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Ridge Push Engine of Plate Tectonics

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Abstract-Convection of the upper mantle drives the tectonic plates. This convection is a thermodynamic cycle that exchanges heat and mechanical work between mantle and tectonic plates. Thermodynamics and observations indicate 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 regenerated at midocean ridges. This energy varies with the temperature of ocean floor, which is correlated with surface temperature. The main objective of this manuscript is to demonstrate that plate tectonics is a thermodynamic engine and can be calculated as such. Unlike existing tectonic models, the thermodynamic model is very sensitive to variations of the temperature of ocean floor, which is correlated with surface temperature. Therefore, the observed increase of geological activities can be projected with surface temperature rise. Other objectives of the manuscript are to calculate the force that drives the tectonic plates, estimate the energy released, and validate the calculations based on experiments and observations. In addition to the scientific merit of projecting the geological activities, a good projection can have a border impact at the societal and economical levels. Investment and insurance related decisions are affected by climate change, and our ability to project the geological activities is of paramount importance for the economy and public safety. This work can thus provide tools to assess the risks and hazards associated with the trend of geological activities with surface temperature rise. Keywords: force, energy, thermodynamics, plate tectonics.

1. INTRODUCTION

Mantle convection as a possible cause of the motion of the tectonic plates is mentioned in McKenzie (1969), who said that “thermal convection in some form is the only source of sufficient energy.” Attempts to explain how the large-scale convection of the mantle actually drives the tectonic plates is an ongoing research subject. A partial list of related publications include Grigné (2005), Bercovici (2002), Schubert (2004), and Bercovici (2010). They suggest that the large-scale convection of the deep mantle drive the tectonic system. Other publications suggest that smaller-scale convection of the upper mantle contributes to the dynamics of plate tectonics. These include Jarvis (1981), Zandt (1993), Fu Rong-shan (2005), and Parsons (1978). Lenardic (2008) explores possible link between climate change, mantle convection, and tectonics. These cited papers reference a large number of publications that can be referred to for further reading on the subject of mantle convection.

Generally the available publications attempt to find a relationship between mantle convection and motion of the tectonic plates. Mantle plumes are thought to rise from the deep mantle and thermochemical plumes, A. A. Kirdyashkin (2013), interact with mantle free convection. Convection cells are generated that provide the energy and power required to drive the tectonic plates. The upper mantle convection is thought to be limited to the thermal boundary layer that occurs at the lithosphere-asthenosphere boundary and at the bottom of the upper mantle. This upper mantle convection is assumed to be made of many cells, Parson (1978), that maintains an almost isothermal region below the lithosphere. In this scenario, the driving force is not associated with small-scale convection; it is assumed that buoyancy forces localized at ridges and ocean trenches that maintain the motion of the tectonic plates. A. A. Kirdyashkin (2014) calculates the forces to which the plates are subjected in subduction zone as a result of mantle convection. Others use isostasy principle and dynamic equilibrium to calculate the force and energy of plate tectonics. The calculated force and energy of tectonics using these methods do not vary significantly with the temperature of the ocean floor and they cannot be used for projecting the observed increase of geological activities with surface temperature rise. The temperature of ocean floor is correlated with surface water temperature through the thermohaline circulation.

There appears to be no discussions in the literature suggesting that plate tectonics is a thermodynamic system driven by forced convection of the upper mantle. Nor are there publications that calculate the tectonic system by the traditional thermodynamic equations. Backus (1974) suggested the possibility that the earth contains at least two heat engines and Frank D. Stacy (2008) assumed the mantle as heat engine. However, forced convection of the upper mantle is not mentioned as a possible thermodynamic cycle that drives the tectonic system. This is a forced convection driven by a thermodynamic engine as opposed to the natural convection commonly addressed in the literature. The tectonic plates, or ocean crust, is forced into ocean trenches and down into the asthenosphere, where it is melted, or destroyed, then recycled to midocean ridges. The cold and mature oceanic plates exchange heat with mantle as they sink into the earth's interior. They become part of the mantle and their temperature increases substantially. As required by mass conservation, the mantle rises at midocean ridges locations and partially melts to form magma that flows up to the crests of the ridges. The pressure increases following mantle partial melting and the force of pressure raises midocean ridges. At the crest of midocean ridges, magma cools and solidifies to regenerate new ocean crust, thus releasing latent heat of solidification to the enclosed magma in the ridges. The developed pressure at midocean ridges drives the tectonic plates and spread them apart. As the new ocean crust matures with time, it is then driven into the trenches and the cycle repeats. During this thermodynamic cycle, heat and work are exchanged between mantle and the surrounding tectonic plates of the oceanic lithosphere. The resulting work exchanged dissipates as geological activities. As will be demonstrated, the forced convection of the upper mantle removes approximately 3.7% of the total internal heat generated in the earth's core. The larger-scale and natural convection of the mantle removes most of the internal heat generated, approximately 96.3/% of the total. While this larger convection does not vary appreciably with the temperature of the ocean floor, the forced convection of the upper mantle does vary to maintain the temperature of the solid earth constant with variations of the temperature of ocean floor. This temperature is correlated with surface temperature through the thermohaline circulation. Therefore, the energy exchanged in the upper mantle convection is variable with surface temperature and the energy of geological activities varies as a result. Presently, surface temperature is increasing with climate change and the temperature of ocean floor is increasing. The convection of the upper mantle must increase to remove heat that otherwise would accumulate in the solid earth. Consequently, the work of plate tectonics, or geological activities, increases in the form of increased seismic activities, volcanic events, and rise of midocean ridges. Observations are in agreement.

Unlike existing tectonic models, the proposed thermodynamic model in this manuscript has the advantage of being very responsive to slight variations of the temperature of ocean floor. This model thus can be used to project the observed increase of geological activities with surface temperature rise. Other existing models are not sensitive enough to project the geological activities.

The objective of this manuscript is to calculate the driving force of plate tectonics using thermodynamics; estimate the energy released; validate the calculations based on experiments, observations, and the work of others; and project the energy of plate tectonics with surface temperature rise resulting from climate change.

2. MODEL, ASSUMPTIONS, AND DATA

The proposed model consists of applying the laws of thermodynamics on existing models of plate tectonics that are available in literature. Figure 1 is a schematic plate tectonics representation based on Floyd (1991, p. 31 and 127). Part of the earth's internal heat, Qi, is exchanged through the oceanic lithosphere, ocean crust and the solid and rocky part of the upper mantle, which will be assumed to constitute the tectonic plates. A mass M0 of oceanic plate 1 is forced convected into the ductile part of the upper mantle and asthenosphere, which will collectively be referred to as upper mantle. M0 is melted, or destroyed, and becomes part of the mantle as it sinks into the earth's interior. Simultaneously and as required by mass balance, 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 of Fig. 1 (a), and sea floor spreading occurs in the process. This sea floor spreading, or plate tectonics' motion, is caused by the large pressure developed during magma generation deep in the mantle below midocean ridges, and there is a correlation between magma pressure and the degree of magma melting. The ductile portion of the mass

M0, or the mantle, that does not melt is recycled internally, R, with the moving mantle and plates, and the heat of convection associated with this motion is rejected to ocean by conduction through the lithosphere. With this heat rejection, the temperature of the tectonic plates and recycled mantle decreases, and the ductile mantle and plates harden. Plate thicknesses increase as they spread away from midocean ridges. With time, the tectonic plates mature and the full mass M0 is regenerated and the cycle repeats. In the process energy is removed from the earth's interior to the surrounding ocean and continents.

The lithosphere consumption and recycling converts the lithosphere from rocks into mantle/asthenosphere consistency. Heat is removed by forced convection from the earth's interior to the surroundings, and the process is treated as a thermodynamic cycle. If the earth's subsystem enclosing the ductile part of the upper mantle including the recycled mantle, R, is considered as the thermodynamic system and tectonic plates as the surroundings, an amount of heat, Qh, is removed from the earth's interior by upper mantle forced convection at the hot temperature Th. An amount of heat, Qc, is rejected by the mantle to the surroundings at the cold temperature Tc, which is reasonably equal to the average temperature of the moving mantle and plates. The difference, Qh-Qc, is converted to work that drives the tectonic plates. As will be demonstrated, this work is equal to the latent heat of solidification of basalt, mass M, regenerated at midocean ridges plus the work of midocean ridges themselves. Also, this work is equal to the latent heat of melting of the mass, M, of basalt calculated at the conditions of the deep mantle below midocean ridges.

The availability of convertible heat or energy to work is a necessary condition but insufficient to obtain mechanical work. The means to convert this heat into mechanical work must also exist. Based on Floyd (1991, p. 31 and 127), the uplifted lithosphere at midocean ridges encloses magma chamber located beneath the ridges. This lithosphere and tectonic plates appear to act as pistons and piston rods that convert the available magma heat at high pressure into mechanical energy. Under pressure, the lithosphere at midocean ridges expands above ocean floor and some of the energy is stored temporarily in the form of potential energy. This energy is released in full when the plates reach ocean trenches.

Like other thermodynamic cycles, the tectonic engine has cycle medium, and the medium is basalt. It is cold rocks at the temperature of the oceanic lithosphere and hot molten magma deep in the mantle. The phase change of basalt in a complete cycle is accompanied by heat and mechanical work exchanged between the hot mantle and colder lithosphere. The mass of the cycle medium remains practically unchanged in the process.

The laws of thermodynamics apply to the plate tectonic engine and they are utilized in the energy analysis. Although the tectonic plates are consumed in the process, they are regenerated in kind. Over the years, the system, as defined, exchanges heat only with its surroundings tectonic plates and matter is not exchanged. The system can be reasonably considered as 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 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. This force drives the oceanic plates under the overriding continental plates 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 under the large force of pressure, F, thus storing massive amount of energy, similar to that stored in a spring. The stored energy can be released instantly in the form of geological activities. The net effect of this process is that earth’s internal heat is converted to work, or geological activities, and this work dissipates as heat in the continents. The heat is then radiated by land and earth’s internal heat relived.

