

Author reply to comments of Referee #1

I would like to thank this appointed Referee #1 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 font.

1) *General comments*

I do not recommend publication of this paper because what's good in it was already known 40 years ago and the author does not refer to that work. There are also many other problems with it, which are listed below.

Author comment

The work presented in the manuscript is authentic and it is based on the work of others. Sec. 2, Model, assumptions, and data clearly references publications that have been influential in determining the nature of the work presented in the submitted manuscript. The tectonic and magma generation models are based on others' work that is referenced throughout the manuscript. The referenced literature by this Referee does not calculate plate tectonics using thermodynamics; they use models that are not sensitive enough to variations of the temperature of ocean floor. While they are correct, they are inadequate for projecting the geological activities with climate change as stated in line 26 of page 138.

The fact that this work agrees with existing and previous work already known 40 years ago should not be a reason for disqualifying the manuscript. On the contrary, it is a good reason for considering the manuscript for publication. It is beneficial for the science to have other methods that can calculate plate tectonics and cross-check existing models. The suggested thermodynamic approach offers an advantage over other models in that the energy of plate tectonics can be projected with climate change, whereas the available methods cannot. The proposed thermodynamic approach is so sensitive to slight variations in the temperature of ocean floor and can provide searchers with a good tool that can help in assessing the risk and hazard associated with the observed increase in the geological activities. Other models do not offer such a tool. This is another good reason for considering the manuscript for publication.

Specific comments

2) *Allan Cox's 1973 book "Plate tectonics and Geomagnetic Reversals" (Freeman, San Francisco) is a collection of the papers establishing the subject with his introductory comments. Section VIII is still worth reading, and it includes McKenzie (1969: Speculations on the consequences and causes of plate motions, Geophys. J. Roy. Astron. Soc. 18, 1-32) who dealt with the thermodynamics and said "Thermal convection in some form is the only source of sufficient energy". His estimate for slab pull was $12.5 \cdot \sin(\phi) \cdot 10^{12}$ N/m, where ϕ is the angle of dip. It is of the same order of magnitude as Harper's (1975: Geophys. J. Roy. Astron. Soc.) $7.5 \cdot 10^{12}$ N/m, which was, I think, the first paper finding slab pull to be more important than ridge push. (Forsyth & Uyeda's work was later, but independent.) Swedan's $5 \cdot 10^{12}$ N/m is of the same order of magnitude as McKenzie's or Harper's. Of course slabs differ greatly in age of subducting lithosphere and significantly in subduction speed. Both age and speed affect slab pull, as shown by various authors.*

Author comment

Agreement between the thermodynamic approach and other models is expected. The plate tectonic system is a thermodynamic system that has an engine and mechanical components. The force calculated at the engine or elsewhere must be equal.

3)Swedan also gives ridge push of $1.61 \cdot 10^{12}$ N/m, again of the same order of magnitude as earlier work. That is of course about 1/3 of his own slab pull, so I do not understand why he implies (p.137 l.3 and l.22, p.139 l.3) that ridge push is what drives plate tectonics. In line 3 he also says it will "fracture plate tectonics". Surely he means "fracture plates", but I find that hard to believe because the Antarctic plate is almost completely surrounded by midocean ridges and it has no large intraplate earthquakes, unlike every other plate bearing a continent.

Author comment

“fracture plate tectonics” can be changed to “fracture tectonic plates” or plates as suggested. Ridge push does not drive tectonic plates because it is an effect not a cause. The force of pressure developed by magma partial melting is what drives plate tectonics. Please see page 147 lines 18-25. The calculated average force by other tectonic models is close to the force calculated in this manuscript. The calculated compressive stress imparted by this force is about equal to the tensile strength of the rocks of the upper mantle, Yoder (1976, p. 171), or it is close to the point of failure of the tectonic plates. Based on observations, the plate tectonic system is made of fractured plates, also please see Floyd (1991, p. 226). What matters is the total energy released, not necessarily the energy of a given plate or two. Most of the energy of plate tectonics is released at locations having least resistance to the motion of the plates. There is no disagreement with observation or the work of others.

4) p.136 l.19 It is claimed that the natural carbon cycle initiated the warming and glacial periods. I think that's a side issue for this paper, and a lot more work would be needed to substantiate the statement. Is it being claimed that the carbon cycle is why we have had glacial periods in the last 2.5 Ma, and from 360-260 Ma, 450-420 Ma, 800-635 Ma, and 2400-2100 Ma, but not in between? The carbon cycle must have been very different over 2000 Ma ago, and I'm under the impression there were no land plants at 635 Ma. Or is Swedan claiming that the glacial- interglacial changes over tens of thousands of years are driven by the carbon cycle, not the Milankovich cycles? But here and elsewhere I wonder why surface temperature changes of order 10 degrees are significant for plate tectonics, which is driven by temperature differences of order 1000 degrees between the mantle and the upper surface of a plate.

