# Can Ocean Tides Drive the Continents?

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## ABSTRACT

Disproof of large-scale convection cells as a continental driving force has left a void. Convective down-drop at trenches supplies a vertical force, but associated "trench pull" seems too attenuated to be viable across oceans and continents. Here I consider an alternative: torques created by ocean tides indirectly provide a horizontal driving force that acts on the entire surface of the globe and explains continental movement in both east-west and north-south directions.

Earth-moon-sun body forces resonate in the ocean basins to create ocean periodic tide height and current effects beyond what would be expected on a uniform planet. These changes in height and flow induce rapid oscillations in the Earth's rotational velocity and axial orientation. And, in turn, the rotational variations induce an oscillating instantaneous inertial force—a force that can be quite high because of the resonant amplification—at every location on the globe.

At present, VLBI measurements and computed simulations provide approximate values for inertial forces—values that follow inherent tidal asymmetry and show a net directed force. In addition, asymmetric secular forces associated with zonal tides, subduction, and bathymetric gradients as well as atmospheric effects provide unidirectional forces capable of creating ratchet-like movement of continents over time.

Interaction with Earth's rheology is as important as the force itself. Early assumptions that the mantle is a generalized Newtonian fluid with a viscosity determinable from glacial isostatic rebound and seismic measurements lead to a conclusion that astronomical forces are too weak to drive the continents. More recent work suggests partial melting in the low velocity zone at the base of the lithosphere that could produce movement at much lower stresses. I suggest here that the horizontally directed inertial force may be sufficient.

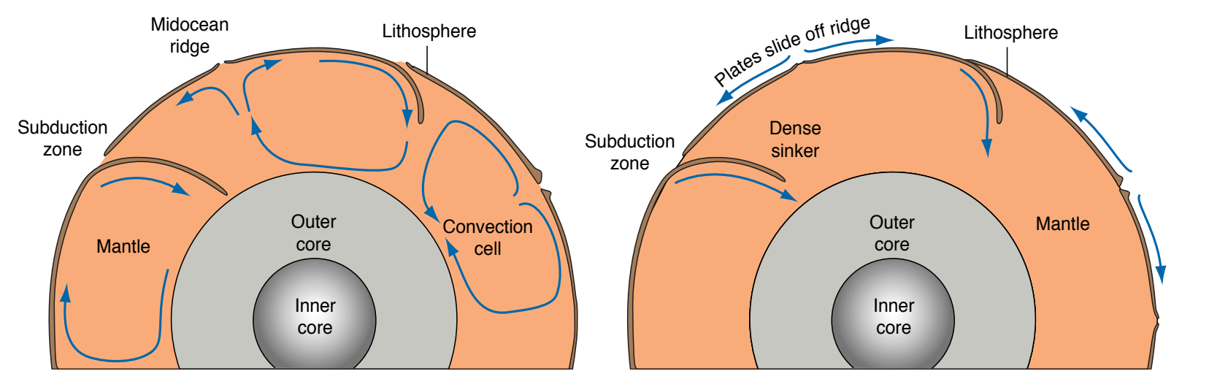
In addition to explaining horizontal movement, this hypothesis explains the formation and propagation of rifts where ratcheting forces oppose. Apparent movement and anisotropy on mid-mantle seismic disconformities make sense as well. Application of the tidal driving force holds promise for a coherent explanation of GPS, seismic measurements and other geophysical measurements.

## Introduction

When Alfred Wegener first proposed that the continents moved, he suggested that the pull of the sun and moon drove their motion. His idea didn't garner much support and probably weakened the notion of drift itself. Later when symmetric magnetic anomalies were found in oceanic crust, the consensus shifted to large scale convection emerging at oceanic ridges as the continental driver.

More recently, seismic, gravimetric and heat flow studies showed results inconsistent with this force. The boundary forces, slab pull and secondary ridge push, were substituted as potential alternative drivers, but the failure of these drivers to explain the motion of continents as well as the the attenuated nature of boundary forces weakened this idea. Because of these questions and others, the driving force itself has remained an important unresolved question in many people's minds.

Other factors must be considered as well. Earth's continental drift is unique in our solar system. The movement of vast areas with little deformation suggests that a body force like gravity or inertial forces rather than contact forces are likely responsible. This poster presents just such a force, the wobble created by ocean tides. It does it in a very basic way—this is a starting point.



**(A)** Convection in the mantle drives the movement of the plates. Many characteristics of plate motion are inconsistent with this hypothesis.

**(B)** Forces generated by the plates themselves cause the plates to sink into the mantle because of their density and to slide off the midocean ridges.

From: http://earthds.info/pdfs/EDS_17.PDF

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## What is Known . . .

### Ocean Basins Are Resonant Harmonic Oscillators of Astronomical Force

Ocean basins present classic harmonic oscillators, alternately storing and releasing kinetic energy derived from the gravitational force of the sun and moon. When the tidal bulge reaches the edge of a basin and can't move on, it is reflected. The result is far from simple, however. Ultimately, the size and shape of the basins control the frequency and damping of the oscillations. A map of the M2 tide (shown to the right)—the largest—shows an apparent spinning pattern to this tide. Other tides have different patterns.

