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Energy of plate tectonics calculation and projection

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Abstract

Mathematics and observations suggest that the energy of the geological activities resulting from plate tectonics is equal to the latent heat of melting, calculated at mantle's pressure, of the new ocean crust created at midocean ridges following sea floor spreading. This energy varies with the temperature of ocean floor, which is correlated with surface temperature. The objective of this manuscript is to calculate the force that drives plate tectonics, estimate the energy released, verify the calculations based on experiments and observations, and project the increase of geological activities with surface temperature rise caused by climate change.

1 Introduction

The earth has always "devised" a way to get rid of its internal heat steadily with time and resorted to different ways to cool itself. Ocean crust subsidence increased the heat transfer area with the surrounding sea water; "digesting" and recycling ocean crust cooled the earth's interior by exchanging latent heat of crust melting; land and continents uplifting radiated heat directly from the earth's interior to space; continental drift and land rearrangement on the surface with time improved the heat transfer by positioning the continents on locations to radiate earth's internal heat more efficiently; and the raised land sustained plants, vegetation, and life, and the natural carbon cycle was established. The cycle initiated the warming and glacial periods with glacial periods having durations longer than the warming periods. A complete warming/glacial period removed ocean heat and cooled the earth.

Over the large geological time, the internal heat of the earth was sufficient to provide the energy required to raise continents and move them around the globe. These geological activities were driven by the earth's urge to get rid of the internal heat steadily and constantly. Presently, about 30 % of the earth's internal heat is radiated by land, 69 % is rejected to the ocean, and the remaining 1 % is relieved by the activities of plate tectonics in the form of seismic and other geological events. The process of digesting and recycling of the earth's crust develops considerable amount of pressure at midocean ridges, large enough to drive and even fracture plate tectonics. The objective of this manuscript is to calculate the driving force of plate tectonics, estimate the energy released, validate the calculations by experiments and observations, and project the energy of plate tectonics with surface temperature rise resulting from climate change.

2 Model, assumptions, and data

The model consists of applying the laws of thermodynamics on suggested models of plate tectonics that are available in literature. Figure 1 is a schematic plate tectonics representation based on Floyd (1991), pages 31 and 127. The earth's internal heat to land is readily radiated to space and therefore it is not shown in the figure. In Fig. 1a, most of the internal heat to the ocean, Q_i, is exchanged with sea water through the lithosphere (ocean crust and the solid and rocky part of the upper mantle) which will be assumed to constitute plate tectonics. A mass $M0$ of oceanic plate 1 is consumed in the "digesting" process and vanishes into the ductile part of the upper mantle and asthenosphere, which will collectively be referred to as upper mantle. $M0$ is assumed to become part of the mantle as it sinks into the earth's interior. Simultaneously, a smaller magma mass, M, rises from the mantle to midocean ridges following the partial melting of the upwelling mantle as it decompresses. The melt, which is assumed to be basaltic magma, flows upwards under high pressure and solidifies to form a new ocean crust above the mantle, shown as the shaded area in Fig. 1, and sea floor spreading occurs in the process. This sea floor spreading, or plate tectonics' motion, is driven by the large pressure developed during magma generation deep in the mantle below midocean ridges, and the pressure is correlated to the degree of magma melting. The ductile portion of the mass $M0$, or the mantle, that does not melt is recycled internally by "riding" on the moving mantle and plates, and the heat of convection associated with this motion is rejected to the ocean by conduction through the lithosphere. With this heat rejection, the temperature of plate tectonics and recycled mantle decreases, and the ductile mass and plates harden. As a result, plate thickness increases as they spread away from midocean ridges. With time, plate tectonics mature and the full mass $M0$ is regenerated and the cycle repeats. In the process heat is removed from the earth's interior to the surrounding ocean and continents.

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, Q_h, is removed from the earth's interior by the mantle at the hot temperature T_h. An amount of heat, Q_c, is rejected by the mantle to the ocean at the mantle's cold temperature T_c, which is reasonably equal to the average temperature of the moving mantle and plates. The difference, $Q_\mathrm{h} - Q_\mathrm{c}$, 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.

The laws of thermodynamics apply to the plate tectonic engine and they are utilized in the energy analysis. Although plate tectonics are consumed in the process, they are regenerated in kind. Over the years, the system, mantle, exchanges heat only with its surroundings plate tectonics and matter is not exchanged. The system can be reasonably assumed to be a closed thermodynamic system.

Magma generation is discussed in Yoder (1976), which provides the physical properties of basaltic rock and basaltic magma. They include specific gravity, tensile strength, shear fracture, specific heat, latent heat of melting, thermal conductivity, phase diagrams, and magma generation model. The data and model are used in this paper. Other tectonic models were examined and found to be inadequate for the objectives of this manuscript.

Given the large ratio of tectonic plate dimensions to thickness, they are represented as a hair line in Fig. 1b. The force applied on these plates is practically axial, and the plates are subjected to compression. The stress produced in the plates is comparable to the tensile strength of the basaltic rock. The plates operate close to their fracture point. This force drives the oceanic plates under the overriding plate and considerable heat of friction is produced between the mating surfaces. If for one reason or another the plates at the subduction zones are not free to move, the plates can buckle or even break under the massive force, F, generated by the partial magma melting at the midocean ridges. Plate buckling or compression is a storage of massive amount of energy, similar to that stored in a spring. The stored energy can be released instantly in the form of seismic energy and tsunamis. 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. The heat is then radiated by land to space and ultimately relieves earth's internal heat. The internal heat exchange with ocean is limited by surface evaporation, which is constant, and surface water radiation is limited by surface water convection as well.

Because the young plates regenerated at midocean ridges are hot, ductile, and relatively thin, major seismic events are less likely to occur in the vicinity of these ridges. The activities are expected to be more pronounced in locations where the plates are mature or approach maturity where they are thick and brittle.

Sea brine will inevitably seep into the earth's interior with the sinking of the oceanic plates. Because the brine is neither part of the mantle system nor part of the surrounding plate tectonics, the heat exchanged with sea water must not be considered in the thermodynamic transformations. The heat exchanged with sea water is a separate cooling cycle of the earth's interior.