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 approach maturity for 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 system as defined nor part of the surrounding tectonic plates, the heat exchanged with sea water must not be considered in the thermodynamic cycle of plate tectonics. 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 considered 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 ^{o}K in one billion years. For all practical purposes, a steady temperature of the solid earth and constant internal heat flow are reasonable assumptions. This assumption is fundamental and our observations confirm its correctness. Presently, the temperature of ocean floor is increasing at about the rate of surface temperature rise, Purkey and Johnson (2010). Assuming that the linear thermal expansion of earth's crust is about 5.4 x 10^{-6} °C^{-1} and surface temperature rise of the order of 0.007 °C annually, then the change in the earth's radius would be equal to about 637 100 000 x 0.007 x 5.4 x 10^{-6} =24.1 cm annually, which is not observed. Therefore, no heat accumulation occurs in the solid earth with the observed increase of the temperature of ocean floor. The earth's internal heat that would accumulate is removed steadily in the form of increased geological activities as observed.

A small increase in the temperature of sea brine adhering to ocean floor affects the thermodynamics of midocean ridges, which are engine chambers. The temperature of ocean floor is correlated with the temperature of surface water through the thermohaline circulation; it is approximately equal to the temperature of surface water of the 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. This is accomplished by increasing convection heat transfer in the upper mantle, which removes heat that otherwise would accumulate in the earth. Consequently, the thermodynamic cycle of the plate tectonic engine per unit time increases and the work produced, which is equal to the energy of geological activities, increases simultaneously. By knowing the trend of surface temperature, the energy of the geological activities can be projected with time.

To validate this work, experimental and observed data are utilized. The data include degree of mantle melting, observed radiated energy of earthquakes, and trend of the geological activities with climate change. These encompass radiated energy of earthquakes, rise of midocean ridges, and increase of volcanic events. Also, the calculated compressive stress, force, and energy of plate tectonics are compared with those computed by others and found to be in agreement.

3. BASALTIC MAGMA GENERATION AND DEVELOPED PRESSURE

The model schematically presented in Fig. 1a, which is not to scale, assumes that the annual rate of magma produced, M, is considerably smaller than the mass of magma accumulated in the magma chamber. Therefore, the flow of magma from its generation point to the point of solidification at midocean ridges is considered to occur at constant volume. Similar to the observed volcanos, a sufficiently large magma chamber can produce force large enough to uplift and shear the lithosphere at midocean ridges and split and spread the mantle apart. The displaced mantle cools 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 the tectonic plates.

The pressure produced as a result of magma partial melting in the deep mantle below midocean ridges is large, of 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:

$dS = Cp\ dT/T - (\partial V/\partial T)_p\ dP$

$dS = dQ/T$

Where

S = Entropy of the system in consideration, J $Kg^{-1}\ {}^oK^{-1}$.

Cp = Specific heat of the system at constant pressure, J $Kg^{-1}\ {}^oK^{-1}$.

T = Temperature of the system, ^oK.

V = Volume of the system, $M^3\ Kg^{-1}$.

P = Pressure of the system, Pa.

Q = Heat exchanged, J Kg^{-1}.

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

The equation is valid only at sites of magma generation where mantle and magma coexist. As the magma rises away and segregates 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 Cp dT/T can therefore be neglected from the 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 mantle. Q has a negative sign because it is removed from the mantle, the thermodynamic system in consideration. The equation simplifies to the following equalities:

$-d(Lfs)/T=-(\partial V/\partial T)_p\, dP$; and $d(Lfs)=(\partial V/\partial T)_p \times T \times dP$

Where Lfs is the latent heat of fusion of the mantle, J Kg^{-1}. This heat of melting varies with the degree of mantle melting as magma forms.

The motion of the plate tectonic cycle occurs ”infinitesimally” with time. At an infinitesimally decreasing pressure, the total 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, which is a continuous function of the temperature, can be developed in a Maclaurin’s series as follows:

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

Where $[dV/dT]_{T0}$, which is constant, 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, $[dV/dT]_{T0}$ is constant that applies throughout the melting temperature range dT. At constant pressure, $V(T)-V(T0)=dV=[dV/dT]_{T0} \times dT$ and $dV/dT=[dV/dT]_{T0}=(\partial V/\partial T)_p$=C=constant. The value of the constant, C, is approximately equal to the volume change of the melt per one degree Kelvin. Therefore $(\partial V/\partial T)_p \times T$ 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% degree of magma melting, which is assumed to be basaltic magma, d(Lfs)=0. The term $(\partial V/\partial T)_p \times T$ is approximately equal to the volume change when basaltic rock melts, and it is known, Yoder (1976, p. 94). Basaltic rock melts at high temperature and the volume of the melt increases by 0.049 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 x 10^{-5} M^3 kg^{-1}. Therefore, $(\partial V/ \partial T)_p$ x T is approximately equal to 4.9 x 10^{-5} M^3 kg^{-1} and d(Lfs)=4.9 x 10^{-5} x dP. The change in mantle pressure at melting can be calculated by integrating this last equality as follows:

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

Where, f, is the degree of mantle melting expressed as percent fraction. If f=0, ΔLfs=0 and ΔP=0, and if the degree of melting is equal to, f, then ΔP=2.04 x 10^4 x f x Lfs. For the mantle, Yoder (1976, p. 107) suggests a partial magma melting of 30% (f=0.3) and 135.4 cal g^{-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}) x 4.18 (J cal^{-1}) x 1 000 (g kg^{-1})=565 972 J kg^{-1}. At 30% magma partial melting, f x Lfs=0.3 x 565 972=169 792 J kg^{-1}, and ΔP=169 792 x 2.04 x 10^4 =3.46 x 10^9 Pa, which is equal to 34 600 bar. It will be demonstrated later in Sect. 4 using the laws of thermodynamics that mantle 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 developed pressure following mantle rising, decompression, and its subsequent partial melting raises the ridges and drives the tectonic plates.

4. TECTONICS AS A THERMODYNAMIC CYCLE

In Fig. 2, tectonics is schematically presented as a thermodynamic cycle. The actual thermodynamic cycle is drawn on the enthalpy-concentration diagram, Fig. 2 (a). The corresponding idealized Carnot cycle is presented in Fig. 2 (b), temperature (T)-entropy (S) diagram. Figure 2 (a), which is not to scale, is a window of a simplified rock phase diagram showing basalt generation from the mantle. The basis of Fig. 2 (a) construction is Yoder (1975), Fig. 4-7, page 65; Fig. 5-4, page 93; and Fig 8-10, page 149.

Referring to Fig. 1 and Fig. 2, the mature tectonic plate rocks at point 4 having mass M0 are made of two components: mass M, which is cold and solid basalt, and recycled mantle, R. Their combined composition is XM0 and it is represented by point M0, which is also equal to point 4. This mass is forced convected into the mantle/asthenosphere to point 3, where it is subjected to considerable pressure, from approximately ocean floor pressure of 350 bars at point 4 to point 3 having pressure in excess of 36 400 bars. Rock average temperature increases from T0, which is approximately equal to Tc, to Th, deep in the mantle. On the T-S diagram, this transformation is represented as adiabatic compression from point 4 to point 3. As required by mass conservation, the mantle rises upwards to point 2 and the pressure decreases to P2, to approximately 5 000 bars. Following this decompression, the mantle at point 3 partially melts to produce liquid basalt mass, M or point 2, and the balance of un-melted mantle R, which is slightly cooler than the paternal mantle. The total volume increases following mantle partial melting. Segregation of liquid magma, M, and, R, occurs and basaltic magma accumulates in the magma chamber. This transformation is represented by the isothermal expansion between point 3 and point 2 on the T-S diagram, and the heat, Qh, is exchanged. Under pressure and the released latent heat of basalt solidification, magma chamber liquid expands from point 2 to point 1. This is represented as the adiabatic expansion from point 2 to point 1 of the T-S diagram, and the work of plate tectonics, Wc, is produced. Finally, the solidified basalt, mass M, at point 1 cools to approximately surface temperature, point 4', which is then combined with the recycled mantle, point R, to regenerate the starting mass M0 at point 4 and the cycle repeats. This last transformation is represented on the T-S diagram by an isothermal cooling from point 1 to point 4. Heat, Qc, is rejected during this transformation. The maximum theoretical work produced by the Carnot cycle Wc=Qh-Qc.

The first law of thermodynamics can be used to analyze the tectonic thermodynamic cycle. 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:

dQ=dU+dW

H=U+PV

Carnot cycle's theoretical efficiency=1-Qc/Qh=1-Tc/Th

Thermal efficiency=η =1-$(Tc/Th)^{1/2}$

W=Qh x η

Where

Q =Heat exchanged with the system in consideration, J.

U =Internal energy of the system in consideration, J.

W =Work exchanged between the system and its surroundings, J.

P =System pressure, Pa.

V =System volume, M^3.

H =System enthalpy, J.

Qh=Heat input into the system at the temperature of the hot reservoir, J.

Qc=Heat rejected by the system at the temperature of the cold reservoir, J.

Th=Temperature of the hot reservoir supplying Qh, ^oK.

Tc=Temperature of the cold reservoir receiving Qc, ^oK.