The liquid and movable nature of the oceans creates an amplification of the astronomical effect. As one can appreciate when standing on a shore with large tides or viewing the force of tidal currents in a narrow channel, the immediate effect is far beyond what would expect from the small gravitational pull of distant bodies.

### Tidal Effect on Earth Rotation Can Be Observed

As one can see from watching a slowly spinning figure skater pull in her arms and turn to a blur of speed, changing the shape of a spinning object changes it's rate of spin, The same is true of movement on a the surface of a spinning object. Ocean tides change the height of the oceans and tidal currents add and subtract momentum and thus affect spin velocity. Cumulatively, the height and current changes of the tides produce measureable changes in the rotational velocity and polar orientation of the Earth. The effect was predicted more than 50 years ago and began to be measureable with the advent of Very Long Baseline Interferometry (VLBI). Now it is possible to measure the effects with GPS as well. A graph of measured changes over a three day period is found in the center section of this poster.

### Tidal Effect on Earth Rotation Can Be Computed

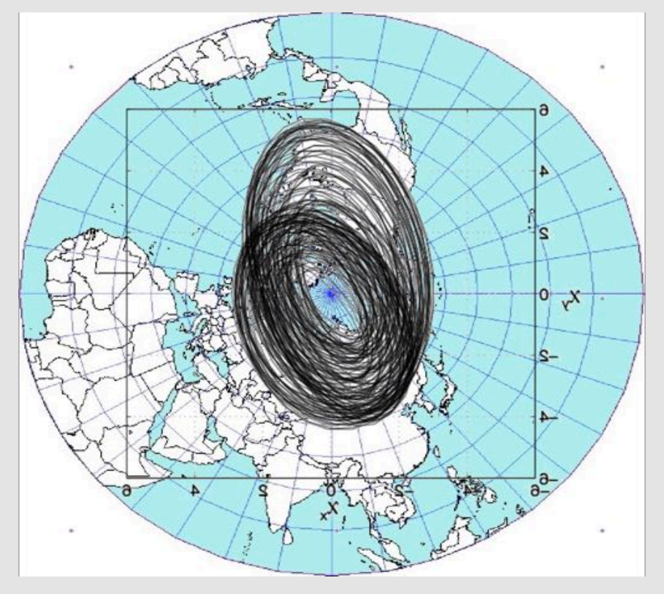
As noted above, the ocean tidal effect on rotation parameters had been predicted prior to its observation. The movement of the tides is fairly well known and has been mathematically modeled over the years. At the bottom of the section to the right, I use modeled velocity changes to compute the torques and resultant stress on the crust-mantle boundary. Additionally, computed changes in moment of inertia have the advantage of showing the asymmetry of the tides without the inherent uncertainty of VLBI and GPS measurements. A graph of computed angular momentum is shown at the bottom of the column immediately to the right.

### Tidal Effects Are Asymmetric

While the resonant oscillations create east-west and north-south torques they do not do it in a symmetrical way. If they did, the continents might move back and forth in infinitesimally small bits, but never make any progress in a given direction. It turns out that over time the tidal oscillations have an inherent asymmetry—they push more in one direction than another—and that is the direction that the continents move. In addition, several "secular forces," including the equivalents of ridge push and slab pull act in a single direction at every point on the earth.

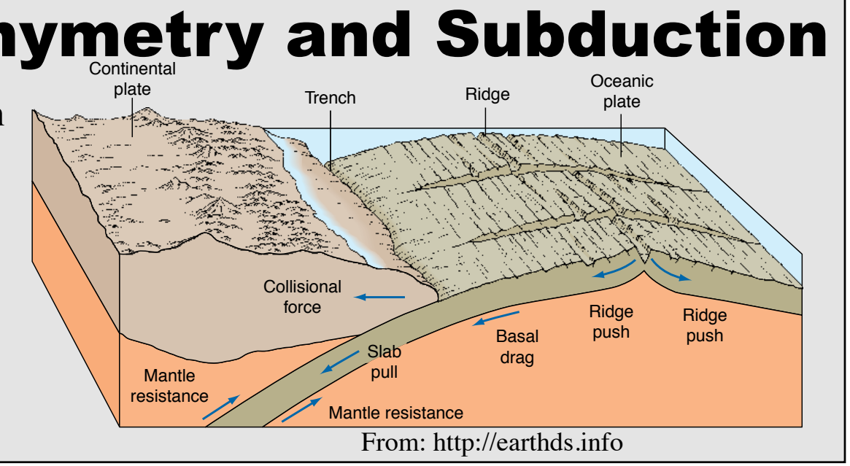
The computed asymmetry of polar motion can be illustrated on a polar projection of the Earth. The scale is in centimeters and is reversed so that the x and y axes match those of the plot.

Because earth materials are most likely elastic below a given stress and plastic above some threshold, the effective magnitude of the asymmetry expresses itself as the predominance of more and higher peak torques in one direction. Torques may be high in both directions—high enough to move continents—but higher, more and longer peaks in one direction will ratchet the motion in a single direction



### Add the Effects of Bathymetry and Subduction

The back and forth force resulting from the ocean tides is only part of the story. At ocean ridges, the crust slopes away from the ridge top and gravity adds its unidirectional force to the inertial force. At trenches, the effect is even more extreme as gravity and convective forces move material downward with no chance of coming back.