For this suggested thermodynamic model, the temperature of the solid earth is assumed to be steady based on Jacobs (1953). This and other studies suggest that the temperature of the solid earth has cooled by less than 200 °K in one billion years. For all practical purposes, a steady temperature of the solid earth and constant internal heat flow are reasonable assumptions.

An increase in the temperature of ocean floor decreases the geothermal gradient across the lithosphere. Even a small increase in the gradient can affect the thermodynamics of plate tectonics. The temperature of ocean floor is approximately equal to the temperature of surface water located in high latitudes of the northern hemisphere, which is presently on the rise with climate change. Because the temperature of the solid earth is unchanged with time, the earth's internal heat must be rejected constantly and steadily with time. This is accomplished by decreasing the thickness, or thermal conductivity resistance, of the lithosphere to maintain the internal heat flow rejected through the lithosphere constant with time, which, in other words, is equivalent to increasing the spreading rate of plate tectonics. As a result, the thermodynamic cycle of the plate tectonic engine per unit time increases and the energy of geological activities released increases simultaneously. By knowing the trend of surface temperature, the energy of the geological activities can be projected with time.

3 Thermodynamics

The model schematically presented in Fig. 1a, which is not to scale, assumes that the rate of magma produced, M, is too small compared with the mass of magma accumulated in the magma chamber. Therefore, the flow of magma from its generation point to the pint of solidification at midocean ridges can be assume to occur at constant volume, and the chamber maintains considerable pressure even with the displacement of the mantle at mid ocean ridges. A sufficiently large magma chamber can produce a force large enough to lift and sheer the lithosphere at midocean ridges and split and spread the mantle apart. The displaced mantle is assumed to cool as it spreads away and it is replaced in kind following the loss of heat by conduction to the ocean. The pressure generated due to magma melting thus provides steady and sustained force that drives plate tectonics.

The pressure produced as a result of magma partial melting in the deep mantle below midocean ridges is massive, in the order of 34 600 bar, which can be calculated using the equations of thermodynamics. Equation 4-148, Sect. 4, Thermodynamics of Perry and Green (1984) will be used. The equation follows:

$$\mathrm{d}S = \mathrm{Cp}\,\mathrm{d}T/T - (\delta V/\delta T)_p \mathrm{d}P; \quad \text{and} \quad \mathrm{d}S = \mathrm{d}Q/T$$

where

- S = Entropy of the system in consideration, $\mathrm{J\,kg^{-1}\,{}^{\circ}K^{-1}}$.
- Cp = Specific heat of the system at constant pressure, $\mathrm{J\,kg^{-1}\,{}^{\circ}K^{-1}}$.
- T = Temperature of the system, $^{\circ}\mathrm{K}$.
- V = Volume of the system, $\mathrm{M^3\,kg^{-1}}$.
- P = Pressure of the system, Pa.
- Q = Heat exchanged, $\mathrm{J\,kg^{-1}}$.

The equation is valid only at sites of magma generation where mantle and magma coexist. As the magma rises away from the remaining un-melted mantle, the equation ceases to apply.

Assuming that the rising mantle deep below midocean ridges as the system, the mantle partially melts to form magma as it decompresses on its way up. The melting occurs at about the temperature of the rising mantle, T, and the temperature change dT during melting is too small compared with T, Yoder (1976, p. 65). The term $\mathrm{Cp}\,\mathrm{d}T/T$ can therefore be neglected from the above equation. The melting occurs adiabatically and the heat exchanged, Q, is in fact equal to the latent heat of mantle melting for there is no other source of heat to exchange with the system. Q has a negative sign because it is removed from the mantle, the thermodynamic system in consideration. The equation simplifies to the following equalities:

$$-\mathrm{d}(L_\mathrm{f})/T = -(\delta V/\delta T)_p \mathrm{d}P; \quad \text{and} \quad \mathrm{d}(L_\mathrm{f}) = (\delta V/\delta T)_p \times T \times \mathrm{d}P$$

where L_f is the latent heat of fusion of the mantle, $\mathrm{J\,kg^{-1}}$. This heat of melting varies with the degree of mantle melting as magma forms.

The motion of plate tectonics occurs "infinitesimally" with time. At infinitesimally decreasing pressure, the volume of the mantle and magma increases infinitesimally over the melting temperature range as the mantle decompresses on its way up. For the last equation, and at a constant pressure, the volume change with temperature can be developed in a MacLaurin series as follows:

$$V(T) = V(T0) + [\mathrm{d}V/\mathrm{d}T]_{T0} \times \mathrm{d}T + R$$

where $[\mathrm{d}V/\mathrm{d}T]_{T0}$ is the slope of the function $V(T)$ calculated at the initial melting temperature $T0$ and R is a remainder that can be neglected for infinitesimal change, which is the case.

Because of the slow nature of the process, $[\mathrm{d}V/\mathrm{d}T]_{T0}$ is constant and applies throughout the melting temperature range $\mathrm{d}T$. At constant pressure, $V(T) - V(T0) = \mathrm{d}V = [\mathrm{d}V/\mathrm{d}T]_{T0} \times \mathrm{d}T$ and $\mathrm{d}V/\mathrm{d}T = [\mathrm{d}V/\mathrm{d}T]_{T0} = (\delta V/\delta T)_p = C =$ constant. The value of the constant, C, is approximately equal to the volume change of magma per one degree Kelvin. Therefore $(\delta V/\delta T)_p \times T$ is reasonably equal to the total change in the volume of mantle when it melts completely at mantle's temperature, T, and mantle pressure, P.

