

The Physics of Lithospheric Slip Displacements in Plate Tectonics

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In this paper, we present physical calculations to support a mechanism of slip displacements of the lithosphere in the plate tectonics model of the earth sciences. In particular, for a lithospheric slip displacement to occur, a force must be applied to the lithospheric plate to overcome the force of static friction that is holding it in place on top of the asthenosphere. The magnitude of the required applied force can be generated by asteroid impact and is found to depend on the mass of the plate, the mass, velocity and angle of incidence of the asteroid, and the duration of the momentum transfer. The distance that is covered by the plate as a result of the lithospheric slip displacement is calculated and provides an explanation for observed sudden changes in direction and/or speed of plate motions. The model calculations presented in this paper provide a framework to analyze lithospheric slip displacements in plate tectonics resulting from asteroid impacts.

1 Introduction

In this paper, we present physical calculations to support a mechanism of slip displacements of the lithosphere in the plate tectonics model of the earth sciences [1–3]. The lithosphere consists of the Earth’s crust of thickness ~10 km and the upper part of the mantle composed of rigid rocks of average density $\rho \sim 3.3 \text{ gm/cm}^3$, with overall average thickness ~100 km [3] [4, p. 76], divided into the tectonic plates covering the surface of the Earth. It rests on the upper part of the asthenosphere of average density $\rho \sim 3.1 \text{ gm/cm}^3$ [4, p. 70], which is plastic and subject to viscous flows due to the nature of the rocks and the heat and densities involved. The asthenosphere becomes more rigid and stronger with increasing depth in the mantle, with average density $\rho \sim 3.4 - 4.4 \text{ gm/cm}^3$. The earth’s crust is differentiated from the lithospheric part of the mantle by the Mohorovičić, usually referred to as the Moho, discontinuity. See Fig. 1.

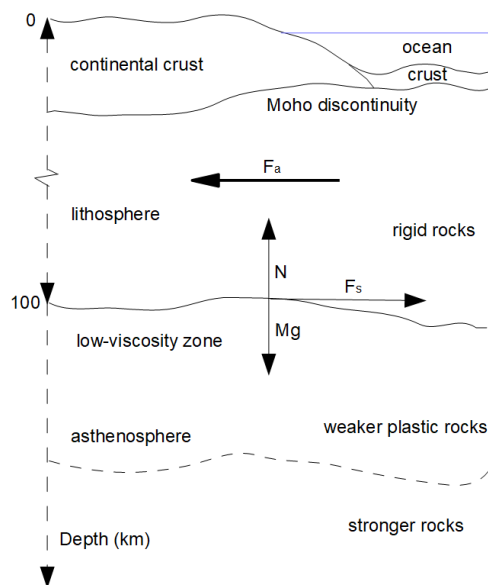
Given the structure of the lithosphere and the plastic and viscous nature of the upper part of the asthenosphere (low-viscosity zone LVZ [5, pp. 11,181]), it is quite conceivable that the lithosphere could move over the asthenosphere by a slip displacement movement, given the appropriate applied force to initiate the process. We calculate the applied force that would be required to initiate this process, and the type and nature of displacement movements that could be generated by such an applied force.

2 Lithospheric slip displacements

As currently understood, plate tectonics is a convective process, thermally driven by colder lithospheric slabs sinking into the interior of the hotter mantle at subduction zones [4, p. 11]. Continental drift and plate tectonics are considered to be sufficient proof of convection in the upper mantle [6, pp. 207–211].

However, as pointed out by Price [4, p. 63], “the models ... are completely unusable to explain the abrupt changes of rate and direction of plate motion which are, from time to

Fig. 1: Cross-section of the layers of the Earth’s upper mantle and crust (not to scale). Force model for the lithospheric slip displacement.



time, exhibited in the geological record”. As stated in [7] quoted in Price [4, p. 191], “Unfortunately, we cannot reproduce the toroidal/poloidal partitioning ratios observed from the Cenozoic, nor do our models explain apparently sudden plate motion changes that define stage boundaries.” [emphasis in Price]. A process of lithospheric slip displacement is needed to explain such sudden plate motions.

