Global tectonics—clarity, not confusion

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I respond to Michael Oard's claim in a recent *Journal of Creation* article that the motions documented by NASA's network of over 2,000 GPS stations do not imply that the plates are moving in a coherent manner, converging at subduction zones and diverging at mid-ocean ridges, primarily because the required plate driving forces do not exist. In a tutorial fashion I attempt to show that the standard gravitational body forces are sufficient to drive plate motion. I also point out that numerical models that account for the forces with great precision and in great detail have validated this same conclusion for well over 30 years. In response to Oard's denial that lithospheric slabs even penetrate into the mantle, I highlight a USGS website that has high-resolution colour images of the 3D shape of the top surfaces of the subducting lithospheric slabs for some 85% of the world's subduction zones derived by processing digitized seismic data from over 150,000 earthquakes. The slabs are resolved, in many cases, all the way to the base of the upper mantle. In response to Oard's alternative impact/vertical tectonics (IVT) model for the Flood cataclysm, I show that the energy which his model implies was delivered via impacts during the early stage of the Flood is enough to melt the topmost kilometer of the earth's surface and completely vaporize the ocean.

In an earlier article,[1] I focused on the narrow question of whether the primary physical processes associated with plate tectonics, namely, subduction and seafloor spreading, are occurring in the present day. I pointed out that restricting the scope of the inquiry to the present eliminates most of the controversies concerning what may or may not have occurred in the earth's past. The benefit of this severe restriction is that it logically removes most issues involving assumptions about the past from the table, including, for example, the age of the earth, the rates and nature of past geological processes, and even whether the Genesis Flood occurred at all. My reason for excluding the past was to focus on the specific question of whether present-day observations reveal that subduction and seafloor spreading are actually taking place today. For many years Michael Oard has been claiming these processes are simply uniformitarian illusions.[2–6] Recently, he has asserted that the GPS measurements of present-day plate motions do not indicate that subduction and seafloor spreading are occurring, but, instead, admit "other, non-PT explanations."[7] My article,[1] which gave considerable emphasis to the GPS measurements, sought to respond to this specific assertion.

Oard has in turn responded to my article with one of his own, entitled, "Is plate tectonics really occurring today?"[8] He devotes little attention, however, to what present-day observations are telling us about present-day tectonics. Indeed, he avoids almost entirely dealing with the GPS measurements and their rather obvious implications. Instead, he reiterates how complex the real earth actually is. He stresses, for example, the complexities of sediment deformation found in subduction zones, of the seismicity associated with subduction zones, and of the distribution of magmatism along the mid-ocean ridge system. In particular, he devotes considerable space seeking to discredit the widely accepted driving mechanisms for plate motion.

I wrote the previous article to clear the table of all these issues, as important as they might be in their proper context, and to focus on the narrow question of whether there is convincing evidence for present-day plate convergence along subduction zones and for present-day plate divergence along the mid-ocean ridge system. Note that this narrow question can be addressed without knowing what the mechanisms responsible for causing plate motion might be. The phenomenon of gravitation, for example, can be validated by observation without having an explanation as to its cause. Newton's finding that the gravitational attraction between two bodies is proportional to the product of their masses and inversely proportional to the square of the distance between their centres of mass can be applied to computing spacecraft trajectories with great precision today, even though modern physics still has no settled notion as to what causes this attraction. Similarly, one can address the question of the reality of plate motions without any settled notion as to what is causing the plates to move. However, as I will discuss below, the driving forces are not at all mysterious and not difficult to understand or to analyze.

Are the GPS measurements of plate motion trustworthy?

How does Oard deal with the GPS measurements? In the short space he devotes to this issue, he first doubts whether the GPS measurements legitimately can be translated into plate motions. He states:

> "… we can reasonably ask whether the local measurements gathered by scientists can be extrapolated into plate motions. Realistically, to do so would require them to zero out all the local influences, such as faults, folding, subsidence, and uplift, which are *not* so thoroughly documented."

However, the publically available data on the JPL website sufficiently answers this objection.[9] It shows the vertical component of motion of each of the more than 2,000 receiver stations. The uplift/subsidence history of each station is documented in detail, contrary to Oard's claim. Moreover, the effects of slip on nearby faults due to earthquakes are also beautifully captured in these datasets. Nearby large earthquakes produce observable jumps in the plate motion histories. Why is it that Oard gives the impression that such behaviour is not represented in these data?

