On Incorrectness in Elastic Rebound Theory for Cause of Earthquakes

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Abstract The elastic rebound theory was developed 100 years ago from the observations of co-seismic surface ruptures induced by the 1906 California Earthquake. It is only partially correct because it associates earthquakes with geological faults. However, it is inconsistent and even violates many other phenomena that were present before, during and after earthquakes. Numerous failures have been encountered and experienced in the tremendous efforts using the elastic rebound theory in the prediction of earthquakes over the past 100 years. Many current seismo-geologist and seismologists have lost their original goals to predict earthquakes and turned to believe that earthquakes are unpredictable with present techniques. All these problems are due to the fact that the incorrect elastic rebound theory for cause of earthquakes was used in the investigation and prediction of earthquakes. The paper also shows that the energy released during earthquake is not the elastic stress and strain energy accumulated in brittle crustal rock solids during relative movements of tectonic plates. The released energy is the volumetric expansion energy of highly compressed and dense natural gas rapidly escaped from its deep crustal traps via fault channels. This gas hypothesis for the cause of earthquakes would make earthquake predicable in the near future.

Keywords Earthquake, Energy, Fault, Heat, Natural Gas

1. Introduction

Earthquake occurs every day. Seismologists have developed and used seismometers to report the locations and magnitudes of earthquakes within minutes of their occurrence. But, they cannot predict earthquakes. Earthquake prediction is to predict where and when the next damaging earthquake will occur and what will be its magnitude. For last hundred and thousand years, earthquakes have frequently hit us without notice and wreaked terrible disasters and numerous fatalities. In addition, there were many false prediction cases and only a few successful prediction cases. Due to numerous failure cases, seismologists have reached a consensus that the next strong earthquake can NOT be predicted.

For example, Chen and Wang [1] wrote, “Few seismologists believe that it is presently possible or forever impossible to predict an earthquake with the time, location, and size specified accurately enough to guide plans for evacuation. Regardless of its scientific merit and future development, governments of most industrial countries consider earthquake prediction to be presently impractical.” Hough [2] also wrote, “Are earthquake predicable? The title of this book implies an answer and suggests a paradox. We cannot say it will always be the case, but, given the state of earthquake science at the present time, earthquakes are unpredictable.” Therefore, the following issue must be asked and addressed: Why are the next damaging earthquakes unpredictable?

In this paper, the author tries to point out the core reason for this earthquake unpredictability issue. The core reason is the inadequacy of the existing theory in explaining the cause of earthquakes. It is the elastic rebound theory developed one hundred years ago in 1910 [3, 4]. It has been regarded as “one of the most fundamental tenets of earthquake science” [2]. The prediction efforts over the last one hundred years have been based on the incorrect cause theory of tectonic earthquakes. Hence, a majority of their results have been unsatisfactory. Furthermore, the theory of plate tectonics, developed in later 1950s and early 1960s, used this elastic rebound theory as one of the foundations. On the other hand, the plate tectonic theory gives the reasons why and how the elastic stress can be built up in crustal fault rocks for cause of earthquakes associated with the elastic rebound theory [5].

The plate tectonic theory has become the dominant theory for the Earth system in geosciences including seismogeology and seismology. Consequently, the belief and/or consensus that earthquakes are unpredictable have become much widely acceptance in recent 40 years.

In the ensuing, the author will give a brief account of the elastic rebound theory, and then show its incorrectness. At the end, the author will put forward his gas hypothesis to explain the cause of earthquakes [6-10].

2. The Elastic Rebound Theory

2.1. The origin

The 1906 California Earthquake was investigated by the State Earthquake Investigation Commission. The two reports [3, 4] are the first comprehensive and systematical documentations of damage earthquakes in modern science. In particular, co-seismic surface ruptures were frequently observed along the northern segment of San Andreas Fault and evidenced the fault motion of right-lateral strike-slip (horizontal motion), as shown by the red arrows in Figure 1. Accordingly to plate tectonics, this fault forms the tectonic boundary between the Pacific Plate and the North American Plate.