At 0 % magma melting, which is assumed to be basaltic magma, $\mathrm{d}(L_f) = 0$. The term $(\delta V/\delta T)_p \times T$ is approximately equal to the volume change when the basaltic rock melts, and it is known (Yoder 1976, p. 94). Magma melts at high temperature and the volume of the melt increases by $0.049\,\mathrm{cm^3}$ per gram, or approximately 14.4 % increase by volume, assuming that the specific gravity of basaltic rock is 2.94 (Yoder, 1976, p. 94). This is equivalent to $4.9 \times 10^{-5}\,\mathrm{M^3\,kg^{-1}}$. Therefore, $(\delta V/\delta T)_p \times T$ is approximately equal to $4.9 \times 10^{-5}\,\mathrm{M^3\,kg^{-1}}$ and $\mathrm{d}(L_f) = 4.9 \times 10^{-5} \times \mathrm{d}P$. The change in mantle pressure at melting can be calculated by integrating this last equality as follows:

$$\Delta P = 2.04 \times 10^4 \times \Delta L_f = 2.04 \times 10^4 \times f \times L_f$$

where f is the degree of magma melting expressed as percent fraction. If $f = 0$, $\Delta L_\mathrm{f} = 0$ and $\Delta P = 0$, and if the degree of melting is equal to, f, then $\Delta P = 2.04 \times 10^4 \times f \times L_\mathrm{f}$. For basaltic rock, Yoder (1976, p. 107) suggests a partial magma melting of 30 % ($f = 0.3$), and 135.4 calories gram^{-1} for the latent heat of basaltic rock melting corrected for mantle pressure (Yoder, 1976, p. 95). The value of the latent heat is equal to 135.4 (cal g^{-1}) × 4.18 (J cal^{-1}) × 1000 (g kg^{-1}) = 565 972 J kg^{-1}. At 30 % magma partial melting, $f \times L_\mathrm{f} = 0.3 \times 565\,972 = 169\,792\ \mathrm{J\,kg^{-1}}$, and $\Delta P = 169\,792 \times 2.04 \times 10^4 = 3.46 \times 10^9$ Pa, which is equal to 34 600 bar. It will be demonstrated later in Sect. 4 using the laws of thermodynamics that the magma partial melting of 30 % and the latent heat of magma melting of 169 792 J kg^{-1} as suggested by Yoder (1976) are reasonable.

The firs law of thermodynamics is used to analyze the plate tectonic system. The law and its related equations are presented in Sect. 4, Thermodynamics, of Avallone and Baumeister (1996) The first law of thermodynamics and other related equations follow:

$$\mathrm{d}Q = \mathrm{d}U + \mathrm{d}W$$

$$H = U + PV$$

Carnot cycle's theoretical efficiency $= 1 - Q_\mathrm{c}/Q_\mathrm{h} = 1 - T_\mathrm{c}/T_\mathrm{h}$

Thermal efficiency $= 1 - (T_\mathrm{c}/T_\mathrm{h})^{1/2}$

$W = Q_\mathrm{h} \times$ thermal efficiency

where

- Q = Heat exchanged with the system in consideration, Joules.
- U = Internal energy of the system in consideration, Joules.
- W = Work exchanged between the system and its surroundings, Joules.
- P = System pressure, Pa.

- V = System volume, M^3.
- H = System enthalpy, Joules.
- Q_h = Heat delivered at the hot system temperature, Joules.
- Q_c = Heat rejected at the cold system temperature, Joules.
- T_h = Temperature of the hot reservoir supplying Q_h, °K.
- T_c = Temperature of the cold reservoir receiving Q_c, °K.

The heat is positive if gained by the system, whereas the work is negative if delivered by the system.

The relationship between thickness of plate tectonics and rate of midocean spreading is important for this work. Based on observations and mathematics, plate thickness at a given distance from the ridge is proportional to the square root of the time required, or age of plate tectonics. This relationship can be derived using basic heat transfer equations. It is available in literature, and, therefore, will not be discussed in this manuscript.

4 Force and energy of plate tectonics:

Referring to Fig. 1, the mass $M0$ 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. At mid ocean ridges, the mantle rises up and partially melt as it decompresses. The melted mantle produces an amount of magma that is equal to M and system pressure increases considerably. This pressure lifts the ridges and drives plate tectonics and the mass M solidifies at mid ocean ridges following the delivery of motive energy to plate tectonics. The remaining un-melted and ductile mantle mass, which is at about magma melting temperature, is recycled internally with the moving plates. Plate thickness increases as the temperature of this mantle mass decreases with the rejection of the sensible heat, Q_c, to the ocean. The ductile part of the upper mantle and asthenosphere can be assumed as the system for this thermodynamic cycle and plate tectonics as the surroundings. The theoretical and thermal efficiencies as well as the work produced by this cycle can be determined from data available.

Floyd (1991, p. 31 and 128) suggests that the average temperature, $T0$, of the mass $M0$, of the mature tectonic plates is approximately equal to 650 °C (923.2 °K) and mantle temperature, T_h, is at about the magma melting temperature of 1280 °C (1553.2 °K). The lowest system temperature, T_c at which Q_c is rejected can be reasonably assumed to be equal to the average temperature of plate tectonics. T_c is approximately equal to the average of sea floor temperature and magma melting temperature, or approximately equal to $(274.2 + 1553.2)/2 = 913.7$ °K. The estimated specific heat of the mantle rock by Yoder (1976, p. 71) is about $0.3\,\mathrm{cal\,g^{-1}\,°C^{-1}}$ which is equal to $1250\,\mathrm{J\,kg^{-1}\,°K^{-1}}$. Therefore $Q_h = 1250 \times (1553.2 - 923.2) = 787\,500\,\mathrm{J\,kg^{-1}}$, and the following applies for this thermodynamic cycle:

Carnot cycle theoretical efficiency $= 1 - T_c/T_h = 1 - 913.7/1553.2 = 0.41$

Thermal efficiency $= 1 - (T_c/T_h)^{1/2} = 1 - (913.7/1553.2)^{1/2} = 0.23$

$W = Q_h \times 0.23 = 787\,500 \times 0.23 = 181\,125\,\mathrm{J\,kg^{-1}}$.

$Q_c = Q_h - W = 787\,500 - 181\,125 = 606\,375\,\mathrm{J\,kg^{-1}}$.

