Driver of Tectonic Plate Fracture and Movement

Xuguang Leng

Abstract—The theory of tectonic plate asteroid driver provides that comet and asteroid collisions have ample energy to fracture, move, and deform tectonic plate. The enormous kinetic energy of an asteroid collision is dissipated through the fracture and violent movement of the tectonic plates, and stored in the plate deformations. The stored energy will be released in the future through plate slow movement. The reflection of plate edge upwards upon collision impact causes the plate to sit on top of adjacent plate and creates the subduction plate. Higher probability and higher energy of asteroid collision in the equator area provides the net energy to drive heavier land plates to higher latitudes, offsetting the tidal and self spin forces, creating a more random land plates distribution. The trend of asteroid collisions is less frequency and intensity as loose objects are merging into the planets and Jupiter is taking ever larger shares of collisions. As overall energy input from asteroid collision decreases, plate movement is slowing down and eventually land plates will congregate towards equator area. The current trajectory of plate movements is the cumulative effect of past asteroid collisions, and can be altered, new plates be created, by future collisions.

Keywords—Tectonic plate, Earth, asteroid, comet.

I. Introduction

It has been more than a century since Alfred Wegener first proposed the idea of continental drift, and pioneered the theory of plate tectonics. The question of the driver of continental drift or plate tectonics movement has been focused on gravity, including Earth's own gravity as well as tidal force [1] of the Moon and/or the Sun.

There are gravity anomalies around the Earth, in both geodesy and geophysics senses [2]. Such anomalies are caused by the less than spherical distribution of mass, after adjustment of shape distortion caused by Earth's self spin. Given both the tidal forces and force from self spin are trying to restore the spherical mass distribution, and Earth has movable plates of different mass density which can compensate for the aberrations in the mantle, the plates movement should result in a more even gravity distribution on Earth. The relations amongst Earth, the Sun, and the Moon have been stable for at least the last billion years, longer than the existence of Pangea. The movement of plates by tidal force should resolve the gravity anomaly towards some kind of tidal lock with the Sun and/or the Moon. Earth's self spin moves the plates towards maintaining and restoring the spherical shape of Earth gravity, which should result in a uniform decrease of gravity from equator plateau to poles valley. Neither Pangea or today's plate distribution meets the requirement of tidal force or the force of Earth self spin, though the plates have moved thousands of km in hundreds of million of years and have ample opportunities to move to the optimum locations in four billion years. Some other forces are in play.

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Huge mass of tectonic plates take tremendous force and enormous energy to move. Besides Earth's self spin and tidal forces from Moon and Sun, comet/asteroid collision is the only natural force that is large enough. In addition, the comet/asteroid collisions have random impact locations, are consistent with the random pattern of plate fractures and movements as well as random distribution of heavier land plates away from the equator. Although the collision impact is instantaneous, the energy of impact can be stored in the plate deformation and released gradually in millions of years. Therefore, comet/asteroid collision is at least one of drivers of tectonic plate fracture and movement, if not the driver.

There are generally two types of loose objects that collide with Earth, icy comets and rocky asteroids. The difference between a comet and an asteroid is the melting/evaporation point of the composite materials. Comets are mostly made of materials of low melting/evaporation point while asteroids are made of materials that have higher melting/evaporation point. The difference in material composition alone does not determine the intensity of collision impact. As people living in the colder climate know, an icicle falling from the roof is as deadly as a piece of brick. The air friction heat of an object traveling at extremely high velocity can melt/vaporize any material, icy or rocky. Other factors like velocity, entry angle, size and structure of the object play equally important roles to determine whether friction heat/force has enough time to melt through before the impact or to cause disintegration, and the final impact energy on the plate. Therefore, the words ”asteroid” and ”comet” are used interchangeably.

II. Ample Energy of Asteroid Collisions

Asteroid possesses enormous amount of kinetic energy due to its huge mass and high relative velocity with Earth. The kinetic energy is ample to fracture and move Earth's tectonic plates.