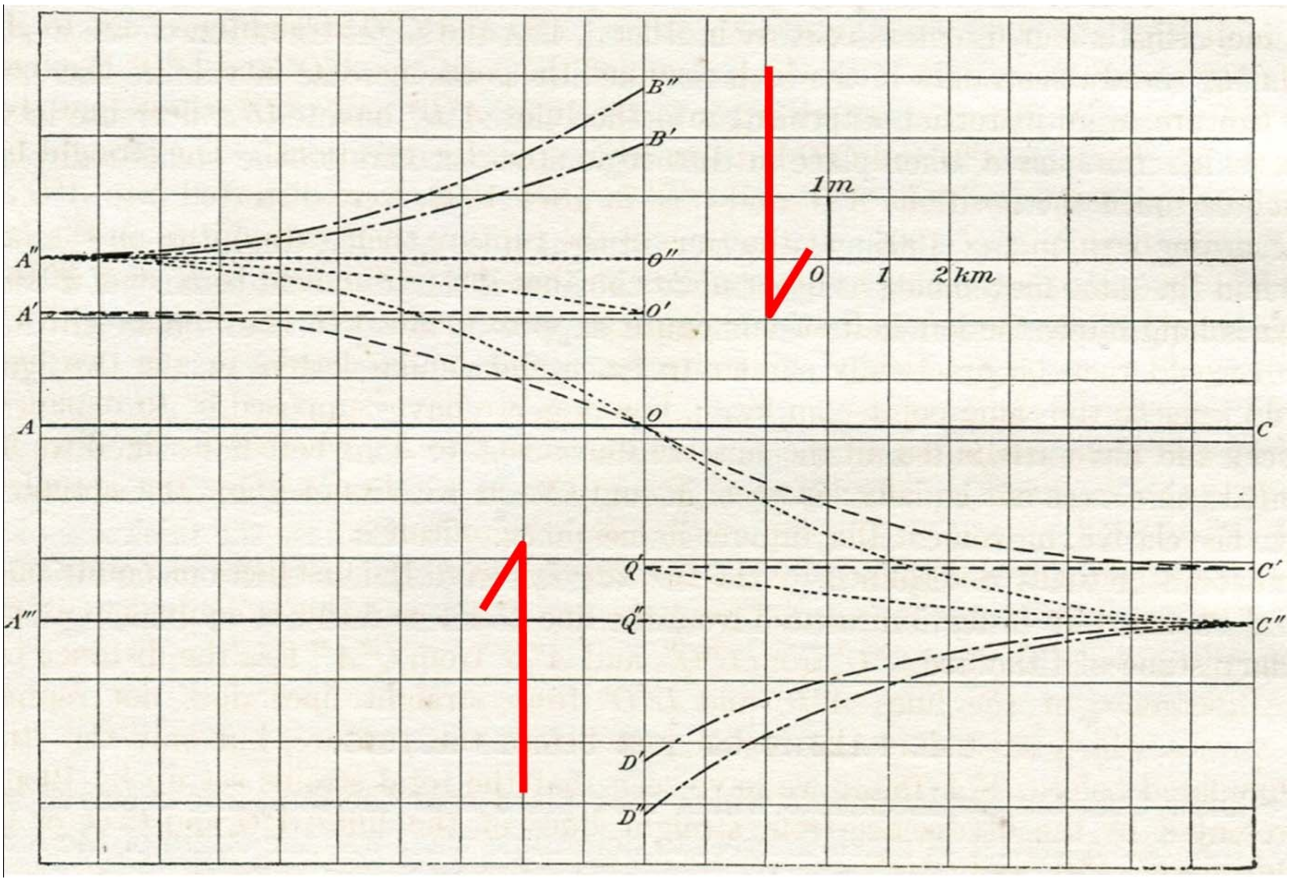

Figure 1. Illustration for elastic rebound for the cause of the 1906 California earthquake [4]

The ruptured fault traversed a part of the region where accurate ground topography surveys were made by the U. S. Coast and Geodetic Survey at various times before and after the earthquake [3, 4]. A summary of the survey results on ground plane is given in Figure 1. The central line passing through the points $B'', B', O'', O', O, Q', Q'', D'$ and D'' is the fault line. The side with the points A'', A', A, and A''' is the Pacific Plate on the west. The side with the points C, C', and C'' is the North American Plate on the east. It was pictured the displacements and the strains experienced at the region before, during and after the earthquake as follows [4].

