Methane Gas Refilling Fault Theory for Cause and Mechanism of Tectonic Earthquakes

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Key Points:

- Infilling of gas into traps of geological fault makes the fault active
- Infilling of gas into traps takes time for the preparation of tectonic earthquakes, different locations have different preparation durations or the reoccurance periods
- Sudden rupture of geological faults by its internal gas of high pressure and escaping and migration of the gas along faults cause tectonic earthquakes of various phenomena including seismic waves, ground ruptures, land subsidence, landslides, and tsunami.
- Geological fault with high tectonic compressive stresses makes the gas pressure high, which cause large earthquakes, such as the subduction zone along the Pacific Rim.

Abstract:

A methane gas infilling fault theory is presented to refine and upgrade the conventional earthquake theory of elastic rebound of active geological faults. It adds the infilling of highly compressed methane gas mass into the deep geological fault zones. Such gas infilling makes the fault active and accumulate the elastic energy. With time, the gas in the fault traps has more and more mass and high and high pressure. The gas pressure can rupture the trap along the geological fault and release some gas mass to migrate along the fault, which causes tectonic earthquakes. The theory shows that the earth-quaking process is a cooling process because of gas expansion. The earthquake magnitude estimated from the seismic waves can have a quantitative relationship with the gas volume from the trap is quantified. The theory can explains mega earthquakes along subducton zones.

Key Words:

Tectonic earthquake, tectonic stress, geological fault, methane gas, infilling, earthquake energy

Plain Language Summary:

The conventional elastic rebound theory of the cause of tectonic earthquakes was developed 100 years ago from the observation of co-seismic surface ruptures and topographical deformation induced by the 1906 California Earthquake. It assumes that the sudden brittle rupture of an active geological fault rock mass is the cause of tectonic earthquakes. The applications of this theory to the prediction of next damaging earthquakes, however, have been unsuccessful. This paper presents a gas infilling fault theory for the cause of tectonic earthquakes. It adds a methane gas mass of high pressure in the traps of geological fault rock mass. The gas makes the geological fault active and rupture and then cause the tectonic earthquakes. Hence, the occurrence of earthquake is the rupturing, expansion and migration of a certain amount of highly compressed methane gas along geological rock faults. The process is an adiabatic process and confined and constrained by the down-ward gravity, in-situ tectonic stresses and the rigidness and strengths of the surrounding rock mass. It is also a cooling process due to gas absorbing heat during expansion and migration. The higher confining tectonic stress can result in the higher trap gas pressure, which causes the higher magnitudes of earthquakes.

1 Introduction

The conventional elastic rebound theory of the cause of tectonic earthquakes has been widely accepted, believed and utilized for the last 100 years. It was developed 100 years ago from the observation of co-seismic surface ruptures and topographical deformation induced by the 1906 California Earthquake (Lawson 1908; Reid 1910). It assumes that the sudden brittle rupture of an active geological fault is the cause of tectonic earthquakes. It has been an essential component of the modern plate tectonic theory of the Earth. The applications of this theory to the prediction of next damaging earthquakes, however, have been unsuccessful (Chen and Wang 2010; Hough 2010).

This paper attempts to present a gas infilling fault theory for the cause of tectonic earthquakes. This gas-fault theory was proposed by the author in 2008 after his investigation of the Wenchuan earthquake of May 12, 2008 (Wu et al. 2009; Yue 2009, 2010, 2013a, 2013b, 2014). It adds a methane gas mass of high pressure in the traps of geological fault zones. These traps can be the apertures, gaps and/or caverns along geological fault zones. The gas makes the geological fault active and rupture and then cause the tectonic earthquakes. It can consistently explain many and different phenomena that observed before, during and after earthquakes.

