rho_{asth} g\lambda \frac{L^3}{12} dx \tag{10}$$

The condition that when the plate reaches equilibrium, the sum of the torques $(\omega_w + \omega tilt_w + \omega buoy_w)$ must vanish, giving:

$$-\lambda g \frac{L^3}{12}(\rho_{asth} + \rho_{lith}) + L\tau_a l + \Omega \frac{L^3}{12} = 0 \tag{11}$$

A more accurate calculation can be done by considering all density boundaries within the plate (i.e. crust-air or crust-water, crust-mantle lithosphere and lithosphere-asthenosphere boundaries), but for simplicity, I assume one representative density (i.e.,ρ_{avg}) for the lithosphere. Equation 5 and 11 indicate that in the absence of normal stres (Ω=0), shear stress (τ_a) on its own can produce topography. If I assume that the average density of the asthenosphere and the lithosphere are equal ρ_{avg}=ρ_{asth}=ρ_{lith}, I can simplify the contribution of the basal shear stress to the plate's topography (h_{basal}) as follows:

$$h_{basal} = \frac{3\tau_a l}{\rho_{avg} g L} \tag{12}$$

where I used the identity $(\lambda = \frac{2L}{h_{basal}})$ from Figure 1. This shows that the induced plate topography scales linearly with the basal shear stress and the distance between the centre (centre of mass) of the plate and the surface, and it is inversely proportional to the plate length.

RESULTS

Estimations on basal shear stress vary between ~0.3 MPa (van Benthem and Govers, 2010) and ~30 MPa (Barba et al., 2008), but this large variation arises from assumptions on the rheology of the plate and asthenosphere (Melosh, 1977). For a conservative shear stress value of 1 MPa acting on the base a 200 km-thick plate, I find that the induced topography is ~±4 m for a 2,000-km-long plate (dashed line in Figure 3). The induced topography increases to ~±9 m for a shorter, 1,000-km-long plate with the same amount of shear stress (Figure 3). For the same plate length (i.e., 1,000 km) and same plate thickness (i.e., 100 km-thick plate), an increase in shear stress from 1 MPa (dashed line in Figure 3) to 5 MPa (solid line in Figure 3) increases the amplitude of topography to ~±23 m. The amplitude of topography predicted by basal shear stress is one to two orders of magnitude smaller than those predicted by dynamic topography models (between 300 m and 2,000 m) and oceanic residual depth anomalies (between 500 m and 1,000 m), (Hoggard et al., 2016), but closer in magnitude (between 20 m and 100 m) to the global sea-level changes (Haq et al., 1987; Haq 2014). These indicate that fluctuations in basal shear stress can trigger elevation changes comparable to changes in sea level over a wide tectonic plate.

Bodur et al. (2023) have shown that the elevation change due to basal shear stress is independent of the lid viscosity for an iso-viscous assumption, although I note that the magnitude of the basal shear stress (and therefore the viscosity) does impact the amplitude of topography. The same study has also shown that the rate of elevation changes can exceed 100 m My^{-1}, especially at longer wavelengths (>1,000 km). This rate is strictly determined by the viscosity of the lid, but the viscosity stratification in the lithosphere had a rather small effect (±10%) on the rate of elevation change at long wavelengths. The solution I provided here using the torque-balance method cannot provide an estimate for the rate of uplift/subsidence due to neglecting the viscosity in the calculations.

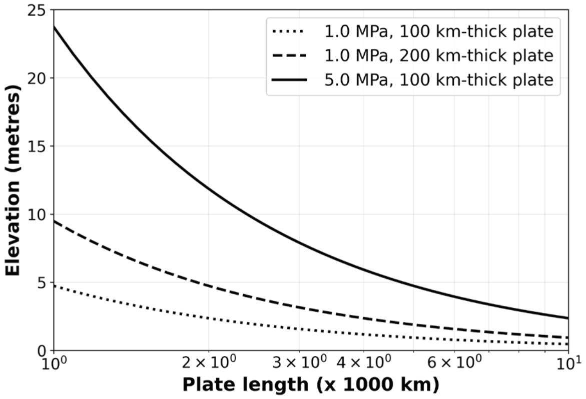

Figure 3. Elevation change in varying plate lengths for different basal shear stress amplitude and plate thickness.

Şekil 3. *Farklı taban kayma büyüklüğü ve levha kalınlıkları için değişen levha uzunluklarında meydana gelen yükseklik değişimlerinin grafiği.*

DISCUSSION

The traditional explanation of dynamic subsidence and uplift of tectonic plates through vertical motion of mantle density anomalies has been challenged by observations of rapid and short-lived elevation changes exceeding 100 m Myr^{-1}. Bodur et al. (2023) have shown that the relative plate motion and associated basal shear stress can explain rapid vertical motions of plates such as the brief immersion of The Eucla Basin of Australia in the mid-Eocene. In this paper, I derived a simple equation for topography induced by relative horizontal plate motion by employing the torque-balance method. Eqn. 12 and Figure 3 show that small fluctuations in basal shear stress can induce elevation changes that can be significant when considered for various relevant Earth systems.

Brief immersions of plates can trigger hydrothermal activity (Zhu et al., 2011), leading to the alteration of rocks and the formation of mineral assemblages. The inherited source-to-sink systems can be significantly altered after a rapid regional or plate-scale uplift/subsidence. The Eucla Basin is one of the prime examples of such, and basal shear stress could be responsible for the deposition of 300 m-thick carbonate (Wilson Bluff Limestone) sediments (Li et al. 2003).

The proposed model challenges conventional stratigraphic interpretations by emphasising the role of episodic tectonic events in shaping sedimentary records. While sea-level fluctuations were long considered the primary driver of stratigraphic sequences since the adoption of the Exxon eustatic model (Vail et al., 1977), extensive studies in the Sverdrup Basin in the Canadian Arctic Islands and comparisons with other global regions indicate that tectonic forces play a crucial role in forming sequence boundaries (Embry and Beauchamp, 2019), challenging the dominance of eustatic explanations. Furthermore, numerous studies have suggested that tectonic processes such as plate subduction and the presence of mantle density anomalies could be the primary factor for sedimentation patterns (e.g., Morgan, 1965; Pysklywec and Mitrovica, 1998; Gurnis et al., 1998; Moucha et al., 2008; Molnar et al., 2015), and Bodur et al. (2023) have introduced a novel mechanism for transient topography driven by basal shear stress underneath tectonic plates. Being independent of regional tectonic configuration or its vicinity to a mantle density anomaly, the mechanism I provided here and in Bodur et al. (2023) is based on horizontal tectonic plate motion, which is a common property of all tectonic plates, and therefore could have been driving global episodic tectonics since the inception of plate tectonics. This newly-proposed mechanism may call for a re-evaluation of stratigraphic frameworks and highlights the need for a better understanding of the interplay between tectonics and sedimentation.

CONCLUSION

Basal shear driven topography challenges the traditional understanding of slow dynamic subsidence and uplift of tectonic plates. Through torque-balance calculations, I have provided a basic yet effective approach to quantify these elevation changes, offering a more robust formula for estimating the impact of horizontal plate motion on Earth's topography. Future research directions could focus on refining and expanding this idea to account for additional factors such as the connectivity of plates and variability of plate-motions on a global scale, and coupling with surface processes. Investigating the implications of rapid elevation changes on the formation of mineral assemblages and interpretation of the stratigraphic record will be critical for advancing our understanding of the Earth's dynamic surface processes.

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