The calculated amount of work, W, delivered to the tectonic engine, $181\,125\,\mathrm{J\,kg^{-1}}$, is approximately equal to the latent heat of the basaltic rock at mantle's pressure and 30 % partial melting suggested by Yoder (1976), which is equal to $169\,792\,\mathrm{J\,kg^{-1}}$, calculated in Sect. 3. This conclusion can also be reached by using a different approach as follows:

The first law of thermodynamics is applied by considering the earth's interior enclosed by the sphere of the ductile portion of the upper mantle as the system and the lithosphere, or plate tectonics, as the surroundings. The first law of thermodynamics follows:

$$dQ = dU + dW$$

$$dH = dU + d(PV),$$

where

- Q = The generated earth's internal heat that is gained by the system, Joules.
- U = Internal energy of the system, the earth's interior, Joules.
- W = The work exchanged between the system, or earth's interior, and the surrounding plate tectonics, Joules.
- H = Enthalpy of the earth's interior, Joules.
- PV = The product of the pressure of the earth's interior by its volume.

Assuming that the system, the earth's sphere enclosed by the ductile portion of the upper mantle is incompressible, then the term $d(PV)$ can be neglected. The differential of the internal energy, dU, can be replaced by the differential of the enthalpy of the system dH. At steady flux of internal heat, $dQ = 0$. Therefore $dW = -dH$. The change in the enthalpy of the system, dH, is equal to $M_s\ [Cp_s dT + d(L_{fs})]$. Where M_s is system mass, kg; Cp_s is the specific heat of the system, $\text{J kg}^{-1}\,^\circ\text{K}^{-1}$; T is system temperature, °K; and L_{fs} is the latent heat of melting of the system, J kg^{-1}. System temperature is reasonably constant as discussed in Sect. 2 and $dT \approx 0$. Therefore, the differential of work exchanged can be expressed by the following equality:

$$dW = -M_s d(L_{fs})$$

The work produced has a negative sign, or it is produced by the mantle and delivered to the surrounding plate tectonics. The amount $M_s d(L_{fs})$ is equal to the latent heat of phase change of the earth system enclosed by the ductile portion of the upper mantle. This system is practically unchanged except at midocean ridges where only the mass M of the mantle changes phase by the mantle partial melting. Or $M_\mathrm{s}\mathrm{d}(L_\mathrm{fs})=M\mathrm{d}(L_\mathrm{f})$, where L_f is the latent heat of melting of basaltic rock, calculated at mantle's pressure, and M is the mass of basaltic rock deposited at midocean ridges. This equation can be integrated and the work obtained. For 0.0 % degree of magma melting, $L_\mathrm{f} = 0$ and the work, W, is equal to zero. For a degree of melting that is equal to f, the work delivered to plate tectonics follows:

$$W = M \times f \times L_\mathrm{f}$$

The factor f is the degree of magma melting expressed as percent fraction. This equation suggests that the work delivered by plate tectonics is equal to the latent heat of melting of the mass M of basaltic rock at about the conditions of the deep mantle below midocean ridges. This work is also equal to the latent heat of solidification of the regenerated basaltic rock at midocean ridges calculated at mantle's pressure. Per kilogram of new ocean crust regenerated, the work delivered by the tectonic engine is equal to $f \times L_\mathrm{f}$, or it is equal to the latent heat of partial melting of basaltic rock calculated at mantle's pressure, in agreement with the conclusion reached earlier.

Because the regenerated mass M solidifies at about the pressure of ocean crust, which is considerably less than that of the mantle, not all of the work is delivered immediately to plate tectonics by the force of magma pressure. The difference in magma latent heat calculated at mantle's pressure and that calculated at ocean crust's pressure, which is approximately equal to 30 % of ($f \times L_\mathrm{f}$) based on Yoder (1976, p. 94), maintains the uplift of the lithosphere at midocean ridges. This uplift exerts "ridge push" on plate tectonics. The total ridge push and magma pressure is equal to the total net force, F, that drives plate tectonics.

The mass, M, can be calculated by knowing the volume of new ocean crust that is formed at midocean ridges, or the shaded area in Fig. 1, and the density of ocean crust. The latent heat of fusion of the basaltic rock, L_f, is available in literature and it is calculated in Sect. 3, Thermodynamics. The work exchanged with plate tectonics, W, can, therefore, be determined. W is equal to the total energy imparted by plate tectonics, which includes the energy radiated by the earthquakes, the seismic energy dissipated as heat through friction, the energy radiated elastically through the earth, and the energy associated with volcanic events.

The suggested density of the basaltic rock by Yoder is approximately 2940 $\text{kg}\,\text{M}^{-3}$. On the other hand, Floyd (1991, p. 116) suggests that the length of midocean ridges is approximately 60 000 km. Floyd (1991, p. 33 and 36) suggests that the thickness of the ocean crust at midocean ridges is 6–7 km. The US Geological Survey suggests that the thickness of ocean crust at midocean ridges can reach 15 km. Floyd (1991, p. 41, 42 and 266) suggests that the observed sea floor spreading can vary between 25 and 50 mm annually, and may approach 200 $\text{mm}\,\text{yr}^{-1}$ in some locations. These data can be used to calculate the annual mass, M, produced at midocean ridges.

In Table 1, the total energy of plate tectonics is presented for different values of sea floor spreading and ocean crust thicknesses at midocean ridges. The shaded rows represent the likely weighted average values based on Dixon (2007, p. 543), which suggests 40 $\text{mm}\,\text{yr}^{-1}$ are normally used in modeling the subduction zones. From Table 1, the likely weighted average value of the energy produced by tectonics is approximately $1.29 \times 10^{19}\,\text{J}\,\text{yr}^{-1}$. Based on the US Geological survey, Table 2, the observed and measured annual energy radiated by the earthquakes alone is approximately equal to $7.55 \times 10^{18}\,\text{J}\,\text{yr}^{-1}$. The two figures are in the order of magnitude. These calculations suggest that approximately 60 % of the energy of plate tectonics is dissipated in the form of energy radiated by the earthquakes.