Author comment

The Referee thinks that the carbon cycle is a side issue for this paper, and lines 18 through 21 of page 136 may be deleted. This deletion has no impact on the content of the manuscript. It is, with all due respect, unfair to hypothesize that surface temperature changes of the order of 10 degrees are insignificant for plate tectonics without presenting a mathematical or observational support. This hypothesis suggests that plate tectonics is an independent and stand-alone earth subsystem, which the mathematical exercise presented in the manuscript clearly shows otherwise.

Based on my extensive reading of climate related literature, there are no publications that can link glaciation/warming cycles to Milankovitch cycles. For an average year, the Earth exchanges a constant

amount of solar energy regardless of orbital eccentricity or Milankovitch cycles. This can be demonstrated with basic astronomical equations as follows:

The instantaneous solar radiations exchanged between the Sun and the Earth, Q_e , is inversely proportional to the square of the instantaneous distance between the Earth and the Sun. $Q_e(t) = C/r(t)^2$, where C is a constant that depends on the radius of the Earth, temperature of the Sun, and radius of the Sun. Back radiations from the Earth to the Sun are negligible. t , is the time of motion. Kepler's second law dictates that the Earth's angular momentum is constant regardless of orbital eccentricity or orbit shape. Therefore, $r(t)^2 \times d\theta(t)/dt = L$, where, L , is a constant and $\theta(t)$ is the instantaneous angle of rotation. $r(t)^2$ can be eliminated and $Q_e(t) dt = (C/L) d\theta$. This last equation can be integrated for a full revolution of the Earth around the Sun as follows:

$$\int_0^T Q_e(t) dt = \int_0^{2\pi} (C/L) d\theta = 2C \pi / L = \text{constant}$$

Where T is the time of one revolution, approximately equal to 3.15×10^7 seconds. The left hand side of the equation is the annual solar radiations exchanged between the Sun and the Earth. It is constant regardless of Milankovitch cycles with eccentricity variations. While the instantaneous solar radiations exchanged between the Sun and the Earth is variable, at the completion of one revolution, every year, the solar radiations exchanged between the Sun and the Earth is constant. Consequently, the solar energy exchanged with the Earth is constant every year. Axial tilt or procession of the Earth will not change the balance. The Earth will remain a sphere and its projection will remain a circle having the same radius. As a result, no change in the energy exchanged with the Earth following all of Milankovitch cycles. Certainly with axial tilt and procession, at a given latitude, say 65 N, the latitude will experience cooling and warming cycle. However, its mirror image, 65 S, will experience exactly the opposite warming and cooling cycle. The total energy exchanged with the Earth remains unchanged and Milankovitch cycles, based on mathematics, cannot be the cause of the glaciation and warming cycles of the Earth as a whole. The work of Petite et. al (1999) presents observational evidence of the correlation between glaciation/warming cycles and the carbon cycle recorded in Antarctica ice core data. These cycles are characterized by uneven periods of the glacial and warming cycles, which is contrary to what is expected from the Earth's motion cycles that are equally spaced in time. Therefore, based on mathematics and observations, it can be confidently concluded that Milankovitch cycles were not the cause of the glaciation/warming cycles of the Earth.

5) p.138 l.9 *If the mantle is the system then its surroundings include the core as well as the plates.*

Author comment

The system can be re-defined to include the core, in a similar way to lines 25-27 of page 145, without affecting the content of the manuscript.

6) p.138 l.20-21 *The mantle is not a closed thermodynamic system - matter leaves it to become oceanic crust and returns to it at subduction zones.*

Author comment

Matter is exchanged in kind and what leaves the mantle is equally returned in quantity and quality. The mass of the mantle or the tectonic plates can be reasonably considered constant for the foreseeable future. Only

heat and work are exchanged between the mantle and plates. Therefore, the mantle meets the definition of a closed thermodynamic system. Please see lines 17-21 of page 138.

7) *p.139 l.13 Why is surface evaporation constant? Surely it's less in glacial periods than interglacials.*

Author comment

The energy balance of the Earth suggests that at the completion of one Earth's revolution around the Sun, the change in the enthalpy of the atmosphere and surface for an average year is zero, it is a repeatable cycle. The only change that occurs in the process is water vapor phase change or precipitation. Precipitation measures how much solar energy is exchanged between the Earth and solar radiations. For an average year, surface evaporation is equal to precipitation. Based on observations, precipitation is constant for an average year, it is approximately equal one (1) meter of rain annually. Please refer to Arnold Gruber, Vincenzo Levizzano: *Assessment of Global Precipitation Products*, World Climate Research Program, Global Energy and Water Cycle, WCRP-128, WMO/TD-No. 1430, May 2008. Therefore, and for the foreseeable future, evaporation is constant based on observations. Evaporation is constant because the solar energy exchanged with the earth is constant regardless of orbital eccentricity. Please refer to the previous discussion presented under Item 4.