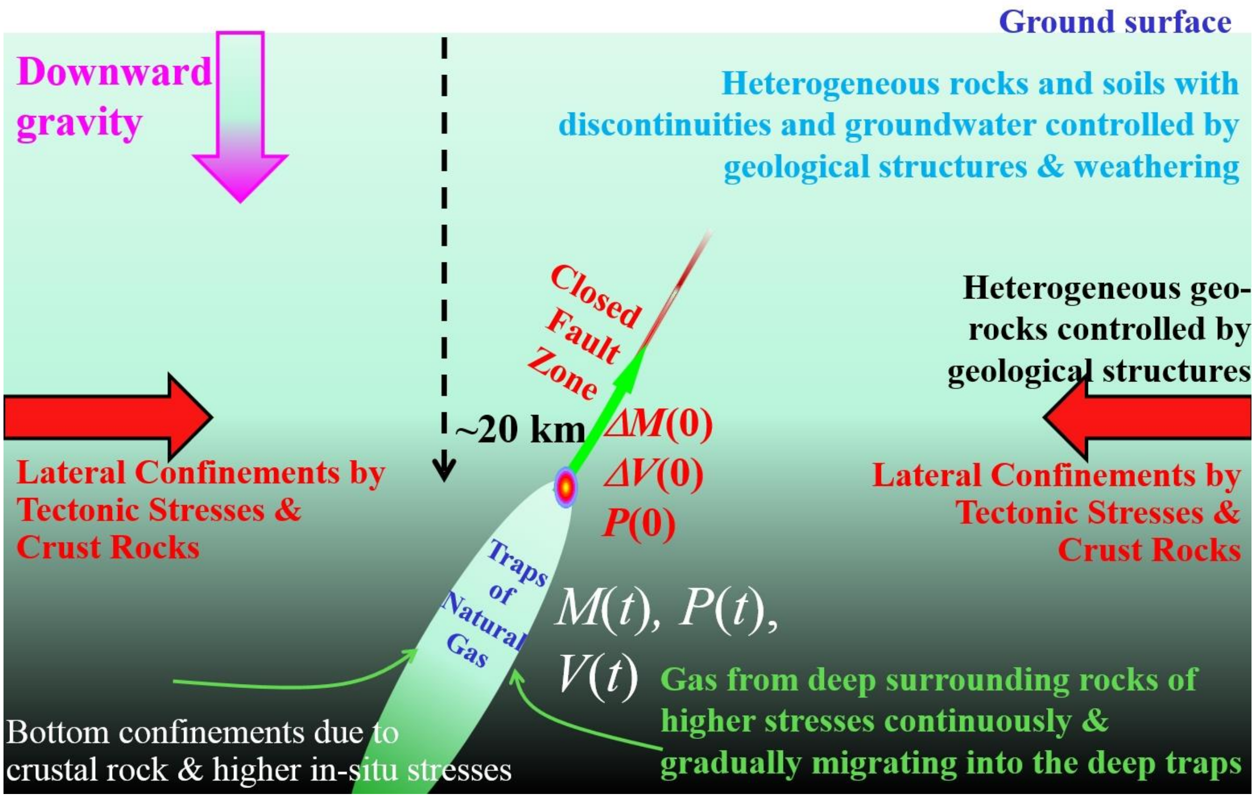

Figure 1: Model of methane gas infilling into deep geological faults for preparation and initiation of tectonic earthquakes

The outline of this paper is given as follows. At first, the preparation of tectonic earthquakes by infilling and accumulation of methane gas into the geological faults is discussed. Secondly, the process of tectonic earthquakes is described using the seismic waves and interpreted using the gas expansion and migration along the fault zones. In particular, the earth-quaking process is a cooling process due to gas expansion. Thirdly, the energy released by tectonic earthquakes is examined using the possible types of energy in the deep ground. In particular, the relationship between the seismic earthquake magnitude and the escaped gas volume from the trap is quantified. Fourthly, the gas infilling fault theory is applied to explaining and understanding the mega earthquakes along the subducton zones.

2 Preparation of Tectonic Earthquakes

2.1 Infilling of gas into traps along geological fault model

Figure 1 shows the infilling of methane gas into the deep geological fault model for preparing the tectonic earthquakes. A gas trap can be formed along a deep crustal and geological fault. Both the fault and its surrounding rocks are compressed by the lateral tectonic stresses and the vertical gravity force. The gas mass $M(t)$ in the fault trap is confined and compressed by surrounding rocks. The gas comes from deep crust and/or mantle. Because of its higher pressure, the gas mass from the deep can penetrate, migrate into and accumulate in the trap. Because of the confinements of surrounding rocks and the compression of the tectonic stresses, the volume $V(t)$ of the gas mass in the trap chamber cannot be increased much by the infilling of the gas mass with higher pressure. So, both the gas pressure $P(t)$ and the gas mass $M(t)$ in the trap chamber can increase to high levels as the gas mass from the deep is infilling into the trap with time.

