Reports

Rotational Inertia of Continents: A Proposed Link between Polar Wandering and Plate Tectonics

Abstract. *A mechanism is proposed whereby displacement between continents and the earth's pole of rotation (polar wandering) gives rise to latitudinal transport of continental plates (continental drift) because of their relatively greater rotational inertia. When extended to short-term polar wobble, the hypothesis predicts an energy change nearly equivalent to the seismic energy rate.*

Rapid developments in geophysical measurements and concepts over the past decade have substantially confirmed Wegener's theory (*1*) of continental drift. A fully acceptable explanation of the cause of drift, however, has not been put forward, although a majority appears to favor thermal convection. This report outlines an alternate mechanism, which links polar wandering and plate movement through the differential rotational inertia of continental plates. In general, the driving mechanism described here may be classified as a Coriolis effect. Several aspects of the problem have been discussed previously, in particular those of the higher moment of inertia of the continents (*2*) and those of the association of motive force with rotational dynamics (*3*).

The physical model consists of a radially uniform sphere rotating at constant velocity with loosely coupled surficial plates having dimensions and locations like those of the earth's continents. The moments of inertia of the plates are equal to the difference in rotational inertia between plates of average continental composition and plates of average oceanic composition. The model implies the presence everywhere of an average crust that is dynamically equivalent to the oceanic crust and that acts as an integral part of the earth under changes in rotation. The loosely coupled plates represent the residual moments of inertia of the continents and react independently of the earth as a whole under changes in rotation. The effects of mantle lateral inhomogeneity and of viscous coupling of the plates are assumed to be secondary.

The differential rotational inertia, ΔI, of a continent is given by

$$\Delta I = \int\int\int \Delta\sigma R^4 (\sin\phi - \sin^3\phi \cos^2\theta)\, dR\, d\phi\, d\theta$$

where $\Delta\sigma$ is the density contrast between adjacent oceanic and continental crustal layers, R is the appropriate radius, ϕ is the longitude, and θ is the latitude. Integration leads to a solution composed of two factors, where the first (1.59×10^{39} g cm^2) depends on the crustal model (*4*) and the second depends on the size and location of the crustal plate ($\pi/3$ for a plate equal in area and geometry to one-quarter of a hemispherical surface). Because of isostasy the first factor may be considered constant for order of magnitude calculations.

The concept of inertial drift is demonstrated in Fig. 1, where the differential angular momentum of a crustal segment at the equator is compared with that of an identical segment which has been displaced 30° toward the axis of rotation (A to A'). As shown graphically by the solid arrows within the plates and numerically at the right of the figure, the differential angular momentum of the displaced segment is reduced by approximately one-third. The basic physical premise of the inertial drift hypothesis is that the energy loss associated with the loss in angular momentum is accounted for by latitudinal transport (in this case easterly) of the continental crustal plate relative to