The weighted average force, F, that drives plate tectonics can be estimated. The calculated average annual energy released, 1.29×10^{19} J, is equal to the force F × annual average of ocean floor spreading of 0.04 meters. Consequently, $F = 1.29 \times 10^{19}/0.04 = 3.23 \times 10^{20}$ N, and the weighted average tectonic force calculated per unit length of midocean ridges is approximately equal to $3.23 \times 10^{20}/60\,000\,000 = 5.38 \times 10^{12}\,\text{N}\,\text{m}^{-1}$. Ridge push is approximately equal to $0.3 \times 5.38 \times 10^{12} = 1.61 \times 10^{12}\,\text{N}\,\text{m}^{-1}$. Based on

Floyd (1991, p. 31 and 33), a mature tectonic plate is approximately 125 km thick. Therefore, the compressive stress associated with the force F is about 4.30×10^7 Pa (430 bar). This calculated compressive stress falls within the range of the tensile strength of the rocks of the upper mantle. Yoder (1976, p. 171), suggests that the tensile strength of the rocks is about 0.5 kbar and the value of the tensile strength may not exceed 1 kbar. The calculated stress of 0.43 kbar suggests that the tectonic system operates in the vicinity of its brittle fracture point.

5 Projection of the energy of the geological activities with surface temperature rise

The earth's internal heat to ocean, Q_i, is approximately equal to 69 % of the total heat produced inside the solid earth. The heat has been constantly removed with time to maintain the observed temperature of the earth unchanged, Jacobs (1953). This suggests that the heat transfer resistance across the lithosphere varies with variations in the temperature of ocean floor.

The heat transfer resistance has three terms. The first is the thermal boundary resistance between mantle and lithosphere, the second is the thermal conductivity resistance of the solid lithosphere, and the third is the thermal boundary resistance between ocean crust and the adjacent ocean water. Convection heat transfer, the first and the third terms, are unlikely to change with small variations in the temperature of the ocean floor, because mantle temperature remains constant, Jacobs (1953), and the thermohaline circulation rate remains unchanged. The circulation rate is a result of mass and energy balance whose objective is to spread the solar energy, absorbed unevenly at surface, between the two hemispheres and evaporate a constant amount of water vapor. This balance is governed by geographical and astronomical parameters that remain constant with time. Small variations in the temperature of ocean crust can, however, increase the geothermal gradients across the solid lithosphere, which in turn reduce the temperature driving force across the lithosphere. To maintain the observed internal heat rejected constant, the thickness, or the thermal conductivity resistance, of the lithosphere decreases with the increase in the temperature of ocean floor and the rate of mantle spreading increases. The subsequent increase in the velocity of plate tectonics increases the power, or energy per unit time, produced by the tectonic engine. Consequently, the energy of geological activities dissipated to land increases and the count and may be intensity of earthquakes increase as a result.

Based on Purkey and Johnson (2010), the temperature of the deep ocean around the world, below 4000 m, is presently warming at about the same rate of surface warming. The temperature of ocean floor is increasing because it has to maintain the density of the adjacent brine equal or less than that of the falling brine of the thermohaline circulation, at about Greenland surface water density. Otherwise the circulation would come to a halt. Therefore, the temperature of surface water has to be about equal to the temperature of the abyssal brine located at ocean floor; consequently, no heat exchange from surface to ocean floor can occur with brine circulation. The observed abyssal warming is caused by earth's internal heat that maintains the density of the brine near ocean floor less or equal to that of surface water at all times. It is reasonable to assume that ocean floor warming occurs virtually totally, readily, and equally to surface warming, otherwise the thermohaline circulation would temporarily cease frequently, which is not observed. Further, the ocean as a whole cannot be engaged in the thermohaline circulation for two reasons: First, the ocean has an inverted temperature profile and cannot exchange energy with ocean crust neither by convection nor by conduction. Therefore, thermal diffusion between ocean floor and ocean water is unlikely to occur. Second, the density of surface water is different than that of deep ocean brine and the two brines do not mix easily. Only a peripheral circulation as shown in Fig. 2 can offer the path of least resistance. A fraction of the internal heat to ocean, Q_i, provides the energy and power required to drive the thermohaline circulation. This power can be thought of as an infinite number of pumps in series located at ocean floor. They provide the hydraulic head to overcome friction of ocean floor and drive the circulation at surface from South to North. The hydraulic head produced by the earth's internal energy appears to raise the observed level of the Pacific and southern waters higher than the northern Atlantic waters by approximately 0.2 meters, enough to induce brine flow at surface. The earth's internal heat delivered to the surface by the thermohaline circulation is then rejected to space by surface water evaporation, which is constant.

To obtain the thermodynamic relationship that correlates surface temperature rise and geological activities, a reference baseline must be defined. The suggested baseline is the period of time between 2000 and 2010 presented in Table 2, which does not include volcanic activities. The equations utilized in the model, Sect. 4, can be used to define the reference period of time, which will be designated by the 0 number. The following are definitions, units, and values of the variables required:

- Q_h0 = Mantle convection energy of the baseline period, $5.61 \times 10^{19} \times 10 = 5.61 \times 10^{20}\,\mathrm{J\,decade^{-1}}$.
- T_h0 = Temperature of the mantle, constant and unchanged with time, 1553.2 °K.
- T_a0 = Temperature of ocean floor of the baseline period, which is about equal to Greenland surface water temperature ≈ 274.2 °K.
- T_c0 = Temperature of the cold reservoir of the baseline period, $(T_a0 + T_h0)/2 = 913.7$ °K.
- T_c = Temperature of the cold reservoir for a given surface temperature rise ΔT_s, $(T_a0 + T_h0)/2 + \Delta T_s$ °K.
- T_h = Temperature of the hot reservoir for a given surface temperature rise, constant, and it is equal to T_h0, °K.
- $W0$ = Energy of geological activities for the baseline period, $1.29 \times 10^{19} \times 10 = 1.29 \times 10^{20}\,\mathrm{J\,decade^{-1}}$.
- Q_c0 = Energy lost by the mantle at the cold system temperature of the baseline period, constant, and it is equal to $Q_h0 - W0 = 4.32 \times 10^{20}\,\mathrm{J\,decade^{-1}}$.