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

Selection of system and surrounding is important in order to obtain the desired geophysical quantities. Cycle medium is the recycled mantle, R, and basalt, M. If the system is assumed to be this cycle medium, the surroundings are lower mantle, ocean, and overriding plates. For this selection, the cold temperature Tc is equal to surface temperature, Ts. The work exchanged with the surroundings includes an undesired fraction exchanged with the lower mantle. This selection of thermodynamic system is inadequate for the objectives of the manuscript. The right selection for the system is the sphere enclosing the mantle including the recycled mantle, R. This system has tectonic plates only as surroundings and basalt as cycle medium. The work exchanged is that to which the tectonic plates are subjected, which is also equal to the sought energy of geological activities. The value of cold temperature Tc for this system will be greater than that of surface temperature, Ts. It is about equal to the average temperature of the mantle and surface water, approximately equal to (Ts+Th)/2. The relationship between thickness of tectonic plates and rate of floor spreading is important for this work. Based on observations and mathematics, plate thickness at any given distance from the midocean ridge is proportional to the square root of the time required or age of the tectonic plate. This relationship is available in literature and thus will not be discussed in this manuscript.

Referring to Fig. 1, the mass M0 of the mature oceanic plate 1 gains heat by convection as it is forced to flow internally through the earth’s interior to midocean ridges. Its temperature increases from T0 to Th. The heat gained by this convective heat transfer is equal to Qh. At midocean ridges, the mantle rises up and partially melts as it decompresses. The melted mantle produces an amount of magma that is equal to M and system pressure increases considerably. Under the pressure, magma flow uplifts the ridges and drives the tectonic plates. The mass M solidifies at mid ocean ridges as it cools and tectonic plates spread away. The remaining un-melted and ductile mantle mass, R, 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 following heat rejection to ocean. The sphere enclosing the ductile part of the upper mantle can be assumed as the system for this thermodynamic cycle and tectonic plates 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 ^{o}C (923.2 ^{o}K) and mantle temperature, Th, is at about the magma melting temperature of 1 280 ^{o}C (1 553.2 ^{o}K). The cold temperature, Tc, at which Qc is rejected can be reasonably assumed to be equal to the average temperature of the surrounding tectonic plates. Tc is approximately equal to the average of sea floor temperature and magma melting temperature, or approximately equals to (274.2+1 553.2)/2=913.7 ^{o}K. The estimated specific heat, Cp, of mantle rock by Yoder (1976, p. 71) is about 0.3 cal g^{-1} ^{o}C^{-1}, which is equal to 1 250 J kg^{-1} ^{o}K^{-1}. Therefore, Qh=Cp x (Th-T0)=1 250 x (1 553.2-923.2)=787 500 J kg^{-1}, and the following applies for this thermodynamic cycle:

Carnot cycle theoretical efficiency=1-Tc/Th=1-913.7/1 553.2=0.41

Thermal efficiency=η=1-(Tc/Th)$^{1/2}$=1-(913.7/1 553.2)$^{1/2}$=0.23

W=Qh x η=787 500 x 0.23=181 125 J kg^{-1}.

Qc=Qh-W=787 500-181 125=606 375 J kg^{-1}.

The calculated amount of work, W, delivered to the surrounding tectonic plates, 181 125 J kg^{-1}, is approximately equal to the latent heat of basaltic rock calculated at mantle's pressure and 30% partial melting as suggested by Yoder (1976), which is equal to 169 792 J kg^{-1}, 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 tectonic plates, 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, J.

U =Internal energy of the system, the earth's interior, J.

W =The work exchanged between the system, as defined, and the surrounding tectonic plates, J.

H =Enthalpy of the system as defined, the earth's interior, J.

PV=The product of the pressure of the earth's interior by its volume.

Because the system, the earth's sphere enclosed by the ductile portion of the upper mantle, is incompressible, Adams L. H. (1926), 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 Ms [Cps dT+d(Lfs)]. Where Ms is system mass, kg; Cps is the specific heat of the system, J kg^{-1} $^{o}K^{-1}$; T is system temperature, ^{o}K; and Lfs is the latent heat of melting of the system, J kg^{-1}. System temperature is reasonably constant as discussed in Sect. 2 and dT≈0. Therefore, the differential of work exchanged can be expressed by the following equality:

$$dW=-Ms\ d(Lfs)$$

The work has a negative sign, or it is produced by the mantle and delivered to the surrounding tectonic plates. The amount, Ms d(Lfs), is equal to the latent heat of phase change of the earth system enclosing the ductile part of the upper mantle. This system is practically unchanged except at midocean ridges where only the mass, M+R, of the mantle changes phase by mantle partial melting. Or, dW=-Ms d(Lfs)=-(M+R) d(Lfs). This equation can be integrated and the work obtained. For 0.0% degree of mantle melting, d(Lfs)=0 and the work produced, W, is equal to zero. For a degree of melting that is equal to, f, the work delivered follows:

$$W=-M \times f \times Lfs-R \times 0 \times Lfs=-M \times f \times Lfs=M\ Lf$$

The factor, f, is the degree of mantle melting expressed as percent fraction. The recycled mantle, R, has zero degree of mantle melting, or f=0. Also, f x Lfs= Lf, where Lf is basalt latent heat of melting, J kg^{-1} calculated at mantle pressure. The last equation shows that the work delivered by the plate tectonic system is equal to the latent heat of melting of the mass, M, of basaltic rock at the conditions of 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 mechanical work delivered to and by the tectonic engine is equal to f x Lfs=Lf, or it is equal to the latent heat of partial melting of mantle rock calculated at mantle's pressure. This is also equal to the latent heat of melting of basalt corrected for mantle 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 the tectonic plates by the force of pressure produced. The difference between magma latent heat of melting calculated at mantle's pressure and that calculated at oceanic crust's pressure, which is approximately equal to 33% of (f x Lfs) based on Yoder (1976, p. 95), maintains the uplift of the lithosphere at midocean ridges. Therefore, the value of the energy of midocean ridges is 0.33 x 181 125=59 770 J kg^{-1}. The mass, M, can be calculated by knowing the volume of new ocean crust that is formed at midocean ridges, or the shaded area of Fig. 1 and the density of ocean crust. The latent heat of fusion of basaltic rock, Lf, is available in literature and it is calculated in Sect. 3. The work exchanged with the tectonic plates, W=f x Lfs=Lf, thus can 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, the potential energy associated with lifting of the midocean ridges, and the energy of volcanic events.

The density of the basaltic rock based on Yoder (1976, p. 94) is nearly 2 940 kg M^{-3}. On the other hand, Floyd (1991, p.116) assumes that the length of midocean ridges is approximately 60 000 km. Floyd (1991, p. 33 and 36) shows that the thickness of the ocean crust at midocean ridges is 6-7 km. Sjöberg (2004) suggests that the average thickness of the lithosphere at midocean ridges is about 15 km. Floyd (1991, p. 41, 42 and 266) indicates that sea floor spreading can vary between 25 and 50 mm annually and may approach 200 mm yr^{-1} in some locations. These data can be used to calculate the annual average 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 lithosphere thicknesses at midocean ridges. The shaded rows represent the likely weighted average values based on Dixon (2007, p. 543), who uses 40 mm yr^{-1} of sea floor spreading in modeling the subduction zones. From Table 1, the likely weighted average value of the energy produced by tectonics is approximately equal to 1.29 x 10^{19} J yr^{-1}. Based on the U.S. Geological survey, Table 2, the observed and measured annual energy radiated by the earthquakes alone is approximately equal to 7.66 x 10^{18} J yr^{-1}. The two figures are of the same order of magnitude. These calculations show 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 the tectonic plates can be estimated. The calculated average annual energy released, 1.29 x 10^{19} J, is equal to the force F x annual average spreading of ocean floor of 0.04 meters. Consequently, F=1.29 x 10^{19}/0.04=3.23 x 10^{20} N, and the weighted average tectonic force calculated per unit length of midocean ridges is approximately equal to 3.23 x 10^{20}/ 60 000 000=5.38 x 10^{12} N m^{-1}. Based on Floyd (1991, p. 31 and 33), a mature tectonic plate is about 125 km thick. Therefore, the compressive stress associated with the force F is of the order of 4.30 x 10^{7} Pa (430 bar).

The calculations reveal that the total heat exchanged in the convection of the upper mantle/asthenosphere, Qh, is approximately equal to 4.35 times the energy delivered to the tectonic plates, W. Therefore, the total heat removed by this convection is equal to 4.35 x 1.29 x 10^{19} =5.61 x 10^{19} J yr^{-1}. Based on Davies (2010), the total internal heat of the earth is equal to 1.5 x 10^{21} J yr^{-1}, or the upper mantle/asthenosphere convection removes about 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, 69% is exchanged with ocean water, and the remaining 1% is relieved by plate tectonics as geological activities.

5. EFFECT OF SURFACE TEMPERATURE ON THE TECTONIC CYCLE

Based on Purkey and Johnson (2010), the temperature of the deep oceans around the world, below 4 000 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. Therefore, the temperature of surface water has to be equal or less than the temperature of the abyssal brine adhering to ocean floor. Consequently, there can be no heat transfer from the surface to ocean floor with brine circulation. The observed abyssal warming is caused by earth's internal heat that maintains the density of the brine near ocean floor equal or less than 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. In Fig. 3, the thermohaline circulation is schematically presented. The circulation brings to surface water earth's internal heat where it is removed by evaporating water.

