On a Possible Giant Impact Origin for the Colorado Plateau

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Abstract

It is proposed and substantiated that an extraterrestrial object of the approximate size and mass of Planet Mars, impacting the Earth in an oblique angle along an approximately NE-SW route (with respect to the current orientation of the North America continent) around 750 million years ago (750 Ma), is likely to be the direct cause of a chain of events which led to the rifting of the Rodinia supercontinent and the severing of the foundation of the Colorado Plateau from its surrounding craton.

It is further argued that the impactor most likely originated as a rouge exoplanet produced during one of the past crossings of our Solar System through the Galactic spiral arms in its orbital motion around the center of the Milky Way Galaxy. Recent work has shown that the sites of galactic spiral arms are locations of density-wave collisionless shocks. The perturbations from such shocks are known lead to the formation of massive stars, which evolve quickly and die as supernovae. The blastwaves from supernova explosions, in addition to the collisionless shocks at the spiral arms, can perturb the orbits of the streaming disk matter, occasionally producing rogue exoplanets that can reach the inner confines of our Solar System. The similarity between the period of spiral-arm crossings of our Solar System to the period of major extinction events in the Phanerozoic Eon of the Earth's history, as well as to the period of the supercontinent cycle (the so-called Wilson Cycle), indicates that the global environment of the Milky Way Galaxy may have played a major role in initiating Earth's past tectonic activities.

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1. Introduction

The hypothesized mantle convection/mantle plume scenario has for a long time been a popular candidate mechanism for driving the terrestrial tectonic motion. An alternative driver for plate movement, that of the giant impacts from Solar-System asteroids and comets, had also been explored in the past few decades (Price 2001 and the references therein). This latter proposal has the advantage of being able to account for the observed sharp change in direction of the Emperor-Hawaii island chain, for example, which was hypothesized to be produced by a stationary subterranean hotspot anchored on the mantel, coupled with the steady movement of the overlying Pacific Plate (Wilson 1963). The mantle convection picture would have difficulty explaining both the stationary nature of the hotspot's anchor on the mantle (since convection is a self-organized pattern, thus is expected to slowly evolve with time), as well as the sudden change in direction of the island chains. World-wide hots spot distributions also show relative fixity over long periods of time (Mueller et al. 1993; Lonsdale 1988), another fact that the self-organized convection cells would have trouble to produce. Further more, many geomorphology features such as the Rocky Mountains are intracratonic, so cannot be explained through subduction and suture (McPhee 1998, pp 384-386). The giant impact scenario, as we will show in this as well as follow-on work, can provide new perspectives on such long-standing difficulties of the traditional plate tectonic models.

One severe limitation of the past impact proposals (Price 2001 and the references therein) is the ultimately achievable magnitude of the impacts, if these were produced solely by objects of the mature Solar System. The Giant Planets of our Solar System have arrived at their stable orbits when the Earth was still in its youth, and the asteroids and comets of the Solar System, while possessing potentially Earth-crossing orbits, are generally small in size and mass, which makes it problematic if we were to hypothesize that both the initial partial loss of crust of the Earth, and the subsequent driver for the supercontinent cycles, were caused mainly by giant impacts.

An examination into the frequency distribution of the major extinction events within the Phanerozoic Eon (see, for example, Bond and Wignall 2014 and the references therein; also Extinction_Intensity.svg on wikipedia), on the other hand, reveals an episodic trend of the most important of these extinction events (especially the closely-clustered groups of events), with the (quasi) period of these events similar to that of the Galactic Year of 250 million years. Later, in section 4, we will discuss in more detail how the periodic crossings of the Solar System through the Galactic spiral arms may have facilitated the periodic productions and invasions of rogue exoplanets into the inner confines of our Solar System, contributing both to the supercontinent cycles and the periodic occurrence of major extinction events in the Phanerozoic Eon.

In this first of a series of papers on possible giant-impact induced plate tectonic activities in the Earth's history, we propose and analyze a likely giant impact origin for the Colorado Plateau (Figure 1).

2. Geological Environment of the Colorado Plateau

The Colorado Plateau is situated around the Four Corners region of the southwestern United States. It encompasses an area roughly 130,000 square miles (or roughly 337,000 km^2). It is an uplifted high-desert plateau of a shallow bowl shape (i.e., with its rims generally of higher elevation than its interior). The elevation of the Plateau ranges from 3000-14000 ft (1 - 4.7 km), with an average elevation around 5000 ft (1.7 km).

One distinguishing characteristic of the Colorado Plateau is its structural stability (Kelley 1979 and the references therein). It was shown to have been little faulted or folded during the past 600 million years, whereas all around it there were vigorous orogenic and igneous events. In the west, the Plateau is delineated by the Wasatch Line, a fault region which marks the inner boundary along which the Rodinia supercontinent split circa 750 Ma (this boundary coincides roughly with the Interstate-15 freeway from Salt Lake City, Utah, to Las Vegas, Nevada), with Australia and East Antarctica broken off, and with the western margin of the ancestral North America plate redefined (Moores 1991); beyond the Wasatch Line to the west is the younger Basin and Range province. In the east, the Plateau boundary is marked by the Southern Rocky Mountains in Colorado, and by the Rio Grande Rift Valley in New Mexico. Its southern boundary within Arizona is delineated by the Mogollon Rim. Its northern boundary is lined by the Uinta Mountains in Utah. The Grand Canyon of the Colorado River is located near its southwestern corner.