"Let AOC be a straight line at some early data when the region was unstrained. By 1874-1892, A had been moved to A' and C to C', and AOC had been distorted into $A'OC'$; By the beginning of 1906, A had been further displaced to A'' and C to C'', then the sum of the distances AA'' and CC'' being about 6 meters; and AOC had been distorted into $A''OC''$."

"When the rupture came, the opposite sides of the fault slipt about 6 meters past each other; $A''O$ and $C''O$ straightened out to $A''O''$ and $C''O''$; and the straight lines which occupied the positions $A''O''$ and $C''Q''$ just before the rupture, were distorted afterwards into the lines $A''B''$ and $C''D''$, these lines being exactly like the lines $A''O$ and $C''O$ but turned in opposite directions."

"The straight lines, which occupied the positions $A'O'$ and $C'Q'$ in 1874-1892, were distorted into $A''O'$ and $C''Q'$ in the beginning of 1906; at the time of the rupture their extremities on the fault-line had the same movements as other points on that line; O' moved to B' and Q' moved to D'."

Subsequently, the elastic rebound theory for the cause of earthquake was developed, established and used by many others. It has been the main stream theory for the past one hundred years.

2.2. Brief description

Correspondingly, the existing elastic rebound theory in association with the plate tectonics for the cause of tectonic earthquakes can be briefly described below. The Earth's crust can be divided into a number of large and/or small tectonic plates. There edges are deep faults. The slow motion of convection currents in the plastic hot material of the mantle drives, pushes and pulls the plates. The tectonic plates can have relative motions in the order of several cm per year. Deep faults with brittle and locked zones can be present in the crust rocks. As the plates move slowly, their fault edges can stay locked, the surrounding crustal rocks can gradually deform for a long time. The elastic stress-strain energy can be built up and stored in rock masses. When the stress on the locked fault zone exceeds its breaking strength, a sudden rupture of the brittle fault part would occur, which causes an earthquake. Its side rocks can abruptly slip into new positions. Such sudden rupture can occur along pre-existing faults or newly formed faults. The larger the earthquake magnitude, the larger the ruptured fault length and the larger the slip offset. They take place at either tectonic plate boundaries or inside plates. So, there are interplate and intraplate earthquakes. The sudden rupture can occur along pre-existing faults or newly formed faults.

2.3. Work and energy

The work (W) done at the time of rupture was given by the following equation [4]:

$$W = \frac{1}{2} FDA, \tag{1}$$

where F is the force per unit area of the fault-plane, A the area of the fault plane and D the slip.

For the 1906 California earthquake, the fault depth was 25 km, the length 435 km, the average shift 4 meters, and the force 1×10^{8} dynes per square centimeter. The work was estimated 1.75×10^{24} ergs (or 1.75×10^{17} joules). "This energy was stored up in the rock as potential energy of elastic strain immediately before the rupture; when the rupture occurred, it was transformed into the kinetic energy of the moving mass, into heat and into energy of vibrations; the first was soon changed into the other two. When we consider the enormous amount of potential energy suddenly set free, we are not surprised, that, in spite of the large quantity of heat which must have been developt on the fault-plane, an amount was transferred into elastic vibrations large enough to accomplish the great damage resulting from the earthquake and to shake the whole world so that seismographs, almost at the antipodes, recorded the shock."[4]

Modern seismology has adopted the fault rupture and/or slip model in the quantitative analysis of seismic waves [5]. A quantitative measure of the size and strength of a seismic shear source is the scalar seismic moment M_0 with the unit Nm (or Joule). M_0 is a measure of the irreversible inelastic deformation in the rupture area and can be expressed as follows [5]:

$$M_0 = \mu \overline{D} A, \tag{2}$$

where μ the rigidity or shear modulus of the rock mass, $\overline{D}$ the average final displacement after the rupture, A the surface area of the rupture. M_0 has the following relations with the surface-wave magnitude scale M_S (or the moment magnitude M_W) and the radiated seismic strain energy E_S (Joule):

$$\log M_0 = 1.5 M_S + 9.1, \tag{3}$$

$$\log E_S = 4.8 + 1.5 M_S \tag{4}$$

Furthermore, the total energy release E_T can be expressed by:

$$E_T = E_S + E_f, \tag{5}$$

where E_f is the friction energy to power the growth of the earthquake fracture ($E_{fracture}$) and the production of heat (E_{heat}).

