

## ***Interactive comment on “Energy of plate tectonics calculation and projection” by N. H. Swedan***

### **Anonymous Referee #2**

Received and published: 24 May 2013

I will respond briefly to a few of the author’s responses to my review (referee #2). My comments are noted as “REPLY”. Needless to say, the author’s responses have not changed my opinion about the paper, but I appreciate the chance to respond to them directly.

AUTHOR: This Referee’s general understanding of the work presented in the manuscript is, with all due respect, incorrect. Basaltic melting is not the driver of plate tectonics. The heat of mantle convection,  $Q_h$ , available at the temperature of the hot reservoir temperature,  $T_h$ , is the driver of the thermodynamic cycle. Some of this heat is lost as,  $Q_c$ , to the surroundings at the cold temperature,  $T_c$ , and the difference,  $Q_h - Q_c$ , is the net thermal energy that can be converted to mechanical work,  $W$ . This work is delivered to the tectonic plates. This work,  $W$ , is also equal to the latent heat of melting of basaltic rock calculated at mantle’s pressure. The heat of convection, as the source of energy that drives plate tectonics, is mentioned repeatedly and has a ded-

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icated symbol,  $Q_h$ , used in the thermodynamic equations throughout the manuscript. Please see Item 6 for more details.

REPLY: This thermodynamic analysis of thermal convection is incorrect. The energy that can be converted to mechanical work is equal to the energy released by potential energy (sinking slabs and rising plumes). The vast majority of this mechanical work is spent deforming the viscous mantle (viscous dissipation). A rather small amount is spent melting rocks, and this amount depends on the relative temperatures of the geotherm and the solidus of mantle rocks. The author is correct (sort of) that the difference in heat transport in hot reservoirs (upwelling plumes) and cold reservoirs (cold slabs) produces net energy – but this is due to the difference in adiabatic decompression and compression at different temperatures, and yields a net cooling. This cooling, however, is balanced by net heating by viscous dissipation. Therefore, the work done to drive plate tectonics (and all deformation in the mantle) is given by the rate of release of potential energy in the convecting system. This is a very different system than is described in this paper. Furthermore, there are many papers that have been written over the past few decades to describe this system. Here are some that come to mind: Conrad, C.P., and B.H. Hager (1999), Effects of plate bending and fault strength at subduction zones on plate dynamics, *Journal of Geophysical Research*, 104, 17551-17571. Backus, G. E. (1975), Gross thermodynamics of heat engines in deep interior of Earth, *Proc. Natl. Acad. Sci. U.S.A.*, 72, 1555-1558.

AUTHOR: The word “viable” implies a hypothesis. The submitted work is not a hypothesis, it is based on proven and validated laws of thermodynamics, physics, and mathematics. The results of the calculations are in agreement with observations, experiments, and the work of others. The work is well beyond a hypothesis.

REPLY: The author does not test a hypothesis here – there is no prediction followed by a test against observations. I would argue that this work is more of an assertion, rather than a hypothesis.

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AUTHOR: Any pressure build up cannot be accommodated by the viscous flow in the asthenosphere because the asthenosphere is incompressible. This is assumed as such in lines 12 and 13 of page 146. The work of Adams L. H. and Gibson R. E. (1926) suggests that earth's rocks are practically incompressible. The reference follows: Adams L. H. and Gibson R. E.: THE COMPRESSIBILITIES OF DUNITE AND OF BASALT GLASS AND THEIR BEARING ON THE COMPOSITION OF THE EARTH, PROCEEDINGS OF THE NATIONAL ACADEMY OF SCIENCES, VOLUME 12, NUMBER 5, P. 275- P. 283, May 15, 1926.

REPLY: Yes, that is true that we usually assume that viscous flow in the asthenosphere is incompressible. However, that does not mean that it does not flow in response to pressure gradients. Water is also incompressible, but it will move out of the way if you push on it. The asthenosphere DOES flow in response to pressure gradients – the resulting flow field is called Poiseuille flow.