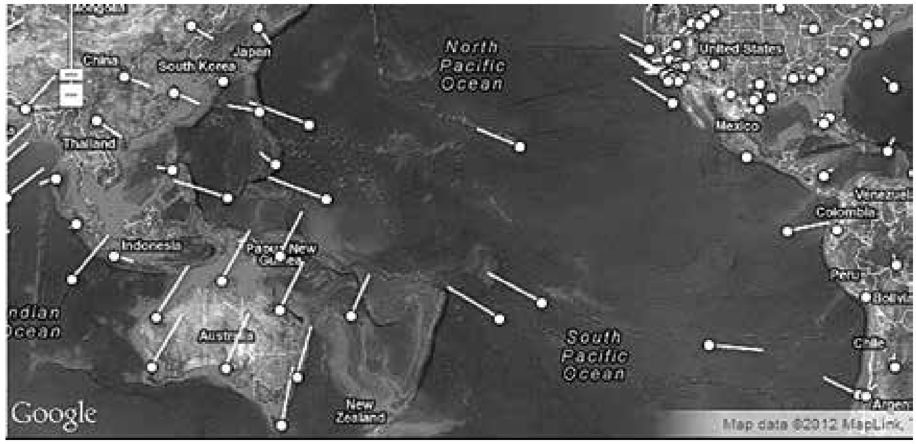

Figure 1. Horizontal displacement rates of some of the 2,000 GPS receiver stations in the NASA geodetic network operated by the Jet Propulsion Laboratory.

Oard's statement contradicts the clear conclusion these GPS measurements so powerfully convey: that the plates indeed are moving in a coherent plate-like manner. The coherence of the individual plate motions is strikingly evident in figure 1. Also apparent in figure 1 are abrupt discontinuities in plate motion at the deep ocean trenches in the western Pacific and the north-eastern Indian Ocean. What other remotely plausible explanation can there be for these patterns other than subduction?

Are the forces acting on the plates today adequate to drive their observed motions?

Oard's primary response to the issue of the GPS measurements is to evade their significance and instead to divert the reader's attention to the issue of the mechanism responsible for moving the plates. In his abstract he states, "GPS motions are not proof of plate tectonics, because the suggested forces to move plates are inadequate." In the body of the article, he adds, "GPS stations do measure absolute movement, but do not say anything about the cause of this movement." As I mentioned above, the possible mechanisms that might be causing the plates to move is a topic separate from the actual motions of the plates themselves. The question of whether the plates are actually converging at subduction zones and diverging along the mid-ocean ridges can be addressed entirely apart from any discussion of mechanism. Oard fails to discuss this key issue of the actual plate motions in his article; instead he raises a plethora of off-topic objections.

What about the side issues Oard has raised? While these may detract from the central importance of the GPS observations and their clear implications, addressing some of these will help the reader see that plate tectonics is a coherent idea. Let's begin with Oard's claim that no scientifically credible mechanisms exist to account for present-day plate motions. To start, many different lines of evidence indicate that the mantle can, and does, deform in a manner that implies large-scale flow. Significant portions of the continental surface that were depressed by ice sheets during the Ice Age, for example, are rebounding in elevation. In the Hudson Bay region the uplift rate currently exceeds 1 cm/yr.[10]

As has been recognized for more than a half-century, rock of the earth's mantle, though solid, deforms under stress by migration of defects within the crystals and by motion along grain boundaries—a process known as solid-state creep.[11] This means that, under stress, rock in the mantle flows in a plastic manner and can realistically be treated as a fluid. Because of the action of gravity upon them, blobs of rock that have a density different from their surroundings have a tendency either to sink or rise, depending on the sign of the density difference, producing a pattern of plastic flow. Subducted slabs of oceanic lithosphere, in particular, because of their large temperature contrasts, and hence density contrasts, relative to surrounding mantle rock, tend to sink. Given the typical density contrast, the magnitude of the gravitational body force acting upon a subducted slab of lithosphere can be huge.