The ratio E_S/E_T (i.e., the seismic efficiency) is perhaps only about 0.01 to 0.1, depending both on the stress drop during the rupture as well as on the total stress in the source region. In other words, only a small fraction of E_T goes into producing seismic waves. For instance, the 2011 off the Pacific Coast of Tohoku Earthquake may have $M_W = 9.0$, Mo = 4.5×10^{22} Nm, and $E_S = 2.0\times10^{18}$ Joule. The 2001 Kunlun Pass W. Earthquake may have $M_S = 8.1$, Mo = 1.8×10^{21} Nm, and $E_S = 8.9\times10^{16}$ Joule.

3. Observations and Comments

Based on the above brief, the existing elastic rebound theory for the cause of earthquakes looks quite simple and straightforward. Accordingly, the classical theories of elasticity, elastodynamics, fracture mechanics and plasticity have been extensively applied to mechanically examine the mechanism of earthquakes and to quantitatively predict the earthquakes since the crustal rocks and soils can be considered as solid materials [5, 11, 12]. Furthermore, the monitoring, testing and modeling techniques and methods have been rapidly developed and used. A huge amount of accurate data such as GPS, satellite images and seismographs have been monitored and measured for the movement of tectonic plates and faults.

Hence, if the elastic rebound theory had been correct or along the right track, the movement and deformation of the massive solid rocks and soils associated with the tectonic plates and faults would have had many regularities and phenomena following the guidance of the classical theories of solid mechanics. The earthquake unpredictable statement would not have become a mainstream consensus in modern seismology and seismo-geology. However, many devastating damage earthquakes still occurred suddenly without pre-warning or pre-notice by human beings. Recent examples are the 2008 Wenchuan Earthquake [1] and the 2011 off the Pacific Coast of Tohoku Earthquake [13-15].

The author has actively participated in the field investigation of the Wenchuan Earthquake of May 12, 2008. He has found many natural phenomena that happened before, during and after Wenchuan Earthquake. These phenomena cannot be logically and consistently explained with the existing elastic rebound theory in association with the plate tectonics. Mostly importantly, the elastic rebound theory violates many phenomena. He has further actively investigated many other earthquakes including the 1976 Tangshan Earthquake, the 2001 Kunlun Pass W. Earthquake and the 2011 off the Pacific Coast of Tohoku Earthquake. The same observations can be made. The existing elastic rebound theory cannot describe many earthquake phenomena and sometimes violates the phenomena [6-10].

As discussed in Section 2, the elastic rebound theory claims that a large amount of heat must be developed on the rupture-plane [4]. The friction energy to power the growth of the earthquake fracture and the production of heat is about 90% to 99% of the total energy release during earthquake [5]. The rupture speed is very fast and can be 2 to 3 km/s over hundred kilometers crustal rock faults according to analysis of seismograph records. Accordingly, the heat must cause some substantial increases in temperatures of the ruptured rocks and soils and the ground air at epicenters. However, field observations did not show any expected increase in temperatures of the ground rocks, soils and air. For example, Rice [16] stated the observations of “low heat outflow from major faults and a scarcity of glass (pseudotachylyte) that would be left from rapid recooling of silicate melts”. The author has further found that temperatures of the ground rocks, soils and air can suddenly drop during and immediately after ground shocking. An example is given below to show the inconsistency between the observed phenomena and the elastic rebound theory.