- W = Energy of geological activities for a given surface temperature rise ΔT_s, J decade^{-1}.
- Q_h = Mantle convection energy for a given surface temperature rise ΔT_s, J decade^{-1}.
- Q_c = Heat lost by the mantle at the cold system temperature when surface temperature increases by ΔT_s, J decade^{-1}, constant, 4.32×10^{20} J decade^{-1}.
- T_a = Instantaneous temperature of ocean floor, which is about equal to Greenland instantaneous surface water temperature, °K $\approx T_a0$ plus surface temperature rise ΔT_s, °K.
- $Z0$ = Average thickness of plate tectonics for the baseline period, cm yr^{-1}. Its value is not required.
- Z = Average thickness of plate tectonics when surface temperature rises by ΔT_s, cm yr^{-1}. Its value is not required.
- $t0$ = Age of plate tectonics for the baseline period, years. Its value is not required.
- t = Age of plate tectonics when surface temperature rises by ΔT_s, years. Its value is not required.
- $V0$ = Average speed of plate tectonics for the baseline period, 4 cm yr^{-1}. Its value is not required.
- V = Average speed of plate tectonics when surface temperature rises by ΔT_s, cm yr^{-1}. Its value is not required.
- Q_h is directly proportional to V.
- V is inversely proportional to t.

- Z is proportional to $t^{1/2}$.
- Q_c is directly proportional to $-(T_h - T_c)/Z$. The constant of proportionality is the weighted average value of the thermal conductivities of the solid portion of the mantle and lithosphere.

$Q_h - Q_c = W$; $Q_h0 - Q_c0 = W0$. Because the heat rejected to the ocean is constant, then $Q_c = Q_c0$ and $W - W0 = Q_h - Q_h0$. The difference, $W - W0 = \Delta W$, is equal to the increase in the geological activities with surface temperature rise. Q_c is directly proportional to $-(T_h - T_c)/Z$. Because $Q_c = Q_c0$, then $(T_h - T_c)/(T_h0 - T_c0) = Z/Z0$. On the other hand, $(t/t0) = (V0/V) = (Z/Z0)^2$ and $Q_h/Q_h0 = V/V0$. Therefore, $Q_h/Q_h0 = [(T_h0 - T_c0)/(T_h - T_c)]^2 = X$, $(Q_h - Q_h0)/Q_h0 = X - 1$, and $\Delta W = Q_h0\ (X - 1)$. Because $T_h0 = T_h$ and $T_c > T_c0$, then $X > 1$, and $\Delta W > 1$. Or the geological activities increases with surface temperature rise ΔT_s.

In Table 3, the projected geological activities, ΔW, are assumed to dissipate readily with surface temperature rise. The projected increase in the energy of the geological activities will increase the count and may be magnitude of earthquakes and volcanic activities, a subject that will not be addressed in this manuscript.

6 Conclusions

The calculated magma partial melting agrees closely with observations. Yoder (1976) suggests 30 % of magma melting based on experiments and observations, which yields to a latent heat of magma melting of approximately 169 800 J kg^{-1} calculated at mantle's pressure. Thermodynamics suggest that the latent heat of magma melting is approximately equal to 181 100 J kg^{-1}. The two are close within 6.0 %. This is a reasonable agreement between theory and observations.

Based on thermodynamics, the maximum Carnot theoretical efficiency of the tectonic engine is 0.41. This suggests that the maximum magma partial melting is 53 %.

In realty, this partial melting can never be achieved, which is in agreement with observation and experiments (Yoder, 1976, p. 112 and 113).

The weighted average force of compression, F, to which the tectonic system is subjected, produces an axial stress in the plates that is comparable to the tensile strength of the tectonic plates. This suggests that the plate tectonic system operates close to its failure point, which may be one of the reasons why tectonic plates are fragmented, particularly in the back-arc basins (Floyd, 1991, p. 226).

From Table 1, the calculated weighted average of the energy of the tectonic engine is estimated at $1.29 \times 10^{19}\,\mathrm{J\,yr^{-1}}$, and in Table 2 the observed radiated energy by the seismic events is approximately equal to $7.55 \times 10^{18}\,\mathrm{J\,yr^{-1}}$ based on the US Geological survey, Earthquake Facts and Statistics. The two figures are in the order of magnitude and they suggest that the radiated seismic energy is approximately equal to 60 % of the total energy released by plate tectonics, a reasonable agreement between calculations and observations.

Based on these agreements with experiments and observations, it is fair to conclude that the work presented in this paper is worthy of consideration and may be used to calculate the energy of plate tectonics at the global and regional levels and project the energy of plate tectonics with climate change. A projection of the geological activities with surface temperature rise is presented in Table 3.

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 $4.35 \times 1.29 \times 10^{19} = 5.61 \times 10^{19}\,\mathrm{J\,yr^{-1}}$. Based on Davies (2010), the total internal heat of the earth is equal to $1.5 \times 10^{21}\,\mathrm{J\,yr^{-1}}$, 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. Approximately 30 % of this internal heat is radiated by land to space, 69 % is exchanged with ocean water, and the remaining 1 % is relieved by plate tectonics.

The earth subsystems land, ocean, plate tectonics, and surface work together in "harmony" to remove the earth's internal heat steadily. If one subsystem undergoes changes, the remaining subsystems adjust accordingly to maintain constant heat removal with time. Surface temperature is presently rising with climate change and plate tectonic cycle is moving faster. Consequently, the geological activities are increasing to maintain the energy balance. Sea floor spreading is about four meters per century. It is realistic to assume for the foreseeable future that the sites of earthquakes and volcanoes remain about where they are at the present time. However, their frequency of occurrence and magnitude will increase with surface temperature rise. History of earthquakes and volcanic events, projection of the energy of plate tectonics, and statistics can predict count and intensity distribution of future geological activities. It is fair to assume that smaller-magnitude earthquakes constitute sites having least resistance and they draw an increase in the energy of geological activities readily. Larger-magnitude earthquakes, on the other hand, are less likely to draw as much energy. The frequency of occurrence, or annual count, of smaller-magnitude earthquakes is expected to increase with surface temperature rise, whereas very high magnitude earthquakes may not increase appreciably in count or intensity.