Earth rotates around the Sun at the velocity of approximate 30 km/s, the muzzle velocity of an AK-47 bullet is only about 670 m/s. If Earth collides with a stationary object in the solar system, the object would be traveling at approximate 45 times the speed of a bullet. Of course, comet and asteroid are not stationary. The relative velocity between Earth and the asteroid depends on the orbit of the asteroid. There are comets that can reach Earth impact velocity of more than 60 km/s [3]. The huge mass of a comet at this velocity carries an enormous amount of kinetic energy that is truly out of this world. For example, the mass of Chicxulub asteroid is estimated in the range of $1.0 \times 10^{15} kg$ to $4.6 \times 10^{17} kg$, kinetic energy is estimated in the range from $1.3 \times 10^{24} J$ to $5.8 \times 10^{25} J$ [4]. In comparison, a magnitude 9.0 earthquake on the Richter Scale like 2011 Tohoku Earthquake has the energy of $0.794 \times 10^{18} J$.

In other words, the Chicxulub asteroid has the energy of at least 1 million magnitude 9.0 earthquakes.

The 2011 Tohoku earthquake was associated with 4.0–5.0 m horizontal offshore movement and 0.4 to over 1.0 m subsidence. [5] To take a linear extrapolation, the Chicxulub asteroid can move the plate edge vertically by at least 400 km, horizontally by at least 4,000 km. Although there are minor factors to the plate movement like air friction, water sitting above the plate, and so on, the dominant factor regarding how far the plate moves is still the mass of the plate. Earth's continental crust is about 30–70 km thick, the oceanic crustal thickness is about 6–12 km. The Chicxulub asteroid may have ample energy to lift the plate of 2011 Tohoku earthquake to the height of its thickness. There could be comets collisions have magnitudes more impact energy than Chicxulub asteroid in the Earth's earlier years as it only takes diameter slightly larger than two times to have ten times more energy.

The kinetic energy of an asteroid, which is function of asteroid mass times the relative velocity between Earth and the asteroid, is dissipated in several ways. First, air friction converts to a large amount of heat. Secondly, compaction of the air and penetration of the plate. Third, fracture and movement of the plate. Fourth, deformation of the plate and other spherical mass disturbances. The first three are spent energy at the moment of impact, the last one is stored energy.

The amount of kinetic energy dissipated in Earth's atmosphere depends on the collision angle. More perpendicular the angle, the less air mass it encounters, the less air to compact, the less time it stays in the atmosphere, the less material being vaporized.

The structure of asteroid also plays a role. A disintegrated and scattered asteroid delivers less energy to the plates. The final impact energy on the plate has many variables, mass, structure, and the orbit of the asteroid all have roles to play.

Deformation of plate, like putting the plate on top of adjacent plate, disturbed Earth's spherical mass. In addition, to the extent the asteroid's mass has entered Earth's crust, or mantle, it also disturbed the Earth's spherical mass shape. The mass of asteroid is minor comparing with the plate, nevertheless, the additional mass is a stored energy.

The instantaneous asteroid impact causing plate deformation is like winding the watch spring, while the plate movement in the form of earthquakes is like the ticking of watch arms releasing spring energy that lasts millions of years.

III. Mechanism of Plate Movement

The tectonic plates move when there is a force behind the movement. The larger the mass, the more energy it takes to move by certain distance. These are the classic Newton's laws of motion.

Earth crust was formed from cooling magma. Like cooling concrete, cracks can be introduced in the curing process. The small cracks extend themselves to become large fractures when constant small asteroid impacts as well as tidal forces shake the Earth crust, eventually separate the crust into different plates. The plates are holding in their respective places by the compression force from neighboring plates caused by Earth's gravity.

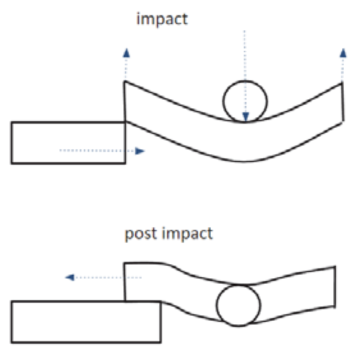

Fig. 1 Plate movement during and post impact

The tectonic plates are not rigid, they are capable of bending and flexing. When a high velocity, large mass object collides with a tectonic plate at the center, the collision force causes the edge of the plate to reflect towards the direction of the impacting object. The mantle underneath the plates is in a mostly incompressible liquid form, acting like hydraulic fluid. The upward movement of the impacted plate at the edge creates a vacuum, causing mantle fluid to flow in. Such upward movement also totally or partially removed the compression force exerts onto the adjacent plates, allowing adjacent plates to swiftly slide under into the vacuum underneath the edge of the impacted plate. Afterwards, the impacted plate edge is being pulled downwards by gravity, it will not be able to bounce back to its original position, rather it would sit on top of the adjacent plates. (Fig. 1)