Additional geological features of the Plateau and its environment include:

1. There exists the so-called Great Unconformity in straitigraphy, reflecting an up to 1.2 Gyr of missing sedimentation between 1700 Ma and 540

Ma. The most well-known display of this phenomenon is in the Inner Gorge of the Grand Canyon of the Colorado River, but its presence is wide-spread over the entire Plateau region (i.e. as far east as the Baker's Bridge near Durango, Colorado. See Figure 2 below). The Great Unconformity is also present in other parts of the US (i.e. Wyoming and New York State, among others), as well as in the rest of the world (i.e., Canada, Ireland, and Africa). See discussions in Ward (2001), Share (2012), Peters and Gaines (2012), and the references therein.

2. In the Grand Canyon region, a so-called Grand Canyon Supergroup sedimentation sequence (see, e.g., Hamblin 2008), with formation time between 1200 Ma and 750 Ma, was found faulted into the basement rock (i.e. the Vishnu Complex) at various locations. Where the Supergroup is present, the time gap in the Great Unconformity is reduced correspondingly.
3. The exposed late-Precambrian crystalline rocks (the so-called Uncompahgre Formation) on the east side of the Plateau, which form some of the highest peaks in the western San Juan Mountains (which, though traditionally classified as part of the southern Rocky Mountains, as denoted in our Figure 1, is structurally part of the Colorado Plateau. See, for example, Kelley 1979), are severely folded, and often show evidence of great contortion. Figure 3 shows a section of upturned rocks along the so-called "million-dollar Highway", CO-550, in the western San Juan Mountains (i.e., near the eastern boundary of the Plateau). Figure 4 shows the faulted and folded Uncompahgre Formation turned vertically, sandwiching a patch of horizontally-oriented bed of sediments, south of Silverton, Colorado, along the route of the Durango-Silverton Narrow Gauge Railroad, also in the western San Juan Mountains. A related example, showing the Devonian Elbert formation unconformably overlying the vertical-turned beds of the Precambrian Uncompahgre Formation near Ouray, Colorado, can be found in the Geologic Atlas of the Rocky Mountain Region, 1972, p. 35). The same Atlas, on p. 39, shows that the major fold axes and faults near the boundaries of the Plateau all curve around the Plateau – though in the north, such folds and faults extend further north beyond the Uinta Mountains region (usually considered to be the northern boundary of the Plateau, but some, such as Dutton 1882, p. 54, considered the Plateau to extend further north) into the Teton Range and northern Rockies.
4. In the exposed younger Precambrian (i.e. Neoproterozoic era) rocks

of the Plateau, evidence of partial melting and shock metamorphism are often seen (Figure 5). In the crystallization map of the North America continent (Kay 1955, see p. 20 of Wilson ed. 1972), the Colorado Plateau region is represented by juxtaposed crystalline ages of two distinct time periods – a feature that is unique across the entire the North America Continent – one around 1.6 Gyr and one around 0.8 Gyr. This bi-model distribution of the crystalline Precambrian rocks (one for the older high-metamorphic-grade Gneiss and Schist, and another for the lower-grade metamorphosed late-Precambrian sediments), can be found across the entire Colorado Plateau region.

5. Love et al. (2003, pp. 38-39) mentioned that on Mount Moran (12,605 ft, or 3,842 m), which is part of the northern Teton Range in Wyoming, the 150 ft (50 meter)-thick black dikes near the summit of the peak, which cut across older Precambrian rocks, are similar to the dikes in Tobacco Root and Beartooth Mountains in Montana, which had been dated by S.S. Harlan at the U.S. Geological Survey to be about 765 Million years old. Similar dikes can also be found cutting through the Grand Canyon Supergroup (Blakey and Ranney 2008, p. 8).
6. In all four states of the Colorado Plateau (Colorado, Utah, Arizona and New Mexico), there exist shales and quartzites of Mesoproterozoic to Neoproterozoic ages (the age dating is complicated by the sometimes milder degree of metamorphism, which can confuse the age of deposition and the age of metamorphism). In Utah, this is the well-known Uinta Mountain Group (Hansen 2005, p. 73, 76; Bennis-Smith et al. 2008). In the western San Juan Mountains of Colorado, this is represented by the Uncompahgre Formation (Baars 1972, pp. 136-137, 140-141). In Arizona, this is represented by the Grand Canyon Supergroup, though its degree of metamorphism is less compared to that found, say, for the Uncompahgre Formation in western Colorado (Baars p. 136). In New Mexico, the cores of Sandia Peaks and Taos Range (which is the New Mexico portion of the Sangre de Cristo Mountains extending into Colorado) are both composed of metamorphosed upper Precambrian sediments. Fackelman et al. (2008) found possibly late Mesoproterozoic impact shatter cones and microscopic shock alteration to rocks northeast of Santa Fe, New Mexico, within an extended section of the Sangre de Cristo Mountains.
7. The uprising of the Colorado Plateau during the Cenozoic extension-dynamics dominated era appears to be in a coherent fashion, in contrast

to the haphazard tectonic activities in its surrounding area, indicating that the basement block underlying the Plateau was severed from the surrounding craton of the continent, and the extension dynamics apparently helped relieve some of the confining pressure from the Plateau's surrounding area, leading to the launching of the Cenozoic igneous activities in the Plateau boundary, as well as the rise of the modern version of the Rocky Mountains.