Brief analysis of slab-pull force

Let us seek to quantify the component of this force, generally referred to as the slab-pull force, which acts in the direction of slab subduction. The gravitational body force F_g acting on the subducted portion of the slab, indicated by shading in figure 2, relative to its surroundings, is given by $F_g = raDTgV$, where r is rock density, a is the volume coefficient of thermal expansion, DT is the temperature difference between the hot upper mantle rock and the slab, g is the gravitational acceleration, and V is the volume of the slab surrounded by hot upper mantle rock. This volume V in turn is given by $V = hc/sinq$, where h is the depth of the upper mantle penetrated by the slab, c is the slab thickness, and q is the angle of subduction relative to the horizontal. The downward gravitational force F_g can be resolved into two orthogonal components, a component $F_{sp} = F_g\ sinq$ oriented in the direction of the subducted slab, which is the slab-pull force, and a component $F_{rb} = F_g\ cosq$, sometimes called the hinge roll-back force, which acts to cause the slab hinge line to migrate backwards. Multiplying F_g by $sinq$, we find that the slab-pull force is given by $F_{sp} = raDTghc$. Choosing realistic values of 3,300 kg/m^3 for r, 3 x 10^{-5} °C^{-1} for a, 800°C for DT, 10 m/s^2 for g, 500 km for h, and 80 km for c, we obtain a value for the slab-pull force F_{sp} of 3.2 x 10^{13} N/m. This is the force in the down-slab direction per metre of slab width in the direction perpendicular to the plane of figure 2.

Brief analysis of basal drag force

How does this slab-pull force compare with the basal drag force F_d acting on the bottom of a plate? One can estimate this force by assuming that all the shear deformation associated with plate motion is accommodated in a weak layer of fixed thickness immediately beneath the plate, as shown in figure 3. Evidence that a weak layer exists immediately beneath the lithosphere was presented in 1914 by the British geologist Joseph Barrell.[12] It was Barrell who gave this weak layer the name asthenosphere, from Greek, asqenhV, for weak. Current estimates for its viscosity are in the range of 10^{17} Pa-s, or less, to 10^{19} Pa-s, depending strongly on the estimated thickness of the layer.[13] The smaller the estimated asthenospheric thickness, the lower is the viscosity that fits the observational data. Let us consider an asthenospheric layer only 30 km thick with a dynamic viscosity of 10^{18} Pa-s and compute the basal shear traction on a slab of lithosphere moving at 8 cm/yr relative to the mantle below the asthenosphere, which we will consider as motionless. As illustrated in figure 3, all the deformation beneath the plate is here confined to the thin asthenospheric layer.

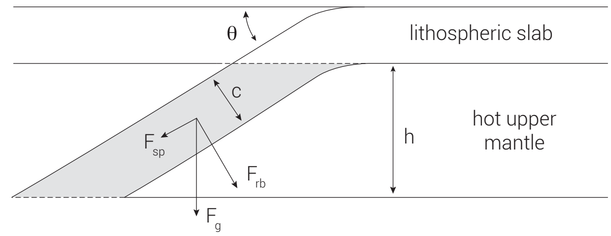

Figure 2. Idealized sketch of subducting lithospheric slab. A section of slab of thickness *c*, shown in grey, occupies a zone of thickness *h* in the upper mantle and dips at an angle q relative to the earth's surface.

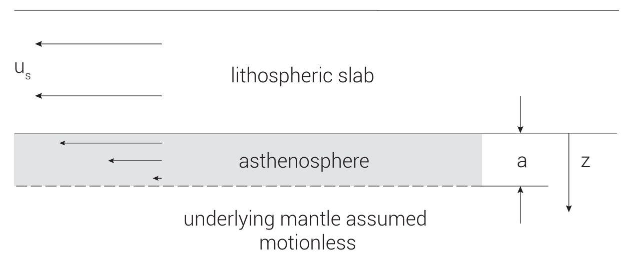

Figure 3. Idealized sketch of the shear flow in the asthenosphere beneath a lithospheric slab moving at a speed u_s relative to the mantle, assumed stationary, beneath a weak asthenospheric layer of thickness *a*

The strain rate du/dz in the layer, where $u(z)$ is the horizontal velocity and z is the coordinate in the downward direction, is given by $du/dz = u_s/a$, where u_s is the slab velocity and a is the asthenospheric thickness. The shear stress t within the layer and on the base of the slab is given by $t = mdu/dz = mu_s/a$, where m is the dynamic viscosity of the asthenosphere, assumed constant throughout the layer. Using the assumed values, we find that t = (10^{18}Pa-s)(0.08 m/yr)/[(3.16 x 10^7 s/yr)(3 x 10^4 m)] = 8.4 x 10^4 Pa = 8.4 x 10^4 N/m^2. The drag force F_d on a plate of length L = 10,000 km with this value of basal shear stress t is given by $F_d = t\,L$ = (8.4 x 10^4 N/m^2)(1 x 10^7 m) = 8.4 x 10^{11} N/m. Note that the estimated drag force F_d for a plate comparable in length to the Pacific plate moving at a speed of 8 cm/yr, consistent with the speed of the Pacific plate according to the GPS observations, is only about 2.6% of the slab-pull force estimated above.

