Author reply to the comments of Referee #2

I would like to thank this appointed Referee #2 for providing the evaluation report. The reply to each comment will be itemized in the order in which the comments were presented. In each item, Referee comment will be presented in italics and author comment follows in regular and bold fonts.

1) This paper presents an argument that the plate tectonics is driven by basaltic melting at mid-ocean ridges. The argument is a bit incoherent and difficult to follow, but it seems that the author is arguing that a large pressure builds up at mid-ocean ridges due to melting and then re-freezing of magma in oceanic crust. The author then argues that this process is sensitive to Earth's surface temperatures, which are rising due to climate change, and thus plate tectonic rates should accelerate in the future.

Author reply

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, Qh, available at the temperature of the hot reservoir temperature, Th, is the driver of the thermodynamic cycle. Some of this heat is lost as, Qc, to the surroundings at the cold temperature, Tc, and the difference, Qh-Qc, 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 dedicated symbol, Qh, used in the thermodynamic equations throughout the manuscript. Please see Item 6 for more details.

2) I do not think that this paper presents a viable physical mechanism for plate tectonics. First, any pressure buildup at the ridges could be accommodated by viscous flow in the asthenosphere (beneath the tectonic plates), rather than a force exerted on the plates.

Author reply

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.

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.

At a pressure of 12,000 mega bars, the reduction in rock's volume, $-\Delta V/V0$, 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 $-\Delta V/V0 \approx 0$. 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, $+\Delta V/V0=0.14$. 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.

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.

3) Second, it is unclear to me how the physics of melting can produce such a large pressure – this is not clearly explained.

Author reply

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^3 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.

4) Third, the paper ignores a vast body of scientific advances in our knowledge of plate tectonics that has been developed over the past 50 years (it only cites 8 papers).

Author reply

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.

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.

5) Fourth, the thermodynamic arguments can't be correct because they predict maximum magma partial melting of 53% based on the "Carnot theoretical efficiency of the tectonic engine" (sentence in the conclusions) – this is clearly incorrect because the degree of partial melting depends on mantle temperatures and the (depth-dependent) solidus of mantle rocks, neither of which are used to compute the partial melting.

Author reply

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. 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.

6) Fifth, plate tectonics is governed by mantle convection (that fact is ignored here),which occurs at rates that depend on the temperature difference between the mantle interior and the surface, which is ~1400 degrees C – this means than a few degrees C of surface warming will make little difference to plate tectonic rates.

Author reply

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:

Lines 6 through line 16 of page 138

The lithosphere digesting and recycling converts the lithosphere from rocks to mantle/ asthenosphere consistency. Heat is removed by convection from the earth's interior to the surroundings, and the process is treated as a thermodynamic cycle. If the mantle is considered as the thermodynamic system and plate tectonics as the surroundings, an amount of heat, Qh, is removed from the earth's interior by the mantle at the hot temperature Th. An amount of heat, Qc, is rejected by the mantle to the ocean at the mantle's cold temperature Tc, which is reasonably equal to the average temperature of the moving mantle and plates. The difference, Qh $-Q$c, is converted to work that drives plate tectonics. As will be demonstrated, this work is equal to the latent heat of melting of the mass, M, regenerated as new ocean crust at midocean ridges plus the work of ridge push.

Line 9 through 10 of page 139

The net effect of this process is that internal heat is converted to work, or geological activities, and this energy is dissipated as heat in the continents.

Line 16 through 18 of page 144

Referring to Fig. 1, the mass *M*0 of the mature oceanic plate 1 gains heat by convection as it flows internally through the earth's interior to midocean ridges. Its temperature increases from *T*o to *T*h. The heat gained by this convective heat transfer is equal to *Q*h.

Line 11 of page 151

– *Q*h0=Mantle convection energy of the baseline period, 5.61×1019 ×10 = 5.61× 1020 J decade−1.

Line 5 of page 152

– *Q*h =Mantle convection energy for a given surface temperature rise Δ*T*s, J decade−1.

Lines 20 through 27 of page 154

The calculations suggest that the total heat exchanged in the convection of the upper mantle/asthenosphere is equal to *Q*h, which is approximately equal to 4.35 times the energy delivered to plate tectonics, *W*. Therefore, the total heat removed by this convection is approximately equal to 4.35×1.29×1019 = 5.61×1019 J yr−1. Based on Davies (2010), the total internal heat of the earth is equal to 1.5×1021 J yr−1, or the upper mantle/asthenosphere convection removes 3.7% of the total internal heat of the earth, which includes the work of plate tectonics that is estimated at 0.9% of the total internal heat generated in the earth's core.

Presently, the geological activities are on the rise with just 0.5 °C of surface water warming. What is the basis of this Referee's hypothesis that a warming of few degrees will make little difference? Any mathematical or observational support?

7) Basically, I find that the physical model that is described here is physically impossible, and it is poorly described as well. I am not adverse to new ideas for plate driving forces, but to be convincing these ideas need to be well-described and physically plausible, neither of which is achieved here. The rich background in this field also cannot be ignored. For these reasons, I recommend rejection.

Author reply

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.

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.

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.