The collision impact has displaced some sizable mass at ground zero. The displaced mass is trying to expand the plate, forming a crater around ground zero. Some mass expands all the way to the edge of the plate, where the compression force from adjacent plates has been removed and the plate is free to expand. The other mass creates wrinkles (mountains) and other deformations on the plate where rigid structures resisting the expansion. The wrinkles are the crumple zones like in an automobile.

The collision location may not be at the center of the plate, and plate structure and thickness are not uniform, the reflection height is not uniform along the plate edge. Some portions of plate edge may have been completely lifted where the expansion is more free, while the other portions may have been only partially lifted where the expansion is more restricted, end up with two plates with slight different elevations (Fig. 2). The adjacent plate will absorbing some of the energy from the impacted plate by forming wrinkles, and the counter force from the adjacent plate causes the impacted plate to form wrinkles as well.

For the portions of plate edge that are sitting on top of the adjacent plates, they are more free to expand on top of the adjacent plates. The adjacent plates then become the subduction plate, as the extra mass sitting on top creates a gravity plateau. The edge of the subduction plate needs to dive into and displace the mantle to restore spherical gravity. As the subduction plate dissolves into the mantle, the support for the impacted plate edge is removed, and the edge slides

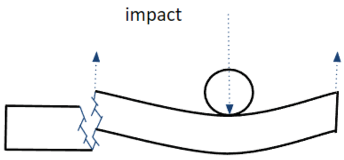

Fig. 2 Plate fracture due to impact

and tumbles, creates earthquakes.

For post impact energy release without subduction, plate movement can only be sliding and grinding against adjacent plates as the wrinkles try to unfold. The sliding and grinding also create earthquakes.

When the asteroid is high in mass and low in velocity, the low energy is unable to completely lift the plate over the adjacent plates, yet there is a large quantity of infused mass that has nowhere to expansion, it will create very large wrinkles on the plates (very high mountains) instead.

The asteroid impact causes plate deformations instantaneously. The plate deformation on a free standing, non-spinning Earth, without tidal forces from the Moon and the Sun, can last forever. The tidal forces and self spin provides the force to release the energy stored as spherical gravity anomaly. The tidal forces also hastens the energy release by causing constant mantle and ocean water tidal movement, loosening and eroding away some of the energy release blocks in the plate, creating the condition for sudden release of stored energy. Such triggers are random in nature, as the result, earthquakes are random in both location and energy intensity. The most deformed, the highest energy stored, are not necessarily be triggered first.

The energy stored in plate deformation will be released through localized plate movements, also known as earthquakes, one step at a time. One earthquake event does not resolve all the deformations on a plate, they may take millions of earthquakes in millions of years to fully resolve. In the mean time, there will be additional asteroid collisions to cause new plate deformations, so it is a never ending process.

When high velocity asteroid collides with the Earth, the mass of the asteroid can penetrate the crust and enter the mantle causing the mantle to expand. The subduction plates also add mass to the mantle. Earth's crust has to expand accordingly to the increased mantle mass. The crust expansion can be in the form of inter-plate fracture enlargement with mantle coming up to surface cooling to new crust. It can also be in the form of intra-plate seams in the areas where gravitational stress has overcome the plate integrity, for example, Lake Baikal. The alternative to crust expansion is directly releasing the mantle to the surface as volcanoes. Mantle material is released like hot steam from a pressure cooker at the weakest point in the container, in case of Earth crust, the weakest points in a gravity basin. Hawaii Islands and Eastern Island are such weakest points. The mantle material release can not only relieve the need for crust expansion, but also acute gravity anomalies as it adds mass at the location of acute mass deficiency.