2.1 The force model

In this and subsequent sections, we seek to understand the lithospheric slip displacement process by performing order-of-magnitude simplified calculations. This first portion is a

simple force model (see Fig. 1).

We consider a tectonic plate of mass M resting on the asthenosphere with a static coefficient of friction μ_s . The force of static friction between the plate and the asthenosphere is then given by $F_s = -\mu_s N$, where the normal force N is given by $N = Mg$ where g is the acceleration due to gravity. Combining these quantities, the force of static friction F_s is then given by

$$F_s = -\mu_s Mg. \quad (1)$$

For the lithospheric slip displacement to occur, a force F_a must be applied to the plate to overcome the force of static friction that is holding it in place. This applied force must be greater than the force of static friction $F_a > F_s$, and substituting from (1), we obtain the slip condition

$$F_a > \mu_s Mg. \quad (2)$$

We consider a sample calculation for the North American plate as an order-of-magnitude estimate of the forces involved. The area of the North American plate is given by $58.8 \times 10^6 \text{ km}^2$ [4, p. 7]. For an average thickness $\sim 100 \text{ km}$ and an average density $\rho \sim 3.3 \text{ gm/cm}^3$ (see section 1), the mass of the North American plate is given by $M = 1.8 \times 10^{22} \text{ kg}$. Using these values and an estimated static coefficient of friction of 0.28 (greasy nickel) [8], the slip condition (2) then becomes

$$F_a > 5 \times 10^{22} \text{ N}, \quad (3)$$

where N is the Newton unit of force. This estimated applied force slip condition could be higher in the case of a higher static coefficient of friction, but it would likely not exceed a factor of two higher (i.e. $F_a > 10^{23} \text{ N}$). For example, the static coefficient of friction between concrete and silty clay is estimated at 0.30-0.35 in [9]. This applied force required for a lithospheric slip displacement to occur is very significant.

The applied force provides the impulse to set the plate in motion. Once the plate is set in motion, the only force that is applicable is the force of kinetic friction between the plate and the asthenosphere which is slowing down the plate's movement. This force is given by $F_k = -\mu_k N$, where the normal force N is again given by $N = Mg$. The kinetic coefficient of friction μ_k is smaller than the static coefficient of friction μ_s . Combining these quantities, the force of kinetic friction F_k is then given by

$$F_k = -\mu_k Mg, \quad (4)$$

which decelerates the plate at the rate $a = -\mu_k g$. For the example previously considered, using an estimated kinetic coefficient of friction of 0.12 (greasy nickel) [8], the deceleration is given by $a = -1.2 \text{ m s}^{-2}$. The deceleration could be greater in the case of a higher kinetic coefficient of friction, but it would likely not exceed a factor of two higher (i.e. $a = -2.4 \text{ m s}^{-2}$). For example, the sliding (kinetic) coefficient of friction between cement and wet clay is estimated at 0.2 in [8].

2.2 The asteroid impact model

As we have seen in (3), the applied force required for a lithospheric slip displacement to occur is very significant. This magnitude of force would only be available in a collision process, such as the impact of an asteroid or comet with the plate. We use the term asteroid impact in a generic fashion to represent both asteroid and comet impacts. Neville Price has considered the effect of major impacts on plate motion in his book [4, see chapters 6–8], but does not consider the lithospheric slip displacement introduced in this paper.

We consider an asteroid impact process which is known to be a low, but greater-than-zero probability event [10, 11]. We assume that the asteroid impacts the plate at an angle of incidence θ with respect to the surface of the plate. For a perpendicular angle of incidence $\theta = 90^\circ$, the impact will cause damage to the crust/lithosphere, with no slip displacement.