4. The 2001 Kunlun Pass W. Earthquake

4.1. Brief description

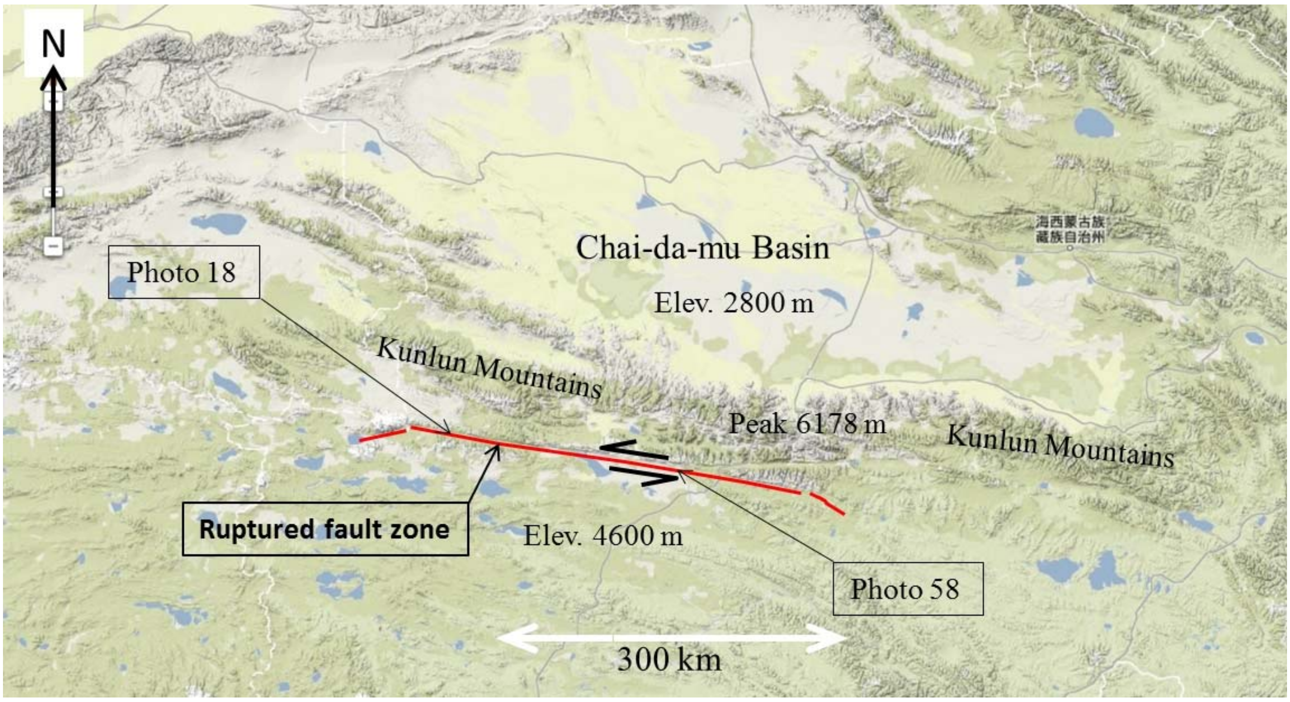

Figure 2. Google topography based seismic rupture zone for 2001 Kunlun Pass W. Earthquake

The Kunlun Pass W. Earthquake of magnitude 8.1 suddenly occurred along the western segment of the Kunlun Mountain Fault at 17 hours and 26 minutes and 14.7 seconds (Beijing time) in the afternoon of November 14, 2011. The epicenter was at (35.6°N, 94.1°E). The focal depth was 15 km. The total duration was about 120 seconds. It released a huge amount of energy and made the grand Kunlun Mountains rupturing and slipping. The released radiated seismic strain energy E_S might be 8.9×10^{16} Joule. It resulted in a surface rupture zone in the south slope of Kunlun Mountains. The seismic surface rupture zone was 426 km in total length and several hundred meters in width (as shown in Figure 2).

On November 16, 2001, a group of scientists from China Seismological Bureau went to the epicenter area for seismological and damage investigation. They observed that the ground deformation and destruction were serious and great in scale. Their widths varied from several tens meters to several thousand meters along the 426 km long surface rupture zone. The maximum left-lateral displacement was 6 to 7 m.

4.2. Ruptured permafrost soils and ice

The Kunlun Mountain is part of the Qinghai-Tibet Plateau, a region of the largest-scale tectonic uplift. The ground elevations along the seismic surface rupture zone were about 4600 m to 5000 m above the sea level. The grounds that were ruptured by the seismic fault movement were dominantly permafrost grounds. Ice layers covered on the rivers were also ruptured. Album showing the seismic surface ruptures and destruction was published by China Seismological Bureau [17]. It contains 140 colored photographs showing the seismic rupture zone from the west to the east. Two photographs 18 and 58 from the Album [17] are represented in Figures 3 and 4, respectively. Their locations are identified in Figure 2.