AUTHOR: At a pressure of 12,000 mega bars, the reduction in rock's volume,  $-\Delta V/V_0$ , is 0.87%. In Table 1, page 278 of this paper, the experimentally measured and theoretically calculated reductions in the volume of rocks at different pressures are tabulated. Pressure values starts from 2000 mega bars and up, because at this and lower test pressures, the reduction in the volume of rocks is too small to be measured or calculated, and, therefore, are not shown in the table. Following basaltic rock partial melting at mantle's pressure, the increase in pressure is about 34.6 Kbars, line 7 and 8 of page 143. This is about 0.04 mega bars, which is too small to be tabulated in Table-1 of Adams L. H. (1926). Therefore, the reduction in volume of the mantle/asthenosphere is negligible and  $-\Delta V/V_0 \approx 0$ . At the same time, the measured increase in the volume following basaltic rock melting is 14.4%, lines 18 through 22 of page 142, (Yoder 1976, p. 94). Or,  $+\Delta V/V_0 = 0.14$ . This suggests that the reduction in the volume of the asthenosphere following basaltic rock melting is too small to accommodate the large increase in volume. Pressure builds up at midocean ridges as a result.

REPLY: Why are we using references from 1926 to quantify the material properties

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of rocks? There are many more recent papers with much more accurate constraints. Nevertheless, I don't have a problem with the incompressibility assumption. But pressure won't build up at a mid-ocean ridge due to melting for two reasons: First, the any pressure buildup will drive asthenospheric flow (Poiseuille flow) that will relieve some of this pressure. But more fundamentally: the melt is erupted on to the surface! So it is no longer around to build up pressure and drive the plate motions.

AUTHOR: Midocean ridges are locations of tectonic plate spreading and separation. They are not locations of plate collisions. Yet, midocean ridges are the highest of the ocean floor. This can only be explained by pressure build up at midocean ridges. Other explanations fall short. Therefore, based on observations pressure build up at midocean ridges following magma generation is not presently being accommodated by the asthenosphere. Also, based on experiments, pressure build up at midocean ridges following magma generation cannot be accommodated by the asthenosphere.

REPLY: The elevation of the mid-ocean ridges is easily explained by thermal contraction of the seafloor as it moves away from the ridge. B. Parsons, J.G. Sclater, An analysis of the variation of the ocean floor bathymetry and heat flow with age, J. Geophys. Res. 82 (1977) 803–827. C.A. Stein, S. Stein, A model for the global variation in oceanic depth and heat flow with lithospheric age, Nature 359 (1992) 123–129.

AUTHOR: When basaltic rock melts, the total volume increases. If this increase in the volume cannot be accommodated by the surroundings, which is the case as discussed under Item 2 above, pressure develops. It is explained in details in Section 3, Thermodynamics, line 26 of page 140 through line 8 of page 143. Yoder 1976, conducted experiments and calculated the increase in the volume of basaltic melt to be about 0.049 cm<sup>3</sup> per gram (Yoder, 1976, p. 94). This is approximately 14.4% increase in volume. Because the mantle is practically incompressible, large pressure develops at mid ocean ridges following mantle partial melting.

REPLY: Much of the melt is erupted to the surface, so it is removed from the system.

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This removed pressure buildup due to melting as a possible driver of plate motions.

AUTHOR: Mathematical or experimental research papers, by their nature, do not require large number of references. They are based on logic or results of experiments and there is no reason to provide references for matters that are obvious to the science. For instance, Adams L. H. (1926) cites seven publications. Should this Referee feel that references related to the work presented worth discussing, the Referee may suggest.

REPLY: It is true that large numbers of references are often not necessary, but it is not ok to omit citations to papers that are directly relevant, or that refute the ideas being presented. I've given the author a few classic papers that are relevant to this topic. There are many more in the literature.

AUTHOR: The current science does not calculate plate tectonics using thermodynamics. The available tectonic models are not sensitive enough to variations in the temperature of ocean floor. While they are correct models, they are inadequate for projecting the geological activities with climate change as stated in line 26 of page 138.

REPLY: Actually, there are lots of paper that address the thermodynamics of plate tectonics and mantle convection. There are even some that address how plate tectonics would change in response to climate change. Here is one: Lenardic, A., A.M. Jellinek, and L.-N. Moresi "A climate change induced transition in the tectonic style of a terrestrial planet." *Earth Planet. Sci. Lett.*, 271 (2008) : 34-42.