8. Sedimentary record shows that the entire North America continent, including the Colorado Plateau region, was in a very flat configuration at around 600 Ma. It is mostly above this flat terrain that the Paleozoic sedimentation was laid.

These characteristics of the Colorado Plateau and its surrounding area, added to the time correlation with the rifting of the Rodinia supercontinent at the western margin of the Colorado Plateau, point to the likelihood of a giant impact event occurring around the 750 Ma centered on the Four Corners area.

3. Characteristics of the Proposed Giant Impact Event

In this section we attempt to constrain the characteristics of the proposed giant impact event using the known properties of the Colorado Plateau, as well as other relevant information.

3.1. Size of the Impactor

We take the size of the Colorado Plateau itself as the approximate size of the impact crater. The Colorado Plateau has an area of approximately 337,000 square kilometers, thus a diameter of about 640 km (adding the section around the San Juan Mountains, increases the Plateau area by about another 11% according to Kelley 1979). Dence et al. (1977) found that for terrestrial impact craters, progressively larger craters tend to have progressively shallower profiles. They quoted results for the 3.6 km Steinheim Basin and Flynn Creek structures (Roddy 1977a,b; Reiff 1977), which has a depth-to-diameter ratio of 1 to 24. In our following estimation, we take the impact crater depth h_{cr} to be 1/40 of its diameter, i.e., $h_{cr} = 16km$. This depth is reasonable considering that the estimated original depth for the Grand Canyon Supergroup is up to 4 km thick, and the Supergroup itself, since it consists of faulted blocks, does not contain the original bottom contact to the basement rock, which is 1.7 Gyr old. Furthermore, we need to consider the possibility that the entire Plateau block may have sunk slightly into the Asthenosphere as a result of the impact, since it is obviously severed from the surrounding craton, judging from its structure integrity.

From a simple geometric consideration (see Figure 6 later), the impactor's radius R_{imp} is obtained as (taking the radius of the impact crater $R_{cr} = 1/2 D_E = 320km$)

$$R_{imp} = \frac{R_{cr}^2 + h_{cr}^2}{2 \cdot h_{cr}} = 3208km. \tag{1}$$

Therefore the hypothesized impactor is slightly smaller than Mars' size ($R_{mars} = 3386km$).

3.2. Energetics of the Impact Event

According to Goldsmith (2001) and the references therein, at low and intermediate range of impact velocities when the fusion or vaporization of the bodies involved can be neglected, the resisting force to the impactor can be expressed by the following empirical formula:

$$\begin{aligned} F &= -M_{imp} \frac{dv_{imp,before,\perp}}{dt} \\ &= B_1 v_{imp,before,\perp}^2 + B_2 v_{imp,before,\perp} + B_3, \end{aligned} \tag{2}$$

where the three terms on the right hand side are contributions due to the acceleration of the target material adjacent to the impactor, the effect of the frictional forces, and the cohesive strength of the target, respectively, and $v_{imp,before,\perp}$ represents the vertical component of the impactor's velocity relative to the target, before the encounter occurs, and M_{imp} is the mass of the impactor.

For higher impact velocities (as is relevant to the Colorado Plateau impact event), on the other hand, it is often postulated that the crater volume is proportional to the kinetic energy of the impactor.

Dence et al. (1977) found that for large impactors the diameter of the excavated crater D_E and the energy of the impact E_{imp} follow roughly the relation

$$D_E(km) = 9.7 \times 10^{-5} E_{imp}^{1/4}(J). \tag{3}$$

Take $D_E = 640$ km, we obtain $E_{imp} \approx 1.7 \times 10^{27} joules$.

Our impactor is likely to have collided with the Earth in an oblique angle, judging from the slightly elongated shape of the Colorado Plateau. Taking the impactor's vertical velocity (relative to the surface of the Colorado Plateau) before the encounter to be $v_{imp,before,\perp} = 5km/sec$ (and we also assume that the impactor's horizontal velocity relative to the Plateau is $v_{imp,before,\|} = 5km/sec$, to be used in later calculations), and taking the impactor mass to be 10% of the mass of the Earth, or $6 \times 10^{26} g$, which is just slightly smaller than that of Mars, the potentially-available impact energy would be (assuming about 91% of the vertical-motion kinetic energy of the impactor is dissipated during the impact event, as our later calculation using equation (8) would suggest):

$$0.91 \times \frac{1}{2} \times 6 \times 10^{26} \times (5 \times 10^5)^2 = 7 \times 10^{37} ergs$$
$$= 6.8 \times 10^{30} joules, \tag{4}$$

which is larger by more than 3 orders of magnitude than the estimation using the Dence et al. (1977) equation which we quoted above. However, we need to keep in mind that the excavation of the Colorado Plateau is not the only usage of the impactor's available kinetic energy. From the global-presence of the Great Unconformity of the late Precambrian period, which we had briefly commented before, it is likely that the entire Earth had lost a significant portion of the late-Precambrian sediments through strain-energy-release induced evaporation (i.e., the Earth will be ringing like a gong after the impact, just like the case of seismic waves after an earthquake. See Stein and Wysession 2003. Note that the initial strain waves are likely to be shock waves, rather than elastic waves. See Melosh 1996, p. 29ff). Furthermore, the impactor itself likely had suffered crustal vaporization as well during to the same impact event, which will also absorb part of the energy budget. Some of the strain energy release will also be dissipated as heat, both along the Plateau's boundaries, as well as in its bottom interface with the Asthenosphere. Still further deposited energy on Earth will be used to accelerate the broken pieces of the Rodinia supercontinent, though there is evidence that there might be a time delay between the time of the impact and the time of the actual rifting of Rodinia.