Figure 3. A tent-shaped mole track typical of the frozen soil layer with a height of 2 m, north of Wuxue Peak (after photograph 18 of [17])

From the site photograph 18 in Figure 3, it can be evidently observed that the frozen soil layer was largely uplifted, bended and then cracked in tension and shear. The broken frozen soil layer was relatively rigid. Their fractured sides and edges were fresh, sharp and angular. There were no signs of melting, thawing, plastic flow, muds, and/or re-freezing. In other words, the seriously broken frozen soil layer maintained its frozen state during and a few days after the ground rupture and shock.

From the site photograph 58 in Figure 4, it can be evidently observed that the frozen soil layer and the ice cover in a gully were largely uplifted, bended and then dislocated in tension and shear. The broken ice plates had fresh, sharp and angular sides and edges. There were no signs of melting, thawing, plastic flow, muds, and/or refreezing in the gully ice plates and frozen soils. In other words, the seriously broken frozen soils and ice plates maintained their frozen states during and a few days after the ground rupture and shock.

Figure 4. The ice in a gully was displaced 1.4 m in left-lateral sense 25 km east of Kusai Lake (after photograph 58 of [17])

The above no melting and thawing phenomena in the broken and deformed permafrost soils and ice covers are typical and can be observed in almost all the 140 photographs collected in the Album [4]. Chen et al. [18] also observed that the earthquake ruptures in frozen soils mainly showed brittle deformation, were composed of shear fractures, tension fracture and seismic ridges.

4.3. Energy analysis for melting frozen soils

Xu and Chen [19] carried out a temporal and spatial rupture process analysis of the earthquake by back-calculating the high signal-to-noise-ratio P-waveform data of vertical components of 20 stations with epicentral distances less than 900 km. Their back-calculated results showed that the earthquake had three sub-rupture events forming 220 km, 120 km and 270 km long fault ruptures. The six rupture speeds were 2.2 km/s to 5.8 km/s.

Secondly, according to fracture mechanics, the energy required for the growth of the earthquake fracture ($E_{fracture}$) in the rocks and soils may be estimated with the following equation.

$$\mathrm{E}_{\text{fracture}} = \frac{AK_c^2}{E}, \tag{6}$$

where A is the total fractured area along the fault plane (m^2), K_c is the rock fracture toughness with the unit MPa m$^{1/2}$, and E is the rock elastic modulus (MPa). If E = 20,000 MPa, K_c = 1 MPa m$^{1/2}$, and A = 6.39 ×10^9 m^2 (=426 km × 15 km), then, E$_{\text{fracture}}$ = 3.2 ×10^{11} Joule. So, E$_{\text{fracture}}$ (3.2 ×10^{11} Joule) is far less than the E$_S$ (8.9×10^{16} Joule).

Thirdly, the specific heat capacity c_p^{frozen} for completely frozen soil can be determined with the following equation:

$$c_p^{frozen} = \frac{c_p^{soil} + w_0 c_p^{ice}}{1 + w_0}, \tag{7}$$

where c_p^{soil} is the specific heat capacity for soil and is equal to 800 Joule/(kg °C), c_p^{ice} is the specific heat capacity for ice and is equal to 2060 Joule/(kg °C), and w_0 is the water (ice) content in the complete frozen soil. Normally, c_p^{frozen} is between 800 and 2060 Joule/(kg °C). The temperature increase ΔT of the frozen soil has the following relation with its mass M_{soil} and the heat increase ΔQ:

$$\Delta T = \frac{\Delta Q}{c_p^{frozen} M_{soil}}, \tag{8}$$

Assuming, w_0 is 15% and its degree of saturation 100%, then c_p^{frozen} 964 Joule/(kg °C) and the unit weight of the frozen soil is about 2209 kg/m^3. Assuming, for a total frozen soil along the ruptured zone, its thickness is 20 m, its length 426 km and its width 100 m. Its total mass is 1.9×10^{12} kg. It might have the temperature from –1°C to –20°C. The heats for the total frozen soil temperature increases 1°C and 20°C are 1.8×10^{15} Joules and 3.6×10^{16} Joules, respectively. The frozen soil has a total of 2.4×10^{11} kg ice. As the latent heat of ice is 3.34×10^5 Joule/kg, the total latent heat required for melting all the ice at 0°C in all the permafrost soil into liquid water is 8.2×10^{16} Joules.

