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AN EMPIRICAL LAW FOR CONTINENTAL PLATE MOTION

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ABSTRACT

An empirical law for continental plate motion is obtained by correlating the observed speed of plate motion with a parameter, the ratio between the effective length of ocean ridge and the continental area. This law predicts the existence of three inequalities, namely: (i) viscosity under ocean part of plate ≪ viscosity under continental part of plate, (ii) fault resistance ≪ ridge push, (iii) trench-arc and mountain belt resistance ≪ ridge push. The first prediction has been verified, but the last two remain to be checked with future observations. A simplified mechanical analysis indicates that the dominant forces acting on a tectonic plate consist of the boundary push along the ocean ridge and the viscous surface drag under the continental part of plate.

In recent years, with the advent of plate tectonic theory, the kinematics of continental drift and sea floor spreading have met with great success. However, rather little is known regarding the driving mechanism of plate tectonics, i.e. the dynamics of plate tectonic theory has not yet been established. Indeed, many geophysicists and fluid dynamicists have directed their effort toward this very research, and various models of driving mechanisms have been advanced.

Some believed that mantle convection due to thermal gradient beneath the lithosphere exerts a viscous force on the lower surface of the plate, thus dragging the latter along like a passive raft. Richter[3] pointed out, however, that such convective cells in the asthenosphere have horizontal scale much smaller than that of typical plates, hence there must exist many such cells beneath a plate. Now the flow from neighboring cells being always oppositely directed, their viscous tractions on the plate mostly nullify each other, resulting in little net contribution, certainly inadequate for driving the plate. Forsyth and Ugeda[1] further pointed out that the viscous drag on lithoscope plate of a large scale mantle flow in asthenosphere is not affected by the presence of small scale convective cells.

Others stressed the pull action of the downgoing slab. This force is called negative buoyancy. The downward pull of sinking slab caused the horizontal part of the lithosphere to move. But this model of driving forces failed to explain the following three facts, e.g. (i) not all plates have a sinking part, certainly Eurasian and African plates do not have such sinking slabs; (ii) geophysical observation and seismic study indicated that a sinking slab sometimes experiences compressive rather than tensile stress; (iii) negative buoyancy acts vertically downward. If ocean plate does not receive a strong push from behind, why should it urge forward slanting beneath a continental plate?

Still others suggested that the gravity sliding produces driving force. They believed that the elevated topography at the ridge possesses excess potential energy, so that the ridge tries to spread out to obtain a lower energy state. Now the elevation of ridge is maintained by the continual advection of heat in the rising mantle material, motions of the plates generated by the ridge force may ultimately be considered to be driven by the forces of thermal convection.

With these different models proposed for driving mechanisms, the viewpoint is very much diversified, and there exists no unique rule for the plate motion. Forsyth *et al.*[1] and Minster *et al.*[9] utilized statistical graphs in an attempt to find a functional relationship between the speed of plate motion and the total area of plate, continental area, lengths of ridge boundary, downgoing slab, and transform fault. But they all failed to uncover a satisfactory law.

Using the data given by [1] and [9], and through analysing the forces acting on continental plates, this paper succeeded in obtaining an important parameter, the ratio between effective ridge length and continental area, that controls the speed of motion of continental plates, and indeed, in finding an empirical law which states that the speed of motion of a continental plate is linearly dependent on this ratio. This law also confirms the conclusion that the driving force for continental plate comes from oceanic ridge. As to the cause of this driving force, we believe it is due to the higher pressure existing in the upwelling channel beneath the ocean ridge, rather than the gravity-induced ridge spread out. We shall discuss this point in a separate paper.

A simplified picture of forces acting on a continental plate is shown in Fig. 1. In this figure ABCDEF constitutes a continental plate, with shaded area representing the continental part of area S_c, and unshaded portion the oceanic part of area S_o. The boundaries AB and EF are ocean ridges, along which act push forces F_R' and F_R'' respectively. BC, DE and FA are transform faults, along which act resistances F_t',

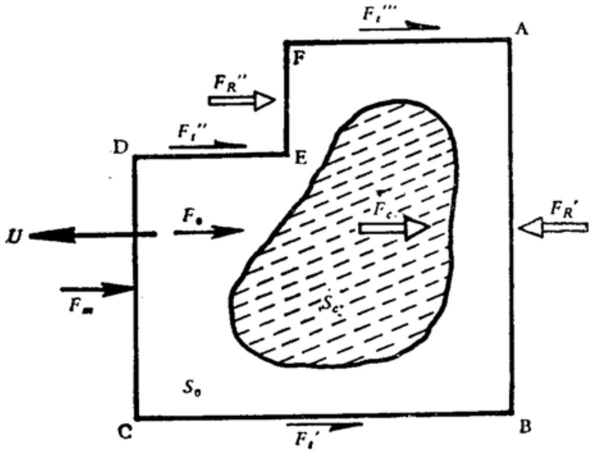

Fig. 1. Simplified picture of forces acting on a continental plate.