If, on the other hand, we use directly the $7 \times 10^{30} J$ potentially-available impact energy, we obtain an equivalent *maximum possible* cratering *diameter* of 4989 km according to the above Dence et al. (1977) equation. This is slightly smaller but of the same order as the *radius* of the Earth at 6371 km. The global Great Unconformity is inhomogeneously distributed, with the energy dissipation right under the Colorado Plateau the most concentrated, and elsewhere the shedding of the late-Precambrian sediments varies by degrees. This is likely a result of the subsequent propagation, reflection and interference of the strain waves produced by the impact, once again similar to the seismic waves produced during normal earthquakes. Therefore, we see that our energetic estimations for the impact event is at least of the correct order of magnitude.

As a comparison, the 65 Ma asteroid impact event proposed by Alvarez et al. (1980), which possibly had led to the extinction of the Dinosaurs, assumed an impactor diameter of 10 km, and roughly 4×10^{30} ergs of impact energy, which is more than 7 orders of magnitude smaller in energy than the possible impact event for the formation of the Colorado Plateau. But then, the 65 Ma event did not lead to the breakup of a supercontinent, or a globally-present Great Unconformity, though its effect may be partly responsible for the subsequent uprise of the Colorado Plateau as well as the Rocky Mountains during the Laramide Orogeny.

3.3. Kinematics and Dynamics of the Impact Event

We now estimate the remaining impact parameters using the energy and momentum conservation relations.

We assume that a fraction k of the vertical-motion kinetic energy of the impactor will be left, after dissipation, to drive the post-impact combined motion of the impactor plus the Earth in the vertical direction (the assumed transverse motion of the impactor with respect to the Earth will help carry it away from the Earth, post impact). We therefore assume that immediately post impact, the impactor and the Earth have the same vertical-motion velocity $v_{out,\perp} = v_{imp,after,perp}$, with respect to the frame of reference of the original equilibrium orbit of the Earth, whereas the pre-impact vertical velocity of the impactor with respect to the Earth is $v_{imp,before,\perp}$ (see Figure 6 below).

In the following calculations, we ignore initially the Earth's orbital velocity of 30.5 km/sec (but will in the end make an estimate of the effect of the impact on Earth's orbit around the Sun). This is equivalent to assuming that the impactor had obtained certain degree of dynamical equilibrium within the Solar System when it reached the Earth's location, apart from its peculiar velocity with respect to the Earth. Due to the large mass of the impactor, the impact speed could not have been much higher than what we assumed here $5km/sec$ for both the vertical and the horizontal component) without causing further damage to both the Earth and to the impactor: We expect the impactor to have survived the impact event as well, because the Mogollon Rim in Arizona, where the impactor exited according to our model, has its corresponding bowl-shape as well, even though not as steep as the north side, i.e., the Uinta Mountains and the Colorado Rocky Mountains where the impactor made its initial landing. Furthermore, across the Plateau, the minor fault lines (as well as many elongated uplifts and basins) have directions mostly aligned perpendicular to the expected trajectory of the impactor across the Plateau, see, e.g. p. 38 of the Geologic Atlas of the Rocky Mountain Region, 1972; or Kelley (1979, Fig.1). This shows that the impactor most likely skidded across the Plateau from NE to SW and made an exit around the Mogollon Rim region, rather than totally evaporated during the impact process.

Furthermore, in the following calculations we will also ignore the Earth's spin velocity at the surface of 0.46 km/sec, because the effect of the Earth's spin velocity upon the impact event will depend on the exact orientation of the impactor's trajectory with respect to the Earth's spin, which in turn will depend on the exact location and orientation of the Rodinia supercontinent at the time of the impact (if our assumption about the NE-SW trajectory of the impactor with respect to the current orientation of the Colorado Plateau is correct), which we have only imprecise knowledge (i.e., certain models suggest that in late Precambrian Rodinia is located near the Equator, and North America is rotated 90 degrees from its current orientation). The magnitude of the Earth's spin velocity will in any case not affect the order-of-magnitude nature of our following calculations.

Using the equations of momentum and energy conservation, and assuming the impactor has a fraction f_{imp} of the mass of the Earth, we have

$$\begin{aligned} & f_{imp} \cdot M_{earth} \cdot v_{imp,before,\perp} \\ & = (1 + f_{imp}) \cdot M_{earth} \cdot v_{out,\perp}, \end{aligned} \tag{5}$$

and

$$\begin{aligned} & k \cdot \frac{1}{2} \cdot f_{imp} \cdot M_{earth} v_{imp,before,\perp}^2 \\ & = \frac{1}{2} \cdot (1 + f_{imp}) \cdot M_{earth} v_{out,\perp}^2. \end{aligned} \tag{6}$$

The solutions of which are

$$v_{out,\perp} = v_{imp,after,\perp} = \frac{f_{imp}}{1+f_{imp}} \cdot v_{imp,before,\perp}, \tag{7}$$

and for the fraction k of energy left for driving both planets' motion,

$$k = \frac{f_{imp}}{1+f_{imp}}. \tag{8}$$

Therefore, if we choose $f_{imp} = 0.1$ (i.e the impactor to have 10% of Earth's mass, which makes it similar in mass as well to Planet Mars), then k=0.09, or about 9% of the impactor's vertical-motion kinetic energy is used to contribute to the residual vertical motion of the Earth plus the impactor. Therefore, 91% of the impactor's vertical motion kinetic energy relative to the Earth is dissipated during the impact event, as we had used previously.