In addition, we consider an asteroid of mass m and speed v with respect to the plate which is assumed to initially be at rest. Then the asteroid's momentum in the plate's local plane is given by

$$p = mv \cos \theta. \quad (5)$$

When the asteroid collides with the plate, the collision's applied force impulse is given by

$$F_a = \frac{\Delta p}{\Delta t} \quad (6)$$

where $\Delta p = mv \cos \theta$ is the change in momentum of the plate assuming it is initially at rest and $\Delta t = \Delta t_p$ is the time interval for the momentum transfer, which is much shorter than Δt_c , the duration of the collision. Thus

$$F_a = \frac{mv \cos \theta}{\Delta t_p}. \quad (7)$$

Combining (2) and this equation, the slip condition for a plate slip displacement to occur in the direction of the collision as a result of the applied force overcoming the force of static friction becomes

$$\frac{mv \cos \theta}{\Delta t_p} > \mu_s Mg. \quad (8)$$

The variables on the L.H.S. are dependent on the characteristics of the asteroid and the collision, while those on the R.H.S. are dependent on the plate impacted.

We return to our sample calculation for the North American plate of section 2.1 to obtain an order-of-magnitude estimate of the effect under consideration. We consider a colliding asteroid of diameter $d \sim 20 \text{ km}$, mass $m \sim 2 \times 10^{16} \text{ kg}$, $v \sim 30 \text{ km/s}$, and use an angle of incidence $\theta = 45^\circ$ [12, 13]. Then substituting into (8) and using (3), we obtain slip condition

$$\frac{4 \times 10^{20}}{\Delta t_p} > 5 \times 10^{22} \text{ N}, \quad (9)$$

which is dependent on the momentum transfer time. We consider three momentum transfer times: 1 s, 1 ms and 1 μ s:

$$\begin{aligned} \text{for } \Delta t_p = 1 \text{ s,} & \quad 4 \times 10^{20} \text{ N} \not> 5 \times 10^{22} \text{ N,} \\ \text{for } \Delta t_p = 1 \text{ ms,} & \quad 4 \times 10^{23} \text{ N} > 5 \times 10^{22} \text{ N,} \\ \text{for } \Delta t_p = 1 \mu\text{s,} & \quad 4 \times 10^{26} \text{ N} > 5 \times 10^{22} \text{ N.} \end{aligned} \quad (10)$$

Price [4, p. 171] notes that two stress waves are generated at the point of impact, one in the asteroid rocks and one in the plate rocks. These he estimates to each propagate at about 8 km/s, which points to a momentum transfer time in the ms range.

The slip condition is satisfied for the two shorter collision times (1 ms and 1 μ s), but not for the longer one (1 s). Thus we find that lithospheric slip displacements are possible in plate tectonics under certain asteroid impact conditions. These are found to depend on the mass of the plate, the mass, velocity and angle of incidence of the asteroid, and the duration of the momentum transfer. The probability of a lithospheric slip displacement would be much higher for larger asteroids. We now investigate some of the details of the resulting motion of lithospheric slip displacements under asteroid impact conditions.

3 The conservation of energy model

In the previous section, we have considered the force model underlying lithospheric slip displacements in plate tectonics. In this section, we examine the motions resulting from the law of conservation of energy.

Before the collision, the energy of the plate-asteroid system, assuming the plate is at rest, is given by the kinetic energy of the incoming asteroid

$$E_i = \frac{1}{2} m v^2, \quad (11)$$

where the variables are as defined previously. The collision is completely inelastic and the kinetic energy of the colliding body is transferred to the plate. In addition, energy is lost in the fracas, cratering and deformation of the plate as a result of the collision. After the collision, the energy of the plate-asteroid system is given by

$$E_f = \frac{1}{2} (M + m) V^2 + E_{rel}, \quad (12)$$

where $m \ll M$, V is the velocity of the plate after the collision, and E_{rel} is the non-kinetic energy released in the collision. It should be noted that the slip of the plate as a result of the collision will reduce the non-kinetic energy E_{rel} released in the collision as the plate will yield to the asteroid and its motion will absorb a proportion of the collision energy.