Brief analysis of ridge-push force

Now let us estimate the size of the ridge-push force F_{rp} that acts in the slab in the vicinity of a spreading ridge. This force arises from the elevation of the slab next to the ridge produced by the higher temperatures in the mantle beneath. The magnitude of this ridge-push force can be estimated by integrating the pressures acting on the two sides of the box enclosing the slab adjacent to the ridge as shown in figure 4.[14] The force F_3 is obtained by integrating the hydrostatic

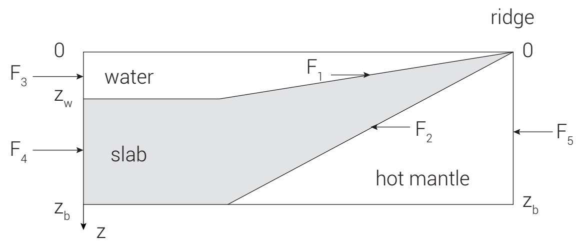

Figure 4. Idealized sketch of lithospheric slab in the vicinity of a spreading ridge. The ridge-push force is given by $F_2 - F_1 - F_4$. Arrows are not scaled to force magnitudes. Vertical scale is exaggerated.

pressure of the water over depth z from 0 to z_w, where z_w equals the difference in elevation of the ridge and where the ocean bottom flattens. That is, $F_3 = \rho_w g \int_0^{z_w} z dz = \frac{1}{2} \rho_w g z_w^2$, where r_w is the water density. Similarly, the force F_4 is given by the integral of the pressure from z_w to z_b, where z_b is the depth to the base of the slab, that is, $F_4 = g \int_{z_w}^{z_b} [\rho_w z_w + \rho_s (z - z_w)] dz = g[\rho_w z_w (z_b - z_w) + \frac{1}{2} \rho_s (z_b^2 - 2z_b z_w + z_w^2)]$, where r_s is the slab density. In a similar manner, the force F_5 acting to the left on the right side of the box in figure 4 is given by $F_5 = \rho_m g \int_0^{z_b} z dz = \frac{1}{2} \rho_m g z_b^2$, where r_m is the density of the hot mantle beneath the ridge. We note that the force F_1 acting on the sloping surface of the slab adjacent to the ridge is equal to F_3 because the hydrostatic pressure of the water depends simply on depth. We can also observe that the force F_2 acting on the sloping base of the slab adjacent to the ridge is equal to F_5 if the hot mantle deforms in a fluid-like manner. Therefore the net ridge-push force F_{rp} is given by $F_{rp} = F_5 - F_3 - F_4$.

Assuming that the difference DT in mean temperature of the rock beneath the ridge and mean temperature of the slab is 500°C and taking the slab density r_s to be 3,300 kg/m^3, water density r_w to be 1,000 kg/m^3, and the volume coefficient of thermal expansion a to be 3 x 10^{-5} °C^{-1}, we can obtain values for r_m and z_w. We have $r_m = r_s(1-aDT)$ = (3,300 kg/m^3)[1 – (3 x 10^{-5} °C^{-1})(500°C)] = 3,250 kg/m^3. Assuming an equilibrium slab thickness $z_b - z_w$ of 80 km and equating the pressures at depth z_b on the two sides of the box in figure 4, we find that P_b/g = (3,250 kg/m^3)(80 x 10^3 m + z_w) = (1,000 kg/m^3)z_w + (3,300 kg/m^3)(80 x 10^3 m), which yields z_w = 1.78 km and z_b = 81.78 km. Evaluating F_5, F_3, and F_4 assuming the gravitational acceleration g to be 10 m/s^2, we get F_5 = 1.0868 x 10^{14} N/m, F_3 = 1.6 x 10^{10} N/m, and F_4 = 1.0702 x 10^{14} N/m and find that the ridge-push F_{rp} = $F_5 - F_3 - F_4$ = 1.6 x 10^{12} N/m. We note that this driving force exceeds by a factor of 1.9 the drag force computed above for a plate 10,000 km in length moving at 8 cm/yr. This suggests that the ridge-push force ought in many, if not most, cases to be sufficient by itself to overcome the basal drag beneath oceanic lithosphere. It is also useful to observe that the ridge-push force is a force that is applied in a distributed manner, typically over an interval of several hundred or even a thousand kilometres adjacent to the ridge axis. In other words, the ridge-push force is not an edge force; it is a distributed body force.