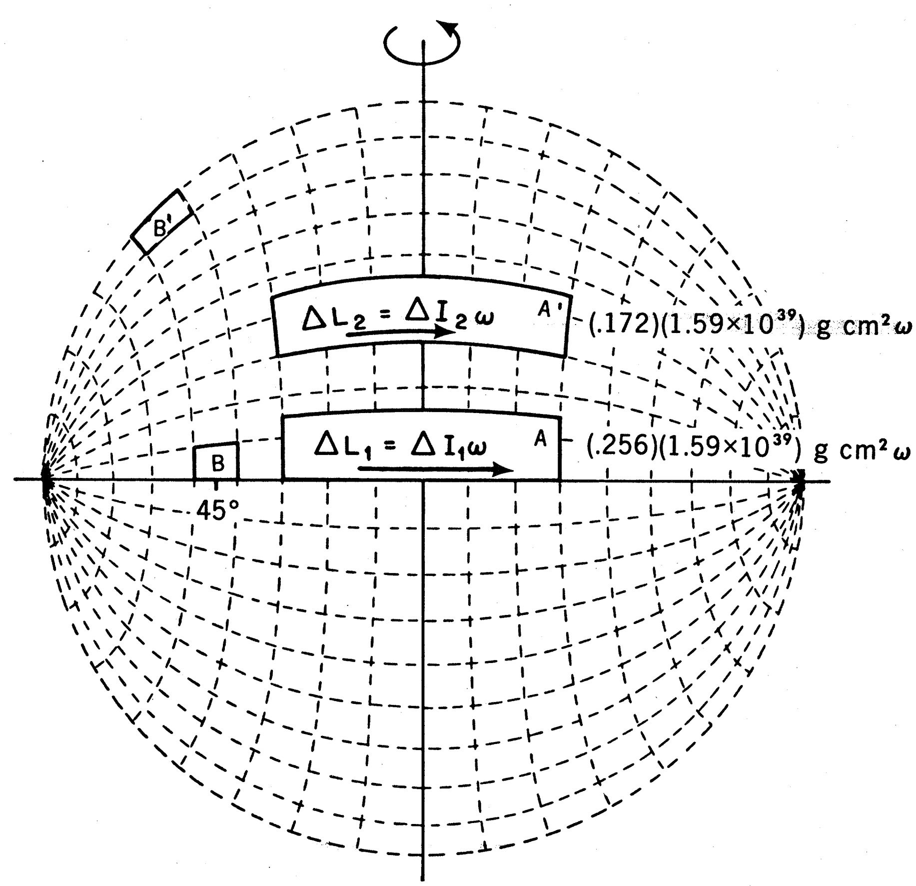

Fig. 1. Physical concept of inertial drift. The change in differential angular momentum, ΔL, caused by displacement between continental plate and rotational pole (A to A') is shown. The plate used in calculating the average change in kinetic energy per degree change in polar shift is shown on the left (B to B'). The angular velocity of rotation, ω, is 7.3×10^{-5} rad/sec.

the surrounding oceanic crust; that is, angular momentum tends to be conserved.

Figure 2 is a representation of continental drift from the beginning of the Triassic period to present (*5*), with an inset showing polar paths measured from North America and Europe (*6*). The singular polar path shown in the inset is estimated from the dual paths. In the uppermost global representation (Triassic), an approximation of polar path from Triassic to Cretaceous is shown by the double-ended arrow near the north pole. According to the inertial drift hypothesis, polar movement of this type would cause the part of the continental plate north of the equator to move east and that south of the equator to move west. The resultant movement would be clockwise rotational and easterly translational (the northern part is larger). The rotation should produce a maximum stress zone near and semiparallel to the equator, which could eventually lead to separation of the protoplate into northern and southern segments. The continent distribution shown for the beginning of the Cretaceous is in reasonably good agreement with that predicted. From Cretaceous to present the polar path is shown to be (i) toward Eurasia, which leads to easterly transport for that plate; (ii) moderately away from North America, which leads to moderate westerly transport for that plate; and (iii) away from South America (that is, the southern pole of rotation is away from South America), which leads to westerly transport for that plate. The African plate would appear to have moved first away from the southern pole of rotation, and then across the equator toward the northern pole of rotation. The meridional motion of the plate would thus lead first to westerly and then to easterly transport. Again, the present continent distribution is in reasonably good agreement with that which is predicted.