To simplify our calculations, from the conservation of energy equation $E_i = E_f$, we write

$$\frac{1}{2} (M + m) V^2 = \frac{1}{2} \epsilon m v^2, \quad (13)$$

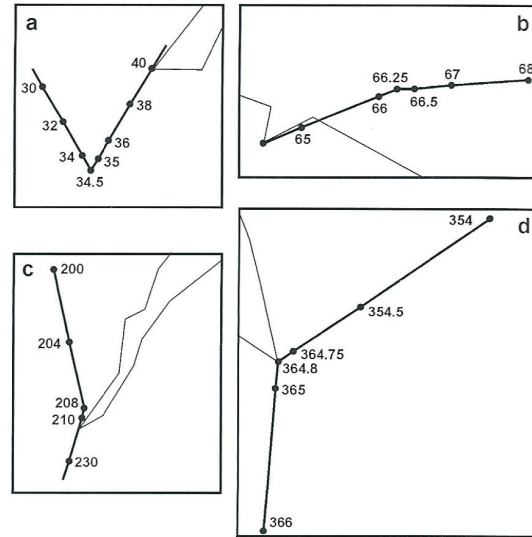


Fig. 2: Figure 6.1 from Price [4, p. 196], caption: “Tracks related to four known impact structures. Examples a, b and c are of *certain* impacts. (a) is that for the Popigai crater, diameter 100 km and age 34.6 Ma. (b) is that of Chicxulub, diameter about 200 km and age 66.25 Ma. (c) is that of Manicouagan, diameter 100 km and age 208 Ma. (d) is for a ‘near certain’ CNCF [Central Nevada Circular Feature] impact, diameter about 220 km and date 364.8 Ma.” Note the significant change in speed of the plate in example (c) after the change in direction.

where $\epsilon \leq 1$ is the proportion of the initial energy transformed into kinetic energy of the plate, with the rest released as non-kinetic energy. Solving for V , we obtain

$$V = \sqrt{\epsilon \frac{m}{M}} v \quad (14)$$

where we have neglected m in the term $(M + m)$.

We wish to calculate the distance that will be covered by the plate as a result of the lithospheric slip displacement. From (4) of the force model of section 2.1, we know that the plate will be subject to a constant deceleration $a = -\mu_k g$. We can thus use the dynamic equation

$$V_f^2 = V_i^2 + 2as \quad (15)$$

where V_i is given by (14) and $V_f = 0$ when the plate stops moving. Solving for the distance s , we obtain

$$s = \frac{\epsilon}{2\mu_k g} \frac{m}{M} v^2. \quad (16)$$

Using the values used in the sample calculation for the North American plate of section 2.1 and $\epsilon = 1$ implying that most of the energy is available as kinetic energy, we get an initial plate velocity $V_i = 32$ m/s from (14) and a lithospheric

slip displacement $s = 420$ m from (16). For $\epsilon = 0.5$ implying that 50% of the collision energy is available as kinetic energy, we get an initial plate velocity $V_i = 22$ m/s from (14) and a lithospheric slip displacement $s = 210$ m from (16). These values would be evident in the analysis of tectonic plate movements in the case of observed sudden changes in direction and/or speed of plate motions. In Fig. 2, we give examples from Price [4, Figure 6.1, p. 196] of plate tracks likely caused by lithospheric slip displacements resulting from asteroid impacts.

4 Discussion and conclusion

In this paper, we have considered simple models for order-of-magnitude proof-of-concept model calculations for lithospheric slip displacements in plate tectonics. We have obtained physically realistic results that provide an explanation for the observations:

- For a lithospheric slip displacement to occur, a force F_a must be applied to the lithospheric plate to overcome the force of static friction F_s that is holding it in place on top of the asthenosphere: $F_a > F_s = \mu_s Mg$.
- The magnitude of the required applied force F_a can be generated in asteroid impacts. Lithospheric slip displacements are then possible under the following slip condition: $mv \cos \theta / \Delta t_p > \mu_s Mg$. The asteroid impact condition is found to depend on the mass of the plate, the mass, velocity and angle of incidence of the asteroid, and the duration of the momentum transfer.
- The distance s that is covered by the plate as a result of the lithospheric slip displacement is given by $s = \epsilon mv^2 / 2 \mu_k g M$, under the action of a constant deceleration $a = -\mu_k g$, which explains observed sudden changes in direction and/or speed of plate motions as seen in Fig. 2.