Assuming 10% lost of the impactor's velocity component parallel to the Earth's surface due to friction (i.e., it should have skidded along its path within the Colorado Plateau for about 30 seconds covering a distance of 150 km, so $v_{imp,\parallel}$ is reduced from 5 km/sec to 4.5 km/sec during the impact process), the total velocity of the impactor before and after the impact are $v_{imp,before} = 7.07\ km/sec$ and $v_{imp,after} = 4.52\ km/sec$, and for the Earth, the excess velocity it gained is on the order of $v_{out} = 0.45 km/sec$. Taking into account of the directional effect, the coefficient of restitution for the impact event is about 64%.

3.4. Effect on Earth's Orbit Around the Sun

Prior to the impact, assume the Earth is on an orbit around the Sun similar to its current orbit. The mass of the Sun is 1.989×10^{33} g, the Sun-Earth distance is $R_{sun-earth} = 1.5 \times 10^{13} cm$, and using a gravitational constant $G = 6.674 \times 10^{-8} cm^3 g^{-1} s^{-2}$, we obtain the gravitational attraction force between the Sun and the Earth to be:

$$\begin{aligned} F_{sun-earth} &= 6.67 \times 10^{-8} \frac{5.98 \times 10^{27} \times 1.989 \times 10^{33}}{(1.5 \times 10^{13})^2} \\ &= 3.6 \times 10^{27} dyne. \end{aligned} \tag{9}$$

On the other hand, the average impact force F_{imp} can be estimated from:

$$F_{imp} \cdot \Delta t = M_{imp} \Delta v_{imp,\perp}. \tag{10}$$

(Our late calculation show that essentially all the impact force will be used to generate the excess rectilinear motion of the Earth, in sharp contrast to the situation with energy, which is mostly dissipated during the impact event).

Taking once again the impact duration to be about 30 seconds, and from the calculation done using equation (6), we obtain $\Delta v_{imp,\perp} = v_{imp,before,\perp} - v_{imp,after,\perp} = 4.55 km/sec$, the mean impact force is thus found to be

$$\begin{aligned} F_{imp} &= \frac{6 \times 10^{26} \cdot 4.55 \times 10^{5}}{30} \\ &= 9.1 \times 10^{30} dyne, \end{aligned} \tag{11}$$

which is significantly larger than the gravitational attraction between the Sun and the Earth. Thus, the Earth will indeed be accelerated to the terminal velocity $v_{out,\perp}$ which we had determined last time,

$$\begin{aligned} v_{out,\perp} = v_{imp,after,\perp} &= \frac{f_{imp}}{1 + f_{imp}} \cdot v_{imp,before,\perp} \\ &= 0.09 v_{imp,before,\perp} = 0.45 km/sec. \end{aligned} \tag{12}$$

The circular velocity of the Earth's orbit around the Sun, on the other hand, is around 30.5 km/sec. The ratio of the after-impact velocity to pre-impact velocity is thus on the order of 1.01. The eccentricity of the Earth's orbit is about 0.0167, and it varies historically between $0.0034 - 0.058$. Therefore, the impact contributes to the variation of the Earth's eccentricity within its normal range of variation.

3.5. Shear Strength and Impact Fracture of the Colorado Plateau and of the Rodinia Continent

As we have obtained previously, the average impact force, assuming a 30 second impact duration and the near total (i.e. about 90%) dissipation of the vertical-motion kinetic energy of the impactor on the Earth, is about $10^{31} dyne$. From the integrity of the Colorado Plateau, it is likely that the entire Plateau block is at least partially severed from its surroundings. Taking the thickness of the partially severed Plateau to be $H_{CP} = 150 km$ (i.e., roughly all the way to the bottom of the Lithosphere), we obtain that the *maximum possible* shear stress experienced by the Colorado Plateau due to the impact event is on the order of

$$\sigma_{CP,max} = \frac{F_{imp}}{2\pi R_{CP} H_{CP}}$$

$$= 3 \times 10^{15} dyne \cdot cm^{-2}. \tag{13}$$

For the Rodinia supercontinent, assuming its severed length to be about 2000 km, and once again taking the severing depth to be $H_{Rodinia} = 150km$, we can similarly estimate the *maximum available* shear stress due to the impact to be

$$\sigma_{Rodinia,max} = \frac{F_{imp}}{L_{Rodinia} H_{Rodinia}}$$
$$= 3 \times 10^{15} dyne \cdot cm^{-2}. \tag{14}$$

Therefore, we see that the maximum-possible shear stress experienced by these two structures are comparable.