Referring to Fig. 4, boundary conditions of the heat diffusion equation vary with the age of the oceanic lithosphere. For a mature and thick plate at location 3, the boundary condition is $-k\ (dT/dz)_{z0}=q=\text{constant}$, where T is the temperature of the lithosphere, ^oK; k is the thermal conductivity of basalt, J m^{-1} s^{-1} $^oK^{-1}$; z0 is the vertical coordinates of the lithosphere at ocean floor, m; and q is the earth's internal heat flux, constant, approximately equal to 0.093 W m^{-2} based on Davies (2010). The temperature profile of most of the thick oceanic lithosphere is barely affected by the observed surface temperature rise. This is not the case for midocean ridges, which are engine chambers and most sensitive components of the tectonic system. At location 1, the lithosphere does not exist; it is a newly recycled and solidified magma and the boundary condition is $-k(dT/dz)_{z0}=h \times [Ts-T]$ where, h is the lithosphere-ocean convective heat transfer coefficient, approximately equal to 7.30×10^{-5} W m^{-2} $^oK^{-1}$ and Ts is surface temperature, ^oK. The boundary conditions at location 2, where the solid lithosphere just forms and cools close to surface temperature, is $(dT/dt)_{z0}=dTs/dt$. Variations of surface temperature with time, dTs/dt, are available in the record. Unlike the thick oceanic lithosphere, the solution of the Fourier equation for midocean ridges is very much dependent on surface temperature Ts. The difference, Ts-T, can be as small as several degrees Kelvin and as large as few hundred degrees Kelvin. The observed variations of surface temperature by 0.007 ^{o}K annually are not, therefore, negligible. They cause tangible and virtually immediate impact on engine chamber thermodynamics. Given the large surface area involved, variations of the energy of geological activities released to the surroundings with surface temperature rise cannot be ignored.

As shown in Fig. 1 and Fig. 5, which are not to scale, the total heat generated in the earth's interior, Qg, splits between the oceanic and continental plates, Qi and Qj respectively. Based on Incropera and De Witt (1985), the following equations can be written for the earth's internal heat exchanged between mantle, ocean, and land:

$$Qg = Qj+Qi = \text{constant};\ Qi = \text{constant};\ Qj = \text{constant}$$

$$Qg = Qo+Ql;\ Ql = W+Qj;\ Qi = Qo+W$$

$$Qo = Uo\ Ao\ (Th-Ts);\ Qc = Uc\ Ac\ (Th-Ts)$$

$$1/Uo = 1/hi+1/ho+Zo/k;\ 1/Uc = 1/hi+1/ho+Z/k$$

Where

Qg=Total heat generated at the earth's interior, J yr^{-1}, constant.

Qi=Fraction of Qg to the oceanic plates, J yr^{-1}, constant.

Qj=Fraction of Qg to land, J yr^{-1}, constant.

Qo=Earth's internal heat to ocean, which is then removed by evaporation, J yr^{-1}.

Ql =Earth's internal heat to land, which is then radiated, J yr^{-1}.

Qc =Heat rejected to ocean at midocean ridges by the tectonic engine, J yr^{-1}, Fig. 1 and Fig. 4.

W =Mechanical energy of plate tectonics, J yr^{-1}.

Uo =Overall heat transfer coefficient between mantle and sea water, J yr^{-1} m^{-2} °K^{-1}.

Uc =Overall heat transfer coefficient between mantle and sea water at midocean ridges, J yr^{-1} m^{-2} °K^{-1}.

hi =Heat transfer coefficient of the large-scale mantle convection, J yr^{-1} m^{-2} °K^{-1}.

ho =Heat transfer coefficient of sea water convection, J yr^{-1} m^{-2} °K^{-1}.

Ao=Heat transfer area of the oceanic lithosphere, m^{2}.

Zo =Average thickness of the oceanic lithosphere, m.

Ac=Heat transfer area of the lithosphere at midocean ridges, m^{2}.

Z =Average thickness of the lithosphere at midocean ridges, m.

k =Average thermal conductivity of the lithosphere, J yr^{-1} m^{-1} °K^{-1}.

Th =Mantle temperature, °K.

Ts =Temperature of surface water or ocean floor, °K.

The area Ac is a small fraction of the total area Ao. The value of the overall heat transfer coefficients Uo and Uc are about equal, of the order of 2 300 J yr^{-1} m^{-2} °K^{-1} (0.3 W m^{-2} °K^{-1}). Ql≈0.31 x Qg and Qo≈0.69 Qg. The heat to the continents, Qj, is approximately equal to 0.3 Qg and the energy of geological activities W≈0.01 Qg. Because Qi is constant, then ΔQo=-ΔW. Or a change in the heat exchanged with the ocean water is equal to the change with opposing sign of the energy of geological activities. If surface temperature and ocean floor, Ts, increases, ΔQo decreases and ΔW increases. Because the temperature of the solid earth is steady and the internal heat flow of the earth is constant, the decrease in the heat to ocean, ΔQo, is also equal to the increase in the upper mantle convection, ΔQh. Therefore $\Delta Qh=\Delta W$ which suggests that all of the increase in the upper mantle convection is converted to work following surface temperature rise. This does not violate the laws of thermodynamics because the process is related to an existing thermodynamic engine having a thermal efficiency η. A small increase in the heat, Qh, available at the hot temperature reservoir can be converted in full to additional mechanical work provided that the efficiency of the existing engine improves. To convert all of the annual heat increase, ΔQh, to work, the efficiency of the tectonic engine has to improve by 0.073%.

As surface temperature increases, the temperature of the ocean floor increases. The efficiency of the tectonic engine decreases with surface temperature rise. The increase in surface temperature also increases the heat, Qh, available for the forced convection cycle of the upper mantle and the cycle moves faster. Midocean ridges rise more as a result and the height of the engine chamber increases, which is observed based on Sjöberg (2004), and engine efficiency increase. Mathematics shows that variations of the engine's efficiency, η, can be expressed by the following equations:

η=Power delivered/Power supplied= F x v/(Qh per unit time)=P x A x v/(Qh per unit time)

$d\eta/dA = P \times v \times 3.15 \times 10^{7} / Qh + (A \times v \times 3.15 \times 10^{7} / Qh) \times dP/dA$

η increases with an increase in the area, A, of the tectonic engine's chamber.

$d\eta/dTs = (d\eta/dTc) \times (dTc/dTs) = 1/[4\ Th\ (\eta-1)]$

η decreases with an increase in surface temperature Ts.

Where Ts is surface temperature; P is magma pressure at midocean ridges, Pa; v is tectonic plate velocity, m s^{-1}; Tc is the average temperature of the lithosphere at midocean ridges, °K; and A is the area obtained by multiplying the length of midocean ridges by the average height measured from crest of midocean ridges to base at the bottom of the tectonic plates. The multiplier, 3.15 x 10^7, is the number of seconds in one year. In the derivation of dη/dA, the ratio *v*/Qh is constant because the heat of the upper mantle convection, Qh, is proportional to the speed of the cycle, *v*. The slope, dP/dA is positive. The observed annual increase of surface water temperature is in the order of 0.01 °K yr^{-1} and the associated decrease in efficiency is negligible. The increase in the efficiency, based on the observed minimum rise of midocean ridges of 5 millimeters annually, is sufficient to increase the efficiency of the tectonic engine by 0.073%, required to convert all of the increase in mantle convection, ΔQh, to additional work, ΔW. The heat rejected Qc thus can remain unchanged and ΔQc=0.

The tectonic system possesses a large inertia and it requires a long time to reach a steady state following surface temperature perturbation. For the foreseeable future, the time of surface temperature rise is small in geological terms and it is a transient period for the tectonic cycle as a whole. The scenario is different for midocean ridges because of their vicinity to magma generation, and the ridges are affected practically immediately. Their heights increase and, at midocean ridges, the lithosphere moves faster with the increase of the convection cycle. Following velocity increase, the thickness of the lithosphere at midocean ridges, Z, decreases. The changes of, Uo, and, Ao, with variations of the temperature of ocean floor are in fact equal to those of, Uc, and, Ac, respectively. The area, Ac, increases and the overall heat transfer coefficient, Uc, at midocean ridges improves as well. Consequently, the flow of the heat rejected by the tectonic engine chamber, Qc, can remain unchanged even with surface temperature rise, or ΔQc can be equal to zero, in spite of the increase in the temperature of ocean floor. Based on this analysis of the engine's efficiency and heat transfer, the projection of the energy of plate tectonics will consider that the heat rejected by the tectonic cycle, Qc, remains constant with surface temperature rise.

6. PROJECTION OF THE ENERGY OF PLATE TECTONICS

To obtain the thermodynamic relationship that correlates surface temperature rise and geological activities, a reference baseline period of time must be defined. The baseline is the period of time prior to the onset of the Industrial Revolution 1750 as suggested by the Intergovernmental Panel on Climate Change. The equations and calculated values in Sect. 4 will be used to define the baseline, whose thermodynamic variables will be designated by the zero suffix. The following are definitions, units, and values of the variables required:

Qh0=Energy of the upper mantle convection of the baseline period, 5.61 x 10^{19} J yr^{-1}.

Th0=Temperature of the mantle, constant and unchanged with time, 1 553.2 ^{o}K.

Ta0=Temperature of the ocean floor of the baseline period, which is about equal to Greenland surface water temperature ≈274.2 ^{o}K.

Tc0=Temperature of the cold reservoir of the baseline period, (Ta0+Th0)/2=913.7 ^{o}K.

Tc =Temperature of the cold reservoir for a desired surface temperature rise ΔTs, (Ta0+Th0)/2+ΔTs, ^{o}K.

Th =Temperature of the hot reservoir for given surface temperature rise, constant, and it is equal to Th0, ^{o}K.

W0 =Energy of geological activities of the baseline period, 1.29 x 10^{19} J yr^{-1}.

Qc0=Energy lost by the upper mantle convection at the cold temperature of the baseline period, constant, and it is equal to Qh0-W0=4.32 x 10^{19} J yr^{-1}.

W =Energy of geological activities for a desired surface temperature, Tc0+ΔTs, J yr^{-1}.

Qh =Energy of the upper mantle convection for a desired surface temperature, Tc0+ΔTs, J yr^{-1}.

Qc =Heat lost by the upper mantle convection at the cold temperature when surface temperature increases by ΔTs, J yr^{-1}, constant, 4.32 x 10^{19} J yr^{-1}.