The model calculations presented in this paper provide proof-of-concept evidence for lithospheric slip displacements in plate tectonics resulting from asteroid impacts. The model depends on many variables including the plates, asteroid and impact involved, and provides a framework to analyze such problems.

Many simplifications have been made that can lead to inaccuracies and complications, such as irregularities of the lithosphere and asthenosphere impacting the friction force, the proportion of collision energy being lost in the inelastic collisional process and not transformed into kinetic energy, *etc.* In addition, subsequent plate collisions resulting from the initial lithospheric slip displacement have to be analyzed for individual event conditions. Subsequent high-speed plate collisions could be a contributing factor to orogeny events resulting from violent plate collisions.

It should be noted that residual plate speeds, believed to be generated by mantle convection, are in the cm/annum range [4, p. 16]. Plates can thus be initially taken to be at rest in

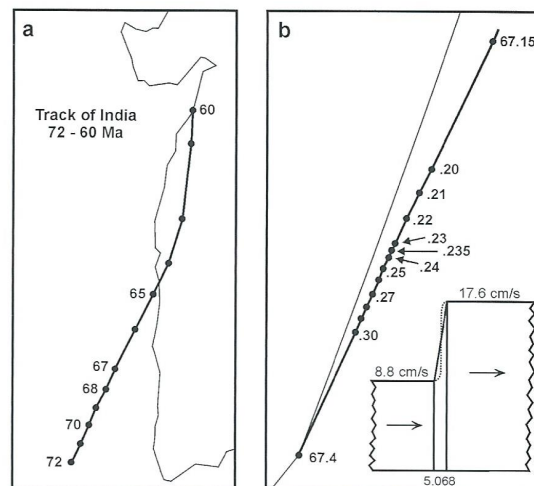


Fig. 3: Figure 6.7 from Price [4, p. 202], caption: “(a) Track of ‘Bombay’ over the period 72–60 Ma. It can be inferred from the distances between the points representing specific times that there was an abrupt change in velocity of the plate at about 67 Ma. (b) A detail of the track shown in (a) reveals that the velocity of plate motion doubled in a period which is assumed to be about 5000 years.” There is an error in the units of the reported plate motion (cm/s instead of the correct cm/a) in the insert in (b).

the calculations in this paper. As Price [4, Figure 6.1, p. 196] notes, plate speed is changed along with direction in impact events. For example, he notes that the Manicouagan impact event (item (c) in Fig. 2) sped up the plate speed by a factor of 4 (in cm/annum), while for the others, the changes were -4-5% for item (a), 5-6% for item (b) and 11% for item (d).

The process of lithospheric slip displacement proposed in this paper would lead to a rapid change in plate direction and speed which would be followed by a change in residual plate speed in the cm/annum range, likely arising from the follow-on plate collisions that occur following a lithospheric slip displacement. The change in direction and the change in speed depend on the particulars of the impact event and cannot be easily calculated, requiring a detailed analysis of the particular impact event of interest.

Price, using the Atlas Version 3.3 software system [4, p. 192] to analyze plate track changes, has studied the Indian Deccan Traps geological structure that he attributes to a major impact event at 67.23 Ma which resulted in a change in plate direction and speed from 8.8 cm/a to 17.6 cm/a, to try to better understand the timeframe involved for the change in plate speed. In Fig. 3, we show the figure from Price [4, Figure 6.7, p. 202] in which he narrowed down the interval of plate speed change to less than 5 000 years (as shown in Fig. 3b). As he mentions, the rise-time would likely follow the S-curve shown in the insert in Fig. 3b, hence over a time interval shorter than 5 000 years. In his analysis, he attributes

a time for acceleration and for deceleration before the plate settles in its new residual plate speed (the short horizontal portions before and after the vertical portion of the S-curve shown in the insert in Fig. 3b).

The change in plate direction and speed is thus extremely short in geologic time. The model suggested in this paper shows that the time duration of the lithospheric slip displacement would indeed be very short both in geologic and in actual event time. This model provides an explanation for the abrupt changes of rate and direction of plate motion observed in the geological record. It provides a physical and mathematical framework for the analysis of lithospheric slip displacements in plate tectonics.

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