F_t'' and F_t'''. CD is trench-arc region and mountain belt, along which acts resistance F_m. According to [1], all these forces are proportional to their respective boundary lengths, i.e.

$$F_k = F_R' - F_R'' = K_R l_R, \tag{1}$$

$$F_t = F_t' + F_t'' + F_t''' = K_t l_t, \tag{2}$$

$$F_m = K_m l_m, \tag{3}$$

where K_R, K_t and K_m are proportional constants; l_R, l_t and l_m are respective boundary lengths; the difference between lengths AB and EF is called effective length of ocean ridge l_R; l_t is the sum of lengths BC, DE and FA; l_m is the length of CD.

Besides, the lower surface of lithoscope plate is under the coupling action of mantle material of the asthenosphere. According to [1], this is a drag force resisting the plate motion. Since the effective viscosities of mantle materials beneath continental and ocean parts are different, the total drag force should be separated into two parts, namely the drag under continental part F_c and the drag under ocean part F_0:

$$F_c = K_\mu \mu_c S_c U, \tag{4}$$

$$F_0 = K_\mu \mu_0 S_0 U, \tag{5}$$

where K_μ is the proportional constant, U the speed of plate motion, μ_c and μ_o the viscosity coefficients of mantle material under continental and ocean parts respectively.

Now the speed of plate motion being effectively constant, so we have

$$F_R = F_t + F_m + F_0 + F_c. \tag{6}$$

Substituting (1)—(5) into (6), the following relation is obtained

$$U = m \frac{l_R}{S_c\left(1 + \dfrac{\mu_0}{\mu_c}\dfrac{S_0}{S_c}\right)}\left(1 - \frac{K_t}{K_R}\frac{l_t}{l_R} - \frac{K_m}{K_R}\frac{l_m}{l_R}\right), \tag{7}$$

where we have put $m = K_R/(K_\mu \mu_c)$.

Table 1 gives the magnitude of all quantities appearing in (7). The data U in the table are taken from [8]: The values of U for India and Arab plates are taken from

Table 1

Parameters of Continental Plate Motion

No.	Plate	U cm/yr	S_c $\times 10^6$ km^2	l_k $\times 10^2$ km	l_k/S_c $\times 10^{-4}$ km^{-1}	S_0/S_c	l_t/l_k	l_m/l_k
1	N. America	2.6	36	86	2.39	0.67	1.42	1.40
2	S. America	2.3	20	71	3.15	1.05	1.51	1.56
3	Antarctica	0.6	15	17	1.13	2.93	7.76	1.00
4	India	6.6	15	108	7.20	3.00	1.16	1.58
5	Africa	1.9	31	58	1.87	1.55	2.05	1.19
6	Eurasia	1.1	51	35	0.69	0.35	1.60	7.86
7	Arabia	4.0	4.4	27	6.14	0.11	1.33	1.19

Note: Data of U from [8], the rest from [1]。

Fig. 10 of [8], the rest from Table 4 of [8] by taking the average. All data except U are taken either directly from, or evaluated indirectly using Table 1 of [1].

It should be pointed out that at present the manner of counting plates is by no means unique. Thus, Morgan[10] suggested a scheme of 20 plates, Le Pichon[11] suggested a scheme of 6 plates, Minster *et al.*[9] suggested a scheme of 10 plates, while Forsyth and Uyeda[1] suggested a scheme of 12 plates. Yin[12] pointed out that while small plates exert only local influence, large plates are the ones that control the basic tectonics on global scale.

This paper adopts the large plate scheme. Forsyth and Uyeda pointed out that during the history of Atlantic split, South and North American plates mostly moved independently. Thus, we adopt the 10 plate scheme advanced by Minster *et al.* According to this scheme, South and North American plates are treated separately, so there are altogether seven continental plates, as indicated in Table 1. There are three oceanic plates, namely, Pacific plate, Nazca plate and Cocos plate.