Ta =Instantaneous temperature of ocean floor, which is about equal to Greenland instantaneous surface water temperature, °K. It is equal toTa0 plus surface temperature rise ΔTs, °K.

Z0 =Average thickness of the tectonic plates for the baseline period, m. Its value is not required.

Z =Average thickness of the tectonic plates after surface temperature has risen by ΔTs, m. Its value is not required.

t0 =Age of the tectonic plates for the baseline period, yr. Its value is not required.

t =Age of the tectonic plates after surface temperature has risen by ΔTs, yr. Its value is not required.

*v*0 =Average speed of the tectonic plates for the baseline period, m yr^{-1}. Its value is not required.

v =Average speed of the tectonic plates after surface temperature has risen by ΔTs, m yr^{-1}. Its value is not required.

Qh is directly proportional to *v*.

v is inversely proportional to t.

Z is proportional to $t^{1/2}$.

Qc is directly proportional to -(Th-Tc)/Z. The constant of proportionality is equal to 2k, where k is the weighted average value of the thermal conductivities of the solid portion of the mantle and lithosphere. The following applies for the plate tectonic system:

Qh-Qc=W; Qh0-Qc0=W0. Because the earth's internal heat rejected, Qc, is constant, then Qc=Qc0 and

W-W0=Qh-Qh0. The difference, W-W0=ΔW, is equal to the increase in the geological activities with surface temperature rise. Qc is directly proportional to -(Th-Tc)/Z. Because Qc=Qc0, then (Th-Tc)/(Th0-Tc0)=Z/Z0. On the other hand, $(t/t0)=(v0/v)=(Z/Z0)^2$ and $Qh/Qh0=v/v0$. Therefore, $Qh/Qh0=[(Th0-Tc0)/(Th-Tc)]^2=X^2$, $(Qh-Qh0)/Qh0=X^2-1$, and $\Delta W=Qh0\ (X^2-1)$. Since Th0=Th and Tc>Tc0, then X>1, and ΔW>0. Or the geological activities increases with surface temperature rise ΔTs.

The rise of midocean ridges with climate change can be calculated by knowing the projected energy of the geological events. The annual increase in geological energy is equal to ΔW, which is also equal to ΔQh. Therefore, the height of midocean ridges can be calculated by e x (0.33 x ΔQh+Qh)/Qh, where e=average elevation of the ridges above ocean floor, about 3 000 m based on Forsyth and Uyeda (1975). The present annual trend of the energy of geological activities, ΔW, is equal to $Qh0\ (X^2-1)$, where X=[(Th-Tc)/(Th-(Tc+ΔTs))] and ΔTs is the total increase of surface water temperature for the present warming trend. Average change of the height of midocean ridges Δe=0.33 (ΔW/Qh0) x e, where e=average height of the ridges above ocean floor. In Table 3, the projected energy of geological activities, ΔW, and average midocean ridges rise are tabulated with surface temperature.

7. DISCUSSION

Schubert G. (2001) summarizes the current state of tectonics understanding. Major driving forces are ridge push and slab pull, or tectonic plates themselves are the main source of their own driving force. This of course is in disagreement with the laws of thermodynamics in that plate tectonics is assumed to be perpetual motion machine, which in practice cannot exist. Energy of slab pull and ridge elevation are equalized by opposing energy of gravity forces as mantle and basalt masses rise at the opposing sides of the cycle. To overcome friction, external energy source is required based on the laws of thermodynamics. Ridge push and slab pull can, therefore, be only effects of the dynamics of plate tectonics and cannot be causes of the motion.

Mantle buoyancy at ridges is unlikely occur. Buoyancy is a thermodynamic transformation where less dense, or buoyant, thermodynamic system is enclosed by more dense surroundings. Mantle does not meet these basic thermodynamic requirements; it has practically uniform temperature and cannot be thermodynamic system and surroundings at the same time. Therefore, mantle buoyancy must be excluded as a driver. Midocean ridges are higher than trenches because of magma generation below the ridges, not as a result of mantle buoyancy. Pressure develops with magma generation and the developed pressure raises the ridges. Similar to volcanoes, they have magma chamber above which crust is uplifted. For the hypothetical scenario that mantle buoyancy is the cause of midocean ridge energy, the calculated potential energy of ridges by buoyancy considerations is significantly smaller than observed. The observed energy of ridges in J kg^{-1} is equal to E_p=g x (e+Z/2), where g is gravity acceleration, 9.8 m s^{-2}; e=average height of the midocean ridges above ocean floor, about 3 000 m based on Forsyth and Uyeda (1975); and Z is basalt thickness at oceanic trenches, approximately equal to 6 000 m, Schubert G. (2001). Energy of ridges caused by mantle buoyancy would be E_b=g x α x t x ΔT, where α is the volumetric thermal expansion about 3 x 10^{-5} K^{-1}, Bercovici (2010); and t, is average plate thickness, m. Tectonic plate thickness is negligible at midocean ridges and approximately equal to 125 000 m at trenches, which yields to average thickness t=62 500 m. ΔT is the maximum temperature difference between average plate temperature at ridges, 1 553.2 ^oK, and that at trenches, 923.2 ^oK. ΔT is about equal to 630 ^oK. Sources of the data used in this section are provided in the Sect. 3 and Sect. 4. The observed energy of midocean ridges E_p=58 800 J kg^{-1} and the hypothetical energy of ridges that would be caused by mantle buoyancy E_b=11 530 J kg^{-1} at the most, because the used ΔT is the maximum possible. The calculated hypothetical energy of midocean ridges that would be caused by mantle buoyancy E_b is too small and cannot be the cause of the observed energy of ridges E_p.

The tectonic engine presented in this manuscript, in principle, resembles thermodynamic engines successfully in operation. In general, there is a correlation between mechanical work exchanged and latent heat of phase change of cycle medium. Similarly, there is a relationship between basalt latent heat of melting and work produced. In a complete cycle, enthalpy and potential energy variations of lithosphere and mantle are about negligible. The lithosphere undergoes transformation from cold and solid rocks to hot mantle, which in turns partially melts. It then solidifies and cools to produce the starting lithosphere and the cycle repeats. The only change that occurs in a complete cycle is lithosphere phase change and mechanical work produced, which is equal to the energy of geological activities. Therefore, the net mechanical work of plate tectonics is equal to the latent heat of basalt. This conclusion is demonstrated mathematically and numerically between lines 333 and 407. Accordingly, Table 1 is prepared and energy and forces of plate tectonics calculated.

Plate tectonics as a thermodynamic engine satisfies all requirements of the laws of thermodynamics, thus qualifies to be the driving force. First, external energy required is available, it is mantle heat; second, system and surroundings are clearly defined; third, cycle medium exists and it is basalt; and fourth, the means to convert mantle heat into mechanical work is also available, they are engine chambers at midocean ridges.

Ridge push and slab pull are only effects of the magmatic process of tectonics, they cannot be drivers. As effects, they can be used to calculate the magnitudes of the cause such as force and energy of plate tectonics. However, the calculated values using ridge push and slab pull do not vary with the observed small variations of surface temperature. Likewise, large-scale mantle convection is unlikely to vary for the lithosphere is too thick. Therefore and based on the current tectonics understanding, no correlation can exist between the observed surface temperature rise and geological activities. This is not the case when the tectonic system is analyzed as a thermodynamic engine. Energy of plate tectonics increases with surface temperature rise.

8. CONCLUSIONS

The thermodynamic cycle of plate tectonics is a reflection of the magmatic processes that occurs deep in the mantle. Therefore, calculations of the geophysical parameters of this thermodynamic cycle must agree with rock phase diagram, experiments, and observations. The calculated mantle partial melting agrees closely with observations. Yoder (1976) estimated that the degree of mantle partial melting is 30% 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 shows that the latent heat of magma melting is approximately equal to 181 100 J kg^{-1}. The two are close within 6.0%. Based on thermodynamics, the maximum Carnot theoretical efficiency of the tectonic engine is 0.41. This indicates that the maximum mantle partial melting is 53%. In reality, this theoretical partial melting can never be achieved. Based on observation and experiments, Yoder (1976, p. 112 and 113) concluded that the maximum degree of mantle rock melting is about 50% by volume, which is approximately equal to 45% by weight. The maximum theoretical value calculated based on Carnot cycle, 53%, is 18% greater than the observed at the most. The actual maximum value of the degree of melting will be less than 53% but greater than 30%, in reasonable agreement with the observed 45%. Therefore, thermodynamics agrees closely with rock phase diagrams, experiments, and observations.

The calculated forces of the plate tectonic system compare closely with those published in the peer-reviewed literature. McKenzie (1969) estimates the total force of slab pull to be of the order of $12.5 \times 10^{12} \sin(45^o) = 8.8 \times 10^{12}$ N m^{-1} for spreading velocity of 10 cm yr^{-1}. Forsyth and Uyeda (1975) estimate of the energy of ridge push is nearly 8.0×10^{18} J yr^{-1} at the assumed floor spreading of 5.6 cm

yr^{-1}. The calculated total force is 5.38 x 10^{12} N m^{-1} and the calculated energy of midocean ridged using thermodynamics is 33% of the total energy, approximately equal to 4.3 x 10^{18} J yr^{-1} for spreading velocity of 4 cm yr^{-1}. These values are of the same order of magnitude of those calculated by McKenzie (1969) and Forsyth and Uyeda (1975). They differ by data source. If spreading velocity is made the same, 4 cm yr^{-1}, the agreement becomes even closer. The calculated weighted average force of compression of the tectonic system, 5.38 x 10^{12} N m^{-1}, produces an axial stress of about 0.43 kbar, which compares with 0.3 kbar used by Forsyth and Uyeda (1975). From Table 1, the calculated weighted average of the energy of the tectonic engine is about 1.29 x 10^{19} J yr^{-1}, and in Table 2 the observed radiated energy by the seismic events is approximately equal to 7.66 x 10^{18} J yr^{-1} based on the United States Geological Survey, Earthquakes Facts and Statistics/Earthquake Archive Search. The two figures are of the same 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.