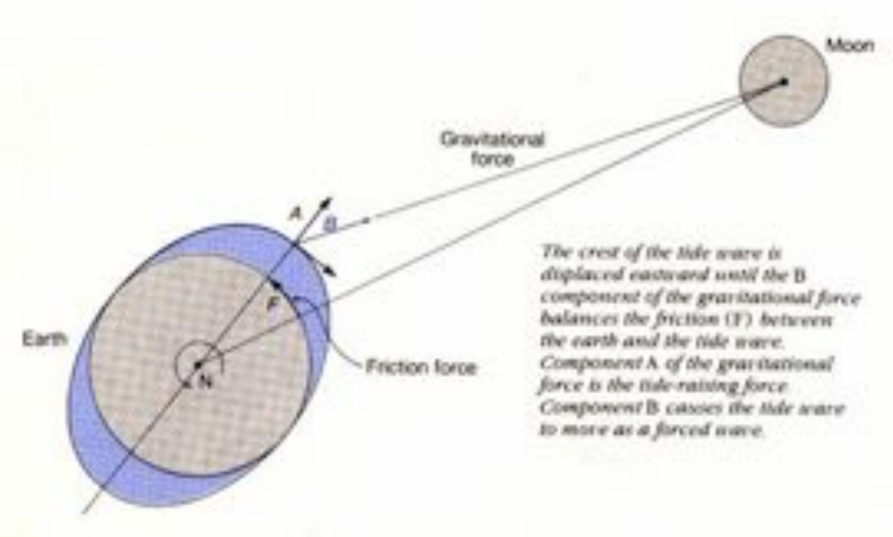
From: http://earthds.info

### Add the Effect of Zonal Tides

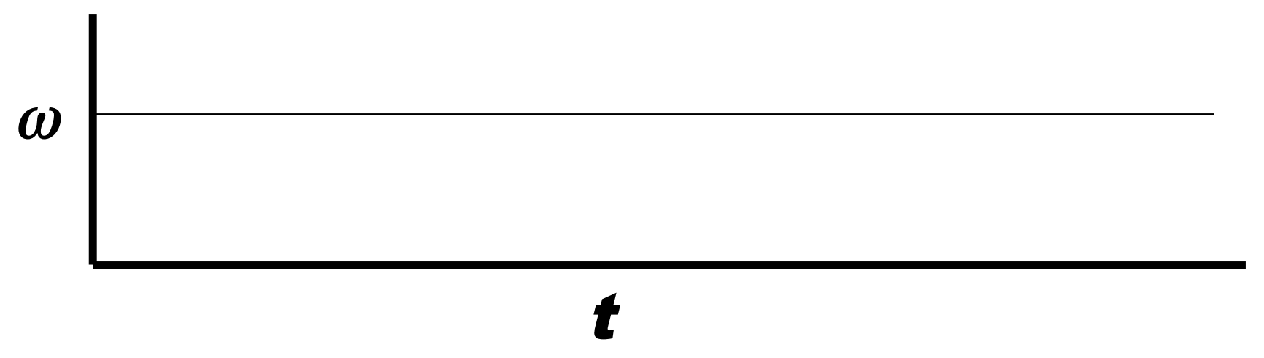
The pull of the sun and moon raise a slight lump in the solid earth—something known as a earth tide or zonal tide. That lump lags the moon because of friction within the earth with the result that the lagging lump is subject to a tidal force itself. The diagram at the top right of the center section illustrates this. Zonal tides too, are a secular force, always pulling in more or less the same direction.

* A note on the angular velocity graph: This graph was constructed by digitizing and interpreting ~hourly VLBI measurements thus much of the variation shown here is at a scale less than the twice a daily computed tidal pattern. These changes appear valid given error bars, but uncertainty remains and some of the apparent variation could be from digitizing. Are there shorter variations that produce significant force? Is smoothing appropriate or does it obscure significant torques?

**If this was a waterless elastic planet, the Moon would deform the Earth without changing its moment of inertia or rotational parameters.**