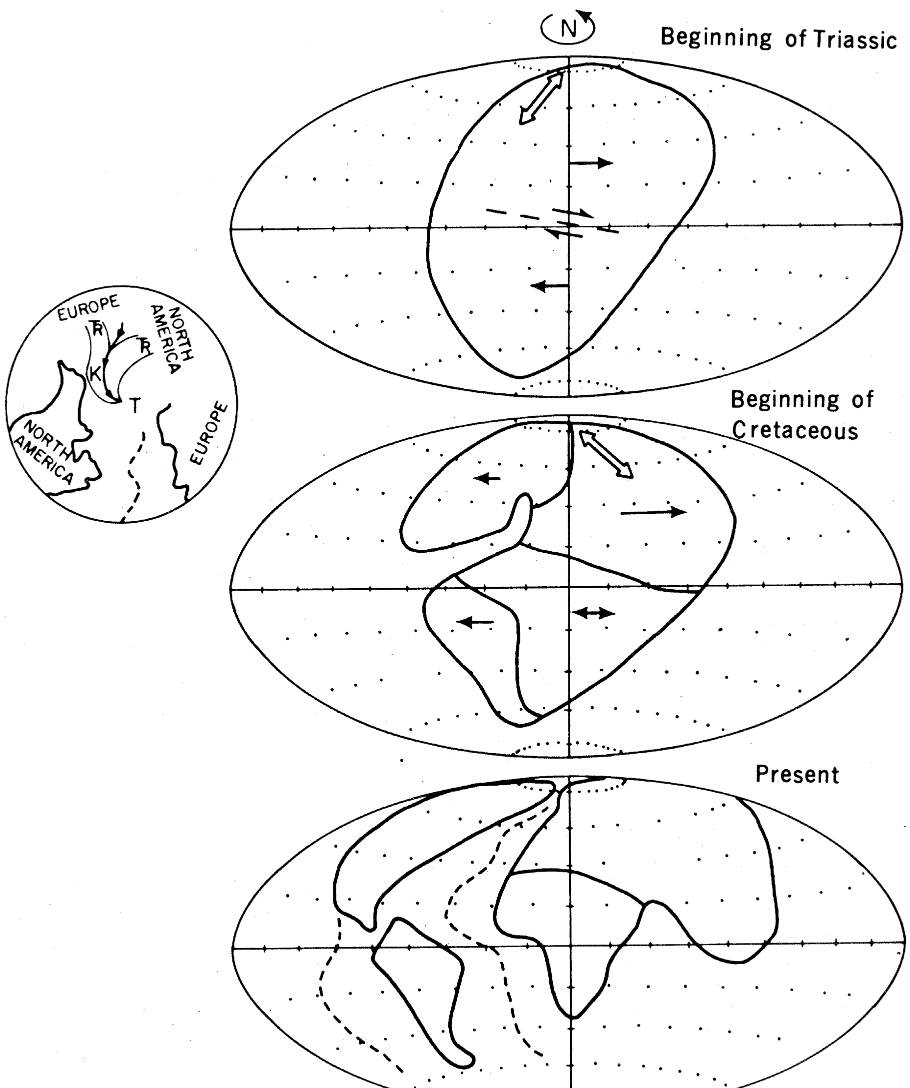

Fig. 2. Depiction of continental drift (*5*), with the polar wandering path (*6*) shown in the inset (*T*, Tertiary; *K*, Cretaceous; *TR*, Triassic). The double-ended arrows in the upper part of the global representations for the beginning of the Triassic and the beginning of the Cretaceous are approximated from the inset. The solid arrows in the global representations show the sense of the predicted movement with the maximum stress zone indicated in the equatorial region of the uppermost representation. The dashed lines in the inset and the lowest global representation show the positions of oceanic ridges.

The kinetic energy change, ΔK, in pole-plate displacement is

$$\Delta K = \Delta I \omega^2/2$$

where ω is the angular velocity of the earth's rotation. The average energy change for all continents per degree in pole-plate displacement can be extrapolated from the energy change of an average plate over an average path (plate *B* in Fig. 1) and is

$$\overline{\Delta K}(\text{per degree}) = 1.08 \times 10^{20} \text{ erg/deg}$$

An estimate of the secular polar wander is 0.003 arc sec/year (*7*), which leads to an annual energy change caused by pole-plate displacement of 9×10^{22} ergs. This energy rate is about two orders of magnitude less than that of seismicity (*8*), but when extended over 2×10^8 years (Triassic to present) is equivalent to the energy released by 2×10^6 major earthquakes.

There may be a relation between short-term polar wobble and seismicity. The mean path length of polar wobble is about 1 arc sec/year (*7*) which, when coupled with the average energy per arc second of pole-plate displacement, leads to an annual energy change of 3.0×10^{25} erg/year. This value is in reasonably close agreement with the observed seismic energy release, which is estimated as about 9×10^{24} erg/year (*8*).

Energy changes due to variations in the earth's rate of rotation (*9*) appear to be an order of magnitude less than those due to displacement.

If continental plates are assumed to be moderately coherent assemblages of large subplates, then interior deformation of continents may be attributed to rotational dynamics as modified by gravity tectonics. The hypothesis also predicts that continental plates may undergo rotation and may explain, for example, island arcs as drag effects at continental-plate edges. Rotation also implies that remanent magnetization directions imprinted in rocks may undergo subsequent spatial rotation, which imposes an additional constraint on the reconstruction of polar paths from paleomagnetic measurements.