For glacial periods, precipitation data are unavailable. We know well that during these cycles, the chemistry of the atmosphere changes. The content of carbon dioxide in the atmosphere decreases with time, and the impact of this decrease on surface evaporation is a current research subject.

8) *p.140 l.5-7 It seems to be claimed that if the cold reservoir of a heat engine changes its temperature but the hot one does not, then the heat flow through it does not change. Surely the temperature difference across the engine changes, and that alters the rate of heat flow.*

Author comment

The temperature of the cold reservoir is not the only thermodynamic parameter that dictates the amount of heat flow through the tectonic engine. This heat rejected to the cold reservoir also depends on the efficiency of the engine, which is variable, and the amount of heat available at the constant-temperature hot reservoir, Q_h . This available heat increases with surface temperature rise, lines 5-12 of page 153.

In principle, the tectonic engine is similar to steam and internal combustion engines. Energy is admitted into a chamber and a fraction of this energy is converted to mechanical work by the piston and piston rod. The efficiency depends on the hot temperature of the cycle medium, cold temperature of the surroundings, and chamber design parameters. The midocean ridge encloses the engine chamber that is situated on a hot magma chamber. Part of the available magma latent heat of melting is converted to mechanical work by the tectonic plates that act as pistons and piston rods. Based on observations, midocean ridges are rising with climate change. Iceland is rising by 5-10 millimeters annually (Sjoberg L. E., Pan M., Erlingsson S., Asenjo E., Arnason K.: Land uplift near Vatnajökull, Iceland, as observed by GPS in 1992, 1996, and 1999. *Geophysical Journal International*, Volume 159, Issue 3, pages 943-948, December 2004, doi:10.1111/J.1365-246 x 2004.02353 x). It is, therefore, reasonable to assume that the efficiency of the tectonic engine varies. A larger chamber provides larger area for the driving force of pressure, and if everything else is the same, efficiency of the tectonic engine improves.

Because the available heat at the hot temperature reservoir, Q_h , increases, the heat rejected at the cold temperature increases, assuming that the efficiency is about the same with surface temperature rise. In this

case, the projected energy of plate tectonics in Table 3 has to be multiplied by the efficiency, 0.23. However, a slight improvement of the efficiency of plate tectonics in the order of 0.9% will maintain the amount of heat rejected to the cold reservoir constant, even though the temperature of the cold reservoir increases. This is done all the time in practical applications and the laws of thermodynamics are well respected. There is no reason why this scenario should be excluded, and therefore, it is considered in the manuscript.

Based on observations, the geological activities are increasing and midocean ridges are rising; consequently, a decrease in the efficiency of the tectonic engine must be excluded.

9) *p.140 l.25 Why "steady and sustained force", when the previous paragraphs explains why Swedan thinks it's unsteady?*

Author comment

This comment appear to be incomplete. An amount of magma is produced following mantle decompression and it is admitted into a magma chamber. Equal amount of magma is consumed at midocean ridges. A large magma chamber having a large residence time acts as a bladder whose volume does not vary substantially with small variations of magma flow rate. As a result, the pressure in the magma system can be assumed to remain steady at any elevation. This provides steady and sustained pressure that drives the tectonic plates. Please see lines 15-25 of page 140.

10) *p.149 l.24-25 Astronomical parameters do not remain constant with time, as Milankovich showed long ago.*

Author comment

This line will be corrected as follows "Astronomical parameters do not alter the energy balance with time." As previously discussed under Item 4, the astronomical parameters such as orbital eccentricity and distance between the Earth and the Sun do change with time. However, the solar energy exchanged with the Earth for an average year remains unchanged, regardless of variations in the astronomical parameters.

11) *p.155 l.4-5 "plate tectonic cycle is moving faster". How much faster, over what time scale. Observational evidence?*

Author comment

Please see the average annual spreading rate in the last row of Table 3. The observed increase in the geological activities is the evidence. Table 2 clearly shows an increase in the energy of seismic activities with time. Using the Smithsonian Volcano Research Database and sampling every five years, the volcanic activities have an increasing trend with time as well. The following is an average per two decades of the samples: from 1990 to 2010, the average number of volcanoes is 65; from 1970 to 1990, the average number of volcanoes is 56; from 1950 to 1970, the average number of volcanoes is 52.

Technical corrections

12) *In many places I suspect "plate tectonics" should be "plates". Plate tectonics is a process, plates are parts of the Earth.*

Author comment

In the manuscript, "plate tectonics" is used as a process and as a system. Will be corrected where required.

13) *p.137 l. 11-14 What does "which" in this sentence refer to? As written it is "lithosphere" but that is probably not what Swedan meant.*

Author comment

Correctly understood. "which" refers to the lithosphere.

14) *p.140 l.18 for "pint" read "point".*

Author comment

Will be corrected.

15) *p.140 l.22 for "sheer" read "shear".*
Interactive

Author comment

Will be corrected.