While icy comets and rocky asteroids have little difference at time of impact, there are differences post impact. The icy comet eventually melts and adds mass to Earth's ocean and air. The rocky asteroid, on the other hand, can adds to Earth's land mass when falls onto land. More comet collisions will cause ocean level to rise. Over short periods of time (millions of years), the collisions interval and collisions composition of comet versus asteroid are random. Such random interval and composition can cause Earth ocean level to fluctuate.

IV. Intensity of Asteroid collisions

The size and frequency of asteroids colliding with Earth determine the overall energy input to movement and fracture the tectonic plates. It is imperatively important to understand how the energy input varies over time in order to understand how the tectonic plates move over time. The asteroid collisions appear to be random events with no set pattern. The solar hydrologic cycle theory provides that there is a trend over a longer time frame, say, a few billion years. [6]

The solar hydrologic cycle theory looks at the mass movements around the solar system, chief among them are comet collisions with the planets. In studying of mass movement, comets are much more important than asteroids because the total comet mass is much larger than the total asteroid mass. The comets count for about two percent of the solar system mass today [7], asteroids have a more negligible share of 12×10^{-10} of solar mass [8].

The comet collision bring mass from outer solar system (Kuiper Belt and beyond) to the planets that are closer to the Sun. There is not an inexhaustible amount of mass in the outer solar system, rather every kg mass delivered to the planets reduces the mass in the outer solar system by the same amount. As the total number of comets decrease over time, there are less comets coming into the inner solar system, there is less chance of comet collision. The comet collision probability trend is down over time. The down trend can be a linear curve or something even steeper, we need to further examine the Jupiter factor to determine.

Jupiter is the predominate planet in the solar system. Outer planets are much larger in mass than inner planets, and Jupiter is the giant amongst giants. The massive Jupiter, its gravity attracts a larger share of comet collisions than the meager Earth gravity. Such collisions increase Jupiter's mass, which in turn attracts even more comet collisions, forming a positive feedback loop. The positive feedback loop boosts Jupiter's mass growth while reduces Earth's share of comet collisions. Over time, the number of loose objects decreases, and Earth's share of loose object collisions also decreases. The combined effect of simple comet number decreasing and Jupiter taking larger share is that the intensity of comet impact on Earth was decreasing slowly at a more linear pace, then the decrease accelerated as Jupiter positive feedback loop reaches its peak, finally the decrease slows down as there are only a fraction of comets left.

The comet collisions are discrete events with different number of Joule or impact energy and different time intervals.

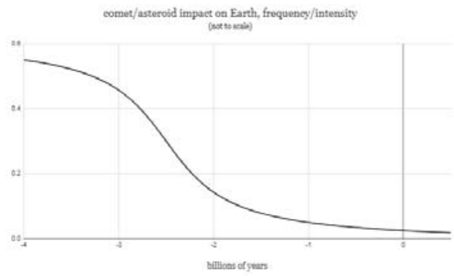

Fig. 3 Frequency/intensity of asteroid collisions

Regression over standardized time interval of a million years as X axis can create smooth curve of Joule as Y axis, the curve should resemble the shape of arctangent (Fig. 3).

The curve is a theoretical prediction from Earth's formative years to the future. Although the actual historic events are unknown, and estimated Joule/million years value is beyond the scope of this paper, the overall shape of curve should be correct. The average event intervals was probably a few thousand years in Earth's formative years, slows down to a few million years now. There were magnitudes more data points in the left portion of the curve than the right portion.

Applying the collision intensity curve to the era of Pangea, about five hundred million years ago, the intensity of comet impact had already decreased significantly from Earth's formative years, yet still much higher than today. There could be a magnitude more frequent large comet/asteroid collisions than today, some could be significantly larger than Chicxulub asteroid. It was a tectonic plates upheaval compared to today. The plates were fractured into new plates, the movement of plates was much faster. With intensity of impact energy in steady decline into the future, the plates movement are slowing further still. Since the speed of plates movement is in proportion of impact energy input, it should follow the curve of Fig. 3. In the era of Pangea, the plates could move magnitudes faster than they are moving today.