Ohnaka (2013, p.75) presented a linear relation between the shear failure strength τ_{p0} for dry Westerly granite at room temperature, which depends linearly on the normal stress σ_n, which is the same as the confining pressure, as (equation unit in MPa):

$$\tau_{p0} = 135.7 + 0.75\sigma_n. \tag{15}$$

For higher ambient temperatures, the slope and intercept of the above equation both decrease progressively. At the deep end of the Lithosphere of 150 km, with temperature around 1000 K, the slope to use is around 0.37 and the intercept is about 50 for the above equation, according to Figure 3.11 of Ohnaka (2013). The normal stress at the depth of 150 km is about 4500 MPa (i.e., about 30 MPa per km increase in depth). Therefore, the maximum shear failure strength for the Colorado Plateau at the boundary of the Lithosphere and Asthenosphere is about 1700 MPa, or $1.7 \times 10^{10} dyne/cm^2$, which is more than 5 orders of magnitude smaller than the maximum shear stress we had calculated above, *if we assume* all the impact force is used to produce the shear. However, this assumption that the total impact force is equal to the shear force is *not at all* reasonable: The Earth, as we know, was (and is) totally unsupported apart from the gravitational attraction of the Sun which keeps it in orbit. And the gravitational force from the Sun is small compared to the impact force, which means that the majority of the impact force will be used to accelerate the Earth to the terminal velocity which we had calculated above according to momentum conservation. Of the total impact force, only a very small fraction acts *differentially* at the boundaries of the Colorado Plateau, due likely to the differential propagation time of the strain waves arriving at the different locations across the Plateau's boundary. It is this differential stress that provided the shear force which led to the severing of the Plateau from the parent craton, as well as the rifting of the Rodinia supercontinent.

Furthermore, since the Colorado Plateau is not entirely severed, the local differential shear force actually present during the impact event should be on the order of the shear strength of the material times the area of the shearing surface (which we had calculated above to be $2\pi R_{CP} H_{CP}$ for the Plateau, and $L_{Rodinia} H_{Rodinia}$ for the boundary of the Rodinia supercontinent). Therefore, the actual shear force should be on the order 10^5 times smaller than the total impact force, i.e., the total shear force (on Rodinia or else on the Colorado Plateau) would be on the order of $10^{26} dyne$ (here we take the high end of the above shear strength estimation, considering that the large mass of the Plateau may give it additional strength due to long-range correlations of the highly metamorphosed basement rocks).

With the average shear strength of the Plateau region thus calculated to be about 1.7 GPa, we compare it to the peak shock pressure estimated for the Santa Fe impact structure (Fackelman et al. 2008), which is about 5-10 GPa. We see that these two estimates are at least not in conflict[1]. Once the critical Griffith crack length is exceeded the cracks can also self-propagate both forward (as in the case of Rodinia) and downward (as in the case both of Rodinia and the Plateau).

4. Origin of the Impactor

Even for a Mars-sized impactor to come close to Earth's orbit, the inevitable question becomes: Where did the impactor originates? At 750 Ma, the Solar System would have already gone through more than 3.8 Gyr of evolution, thus it should have long since come into a dynamically stable configuration, at least for the giant planets.

We argue that a more plausible origin for the impactor is the encounter of our Solar System with the spiral density wave crest as the Sun orbits (together with its neighboring material) the Milky Way Galaxy. Recently-advanced theories of the dynamics and evolution of spiral galaxies (Zhang

[1]Since shock metamorphism is caused by the direct impact force, rather than differential force between the direct acceleration of the material of the Plateau by the impactor, versus the indirect propagation of strain waves, we expect the former to be bigger in magnitude.

1996, 1998, 1999, 2016, 2017; Zhang and Buta 2007, 2015; and the references therein) indicate that galactic spiral arms are sites of gravitational (collisionless) shocks, due to an intrinsic azimuthal phase offset between the density and spiral perturbation patterns of the galactic density wave mode (Figure 7). This inherent phase offset, and the resulting shocks on the streaming disk matter crossing the spiral arms, can both directly perturb the stellar orbit, and also trigger the formation of massive stars. Massive stars evolve quickly and die in spectacular explosions as supernovae. The blastwave of a supernova (a rapidly expanding shock wave of material consisting of most of the mass of the original exploding massive star) can further perturb the orbits of nearby stellar objects, or else can lead to the formation of new objects out of debris material, which may acquire significant peculiar velocities with respect to the regular orbits of the streaming matter around the center of the Galaxy, leading to the possibility of the invasion of rogue exoplanets into the confines of our Solar System.

The period of the largest extinction events on Earth is approximately the same as the period that the Solar System encounters a Galactic spiral density wave arm or spur[2]. These facts lend support to the idea that the Galactic environment might have provided periodic sources of impactors to power both the major extinction events, as well as plate-tectonic cycles, on Earth. Solar-System giant planets, such as Venus, might have experienced similar giant impact event as well, since Venus is known to have a young crust of around 500 million years.

Because the spiral arms or spurs in galaxies have finite width, multiple impactors produced during the same spiral-arm crossing episode of the Sun can invade Earth's orbit during a short (from a geological standpoint) period of time. This may explain the near coincidence of the occurrences of the Decaan Traps and the Chicxulub Crater which were both dated to the K/T boundary but are spatially separated; or else the Emeishan Traps and the

[2]This assumes the Milky Way has a two-armed spiral structure. There are also spurs between the major arms, which may account for the minor peaks in the extinction plot. The minor peaks of the extinction plot may also be related to the Sun's periodic crossing of the Galactic plane in the vertical direction. Using a pattern speed for the Galactic spiral structure of $\Omega_p = 13.5 km/sec/kpc$, and the circular speed of stars at the Solar neighborhood of $\Omega = 220 km/sec/8.5 kpc$, we obtain (for two-armed spiral) that $2(\Omega - \Omega_p) = 2\pi/250 Ma$, or that the spiral-crossing period is similar to the Galactic Year at the Solar radius.