2.2 Source of methane gas in the deep of the Earth

The core and mantle materials have huge amount of materials of extremely high temperature and pressure. In particular, the outer core materials are in the state of liquid. They would experience chemical reactions and their chemical reactions would produce new materials in the state of gas. According to the second law of thermodynamics, the gas, as a fine, lighter and deformable material, would migrate outward (in opposite to the inward gravity direction to the Earth center). As it migrates outward or upward, the gas would encounter lower and lower surrounding pressure. It would expand and absorb heat from surrounding core/mantle materials. It can be accumulated and trapped in some weak zones and/or apertures of deep geological faults and form gas traps there. As it is in high compression state, the upper portion of fault rocks can be impermeable and forms solid walls or covers to seal the gas in the traps.

The gas in the trap causing earthquakes is mainly methane (CH_4) gas, which is found on the basis of the following facts and arguments. The shallow crust rock mass contains a huge amount of nearly pure methane gas only in many gas field reservoirs. The methane gas can be produced in liquid outer core and accumulated quickly in the voids, cavities and traps of rock mass, which is consistent with the fact that hundreds and thousands earthquakes with their focal depths up to 700 km below the ground surface occur each year. Methane gas is colorless, odorless and lighter than air, which is consistent with the fact that it was not noticed by people during earthquake. Methane gas is not toxic, which is consistent with the fact that people are not injuries by toxic gas at epicenter areas. Methane gas escaped from deep rock ground can carry electric ions, which is consistent with the fact that colored lightening can be observed during earthquakes. Methane gas (5–15%) and air mixture can be self-explosive, which is consistent with the fact that explosions and fires can be observed during earthquakes. Methane gas has much higher specific heat capacity than air, which is consistent with the fact that the air temperature can decrease immediately after earthquakes. Methane gas is lighter than air and can react with oxygen for water, which is consistent with the fact that several hours after earthquakes, heavy rainfall or snow can occur at epicenter areas.

2.3 Global stress and local stress fields along faults

Two stress fields can be developed in the fault rocks as the infilling of deep gas mass into the traps continues. The first stress field is the global stress-strain field due to the downward gravity and the tectonic stresses. In general, the global stress field is a compressive stress field and has either little or slight change with time. The second stress field is the local stress field in the surrounding rocks. It is induced by the internal expansion loading of the compressed gas mass in the fault trap. It can be changed greatly with time as long as more and more gas mass $M(t)$ can be infilled into the fault trap. Due to the rock confinement of the trap chamber, the gas volume $V(t)$ in the chamber can be increased slightly only with time. Hence the gas pressure $P(t)$ can be increased significantly as the gas mass $M(t)$ increases with time. The second stress field is a tensile stress field in the surrounding rocks. It can decrease quickly as the rock distance to the gas trap. Its decrease rate is inversely proportional to the square of the distance. Hence, its change with time usually cannot be observed, measured and noticed by people on the ground surface.

2.4 Duration of gas infilling for preparation

The infilling of methane gas into traps along geological faults for the preparation of outburst or tectonic earthquakes is quite and takes years. The duration of the gas infilling time is different at different geological regions and fault zones of the Earth. The duration is dependent on the infilling rate of deep gas mass into the fault trap and the pressure of the global stress field applied to the fault zone. The duration at a geological fault zone or region can be equal to reoccurrence period of earthquakes at this zone or region. For geological regions or fault zones with short reoccurrence periods of great earthquake, their infilling rates must be high. Such regions include the ring of fires along the Pacific Ocean and its subduction fault zones.

3 Process of Tectonic Earthquakes

3.1 Seismic waves

The process of tectonic earthquakes can be understood from seismic waves. Seismic waves produced by tectonic earthquakes have been well recorded and examined with seismograph (Aki and Richards 2002). Four types of seismic waves have been recognized in a seismogram output by seismograph for more than 100 years. They are the primary waves (P-waves), the secondary waves (S-wave), the Rayleigh waves (R-waves) and the Love waves (L-waves). The P-waves are compressional waves and longitudinal in nature. The S-waves are shear waves and transverse in nature. They are the body waves traveling in the interior of the Earth. The R-waves and the L-waves are the surface waves and travel along the ground surface of the Earth. The cause and mechanism of these four seismic waves can be interpreted and explained with the gas-fault theory as follows.