Brief analysis of slab-resistance force

What about the force F_r that resists the motion of a subducted slab as it penetrates into the upper mantle? Numerical models are designed to enforce a precise balance of forces in each computational cell at each time step and therefore simultaneously compute all the forces with high precision and in great detail. However, let us continue to treat the issue of slab force balance in a piecemeal fashion using simple geometries and boundary conditions. To estimate the force F_r resisting the penetration of a lithospheric slab into the mantle, let us follow the approach we previously used to estimate the basal drag force on horizontally moving lithosphere. Let us assume a zone of uniform shear adjacent to the penetrating slab, but in this case on both sides. As before, the shear stress t within the shear layer and on the slab is given by $t = mu/w$, where m is the dynamic viscosity of the shear layer, assumed constant throughout the layer, u is the slab speed, and w is the shear layer thickness. Choosing m = 10^{21} Pa-s, appropriate for the upper mantle,[15] u = 8 cm/yr, and w = 100 km, we find t = (10^{21} Pa-s)(0.08 m/yr)/ [(3.16 x 10^7s/yr)(1.0 x 10^5 m)] = 2.5 x 10^7 Pa. If we assume that this shear stress acts over 600 km distance on each side of the slab, the resulting slab resistance force F_r = (2.5 x 10^7 N/m^2)(2 x 6 x 10^5 m) = 3.0 x 10^{13} N/m.

The resistive slab-slab force F_{ss} that arises from the shear between the subducting slab and the overriding slab at a subduction zone also depends on the plate speed and so is similar in character as the penetration resistance force F_r. But in general it is significantly smaller in magnitude.

This suggests that most of the large slab-pull force F_{sp} is cancelled by the resistance force F_r required to deform the upper mantle as the slab moves through it. A basic mechanical principle is that the steady-state speed of the plate adjusts itself such that the forces acting on the plate sum to zero. That is, the forces tending to cause the plate to move are exactly balanced by forces that resist the motion. From the simple analysis we have considered, the two largest forces are the slab-pull force F_{sp} and the force F_r that resists the penetration of the subducted portion of the plate into the mantle. To the extent that these two forces actually are dominant, the plate speed will tend to adjust itself such that the resistive force F_r, which increases with plate speed, cancels most of the slab-pull force F_{sp}, which is essentially independent of plate speed.

The preceding analysis is in direct conflict with Oard's statement, "there is no mechanism sufficient for PT". The analysis demonstrates that the main forces acting on the plates can be estimated in a straightforward manner. Such estimates have been available for three decades in standard undergraduate textbooks on geodynamics.[16] Moreover, the reality that gravitational forces are more than sufficient to drive plate motions has been demonstrated in a cleaner and even more convincing way by numerical models for more than three decades. Since 1983 in publications to which I have contributed, I and my co-authors have clearly and repeatedly authenticated this result.[17–28] Central to all these numerical simulations is the finding of velocities and pressures that yield an exact balance of forces at each grid point or centre of each computational cell, a balance that is enforced at each new time step. At a minimum these forces include those involved in deforming the rock, the force resulting from gravity, and the force arising from local pressure differences. This approach of subdividing the domain into thousands, or even millions, of cells and enforcing a balance of forces at every grid point is powerful and applied widely in science and engineering fields. Why does Oard not comment on all these numerical results? Is the physics somehow defective or irrelevant? Are there essential features missing? Are the numerical techniques somehow faulty? If so, he should have long ago spelled out the shortcomings. If there are problems, why has he not pointed them out?

Quotations out of context

So how does Oard attempt to justify his claim, "there is no mechanism sufficient for PT"? In part he quotes his references out of context. Consider his quotation from a paper by W.B. Hamilton:[29]

> "Oceanic lithosphere is strong in compression but weak in tension, so 'slab pull', although often invoked, can be only a minor complication. 'Ridge push' is another popular misconception."