Siberian Traps in the late-Permian/early-Triassic period. On the extinction-intensity plot, this trend shows up as closely grouped major extinction events, around especially 250 Ma and 500 Ma. Our 750 Ma event continues this trend, even though at this Precambrian period there was not yet biological fossial record.

One potential issue is the phase of the Sun relative to the spiral arms of our Galaxy, which, depending on the model used, may not always put the Sun near a major spiral arm at the current epoch. However, since we do not yet know the amount (or the actual cause) of the delay between arm-crossing and the invasion of a rogue planet, we can for now at least take face value of the statistical correlation of the period of the major extinction events (especially the most-clustered of these events), and the period of the supercontinental cycle (i.e., from the formation to the rifting of a supercontinent), with the period of the Galactic spiral-arm-crossing at the Sun's orbital radius. Or at the very least, we know now that there is a possible source for large impactors from our Galactic environment.

5. Aftermath of the Impact and Further Supporting Evidence

The initial impact event, apart from splitting Australia and East Antarctica from the Rodinia supercontinent, as well as dislodging the Colorado Plateau from its surrounding craton, may also be responsible for the breaking up (after 600 Ma) of the rest of the Rodinia into Gondwana and Laurentia, which led to the formation of the proto-Atlantic Ocean, the Iapetus Ocean. These breakups may have resulted from weaknesses in the Lithosphere created by the impact, as well as isostasy effect due to the redistribution of the landmass, which could account for the apparent delay between the time of shock metamorphism (0.7-0.8 Ga) and the time of the actual rifting (0.6-0.7 Ga) of both Rodinia and the proto-Atlantic.

The dislodged Plateau did not start its uprise right away, due to the confining pressure from its surroundings. Immediately after the impact, though, in a flattened landscape (due mostly to impact-induced evaporation of material) there would be no tall mountains to erode, thus no immediate re-sedimentation after 750 Ma, until the beginning of the Cambrian (540 Ma). This explains the widespread "Great Unconformity" which is a gap in sedimentation generally between 540 Ma and 1.4-1.7 Ga (depending on locales). On the other hand, metamorphosed late-Precambrian sediments are represented by the Grand-Canyon Supergroup, Uinta Mountain Group, and Uncompahgre Formation on the Colorado Plateau, their varying degrees of metamorphism likely produced by their varying locations during impact event, with, say, the Grand Canyon Supergroup dropped into a fault and thus was protected from high-grade metamorphism, and the Uncompahgre Formation of the San Juan Mountains apparently suffered a higher degree of impact shock metamorphism (Baars 1972, pp. 136-137). On a field trip, the author discovered that on UT-191 near the Flaming Gorge area, the degree of metamorphism of the Uinta Mountain Group rocks can change drastically within the distance of several hundred feet (a hundred meters), due apparently to the differing positions of the rocks with respect to the local faults (thus their varying degrees of being shielded by the faults during the impact shock metamorphism process).

Further north from the Colorado Plateau, in Wyoming, younger Precambrian quartzite pebbles litter the Teton Village and Jackson Hole community. Love et al. (2003, p. 59) stated that the origin of these quartzite pebbles was not local, and they appeared similar to the metamorphosed Proterozoic sedimentary rocks in southwest Montana and nearby parts of Idaho. It is possible that in these northern neighborhoods of the Colorado Plateau some of the quartzites may have been thrown out of the impact crater (the Colorado Plateau), which would explain the nonlocal nature of the quartzite pebbles in the Jackson Hole area. One might question whether the current distance of the Jackson Hole area to the boundary of the (traditionally defined) Colorado Plateau might be too far for this scenario to be possible. Here we must take into account that the Basin-and-Range extension dynamics in the Cenozoic Era has led to enlargement of the distance between landmarks by about a factor of two, and the Yellowstone-Teton-Snake River Basic area have been shown to be fully affected by such extension dynamics, just as in the neighboring Navada. Once this is taken into account, the distances involved become entirely within the dimensions common to impact-excavated crater outer rims (Dense et al. 1977; Melosh 1996). Furthermore, Dutton (1882)'s original consideration to include part of the Rocky Mountains north of the Uinta Uplift into the definition of the Colorado Plateau may have some grains of truth if this northern addition to the Plateau (put into its right place before the Basin and Range extension dynamics had stretched it northwest of its original location at the late Precambrian time) had been the initial touch-down spot of the impactor.

6. Conclusions

We have proposed and demonstrated that a diverse range of geomorphology features of the Colorado Plateau can be naturally accounted for if they are the results and aftermath of a giant impact event at 750 Ma. These features include: (1) The surprising structural integrity of the Plateau during the past 600 Ma, despite the vigorous igneous and orogenic activities at its boundaries; (2) The occurrence of the so-called "Great Unconformity" throughout the Plateau region, as well as elsewhere in the world; (3) The wedged insertion of large chunks of the late-Precambrian Grand Canyon Supergroup sedimentation sequence into the basement rocks of the Vishnu Complex, as well as the similarity in age of the upper-most deposition layer of the Supergroup to the rifting of the Rodinia supercontinent at 750 Ma from the Plateau's western edge; (4) The Plateau-wide presence of metamorphosed late-Precambrian sediments which often display evidence of shock metamorphism; (5) The thick basalt dikes cutting through basement rocks on the Plateau, as well as further north in the Rocky Mountains, which can be dated to about 750 Ma. We further demonstrated that a Galactic spiral-density-wave induced, Mars-sized rogue planet is likely to be the impactor colliding with the Earth at about 750 Ma, that ultimately led to the formation of the Colorado Plateau we see today.