3.2 Initial rupturing of the geological fault by internal gas

As shown in Figure 1, the initial rupturing at the focus of an earthquake can be understood by the rupturing of the fault rocks at the upper portion of the gas trap. The global and local stress fields form the combined stress field in the crustal rocks. Because the gas pressure $P(t)$ in the trap can increase monotonically with time, it can eventually make the trap upper rock faults closely compressed and tightened by the global pressure and rock rigidity experience sudden and brittle shear and/or tensile failure according to the Mohr-Coulomb failure criterion, tensile failure criterion or Griffith crack failure criteria. This rupturing can generate the initial seismic waves that is recorded by a seismograph.

When the rupture suddenly occurs in the geological fault, a train of certain amount of highly compressed gas mass $\Delta M(0)$ can quickly escape the gas trap and rapidly migrate into the upper and lateral fault where the compressive stresses and rock resistance are lower. Subsequently, an earth shocking happens. The mass $\Delta M(0)$ and volume $\Delta V(0)$ and pressure $P(0)$ of the dense gas escaped from the gas trap determine the magnitude and duration of the earthquake. On the other hand, the reduction of the gas mass and pressure in the trap can induce the surrounding rock to immediately deform and subside due to the almost constant loading of the gravity and tectonics stresses (i.e., the global stress field) at the far field, which can re-tighten and re-seal the newly fractured trap zone and keep the remaining gas mass in the gas trap for aftershocks and future earthquakes. These change can cause a tectonic stress drop $\Delta\sigma$ in the global stress field. The stress drop is usually about 2 to 6 MPa and can equal to the tensile strength of hard rock specimens in laboratory without any confinements and constraints. Hence, the tectonic stress drop can also equal to the drop of the gas pressure $\Delta P(0)$ in the gas trap due to the escape of the gas mass $\Delta M(0)$. Then, the local stress field would be extremely dynamic and variation during the escaping and migrating and shaking of the dense gas from the trap. It then would quickly return to quasi-static for the preparation of next earthquake. The global stress field would experience some limited changes correspondingly.

3.3 Migrating and flowing of highly compressed gas from deep to shallow depth

After the initial rupturing and the escaping of the gas mass $\Delta M(0)$ from the trap, the subsequent process of a tectonic earthquake can be described using the mechanism of rapid migration and flow of the highly compressed gas mass along the faults as shown in Figure 2. As shown in Figure 2, after the gas ruptures the weak rock zone of its trap, its part would quickly escape and release the trap and forcefully seep and migrate upward and laterally along the geological fault or discontinuous weak zones. The high pressure difference between the compressed gas and its front opening tip in the fault or rock mass that is being fractured makes the gas migration speed very high. The flow speed of the gas train can be 1 to 3 km/second and/or close to the rock cracking speed in linear elastic fracture mechanics.