In context, Hamilton is critiquing a common misunderstanding of ridge push as a force localized to the ridge rather than as a gravitational body force. The preceding sentence in his paper reads:

> "The lithostatic head of seafloor relief and of the trenchward inclination of the base of the dense oceanic lithosphere atop the light asthenosphere, products of the thickening of asthenosphere with time as a result of top-down cooling, provides an additional gravitational body force, ridge slide."

The force to which the ridge slide force is additional is the slab-pull body force. The sentence immediately following the two sentences Oard quotes reads, "Body forces do the job." Hamilton prefers to call the force acting adjacent to the ridge 'ridge slide' instead of 'ridge push'. He correctly emphasizes it is a gravitational body force. His description is entirely consistent with figure 4, above, and my analysis of it. Further, the reason Hamilton minimizes slab pull, other than its being largely balanced by mantle resistance, is his emphasis on the importance of hinge rollback throughout his paper.

A second quote by Oard from the same paper is also taken out of context. This quote reads:

> "The lack of compressive deformation in young, thin oceanic lithosphere precludes the shortening that would occur were there a ridge-push force."

Hamilton is again disparaging the term 'ridge push' force because he correctly understands that the force acting at the ridges is a gravitational body force and not an edge force. He prefers instead to call this body force 'ridge slide'. There is no compressive deformation in young, thin lithosphere precisely because there is no compressive edge force acting at a ridge! Most geophysicists who work in global tectonics are fully aware of this reality. Most geophysicists choose to continue to use the term 'ridge push', however, because it has become part of the standard vocabulary, even though it can be misleading to those who are not close to the field. Hamilton is clearly on a campaign to have the community revise its vocabulary. Oard seems to have missed this nuance entirely. Hamilton, contrary to Oard's interpretation, argues that what he calls the ridge slide force is very real, is straightforward to characterize, and plays an important role in plate motion. Again, *contra* Oard, Hamilton does not question the reality of plate tectonics, subduction, or seafloor spreading. In fact, the beginning sentence of Hamilton's paper reads:

> "The reality of plate tectonics, as a description of relative motions of those parts of Earth's outer shell that are internally semi-rigid, has been proven."

These are not the only examples where Oard has failed to properly understand the authors he quotes. However, they provide a representative sample for the reader to see Oard's lack of understanding of the plate tectonics literature.

Should plate motions that occurred during the Flood have now come to a complete stop?

For Oard to maintain that "the suggested forces to move plates are inadequate" is bewildering enough. His quoting experts out of context is extremely grievous. Perhaps even more startling is his claim that any plate motions that may have occurred during the Flood "should have come to a *complete stop* [emphasis his]". He provides no explanation whatever as to how he has reached such a bizarre conclusion. This makes no sense given basic crustal mechanics.

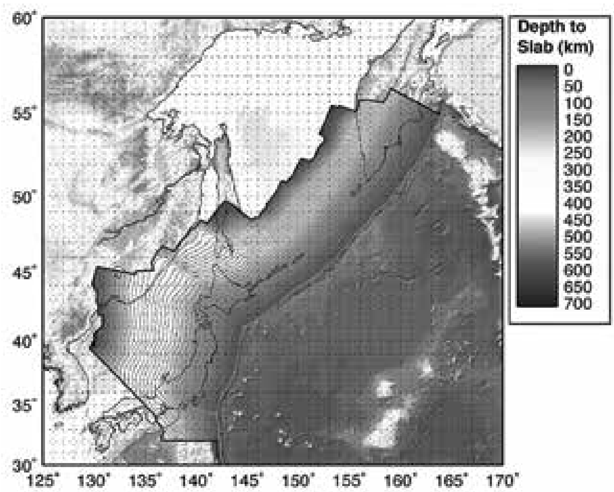

Figure 5. Geometry of the top surface of the slab subducting into the Kamchatka-Kuril-Japan trench. Surface, shaded according to depth and contoured at 20 km intervals, is constructed from individual two-dimensional profiles perpendicular to the trench and spaced 10 km apart.