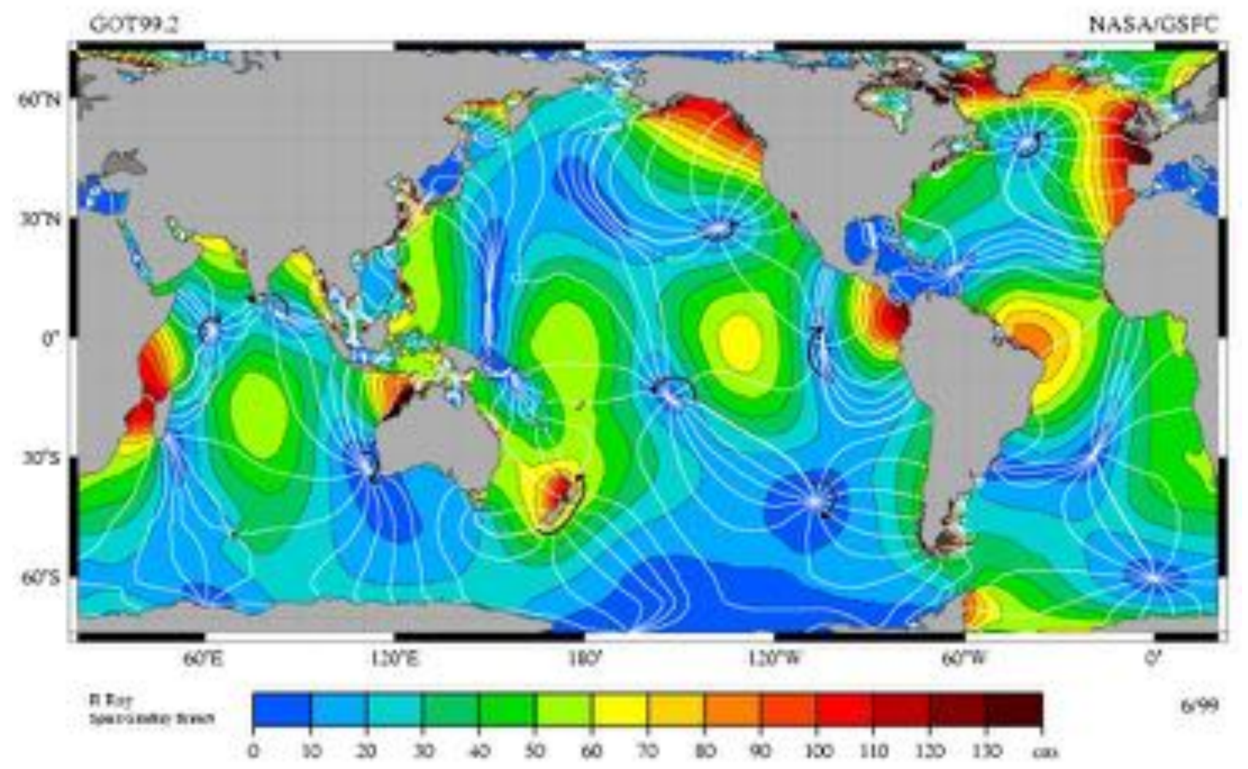


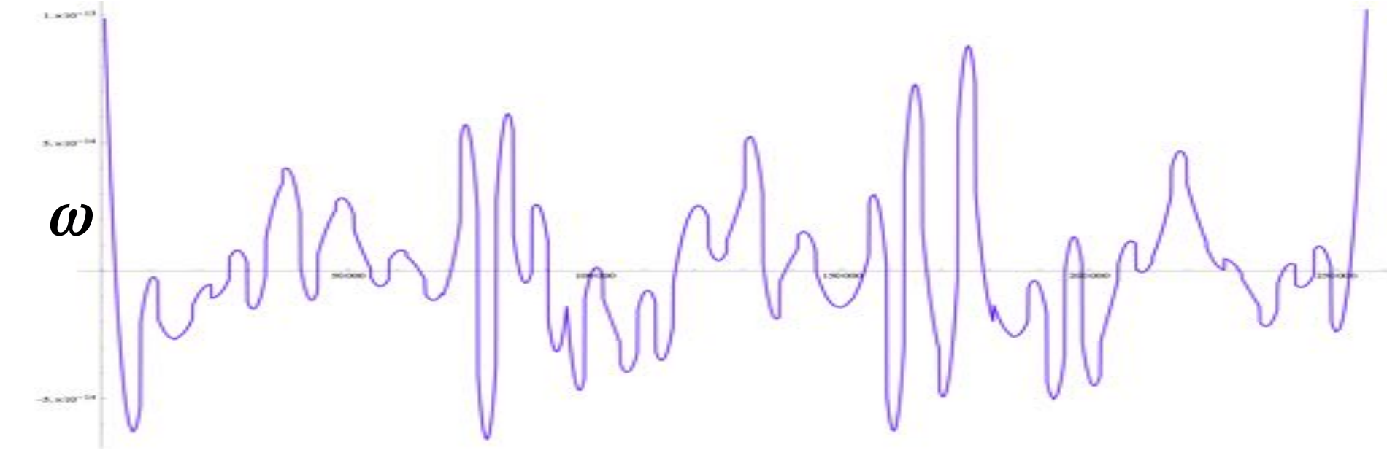
*The crest of the tide wave is displaced eastward until the B component of the gravitational force balances the friction (F) between the earth and the tide wave. Component A of the gravitational force is the tide-raising force. Component B causes the tide wave to move as a forced wave.*