AUTHOR: Magma generation and calculation of the degree of mantle partial melting is widely available in the literature, and there is no reason to calculate it in the manuscript. This will only add unnecessary pages and distraction off the subject matter. Yoder 1976 on page 107 suggests a degree of mantle partial melting of 30% based on rock phase diagrams, thermodynamics, mantle pressure, mantle temperature, and experiments. The calculated degree of partial melting using thermodynamics is in agreement. Please see line 21 through 24 of page 145. Based on lava samples, Yoder (1976, p.

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112 and p. 113) concluded that the maximum degree of rock melting is in the order of 50% by volume, which is approximately equal to 45% by weight. The maximum calculated theoretical value based on Carnot cycle is 53%. Or, the maximum deviation from the observed is nearly 18%. Please note that the 53% is only a theoretical value that can never be achieved as stated in lines 24 of page 153 through line 2 of page 154. The actual maximum value of the degree of melting will be less than 53% but greater than 30%, in reasonable agreement with the observed of 45%. This is close enough and the thermodynamic argument is correct.

REPLY: You are not using any information about the solidus of mantle rocks in your calculations. Therefore, it is impossible to know how much melting will occur.

AUTHOR: Mantle convection is not ignored; it is the heart and core of the subject matter. The heat of mantle convection is what drives the tectonic plates. The following are sample paragraphs extracted from the submitted manuscript:

REPLY: You are ignoring the work done to deform the mantle – this is an essential part of the energy balance of plate tectonics.

AUTHOR: I respectfully have to disagree and this comment should be given no consideration. First, the work presented in the manuscript agrees closely with observations, experiments, and the work of others. The agreement is substantial and robust. Second, this Referee has not dedicated sufficient time to read the manuscript as it is evident from this reviewer's comment under Item 6. Third, unfortunately the existing tectonic models do not use thermodynamics; they are not sensitive enough to the temperature of ocean floor and cannot be used to project the geological activities with climate change, a major objective of the manuscript. And fourth, there are ongoing controversies with the current tectonic science and unanswered questions.

REPLY: I think my comments above show that I do not agree with these statements. Note that the author has not demonstrated that the work presented here "agrees closely with observations, experiments, and the work of others". In my view, this paper is far

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from being publishable in a major scientific journal.

AUTHOR: For instance, there is no universal agreement among scientists as to the nature of energy or force that drives plate tectonics. Some tectonic plates do not have slabs, yet they move. What drives these slab-less plates? Basic mechanics suggests that under the pull of slabs, midocean ridges must level off with time, but they do not. Midocean ridges are rising instead. What maintains the observed lithosphere uplifting at midocean ridges? Midocean ridges are locations of tectonic plate spreading and separation. They are not locations of plate collisions. Yet, midocean ridges are the highest of the ocean floor. What maintains the observed lithosphere uplifting at midocean ridges? Why ridge push exists in the first place? Is ridge push a cause or an effect? Plate tectonic motion is a closed loop. The available positive potential energy of gravity is equal to the negative potential energy of gravity required for the motion. They are exactly equal and cancel out. What is the nature of external force that causes the observed tectonic motion? And finally, the existing tectonic models fail to explain the observed increase in geological activities with climate change, not to mention calculating them.

REPLY: Some of these points are well-explained by our current understanding of plate tectonics (such as the elevation of the mid-ocean ridges) and some are still under debate (forces that drive plate tectonics). There is little discussion of what is known and not known about the mantle – the paper starts at a very different point of understanding compared to our current knowledge. For example, the basic explanation for the elevation of the mid-ocean ridges is not the subject of debate and there are many papers showing that it is explained by cooling of the oceanic lithosphere – yet none of this work is cited in the paper.

AUTHOR: All what it takes is just one unexplained observation to render a theory obsolete, or at least be skeptical. The current tectonic science has many unanswered questions and many observations to explain. The submitted manuscript, on the other hand, answers all of these questions and calculates the observations as well.

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REPLY: Obviously I disagree with the last sentence here.

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Interactive comment on Solid Earth Discuss., 5, 135, 2013.

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