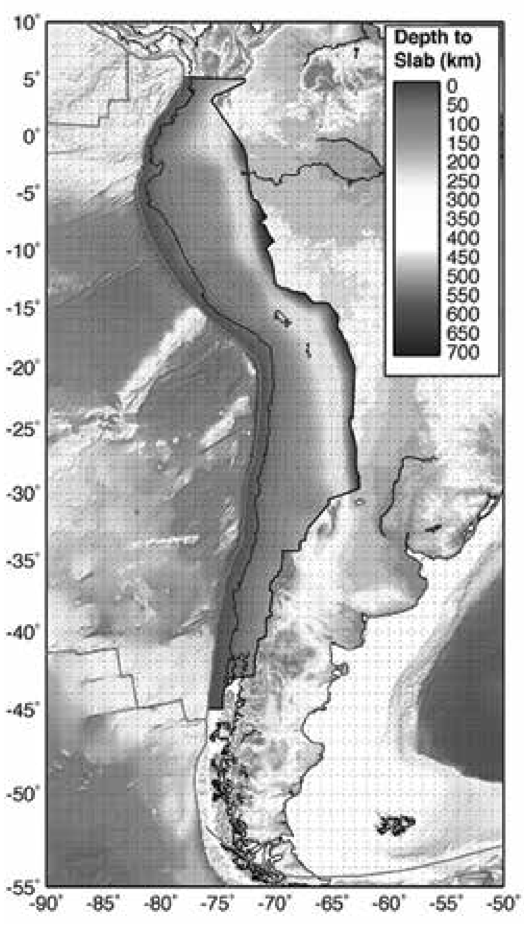

Figure 6. Geometry of the top surface of the slab subducting beneath South America. Surface is constructed from approximately 600 individual two-dimensional profiles perpendicular to the trench and spaced 10 km apart. Surface is shaded according to depth and contoured at 20 km intervals.

Do lithospheric slabs currently penetrate into the upper mantle?

In addition Oard dismisses the idea that slabs of oceanic lithosphere even penetrate into the mantle at all. Yet the seismic evidence that lithospheric slabs do plunge into the mantle at subduction zones is overwhelming. The large temperature contrasts between lithospheric slabs and the underlying mantle lead to large contrasts in seismic velocity between the two. This means that detection of lithospheric slabs by seismic methods today is a straightforward task, especially with the present density of seismic stations and the computer power available to process the vast amounts of seismic data. Recently a group at the National Earthquake Information Center of the U.S. Geological Survey located in Golden, Colorado, has released high-resolution 3D representations of subducting slab geometries for 85% of the earth's subduction zones derived from this wealth of seismic data.[30] Figure 5 shows the geometry of the top surface of the slab subducting into the Kamchatka-Kuril-Japan trench in the western Pacific. The surface is constructed from some 600 individual 2D profiles oriented perpendicular to the trench and spaced 10 km apart. The EHB earthquake database (www.isc.ac.uk/ehbbulletin), containing more than 140,000 events, and the Global CMT database (www.globalcmt.org), containing more than 25,000 events, are combined together to generate the 2D profiles. Figure 6 displays the geometry of the top surface of the slab subducting beneath the western margin of South America using the same databases. Geometries of eleven other subduction zones are posted on the USGS website.[31] In view of such powerful observational evidence for lithospheric slabs having penetrated at least to the base of the upper mantle, how can Oard ignore the clear significance of these observations?

Was the earth's surface a magma ocean early in the Flood?

Near the end of his article, Oard mentions his alternative model to account for the tectonics of the Flood. He refers to it as his impacts/vertical tectonics (IVT) model. This model postulates that the same population of objects that impacted and cratered the moon also impacted and cratered the earth during the early part of the Flood, somehow leaving the earth in a state of extreme isostatic imbalance. Then, after the Flood, the model posits that isostatic adjustment produced sufficient vertical motion to cause the continents to rise, the ocean basins to sink, and the floodwaters to retreat. In a 2009 *Journal of Creation* article,[32] Oard, estimates, based on analysis of the lunar craters, that the cratering of the earth likely involved some 36,000 asteroid impacts large enough to produce craters 30 km in diameter and larger, all within a span of a few days' time. Hundreds of thousands of smaller impacts accompanied these larger ones. He correctly concludes that the resulting crater density would be at a saturation level; that is, craters would significantly overlap one another over the entirety of the earth's surface, a density exceeding that of the back side of the moon, of the southern hemisphere of Mars, and of Mercury.