**A plot of rotational velocity over time would look like this.**

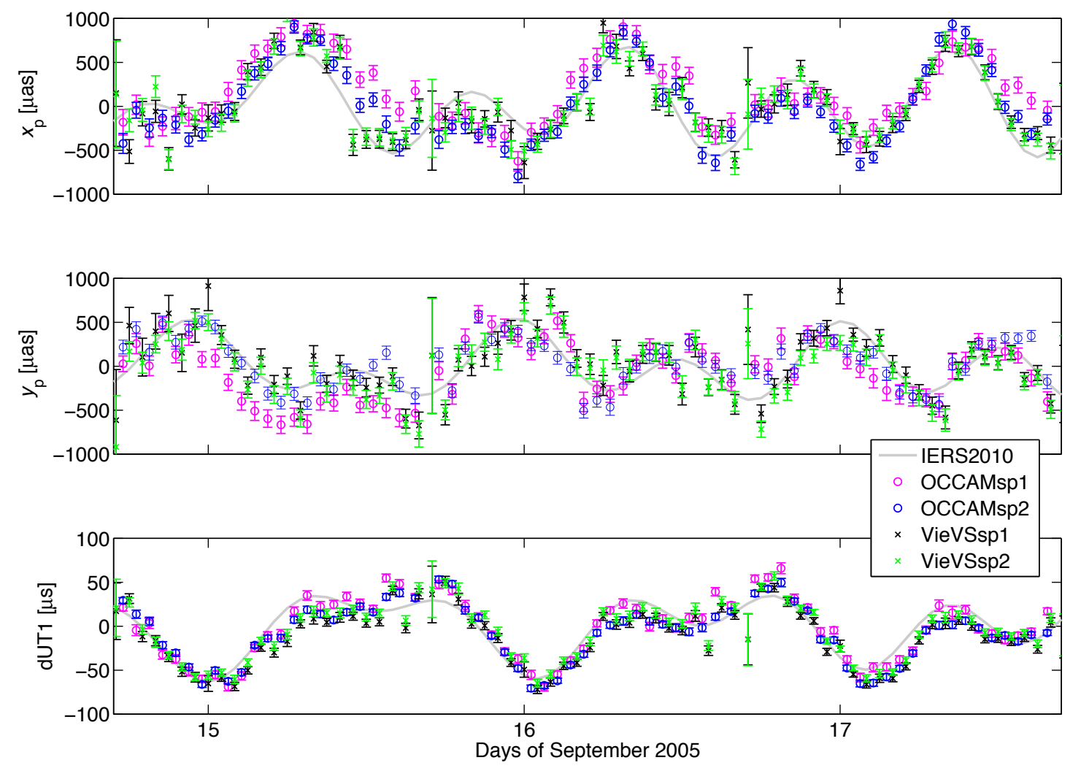
**But the Earth is covered with water and its oceans are divided by the continents into basins, each with a resonant frequency which affects the Earth's moment of inertia and thus its rotational velocity**



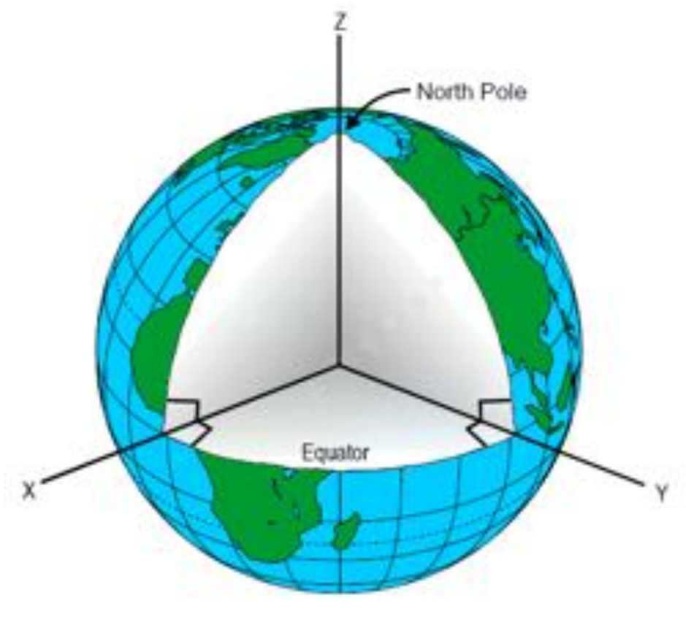


**An approximate plot of the Earth's rotational velocity ($\omega = dUT1/dt$) over three days looks like this.***

**Changes in moment of inertia affect the Earth's polar orientation, too. In three dimensions tidally induced motion looks like this:**