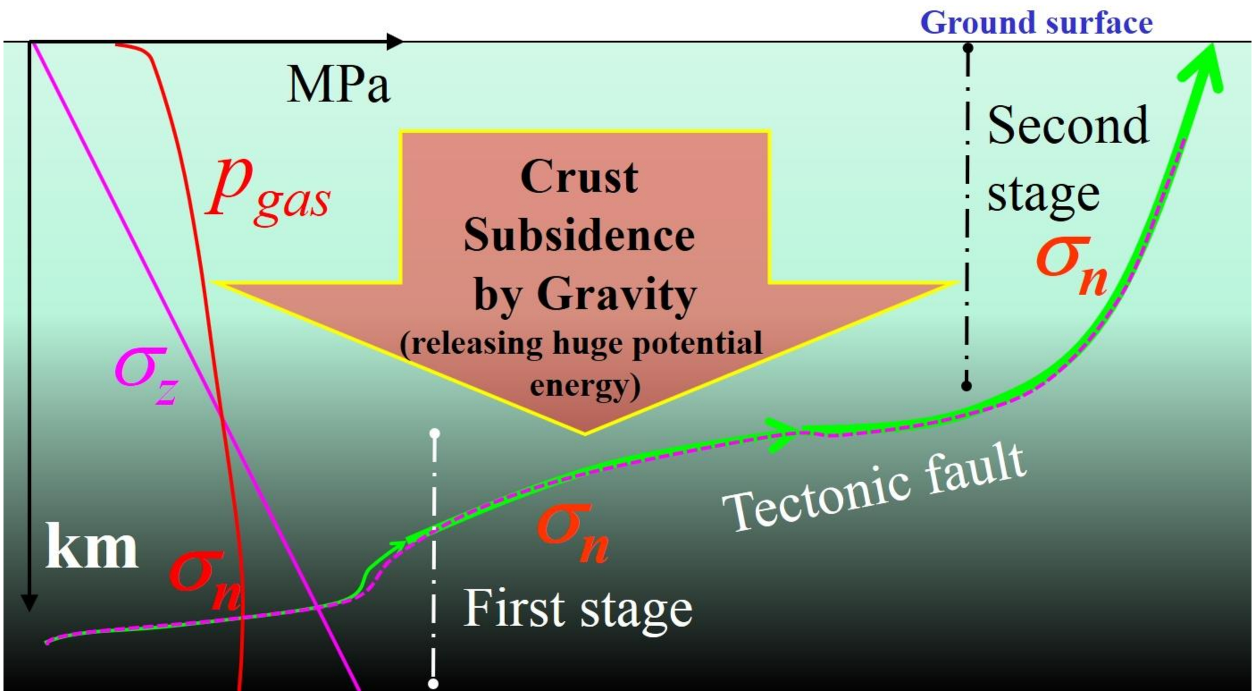

Figure 2: Lateral and upward migrating and flowing of highly compressed gas along geological fault for occurrence of seismic waves

Simultaneously, the dense gas would expand and its pressure would reduce according to the surround tectonic stresses. Such gas expansion and pressure reduction are confined by the deformation and compressive stresses of the rocks surrounding the fault that is being fractured. The following equation of idealized gas theory may be applicable to the relationship between the volume $\Delta V_{gas}(x, y, z, t)$ and pressure $p_{gas}(x, y, z, t)$ of the escaped gas mass at the time t and the location (x, y, z).

$$\Delta V_{gas}(x, y, z, t) = \left(\frac{P(0)}{p_{gas}(x, y, z, t)} \right)^{1/\kappa} \Delta V(0) \tag{1}$$

where κ is the gas specific heat ratio and depends on temperature.

The confinement of the surrounding rock mass can be divided into two stages with respect to the crustal rock depth since the surrounding tectonic and gravity stresses reduce linearly and the crustal rocks change from hard and rigid to weaker and/or softer as the rock depth decreases.

3.4 Two stages of migrating and flowing from deep to shallow

The first stage is the gas fracturing and flowing from deep traps to shallow ground, which is represented sometimes with earthquake sounding of frequency 12-20,000 Hz and small amplitudes of the seismic body waves before the arrival of the surface waves with large amplitudes. During the first stage at deep depth, the gas pressure can be greater than the minimum principal compressive stress but less than the maximum compressive stresses of the global confining stress field in the fault rocks. The gas would mainly rupture and fly upward and laterally along fault weak zones. The rapid upward and lateral moving gas mass is under the lateral confinements and control of tectonic stresses, crust fault rocks and gravity. When the compressed gas mass is rapidly fracturing, shearing and migrating in the lower to middle crust (about below 7 km deep), its volume expansion and pressure reduction are also controlled by the small elastic deformation and higher compressive stresses of the strong crustal rocks. The changes are small and slow. The mechanical and kinetic interaction between the gas and the rock is forcefully vibrating, has very high frequencies but small amplitude. Such strong interaction between the fast moving and expanding dense gas and the hard fault rocks would generate the initial minor ground motion (i.e., the initial seismic body waves in the seismographs) and rumbling earthquake sounds that were heard by people immediately before they felt ground shocking.

The second stage is the gas expanding and uplifting in shallow ground, which is represented by no earthquake sounding, people's feeling of ground motion and the presence of the seismic S-waves, R-waves and L-waves. During the second stage at the shallow depth, the gas pressure, although it is decreasing, can be much greater than all the three principal compressive stresses of the global stress field in the fault rocks. Its penetration and expansion power would become larger and larger. Quickly, the gas mass of higher pressure cannot be tightly confined and constrained by the tectonic stresses and surrounding geo-materials. The gas expansion is becoming the dominant and controlling power in the weak/soft fault rocks and soils at the shallow depth. The gas would forcefully penetrate, uplift, dislocate, gasify, liquefy, shake and wave the upper fault weak rocks and soils. Because it can expand substantially, the powerful dense gas largely expands, moves, deforms and displaces the rocks and soils over much wider ground areas along the entire fault, which shows up as the strong seismic waves of the S-waves, Love and Rayleigh waves after the initial body waves in the seismograms.