The calculated present annual trend of geological activities, at least 1.0 x 10^{17} J, is of the same order of magnitude of the observed present annual trend of 3.0 x 10^{17} J, Fig. 6. The actual increase of the temperature of ocean floor is greater than average surface temperature used in the calculations, for sea temperature rise of the northern latitudes, which is unavailable, is greater than average. If the actual increase of ocean floor temperature is used instead, the calculated annual trend will approach closer to the observed one. The calculated present annual rise of midocean ridges of 16.0 mm is in agreement with the observed annual rise of 5-20 mm, Sjöberg (2004) and Árnadóttir (2009).

Volcanic events are on the rise as well. Using the Smithsonian Volcano Research Database and sampling every five years, the volcanic activities have an increasing trend with time. The following is an annual average per two decades of the samples: From 1990 to 2010, the annual average number of volcanoes is 65; from 1970 to 1990, the annual average number of volcanoes is 56; from 1950 to 1970, the annual average number of volcanoes is 52. This observed increase of geological activities is predicted by thermodynamics presented in this manuscript.

Based on these agreements with observations, experiments, and the work of others on tectonics, it is fair to conclude that the plate tectonic system is a thermodynamic engine that has engine chambers and mechanical components. The geophysical variables of this engine can be calculated by the traditional thermodynamic equations. This provides another method of calculating tectonics, sensitive enough to small variations of surface temperature. The geological activities can be calculated at the global and regional levels. Accordingly, a suggested projection of the geological activities with surface temperature rise is presented in Table 3.

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Table 1. Calculated annual average energy dissipated by plate tectonics at different sea floor spreading rates. (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.

a)

Annual sea floor spreading, mm	Length of mid-ocean ridges, km	Mantle latent heat of fusion, J/kg	Mantle melting percent	Ocean crust density kg/cubic meter	Ocean crust thickness at midocean ridges, km	Energy to tectonics, J/yr
20	60,000	565,973	30	2940	6.5	3.894E+18
30	60,000	565,973	30	2940	6.5	5.841E+18
40	60,000	565,973	30	2940	6.5	7.787E+18
50	60,000	565,973	30	2940	6.5	9.734E+18
60	60,000	565,973	30	2940	6.5	1.168E+19
70	60,000	565,973	30	2940	6.5	1.363E+19
80	60,000	565,973	30	2940	6.5	1.557E+19
90	60,000	565,973	30	2940	6.5	1.752E+19
100	60,000	565,973	30	2940	6.5	1.947E+19

b)

Annual sea floor spreading, mm	Length of mid-ocean ridges, km	Mantle latent heat of fusion, J/kg	Mantle melting percent	Ocean crust density kg/cubic meter	Ocean crust thickness at midocean ridges, km	Energy to tectonics, J/yr
20	60,000	565,973	30	2940	15	8.985E+18
30	60,000	565,973	30	2940	15	1.348E+19
40	60,000	565,973	30	2940	15	1.797E+19
50	60,000	565,973	30	2940	15	2.246E+19
60	60,000	565,973	30	2940	15	2.696E+19
70	60,000	565,973	30	2940	15	3.145E+19
80	60,000	565,973	30	2940	15	3.594E+19
90	60,000	565,973	30	2940	15	4.043E+19
100	60,000	565,973	30	2940	15	4.493E+19

Table 2. Observed annual number of earthquakes, obtained from the United States Geological Survey, Earthquakes Facts and Statistics/Earthquake Archive Search. The energy radiated is calculated by Log (Es)=4.8+1.5 Ms, where Es is the seismic energy in Joules and Ms is the magnitude of the earthquake.

Earthquake Magnitude Limits	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	Avera-ge	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	1.3	6.31E+16	1.12E+19	7.18E+18
7.0 to 7.9	14	15	13	14	14	10	9	14	12	16	23	14.0	2.00E+15	4.47E+16	3.27E+17
6.0 to 6.9	146	121	127	140	141	140	142	178	168	144	151	145.3	6.31E+13	1.41E+15	1.07E+17
5.0 to 5.9	1,344	1,224	1,201	1,203	1,515	1,693	1,712	2,074	1,768	1,896	2,200	1,620.9	2.00E+12	4.47E+13	3.78E+16
4.0 to 4.9	8,008	7,991	8,541	8,462	10,888	13,917	12,838	12,078	12,291	6,805	10,164	10,180.3	6.31E+10	1.41E+12	7.51E+15
3.0 to 3.9	4,827	6,266	7,068	7,624	7,932	9,191	9,990	9,889	11,735	2,905	4,341	7,433.5	2.00E+09	4.47E+10	1.73E+14
2.0 to 2.9	3,765	4,164	6,419	7,727	6,316	4,636	4,027	3,597	3,860	3,014	4,626	4,741.0	6.31E+07	1.41E+09	3.50E+12
1.0 to 1.9	1,026	944	1,137	2,506	1,344	26	18	42	21	26	39	648.1	2.00E+06	4.47E+07	1.51E+10
0.1 to 0.9	5	1	10	134	103	0	2	2	0	1	0	23.5	8.91E+04	1.41E+06	1.76E+07
Total															7.66E+18

Table 3. Suggested trend of the energy of geological activities with surface temperature rise. The baseline year is 1750 at which year surface temperature rise is zero and trend of geological activities is zero. Average height of midocean ridges is 3 000 meters for this baseline year. The source of surface temperature trend is the average of the scenarios as projected by the Intergovernmental Panel on Climate Change, Climate Change 2013: The Fifth Assessment Report, AR5, Fig. SPM.4 (b).

Description/Year ending Basline year is 1750, Tc for 1750 is equal to 913.7 ^{0}K	2010	2020	2030	2040	2050	2060	2070	2080	2090	2100
Surface temperature rise, ^{0}C	0.55	0.60	0.65	0.80	1.00	1.20	1.41	1.63	1.88	2.18
Temperature of the cold reservoir, Tc, ^{0}K	914.25	914.30	914.35	914.50	914.70	914.90	915.11	915.33	915.58	915.88
Annual energy trend, J	9.66E+16	1.05E+17	1.14E+17	1.41E+17	1.76E+17	2.11E+17	2.48E+17	2.87E+17	3.31E+17	3.84E+17
Observed increase of the annual average, J		***3.00E+17***								
Annual average spreading of ocean floor, cm/yr	4.000	4.008	4.008	4.010	4.013	4.015	4.018	4.020	4.024	4.027
Average rise of midocean ridges, m	1.72	1.88	2.03	2.50	3.13	3.76	4.42	5.11	5.90	6.85
Annual rise of midocean ridges, mm/yr	6.6	15.7	15.7	47.0	62.8	62.8	66.0	69.2	78.8	94.6
Observed annual rise of midocean ridges, mm/yr	***5 -20***	***15 -20***								

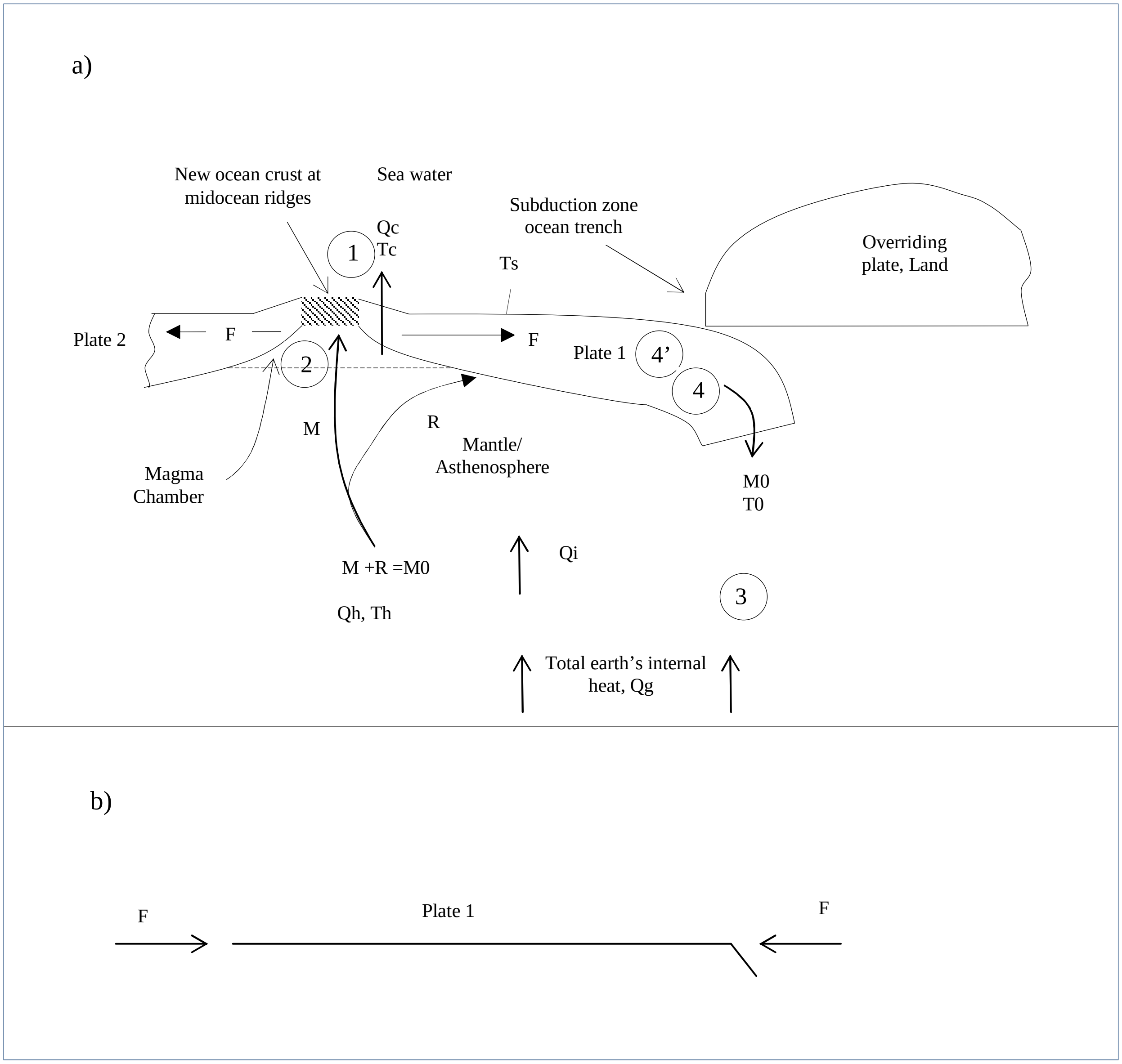

Fig. 1. (a) A schematic of sea floor spreading at midocean ridges and a subduction zone, not to scale, based on Floyd (1991, p. 31 and 127). (b**)** a free body diagram of the oceanic plate 1. The plate is subjected to a large force of compression, F.