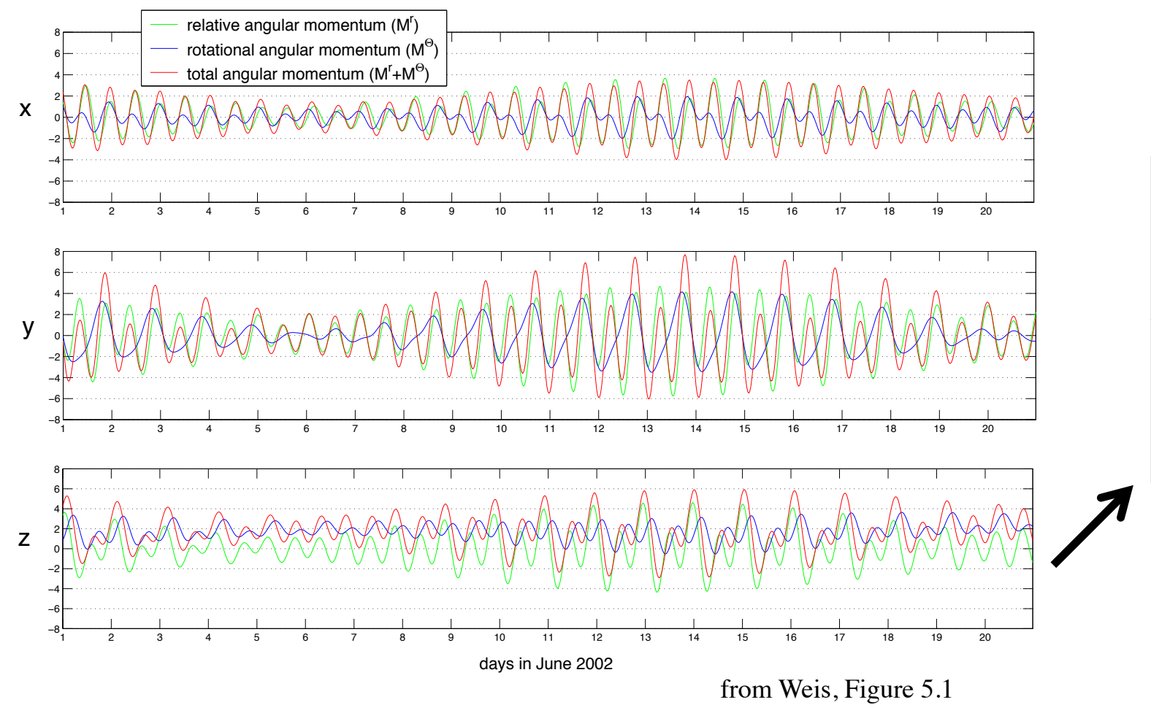


From Böhm, figure 4.7



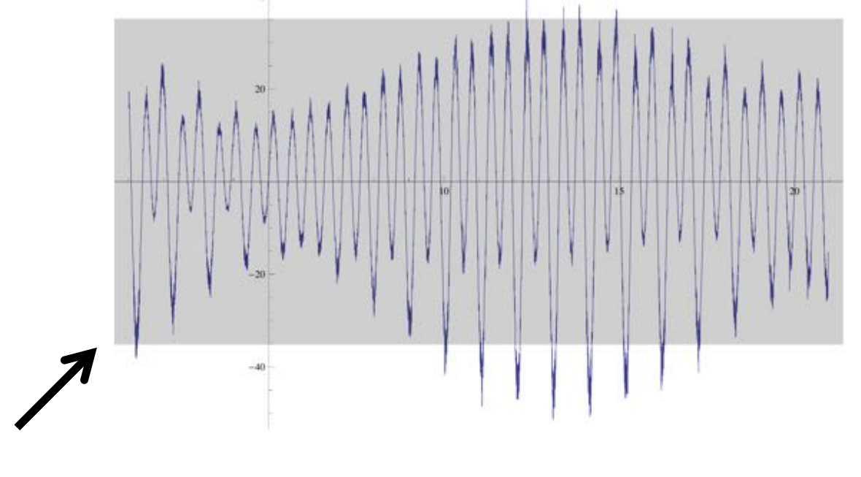
**Earth Orientation Parameters are measured on three sets of cylindrical coordinates**

**These variations produce torques that are inherently asymmetric. If one plots them over time, assuming an elastic response up to a fixed yield stress, they show ratchet-like movement.**

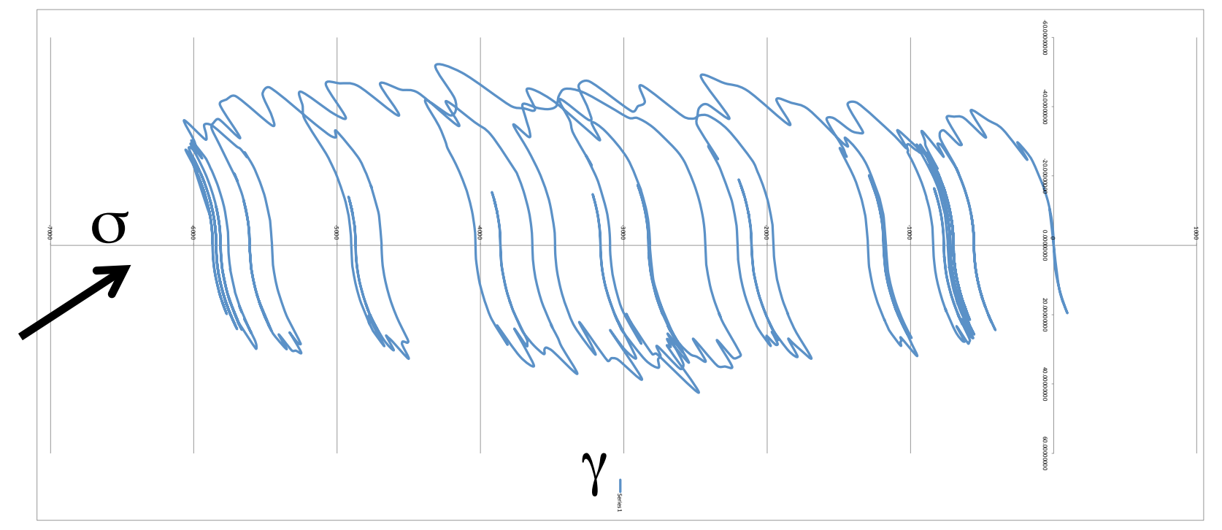


from Weis, Figure 5.1

This is a plot of variations of the Earth's angular momentum computed from ocean tides. The inherent asymmetry is apparent in these plots. Torque is the time derivative of angular momentum. From Weis, 2006.



This is a plot of the time derivative of the z axis angular momentum and represents torque in the z direction. The shading is placed to give an idea of the asymmetry.



This stress-strain plot was created from the torque derived from the graph at the left. It assumes an elastic response below an arbitrary "yield stress" and a plastic response above. The movement is both positive and negative, but over time it is has a net movement in a single direction.