A provocative question in plate tectonics is the ultimate source of energy. In this report it is suggested that the differential rotational inertia of continents coupled with pole-plate displacement leads to continental-plate movement and seismicity. Others (*10*) suggest that earthquakes may cause short-term polar (Chandler) wobble and secular polar movement. Munk and Hassan (*11*) conclude that the annual component of polar wobble (making up about one-third the amplitude of polar wobble) is excited by atmospheric loading. This component is large enough to cause significant displacement energy in continental plates and may be the continuous forcing function in plate tectonics. If so, the ultimate energy source would be solar.

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System Approach for Reducing Car Pollution

Abstract. *Federal policy emphasizes more exacting specifications for new cars to combat pollution. Some doubts are cast on this approach, and alternatives are suggested. Ease of maintenance, high reliability, and inspection are essential to pollution control and must be provided for in the specifications. A total system approach to reduce car pollution is outlined.*

There are serious questions as to the most practicable way of reducing automobile pollution. Present federal policy emphasizes tougher emission standards for new cars (*1–3*), but it lacks adequate provisions for the enforcement of suitable standards throughout the life of the cars. My intent here is to cast doubts on this approach and to suggest alternatives.

None of the designs that are now being conceived to meet 1975–76 federal regulations is inherently pollution-free. Without proper maintenance and inspection these cars will be especially liable to excessive emissions.

Ease of maintenance, high reliability, and proper inspection are as important as suitable emission standards, and it is essential that they be incorporated into a general policy, as is the case in the aerospace industry. Our experience with the diesel engine furnishes a case in point. The diesel engine is designed to give a clean exhaust. Yet everyone is familiar with the sight of a diesel emitting a dark smoke or a fog of hydrocarbons. A diesel engine requires careful and skilled (and often unavailable) maintenance if it is to stay nonpolluting. Furthermore, one wonders if the frequent appearance of smoking diesels might not be related to the fact that the highest power output of the diesel engine is favored by conditions that promote excessive emissions. Whatever the exact reason, this example illustrates the need for both maintenance and inspection.

Any attempt to reduce car pollution will prove expensive. Estimates of the cost of the changes needed to meet federal specifications for 1975 vary from \$300 to \$800 for a single car, or \$3 billion to \$8 billion in investment cost for 10 million cars. Decreased fuel efficiency and improved maintenance may each cost \$3 to \$6 billion a year. Fuel modification [suggested by General Motors (*2*)], if adopted, would cost another \$3 billion to \$10 billion a year. It is important that these enormous sums are spent effectively.

What design options can the automobile manufacturer exercise as he endeavors to satisfy compulsory emission standards? In general, he may modify the design and the operation of the present spark-ignition engine, or he may seek new design alternatives.

At present it appears that none of the new designs, such as the steam engine or the gas-turbine engine, will have commercial importance within the coming decade. Further, with the exception of the electric car, all these new designs, like the present spark-ignition engine, will require strict maintenance if their exhaust is to stay clean. As for electric cars, their widespread use might cause the source of pollution to be transferred from the car to the power plant (*4*).

One hopes that future breakthroughs will provide us with a nonpolluting car. In the meantime we should continue to improve the spark-ignition engine. Some significant improvements have already been made, or are in the process of being adopted. These include the elimination of the gases escaping from the crankcase and the reduction of hydrocarbons evaporating from the fuel system. The main problem still remains, namely, the reduction of emissions of hydrocarbons (HC), carbon monoxide (CO), and nitrogen oxides (NO_x) from the exhaust (*2, 3, 5, 6*).

Engine modifications alone would not cut these emissions to the low levels that will become mandatory in 1975–76. Present design proposals envision HC and CO emissions as being reduced by a suitable afterburner and rely on engine modifications to mitigate NO_x emissions. This is mainly due to the inherent limitations of the combustion process itself.

Hydrocarbons and CO are the products of incomplete combustion whereas NO_x is formed in the combustion process. Excess oxygen and higher flame temperatures will promote more thorough combustion; these, in turn, depend on the air/fuel ratio. Figure 1 shows qualitatively the effect of the air/fuel ratio on emissions of HC, CO, and NO_x. Hydrocarbon and CO levels decrease at first as the air/fuel ratio increases. At high air/fuel ratios HC emissions may increase again because dilution lowers the flame temperature. On the other hand, the for-