3.5 Escaping of highly compressed gas from ground into sky and/or water

Eventually, the gas mass would emit and/or erupt out of ground rock mass and soils into the sky, and/or enter into the voids, caverns and reservoirs of rock and soils at the shallow grounds, which is represented by the rapid finishing and vanishing of the strong ground movement, shaking and deformation and disappearing of the four seismic waves in the seismograms. At the location of the gas emitting and erupting out of the ground, its ground would have heavily damages. These damages include co-seismic ground ruptures in soil grounds, rock avalanches and rock landslides in rock mass hillsides and mountainous slopes, and collapses of buildings and bridges. Furthermore, the sky at epicenters can suddenly become dust and dark during and immediately after ground shaking. The air temperature at epicenters can cool down quickly and substantially during and after ground shocking. Heavy rainfall and snow can happen in the epicenter zones few hours after earthquake. If the gas mass erupts in deep seabed and deep lake/reservoir beds, its pushing and expanding power can make large movement of water and induce tsunami in the sea and reservoirs.

Sometimes, the gas mass can completely trapped in shallow voids, cavities and gas field reservoirs due to some special geological formations and structures. The gas mass cannot reach to the ground surfaces and enter into the water and sky, which is represented by almost no appearance of co-seismic ground ruptures, no collapses and heavy damages of mountainous rock mass, buildings and bridges.

3.6 Aftershocks and foreshocks

The continued escaping and flowing and expanding of the highly compressed gas masses in various existing or new gas traps induce numerous aftershocks. With time, the aftershocks become less and less, which shows the gases in various reservoirs gains compatible and equilibrium with trap strengths and the confining tectonic stresses. In the meantime, the fault traps re-collect and re-accumulate new gas masses from deep and surrounding rocks. Therefore, it takes time to rebuild fault gas mass and pressure to the level of trap rock rupture, which is consistent with great earthquakes of long recurrence intervals. In general the well established equilibrium of the compressed fault rocks and the compressed gas in the traps can reduce the occurrence of foreshocks. The localized occurrences of a few small foreshocks sometimes can or cannot change the equilibrium. Some substantial changes can trigger the main shock and the main shock can induce many aftershocks. Other minor changes can trigger many small shocks but cannot trigger a big main shock.

3.7 Cooling process of tectonic earthquakes

The process of the expansion and migration of the highly compressed gas mass in the ground or into the sky is rapid and can be completed within few to hundred seconds. This process must be an adiabatic process. Such rapid expansion of the gas can cool down its temperature. Using the idealized gas theory, the temperature $T_{gas}(x,y,z,t)$ of the escaped gas mass at the time t and the location (x, y, z) can be estimated using the following equations with its initial temperature $T(0)$ in the gas trap.

$$T_{gas}(x,y,z,t) = \frac{p_{gas}^{1-1/\kappa}(x,y,z,t)}{P^{1-1/\kappa}(0)} T(0) \tag{2}$$

The drop down of the gas temperature has to make the gas mass absorb heat from the surrounding rocks and soils and the atmosphere, which can reduce the temperature of the surrounding rocks and soils and the temperature and cool them accordingly. Hence, the process of the tectonic earthquake is a cooling process. This cooling process of this gas-fault theory of tectonic earthquakes is an exact opposite nature to the heating process associated with the conventional elastic rebound theory of tectonic earthquakes. The conventional theory adopts the active frictional slip, dislocation and rupture of geological fault rocks under compressive tectonic stresses, which must induce a huge amount of heat during the frictional movements of the fault rocks (Heid 1910, Rice 2006).

4 Energy of Tectonic Earthquakes

4.1 Nature of the earthquake energy

An earthquake can suddenly release a large to extremely large amount of energy in the Earth's crust and near ground surface. The energy released by earthquake is in the form of kinetic energy. The kinetic energy can suddenly go outburst and rapidly release and vanish in the Earth's crust within a few seconds to a few tens seconds over an extremely large area. It can generate seismic waves globally, and induce ground rock/soil displacement and damage over a narrow area of tens to hundreds kilometers long and few to tens kilometers wide. Its preparation of such sudden releasing, however, cannot be observed and noticed by human beings and various instruments on the ground before its out-bursting.