## The Physics . . .

### Body Forces Drive the Continents

Despite the prevalence of the idea that contact forces—i.e., the boundary forces, trench pull and ridge push—drive the continents, there much circumstantial evidence that body forces—i.e., astronomical or inertial forces—are responsible. Among this is

- The pattern of rifts and trenches is global in scale with linear and uninform features spanning thousands of kilometers. Convective down-drop would produce a Venus-like planet
- Stress regimes within plates are relatively uniform
- Patterns of deformation reflect a globally uniform force very different than that modeled for boundary forces

### What is inertial force and why is it effective?

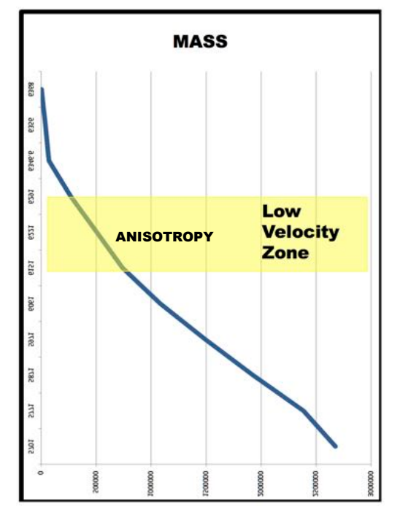
Forces are generally divided into contact forces—that would be like pushing or pulling on something—and body forces—gravity would be an example. Body forces act on every point in a body. While the gravitational force of the sun and moon are the origin of the apparent force here, the actual force applied comes from a shift in the spherical frame of reference of the Earth. Such forces are also called fictitious forces. The force on passengers from the speeding and slowing of an airport train is more than a little noticeable.

In the case of circular frames of reference, the inertial force is called the Euler force.

$$\mathbf{F}_{\mathrm{Euler}} = m\mathbf{a}_{\mathrm{Euler}} = -m\frac{d\omega}{dt} \times \mathbf{r}.$$

Where [omega] is the angular velocity of the Earth and **r** is the radial distance.

The differential stress or force per unit area at a given point increases proportional to the affected mass. Where the crust retains the strength to function as a single mass, the differential stress will increase with depth. At some point it may exceed the yield stress of Earth materials and the mass will move. That point, by the theory advanced here, is the crust-mantle boundary.



### Ocean Tidal Force Is Additive to Trench Pull, Bathymetric Gradient, and Zonal tides

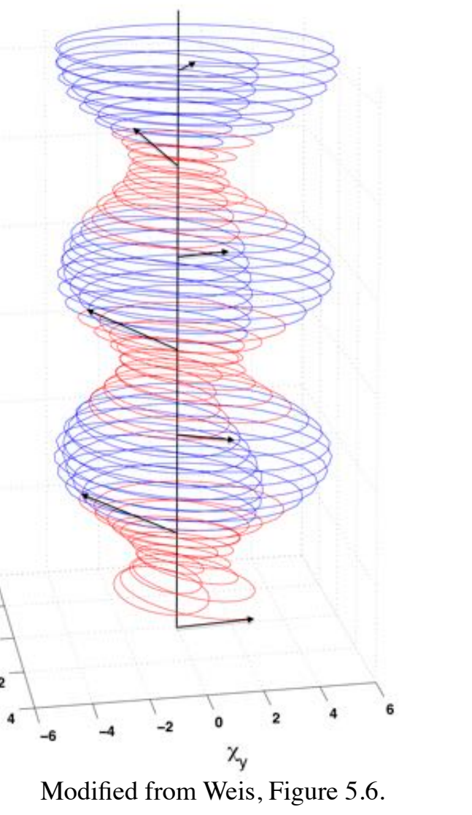
The total effect looks like this:

$$\mathbf{F}_{\mathrm{Total}} = \mathbf{F}_{\mathrm{Euler}} + \mathbf{F}_{\mathrm{Ridge\ push}} + \mathbf{F}_{\mathrm{Slab\ Pull}} + \mathbf{F}_{\mathrm{Zonal\ Tide}}$$

The Euler force, bathymetric gradient (ridge push) and zonal tides are all body forces that affect the entire crust. Slab pull may be contact force or may serve as a sort of ratchet pawl. The Euler force is weak, but it is both a body force and additive to other forces. This potentially gives it a determinative power.

### The Force Is a Vector, Unique to Every Point on the Earth, that Oscillates Twice a Day

The diagram to the right represents polar motion over a six week period in 2002—i.e., motion at the north pole. The force would be the second derivative of this, but for functions that are more or less sinusoidal, would be approximately the same form. One vector for each week has been added as an example.



Modified from Weis, Figure 5.6.

**References**

Böhm, S. (2012). Tidal excitation of Earth rotation observed by VLBI and GNSS. PhD thesis, Technischen Universität Wien.

Weis, P. (2006). *Ocean Tides and the Earth's Rotation – Results of a High-Resolving Ocean Model forced by the Lunisolar Tidal Potential*. Ph.D. thesis, Universität Hamburg.