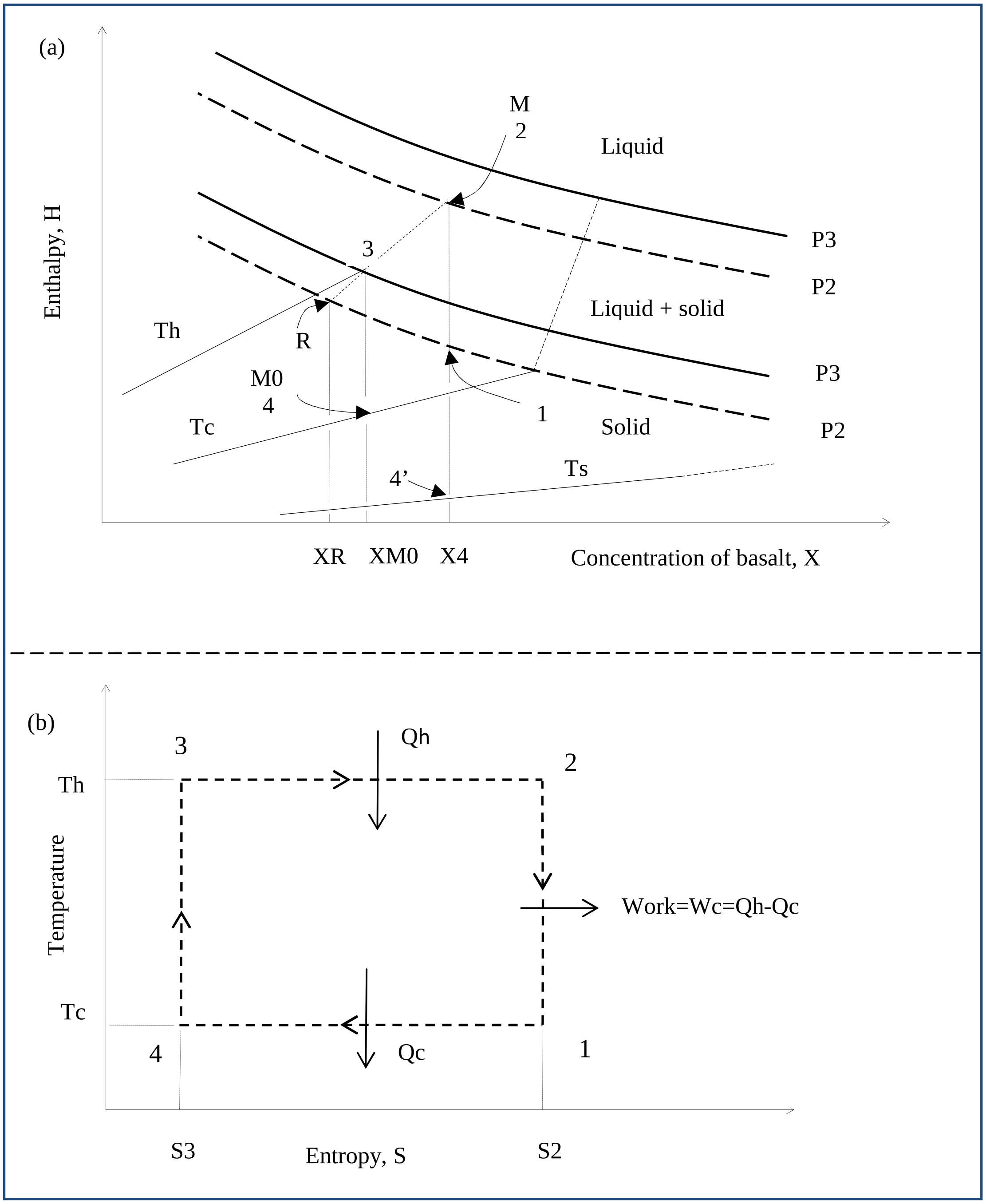

Fig. 2. (a) A schematic representation of the tectonic thermodynamic cycle on the enthalpy-concentration diagram and (b) on the temperature-entropy diagram. Details are explained in Sect. 4.

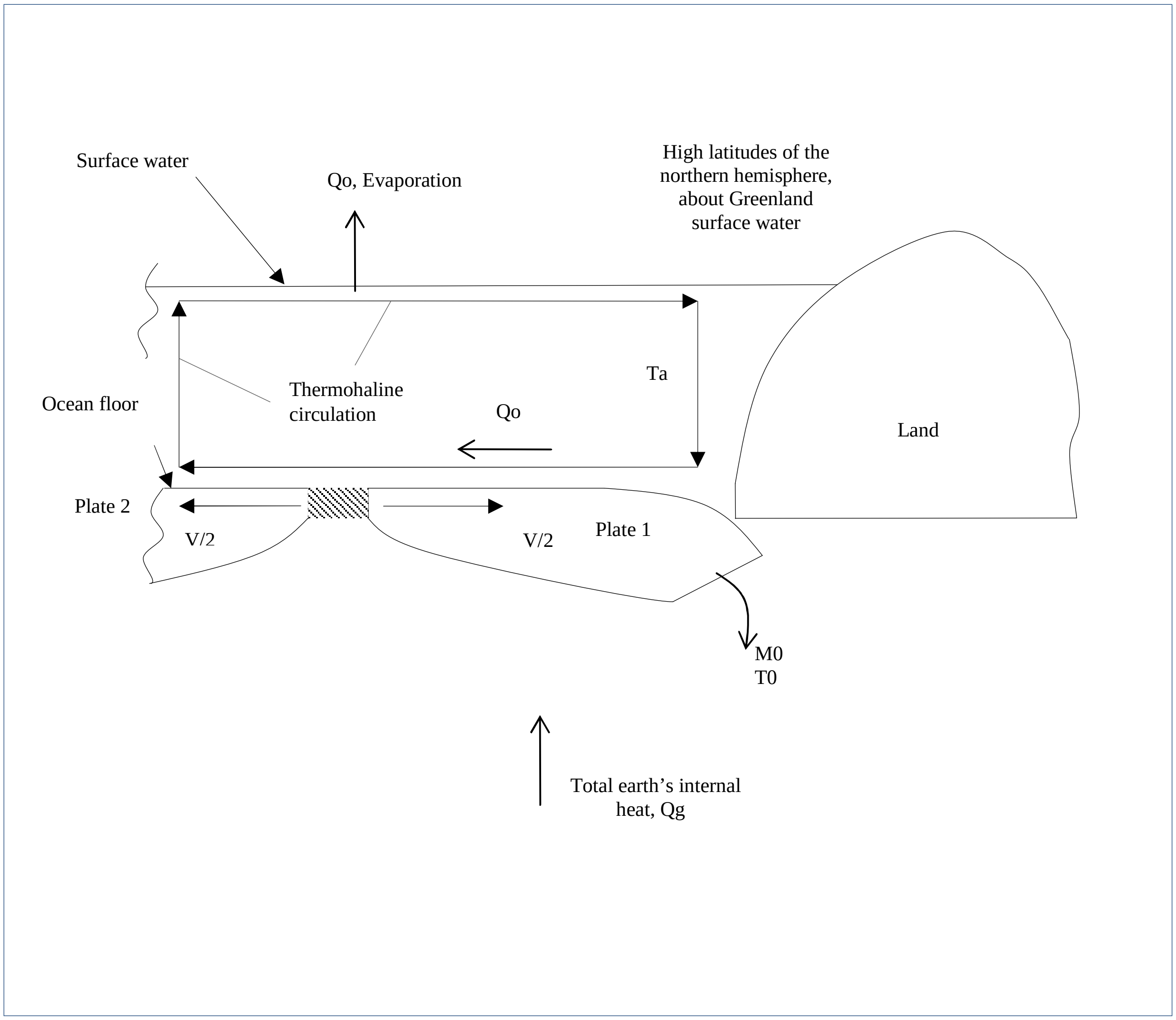

Fig. 3. A schematic cross section North-South of land and ocean, not to scale. The thermohaline circulation links surface water temperature with the temperature of ocean floor. The temperature of ocean floor is equal to surface water temperature of the high latitudes of the northern hemisphere. The circulation brings the earth's internal heat exchanged with sea water, Qo, to surface where it is evaporated.