4.2 Sources of earthquake energy

What is the source of the released kinetic energy? This is one of the most important and basic questions and has been asked, addressed and examined over the past more than 100 years. Some possible sources include

(a) elastic stress-strain energy of the deformed fault rocks under tectonic stresses loading,

(b) potential energy of rock mass due to gravity,

(c) volumetric expansion energy of compressed gas and

(d) energy due to nuclear or chemical reactions or phase changes of geomaterials.

The elastic rebound theory adopts the elastic stress-strain energy of the deformed fault rocks as the earthquake energy (Reid 2010). The source of the earthquake energy released during Wenchuan Earthquake mainly was the volumetric expansion energy of highly compressed methane gas mass escaped from deep fault traps. The sudden escaping of the gas mass $\Delta M(0)$ from the deep fault trap (or cavity or chamber) would reduce the bearing capacity and support of the upper crustal rocks above the gas trap. As shown in Figure 2, the upper crustal rocks can experience subsidence of up to centimeters to meters, which can induce the release of a large to huge amount of gravitational potential energy of the upper rock mass. The release of the elastic stress-strain energy of the crustal rock mass can be very limited and cannot be concentrated over some local areas since the change of the global stress field is very limited and over a large volume of the rocks.

4.3 Relationship between escaped gas mass and earthquake magnitude

The earthquake energy can be estimated using the seismic waves recorded with the seismograph and has been co-related to the magnitude of earthquake with specific equations (Bormann 2012). The volumetric expansion energy *W* of the highly compressed methane gas escaped from the trap can be expressed as follows using the ideal gas theory.

$$W = \frac{P(0)}{\kappa - 1}\left[1 - \left(\frac{p_a}{P(0)}\right)^{1-1/\kappa}\right]\Delta V(0) \qquad (3)$$

where p_a is the atmospheric pressure.

It can be assume that the seismic energy estimated by the seismic waves is equal to the volumetric expansion energy of the highly compressed methane gas. This assumption leads $\Delta V(0)$ to the relationship between the earthquake magnitude (M_s) and the escaped volume $\Delta V(0)$ of the highly compressed methane. In particular, for the 2008 Wenchuan earthquake of

Ms 8.0 or 7.9, the $\Delta V(0)$ is about 0.5 km^3 to 0.1 km^3, the $\Delta M(0)$ is about 100×10^9 to 500×10^9 kg, and $P(0) = 300$ MPa.

5 Mega Earthquakes along Subduction Faults

This section attempts to apply the gas infilling fault theory to interpret and explain the frequent occurrence of great earthquakes at subduction faults with short recurrence periods. The subduction faults between the continental and oceanic rock crusts can have traps for collection and accumulation of methane gas generated in the deep (liquid outer core) materials. The mass $M(t)$, volume $V(t)$, pressure $P(t)$ and temperature $T(t)$ of the gas in the traps can change and increase because of the high confining compressive tectonic stresses and the low permeability of the continental and oceanic rocks. The extremely high compressive tectonic stresses can make the $M(t)$, $V(t)$ and $P(t)$ become extremely high too, which can induce the great earthquakes.

5.1 Extremely low apparent friction coefficient in subduction faults

The frequent occurrences of many great damaging earthquakes at subduction faults in last decade allowed us to have acquired massive observational data and greatly improved our understanding about subduction zone process. In the Birch Lecture of the 2015 AGU Fall Meeting, Wang (2015) presented his finding that all subduction faults are extremely weak and the faults that produced giant earthquakes are the weakest and the smoothest. The fault weakness can be represented with apparent friction coefficient μ' lower than 0.05 in Byerlee's law (Byerlee 1979) and/or the Mohr-Coulomb shear strength criterion as follow,

$$\tau = \mu' \sigma_n \tag{4}$$

where τ is the fault shear strength and σ_n is the normal compressive stress acting on the subduction faults.

Using the effective stress principle (Yue et al. 1994), the Byerlee's law at the fault zone can be expressed by the following equation with the actual frictional coefficient μ of the fault rocks.

$$\tau = \mu\left[\sigma_n - P(t)\right] \tag{5}$$

Using the equations [4] and [5], we can have $P(t) = (1 - \mu' / \mu)\sigma_n$. At the critical moment of the fault rupturing of great earthquakes, we have $P(0) = (0.90 \sim 0.95)\sigma_n$ since μ usually equals 0.6 to 0.8. If the tectonic compressive normal stress $\sigma_n = 400\,\text{MPa}$, then $P(0) = 360$ to 380 MPa, which is reasonable.