## The Rheology . . .

### The Key to Whether this Can Work is in the Low Velocity Zone . . .

The nature of the Low Velocity Zone is a matter of debate that is beyond the scope of this poster. Numerous authors have surmised that the LVZ contains a fraction of partial melt and may provide a low viscosity sliding surface to facilitate plate movement. The effect of an oscillating body force on the LVZ is at the very least a difficult problem of materials science. Given the present state of knowledge, it seems permissive that movement could take place. As the idea presented here is developed, I hope to address this further.

## And . . .

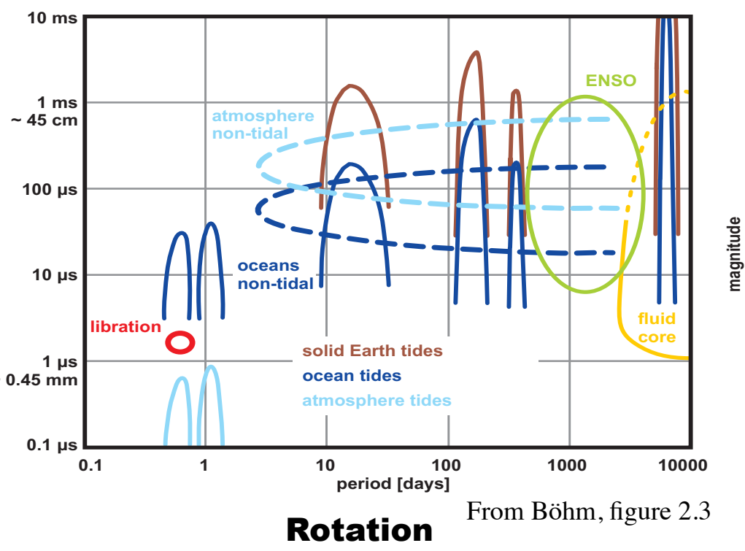
### How strong is the force . . .

Well, the answer is not too strong, at least as I have been able to calculate so far. Calculating the Euler force for a given point and a given moment is not difficult if one has the data. Preliminary calculations suggest a peak stress of less than 100 pascals. This number needs to be added to the secular forces at each point. All-in-all, calculation of a complete picture is a formidable computation project. So is this low number the answer? I don't know. Perhaps there is some way to bulk it up as happened with slab pull.

### This Is an Idea in a Formative Stage—Much Remains to Be Done

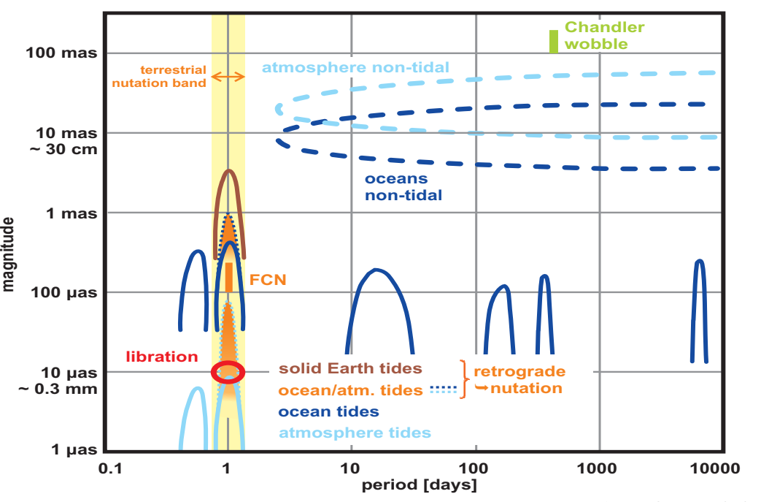
What is presented here is little more than an idea and much more remains to be done than has been done. For example, what is the net direction of the force at a given point on the Earth? This can only be approximated by analyzing the asymmetries over an appropriate period of time, adding the secular forces, and at least having some idea of the resistive strength. Each of these things raises more problems. For example, are there variations in orbital parameters that operate on an the scale of hours or less that are not yet measurable? Are estimates of secular forces such as slab pull reasonable? What are reasonable assumptions for the Low Velocity Zone? Are harmonic and elastic factors important?

I hope to be able to pursue these questions in the future and present them in a more complete and rigorous way. Comments or discussion resulting from this poster should give some direction. And I also hope that others will take this up and carry it forward.



**Rotation**

From Böhm, figure 2.3



**Polar Motion**

From Böhm, figure 2.2

## Conclusions

Because a satisfactory coherent continental driving force has yet to be found, we need to look in new places. There is no question that the tides—and to a lesser extent the atmosphere—wobble our planet and that wobbling creates a directed force on the surface of the Earth. Here I suggest that this may be the continental driving force. The questions remains, is this force strong enough and in the right direction to move continents?

The first question cannot be answered until we know what the force is pushing against. And because the answer to that question lies more than 100 km below the surface in the Low Velocity Zone, we will be hard-pressed to know for some time. The second question—the direction—is answerable if computing can resolve the magnitude and the asymmetries of the force. That is a task that can be approached with current knowledge and a lot of computing power.

Until we get some resolution on these questions, there is substantial circumstantial evidence that the continents are driven by body forces—directly or indirectly by astronomical forces. Global tectonic patterns suggests a force on the scale of the Earth and there are relatively few candidates. Asymmetric force generated by ocean tides needs to be seriously considered as a candidate in order for the requisite support to be established—in essence, supporters are needed to develop this ideal. That is the purpose of this poster.