Supplementary material related to this article is available online at: http://www.solid-earth-discuss.net/5/135/2013/sed-5-135-2013-supplement.zip.

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Table 1. Calculated annual average energy dissipated by plate tectonics, (a) for an average ocean crust thickness of 6–7 km at midocean ridges, (b) for an average ocean crust thickness of 15 km at midocean ridges.

	Calculated total annual energy of the geological activities						
	Annual sea floor spreading, mm	Length of mid-ocean ridges, km	Basalt latent heat of fusion, $\mathrm{J\,kg^{-1}}$	Magma melting, %	Ocean crust density, $\mathrm{kg\,m^{-3}}$	Ocean crust thickness at midocean ridges, km	Energy to tectonics, $\mathrm{J\,yr^{-1}}$
(a)	20	60 000	565 973	30	2940	6.5	3.894×10^{18}
	30	60 000	565 973	30	2940	6.5	$5,841 \times 10^{18}$
	40	60 000	565 973	30	2940	6.5	7.787×10^{18}
	50	60 000	565 973	30	2940	6.5	9.734×10^{18}
	60	60 000	565 973	30	2940	6.5	1.168×10^{19}
	70	60 000	565 973	30	2940	6.5	1.363×10^{19}
	80	60 000	565 973	30	2940	6.5	1.557×10^{19}
	90	60 000	565 973	30	2940	6.5	1.752×10^{19}
	100	60 000	565 973	30	2940	6.5	1.947×10^{19}
(b)	20	60 000	565 973	30	2940	15	8.985×10^{18}
	30	60 000	565 973	30	2940	15	1.348×10^{19}
	40	60 000	565 973	30	2940	15	1.797×10^{19}
	50	60 000	565 973	30	2940	15	2.246×10^{19}
	60	60 000	565 973	30	2940	15	2.696×10^{19}
	70	60 000	565 973	30	2940	15	3.145×10^{19}
	80	60 000	565 973	30	2940	15	3.594×10^{19}
	90	60 000	565 973	30	2940	15	4.043×10^{19}
	100	60 000	565 973	30	2940	15	4.493×10^{19}

Table 2. Observed annual number of earthquakes obtained from the United States Geological Survey, Earthquakes Facts and Statistics. The energy radiated is calculated by Log E_s = 4.8 + 1.5 M_s, where E_s is the seismic energy in Joules and M_s is the magnitude of the earthquake.

Observed total annual energy radiated by earthquakes																
Earthquake Magnitude Limits	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	Average	Enegy radiated J		Average annual energy radiated, J
														L. limit	U. Limit	
8.0 to 9.5	1	1	0	1	2	1	2	4	0	1	1	1	1.3	6.31×10^{16}	1.12×10^{19}	7.05×10^{18}
7.0 to 7.9	14	15	13	14	14	10	9	14	12	16	23	19	14.4	2.00×10^{15}	4.47×10^{16}	3.36×10^{17}
6.0 to 6.9	146	121	127	140	141	140	142	178	168	144	151	185	148.6	6.31×10^{13}	1.41×10^{15}	1.10×10^{17}
5.0 to 5.9	1344	1224	1201	1203	1515	1.693	1.712	2.074	1.768	1.896	2200	2276	1675.5	2.00×10^{12}	4.47×10^{13}	3.91×10^{16}
4.0 to 4.9	8008	7991	8541	8462	10 888	13 917	12 838	12 078	12 291	6805	10 176	13 315	10 443	6.31×10^{10}	1.41×10^{12}	7.70×10^{15}
3.0 to 3.9	4827	6266	7068	7624	7932	9191	9990	9889	11 735	2905	4336	2791	7046.2	2.00×10^{9}	4.47×10^{10}	1.64×10^{14}
2.0 to 2.9	3765	4164	6419	7727	6316	4636	4027	3597	3860	3014	4623	3643	4649.3	6.31×10^{7}	1.41×10^{9}	3.43×10^{12}
1.0 to 1.9	1026	944	1137	2506	1344	26	18	42	21	26	39	47	598.0	2.00×10^{6}	4.47×10^{7}	1.40×10^{10}
0.1 to 0.9	5	1	10	134	103	0	2	2	0	1	0	1	21.6	8.91×10^{4}	1.41×10^{6}	1.62×10^{7}
Total																7.55×10^{18}

Table 3. Suggested trend of the energy of geological activities with surface temperature rise as a result of climate change. The baseline decade is the decade ending 2010. For this decade, the annual average energy of geological activities is $1.29 \times 10^{19}\,\mathrm{J\,yr^{-1}}$. The total cumulative energy increase through 2150 AD, 8.34×10^{18} J, is about equal to one (1) 9.4 magnitude earthquake. This energy is expected to dissipate with time. On annual basis, the maximum increase in the geological activities, 1.52×10^{17} J, is equivalent to one (1) 8.3 magnitude earthquake. However, most of the increase in the geological activities is anticipated to increase the frequency and count, and may be intensity, of earthquakes having magnitudes between 1.0 and 7.0.