5.2 Movement changes of continental arc crusts after and before great earthquakes

The continental arc crusts generally experience the landward and upward movement or deformation for many years. Immediately after a great earthquake, however, the continental arc crusts can rapidly reverse their movement directions and become downward and seaward movements. With time, the continental arc rocks can gradually stop the settlement and seaward movement and then change to swell upward and move landward. Such reversing change of the crust movement can be explained with the loss of the support of the highly compressed gas in the traps of the subduction fault zones.

The escaping of the gas with the mass ΔM (0) and the volume ΔV (0) out of the gently declined subduction fault zones can reduce the upward and lateral support of the continental arc crust rocks. So, the crust would change its upward and landward movements to the downward and seaward movements. With time, new gas mass from the deep can migrate and accumulate in the traps along subduction faults again. Once the gas mass accumulates enough, the gas pressure in the traps can become high enough and can uplift the continental arc rocks and push them to move landward. Such upward and landward continental deformation can indicate the potential occurrence of the next great earthquakes.

5.3 Infilling rate of methane gas into subduction faults

According to equation (3), the escaped gas mass $\Delta V(0) = 35 \text{ to } 45\,\text{km}^3$ at $P(0) = 300$ MPa for a great M_s 9.0 earthquake. If it needs 100 years to rebuild the highly compressed gas mass of 36.5 km^3 and 300 MPa at a particular subduction zone for next great earthquake, the accumulation rate of the highly compressed gas in the fault traps can be about 1,000,000 m^3 per day. The rebuilding process of gas mass and pressure in the traps along the subduction faults is strongly affected by the chemical reactions and physical conditions of the deep materials, which makes the reoccurrence periods be different at different subduction faults.

5.4 Estimation of gas volume in traps of subduction faults

The rupture-zone average drop of the tectonic stresses by great earthquakes are 2 MPa to 5 MPa. Using this stress drop, the relationship can be obtained between the total gas volume V(0) in the trap and the escaped gas volumeΔV (0) from the trap along the fault zone. It can be expressed by equation [6] below.

$$V(0) = \frac{P(0) - \Delta\sigma}{\Delta\sigma}\Delta V(0) \qquad (6)$$

If P(0) = 300 MPa, we have V(0) = 60ΔV(0) to 150ΔV(0). For 2008 Wenchuan earthquake, ΔV(0) = 0.5 km^3 to 1.0 km^3, its V(0) = 30 km^3 to 150 km^3. For 2011 East Japan earthquake, ΔV(0) = 35 km^3 to 45 km^3, its V(0) = 2100 km^3 to 6750 km^3. Since ΔV(0) is only a few percentage of V(0) in the traps along the faults, the remaining gas mass in the traps can generate many aftershocks over many year until the new equilibrium. This estimation uses the assumption of uniform gas pressure in the trap. This assumption and estimation can be incorrect since the highly compressed gas can have very high density of several hundreds kg/m^3.

6 Conclusions

The occurrence of earthquake is the rupturing, expansion and migration of a certain amount of highly compressed methane gas along geological rock faults. This process is an adiabatic process and confined and constrained by the down-ward gravity, in-situ tectonic stresses and the rigidness and strengths of the surrounding rock mass. It is also a cooling process due to gas absorbing heat during its expansion and migration. The gas is generated in the deep (possibly the liquid outer core) and migrates and accumulates and stores in deep rock traps along the geological fault zones. The gas suddenly expands and ruptures the trap rocks, which leads a small portion of the trapped gas rapidly escapes out of its trap. The high the confining tectonic stress and the high the rigidity the fault rocks, the high the trap gas pressure and the high the earthquake magnitude. This methane gas infilling fault theory for the cause of tectonic earthquakes can explain and link together all the observed phenomena of different tectonic earthquakes at different locations of the Earth. It can further gives new ideas and new methods for prediction, mitigation and reduction of damaging earthquakes. Moreover, it can generate new knowledge and new horizons for the origin, magnitude and accumulation of methane gas mass in the interior of the Earth.

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