As a result, the total heat required for melting all the frozen soil is between 8.3×10^{16} Joules and 11.8×10^{16}, which is similar to the released radiated seismic strain energy E$_S$ 8.9×10^{16} Joule. Furthermore, if E$_S$ is perhaps only about 0.01 to 0.1 of the total released energy E$_T$ [5], there would be enough heat energy to melt and thaw the entire frozen soils along the surface ruptured zone. But, no melting or thawing phenomena were observed in the 140 site photographs [17]. The theoretical results and field observations can demonstrate that the elastic rebound theory is incorrect.

5. The Gas Cause of Earthquakes

A further question may be asked: what type of loading can rapidly crack the crustal fault for tens to hundreds km long and tens km deep, generates the strong seismic waves, but does not produce heat? One most possible and feasibility loading is the rapid expansion and migration of highly compressed natural gas from deep crustal traps via tectonic fault channel. This is the internal loading associated with the gas hypothesis for cause of earthquakes [6-10]. The hypothesis can be briefly described below.

An earth quaking is an adiabatic process of interaction between rapid upward expansion and migration of compressed natural gas and its surrounding crustal rocks and ground soils. The natural gas is produced in core and/or mantle and gradually accumulated in the traps below crustal fault rocks. It escapes from its traps in deep fault zones of the lower crustal rocks. Because of the extremely high pressure drops in front of the moving gas mass, the gas migration speed in the fault zone can be several km/s. The interaction is instantaneous and flashing. It can be complete within few to tens and to hundreds seconds. The gas expansion and migration are confined and constrained by the inward gravity, the tectonic stresses and the rigidness and strengths of the crustal rocks. The energy of earth quaking is mainly the physical expansion energy of the highly compressed methane gas. The gas expansion is a cooling process, which reduces the temperatures of ground rocks and soils and air during and immediately after the shock. All the earthquake phenomena can be logically and consistently explained and predicted with the gas hypothesis. Specially, the broken permafrost soils and ices along the 426 km long surface rupture zone in south slope of Kunlun Mountains could keep sharp, angular and fresh immediately after the earthquake on November 14, 2001.

6. Concluding Remarks

The author would like to recall the four rules of reasoning in philosophical inquiries of nature summarized by Sir Isaac Newton about 300 years ago [20].

- RULE I. *We are to admit no more causes of natural things than such as are both true and sufficient to explain their appearances*.
- RULE II. *Therefore to the same natural effects we must, as far as possible, assign the same causes*.
- RULE III. *The qualities of bodies, which admit neither intensification nor remission of degrees, and which are found to belong to all bodies within the reach of our experiments, are to be esteemed the universal qualities of all bodies whatsoever*.
- RULE IV. *In experimental philosophy we are to look, upon propositions inferred by general induction from phenomena as accurately or very nearly true, notwithstanding any contrary hypotheses that may be imagined, till such time as other phenomena occur, by which they may either be made more accurate, or liable to exceptions*.

We may have to follow these four rules in our scientific inquiry of the nature of earthquakes. The elastic rebound theory was developed one hundreds year ago from the observations of co-seismic surface ruptures induced by the 1906 California Earthquake. It is only partially correct because it associates earthquakes with faults. It is inconsistent and even violates many other phenomena that were present before, during and after earthquakes.

Numerous failures have been encountered and experienced in our tremendous efforts using the elastic rebound theory in the prediction of earthquakes. Many current seismo-geologist and seismologists have lost their original goals to predict earthquakes and turned to believe that earthquakes are unpredictable with the present techniques. All these problems are due to the fact that the incorrect elastic rebound theory for the cause of earthquakes was used in the investigation and prediction of earthquakes.

It is evident that the energy released during earthquake is not the elastic stress and strain energy accumulated in brittle crustal rock solids during relative movements of tectonic plates. The released energy is the volumetric expansion energy of highly compressed and dense natural (methane) gas. The gas rapidly escaped from its deep crustal traps and was migrating via deep faults into shallow grounds and the sky. The author trusts that this gas hypothesis for the cause of earthquakes would make earthquake predicable in the near future.

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