Projected energy of geological activities with global warming – the decade ending 2010 is the baseline									
Geological activities/ decade ending year	2010 Baseline	2020	2030	2040	2050	2070	2100	2120	2150
Cumulative surface temperature rise at year's end, ˚C	0.45	0.52	0.70	0.81	0.96	1.35	2.21	3.11	5.15
Temperature of the cold reservoir, ˚K	913.70	913.77	913.95	914.06	914.21	914.60	915.46	916.36	918.40
Cumulative increase in energy at year's end, Joules	0.00	1.23×10^{17}	4.39×10^{17}	6.32×10^{17}	8.96×10^{17}	1.58×10^{18}	3.10×10^{18}	4.70×10^{18}	8.34×10^{18}
Projected energy increase per decade, Joules	0.00	1.23×10^{17}	3.16×10^{17}	1.93×10^{17}	2.64×10^{17}	3.52×10^{17}	5.83×10^{17}	8.52×10^{17}	1.52×10^{18}
Projected increase of the annual average, Joules	0.00	1.23×10^{16}	3.16×10^{16}	1.93×10^{16}	2.64×10^{16}	3.52×10^{16}	5.83×10^{16}	8.52×10^{16}	1.52×10^{17}
Ratio of annual increase with respect to that of 2011	0.00	1.00	2.57	1.57	2.15	2.87	4.75	6.93	12.39
Annual increase as percent of total energy of 2011	0.000	0.10 %	0.24 %	0.15 %	0.20 %	0.27 %	0.45 %	0.66 %	1.18 %
Annual average spreading of midocean ridges, $\mathrm{cm\,yr^{-1}}$	4.000	4.001	4.003	4.005	4.006	4.011	4.022	4.033	4.059

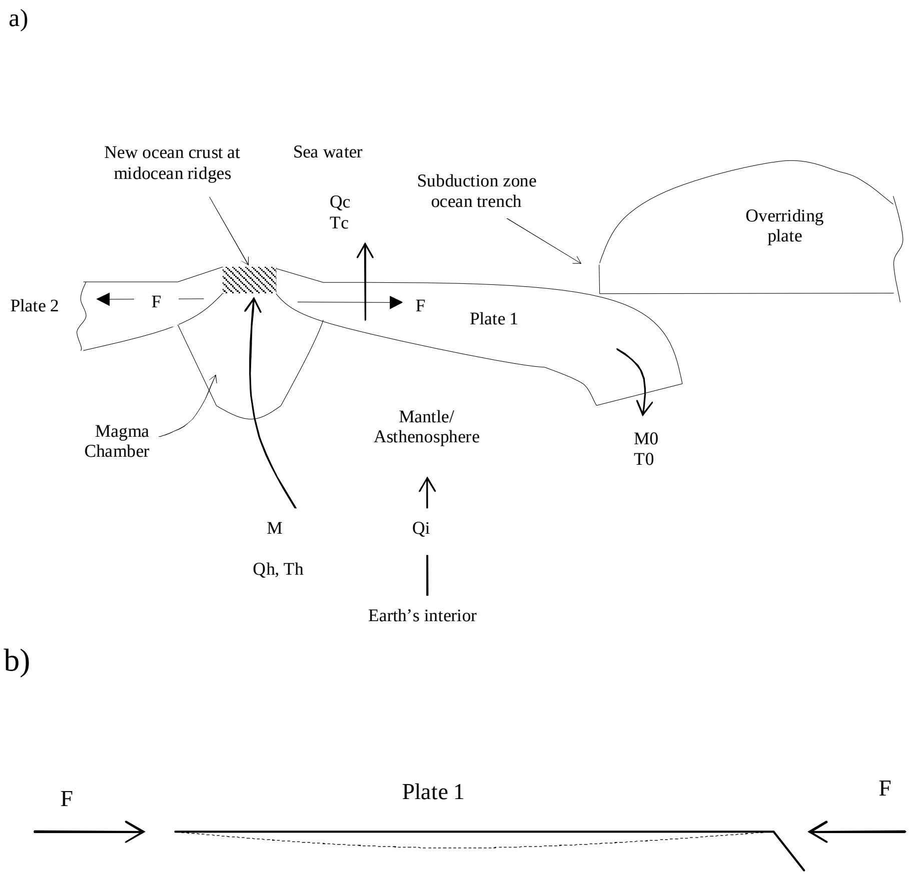

Fig. 1. (a) A schematic of sea floor spreading at midocean ridges and a subduction zone, not to scale. **(b)** a free body diagram of the oceanic plate 1. The compressive force, F, is large enough to buckle and even break the tectonic plates in the event that the plates are not free to spread.

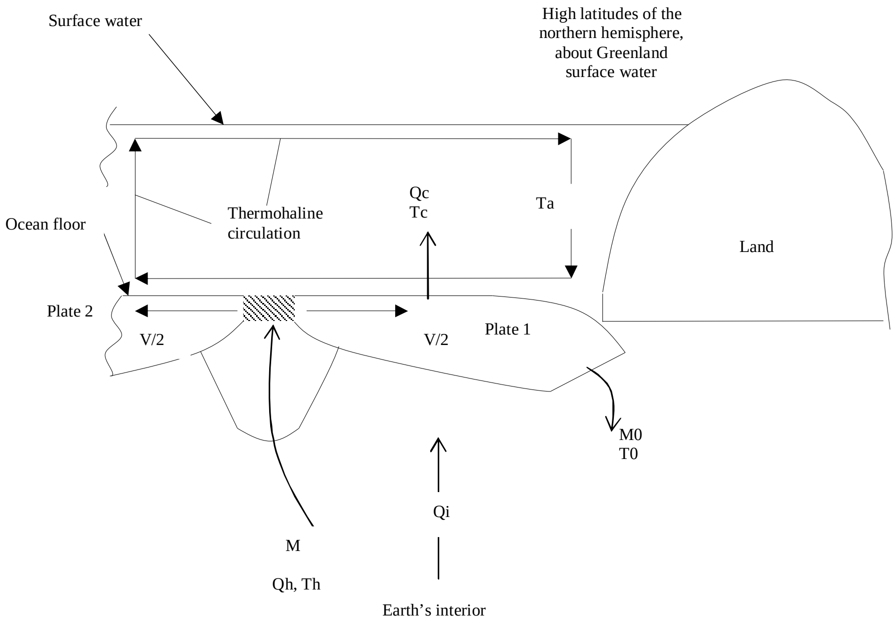

Fig. 2. A schematic cross section North–South of land and ocean, not to scale. The thermohaline circulation links surface temperature with the temperature of ocean floor. The temperature of ocean floor is about equal to that of the surface water located in the high latitudes of the northern hemisphere.