As a conservative value for the volume of material that impacted the moon to produce its craters, Oard offers an estimate by Samec[33] equal to that of a single 70-km-diameter asteroid, or 1.8×10^{14} m^3. To obtain a value for the amount of material that would have impacted the earth from the same population of objects, Oard multiplies the value for the moon by a factor of 13.5 to account for the ratio of the cross-sectional area of the earth to that of the moon and another factor of 1.4 to account for the earth's stronger gravity field. This implies a total volume of 3.4×10^{15} m^3, sufficient to cover the earth everywhere to a depth of 6.6 m. Although Oard does not run the numbers, it is straightforward to compute the amount of energy these impacting objects would deliver to the earth's surface. Oard suggests the speed of the incoming objects may have been similar to that observed currently for asteroids, or about 20 km/s. This value for the speed v of the incoming objects implies that their specific kinetic energy, given by $0.5v^2$, is 2×10^8 J/kg. If we assume the impacting material is mostly silicate with a mean density of 3,300 kg/m^3, we find the average amount of energy delivered to the earth's surface is (2×10^8 J/kg) (3,300 kg/m^3) (6.6m) = 4.4×10^{12} J/m^2 = 4.4×10^{18} J/km^2.

With 4.18×10^{15} J equal to one megaton, this corresponds to an energy density of more than the yield of 1,000 megaton bombs *for each square kilometre* of the earth's surface! Granite and basalt require only on the order of 1.3×10^6 J/kg to melt.[34] Hence, the impact energy density is sufficient to melt a layer of rock (4.4×10^{12} J/m^2)/[(1.310^6 J/kg) (3,000 kg/m^3)] = 1.1×10^3 m = 1.1 km thick over the entire earth. This would obviously turn the earth's surface into a transient magma ocean. It would also vaporize all the ocean water. An average water depth over the earth of 2,750 m and 2,675 J/kg to vaporize 0°C water implies that only (2,750 m) (2,675 J/kg) (1,000 kg/m^3) = 7.4×10^9 J/m^2, or 0.17% of the total impact energy is needed. Such a catastrophic bombardment would disrupt and melt the earth's surface to such an extreme degree that essentially none of the macroscopic pre-Flood forms of life could possibly survive intact. Apart from possibly a few bacteria below the melt zone, it is difficult to imagine how any trace of any sort of organism could survive such conditions to be fossilized later during the Flood. But, by the same token, neither would there be any water or sediment around to bury an organism, even if somehow one did survive. Moreover, I am aware of no physical mechanism by which such a massive bombardment of the earth might result in a large, spatially coherent isostatic imbalance between the continental portion of the earth and that which had been deep ocean basin. Oard applies the designation 'impact/vertical tectonics', to his ideas concerning Flood tectonics. Yet just where does he offer any mechanism to drive vertical tectonics? As far as I can discern, he has never sketched such a mechanism, not even at a concept level.

Summary

Oard, in his article, evades the obvious implications of the results of NASA's network of over 2,000 GPS stations that the plates are moving in a coherent manner, converging at subduction zones and diverging at mid-ocean ridges. In a seeming attempt to divert attention away from this, he raises a host of side issues, some that relate directly to the state of the earth today and some that do not. In response to his astonishing claim that no mechanisms exist that can drive present-day plate motion, I seek in a tutorial fashion to show that the standard gravitational body forces do the job quite nicely. I also point out that numerical models that account for the forces with great precision and in great detail have also validated this conclusion for well over 30 years. I point out that Oard, when quoting from the professional earth science literature, frequently quotes authors out of context and often severely misrepresents their words. In response to Oard's reluctance to accept that lithospheric slabs penetrate into the mantle, I point the reader to a USGS website with high-resolution colour images of the 3D shape of the top surfaces of the subducting lithospheric slabs for some 85% of the world's subduction zones derived by processing digitized seismic data from over 150,000 earthquakes. In many cases the slabs are resolved all the way to the base of the upper mantle. Finally, I show how much energy Oard's IVT model implies was delivered via impacts during the early stage of the Flood, a number Oard has not heretofore disclosed. I find that it is enough energy to melt the topmost kilometre of the earth's surface and to vaporize the oceans entirely. To me it is time for clarity, not confusion, regarding these issues that are so crucial to understanding the earth's structure, dynamics, and history in light of Scripture.

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