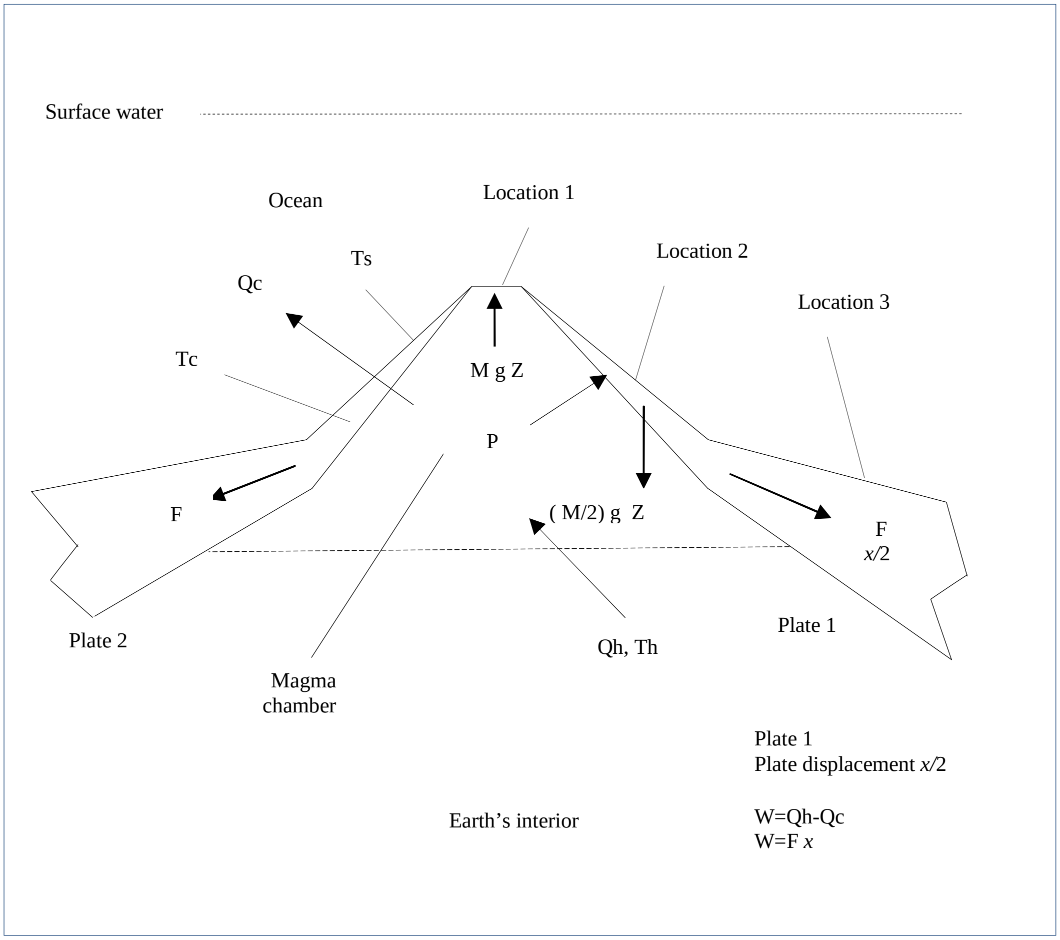

Fig. 4. A schematic of midocean ridges as tectonic engine chambers based on P. A. Floyd (1991 p. 31 and 127), not to scale. Midocean ridges enclose engine chambers that convert mantle heat, Qh, to work. Pressure is produced following mantle partial melting underneath the ridges, which raises the ridges that act as pistons of engine chambers. The mature plate at location 3, conveys the work produced, W, to oceanic trenches, Fig. 1 and Fig. 5, where the work is released as seismic and volcanic activities.

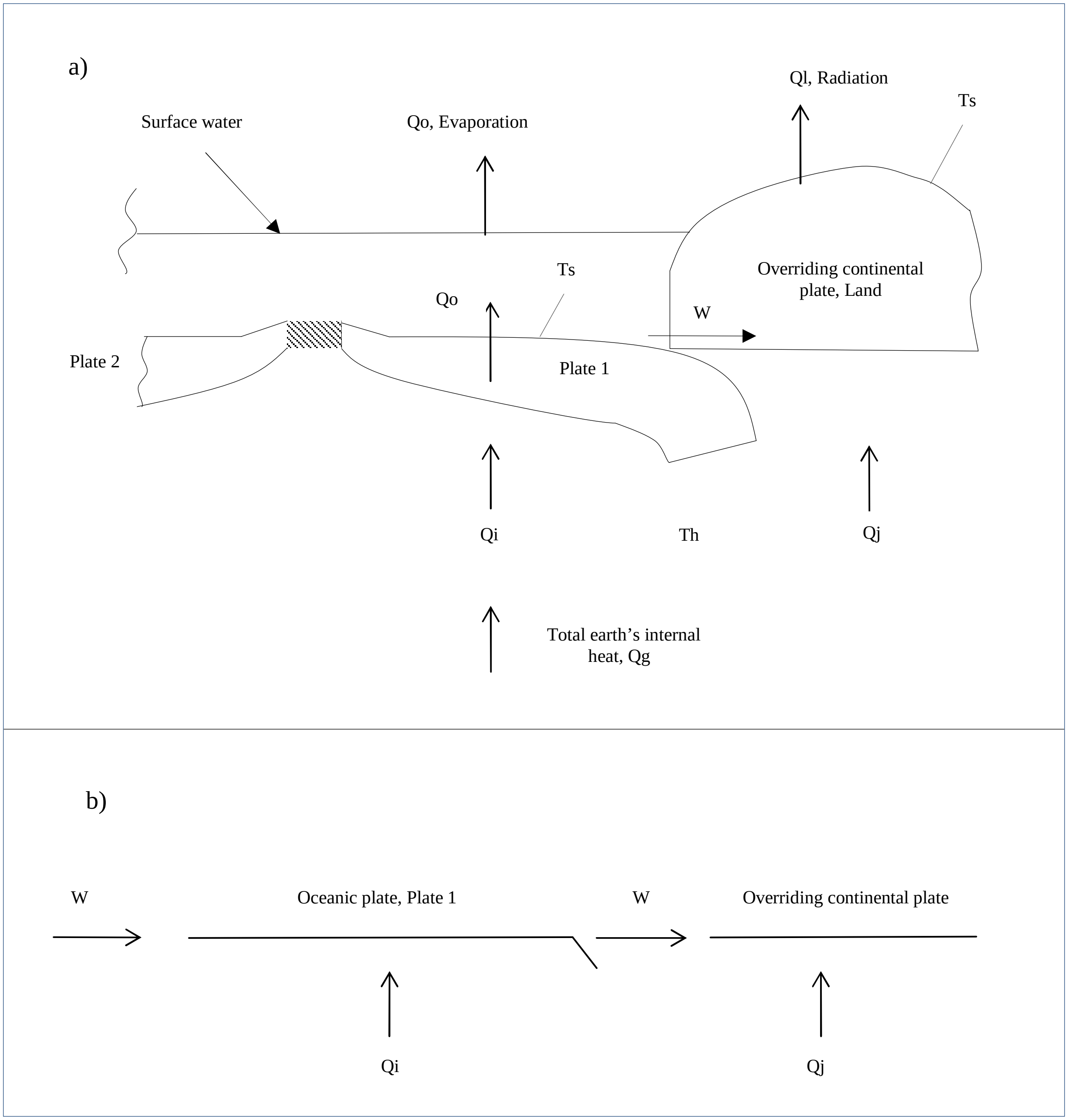

Fig. 5. A schematic of oceanic plates 1 and 2, continental plate, and distribution of the earth's internal heat. Symbols are defined under Sect. 5.

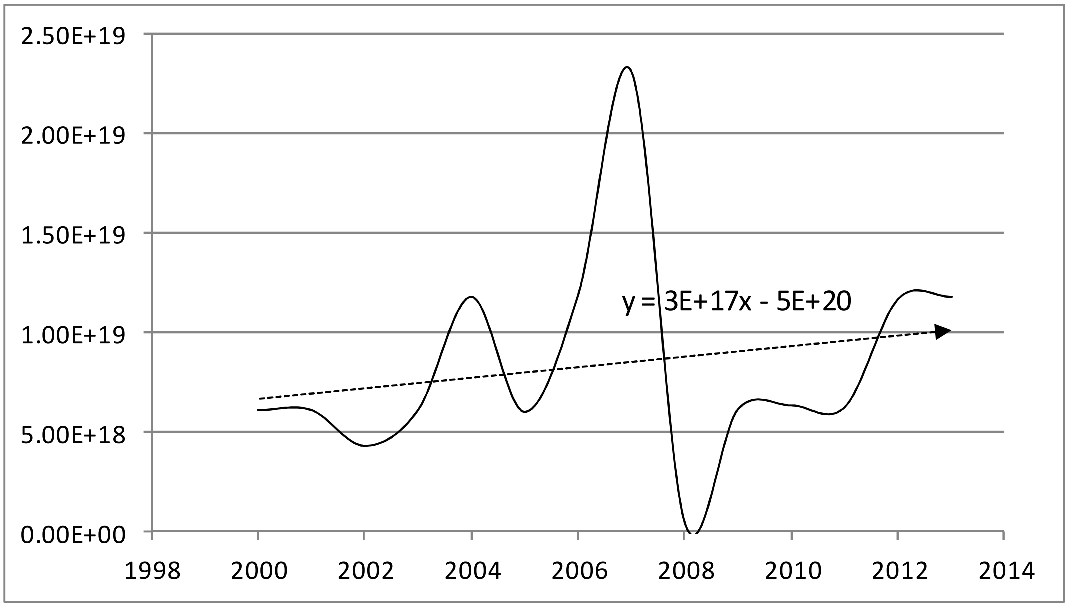

Fig. 6. Observed trend of the annual energy radiated by earthquakes between the years 2000 and 2013 in Joules. Source: United States Geological Survey, Earthquakes Facts and Statistics/Earthquake Archive Search. The annual increase is 3.0×10^{17} Joules.