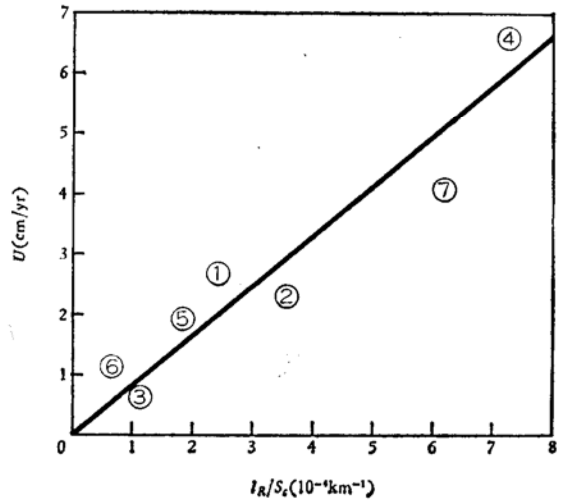

Fig. 2. Relationship between plate speed U and parameter.

Fig. 2 shows the seven observed values of speed of motion of continental plates plotted against the parameter l_R/S_c. In the figure each point represents one continental plate, the order number being identical to that used in Table 1. From Fig. 2 it can be seen that the seven points all lie in the neighborhood of a straight line through the origin. We hope that this phenomenon is not merely a coincidence, but rathar that it actually reflects the law of continental plate motion. The straight line was actually drawn on the basis of least square principle for these seven points.

From (7) it can be seen that U is originally a multi-variable function, containing variables l_R/S_C, $\mu_0 S_0/(\mu_C S_C)$, $K_t l_t/(K_R l_R)$ and $K_m l_m/(K_R l_R)$. However, for the seven continental plates, although the variations of S_o/S_c, l_t/l_R and l_m/l_R are considerable (see Table 1), the relationship between U and l_R/S_c is found to be a linear one as shown in Fig. 2. This indicates that the effect on U of parameters $\mu_0 S_0/(\mu_C S_C)$, $K_t v_t/(K_R l_R)$and $K_m l_m/(K_R l_R)$ can all be neglected. This in turn requires that the following three relationships be satisfied, i.e.

$$\frac{\mu_0 S_0}{\mu_c S_c} \ll 1, \tag{8}$$

$$\frac{K_t l_t}{K_R l_R} \ll 1, \tag{9}$$

$$\frac{K_m l_m}{K_R l_R} \ll 1. \tag{10}$$

Now from Table 1, the maximun value taken by S_0/S_c is found to be approximately 3.00. In order to meet the inequality (8), we must have $\mu_0/\mu_c \ll 1$. In other words, the effective viscosity for mantle material under continental part of plate must be higher than that under oceanic part of plate by at least an order of magnitude. This conclusion has been found to be in agreement with the results obtained by the surface wave study for low speed layer[13,14]. Indeed, many authors did accept this fact[6,9,15].

Noticing (1)—(3), (9) shows that the drag along transform fault is much smaller than ridge push, and (10) shows that the resistance along trench-arc or mountain belt is much smaller than ridge push. These two predictions, however, have to be checked with observations.

Using (8)—(10), (7) can be approximately written as

$$U \approx m \frac{l_R}{S_c}. \tag{11}$$

From Fig. 2, we obtain $m = 0.0832\ \text{km}^2/\text{yr}$.

In the theory of plate tectonics, l_R/S_c is found to be an all important parameter. Small values in l_R/S_c means either a small l_R (small push) or a large S_c (large drag). Hence, for a continental plate, the smaller the value of l_R/S_c, the more stable will be the plate, while the higher the value of l_R/S_c, the bigger will be the colliding force of the plate. From Table 1 or Fig. 2 it can be seen that among the seven continental plates, Eurasian plate possesses the least value of l_R/S_c, and the Indian plate the greatest value of l_R/S_c. When these two plates collide, the strongest mountain building action witnessed in the world takes place, resulting in the high raised Tibet Plateau and the towering Mount Qomolangma.

(11) can also be written as

$$F_c \approx F_R. \tag{12}$$

This indicates that the main driving force for continental plate comes from ocean ridge push, while the main drag comes from the viscous traction under the continental part of the plate. Compared with these two forces, the rest of the forces acting on a lithoscope plate becomes insignificant.

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