V. Historic and Future Plate Movements

The speed of tectonic plates movement is determined by the intensity of impact energy, the direction of plates movement are determined by the locations impact energy applied on Earth. The combination of these factors determines the trajectory of plate movement. Today's plate pattern and movement trajectory are the results of all historical asteroid collisions on different locations with different intensities.

Collision location distribution determines fracture and plate pattern. For example, if the collisions only happen on the equator, there would be very little land mass on the equator, the direction of plates movement would be towards the poles.

The location of individual asteroid collision on Earth is random and can not be predicted. The distribution of collision locations can nevertheless be determined based on the orbits of comets/asteroids in relation with Earth's orbit and from empirical evidence.

There are many variables to determine the collision location, first and foremost is the orbit of the comet/asteroid. The simplest orbit is on the same plane as ecliptic. Given most comets/asteroids are located in the disk within a few degrees of ecliptic, this could be the mean or average orbit plane. This plane simplifies the relationship with Earth to two dimensions. Collision is possible when asteroid perihelion is inside Earth orbit. The collision location would be approximately between Tropic of Cancer and Tropic of Capricorn with the equator having the highest probability.

Most comet orbit planes have inclination with ecliptic, from slight to perpendicular. The axis of inclination goes through the Sun, but may not be in the ecliptic. The three dimensional relationship creates numerous scenarios that comet/asteroid can collide with Earth, each scenario with a different collision location distribution. The exact current distribution of comets/asteroids on different orbital planes is unknown, the historic distribution dates back to at least five hundred million years to the era of Pangea is even harder to estimate.

An additional level of complexity is that the asteroid orbit plane is not perfectly two dimensional, but influenced by the gravitational pull of objects other than the Sun. Accurate historic picture of all the objects in the solar system going back to several billion years is impossible to obtain. As loose objects collide and merge with each other and planets, the gravitational interaction amongst billions of objects changes every moment, making even a rough approximation impossible.

The final factor is the significant gravitational pull from Earth when the two come in close proximity, prior to collision, which can alter comet's velocity as well as direction. Such gravitational pull varies depending on the comet approaching direction and speed.

All the factors combined favor the equator area for collision distribution, yet accurate estimation of collision distribution is impossible. Statistics of actual meteorite collision location distribution is a good proxy for the larger comet/asteroid collision location distribution. Study has shown collision frequency per unit area decreases as the latitude rises, to about 65% of the equatorial frequency at the poles [9].

The historical collision location distribution may skew even more towards the equator area than the current meteorite distribution as the comet/asteroid whose orbit is destined to hit the equator area has a higher probability of collision and shorter lifespan. In other words, today's meteorite distribution has a survivor's bias.

The collisions on the ecliptic plane are correlated with higher conversion rate of kinetic energy to impact energy. The collision on the ecliptic plane has the most perpendicular impact angle, the shortest path through atmosphere, everything else being equal, thus has the least amount of energy dissipated in Earth atmosphere, retains the most amount of asteroid mass, conveys the most amount of the kinetic energy onto plate. The collision of inclined asteroid orbit, on the other hand, converts less kinetic energy to impact energy.

The higher collision probability and higher kinetic conversion rate in the equator area means higher intensity and more frequent energy input into the plates in the equator area, providing the net energy to drive heavier land plates to higher latitudes towards poles, offsetting tidal force and self spin gravity force, resulting in a more random distribution of heavier land plates.

While there is an overall net impact energy to move the plates from equator to the poles, the tectonic plates movement is rather chaotic regarding speed and direction. Current trajectory of plate movement can be altered, even new plates can be created, by future asteroid impacts. The location and intensity of future asteroid impacts are unpredictable, therefore, the future trajectory of plates is unpredictable. One thing is predictable, the winding of watch spring is less and less frequent, the watch arms are moving slower and slower. With less impact energy input, the overall plates movement activities will slow down.

As the overall intensity of comet/asteroid collisions decreases further into the future, the net force driving the plates towards the poles are weakening. The gravitational forces may finally overpower the collision impact force. We may already at this point without the stored energy from surplus hundreds of millions years ago. The future will be for heavier land plates to congregate towards the equator, in perhaps another billion years.

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