Acknowledgment

The work described in this paper was inspired by the pioneering studies of Professor Hongren Zhang (1934-2016), the author's father, on a possible giant impact origin of the eastern China geomorphology. The proposed impact event, termed Yan Shan Event by Prof. Zhang (H. Zhang [1998, 2016]; H. Zhang et al. [2013]; Li et al. 2014), was a possible precursor to the more well-known Yanshan Movement, a designation referring to a series of major tectonic and orogenic activities in East Asia starting from the middle Jurassic period.

The idea of a possible giant impact origin for the Colorado Plateau came to the author independently, during an Oct. 2016 field trip to the southwest of the US, following her decision to carry on her late father's unfinished quest in exploring the possibility of giant-impact-induced plate tectonic motion, even though her previous expertise was mostly in astrophysics. After more than a year of intensive study and several additional field trips, which resulted

in the current manuscript, the author came upon recently a popular-science article on the Smithsonian Air and Space Magazine website, by Paul D. Spudis, a senior staff scientist at the Lunar and Planetary Science Institute in Huston, TX (Spudis 2015). The article speculated on the possibility that the Colorado Plateau might be an ancient impact scar, though giving no quantitative information to support this hypothesis. Spudis also mentioned that the idea of a giant impact origin for the Colorado Plateau had been in the air, and he first learned it years earlier from Professor Carleton Moore, then Director of the Center for Meteorite Studies at Arizona State University. So far the author has been unable to find a mention of this idea in scholarly articles published to date.

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Figures

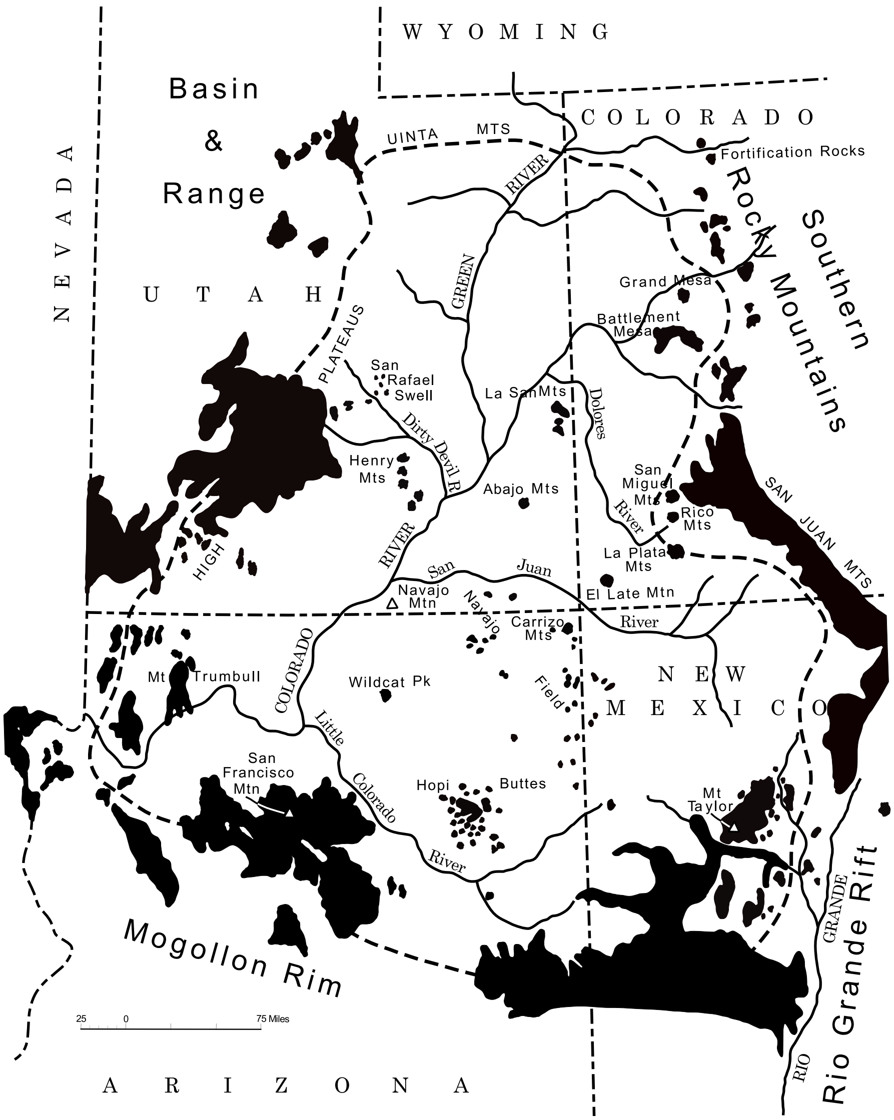

Figure 1: The Colorado Plateau, enclosed within the dashed line, and its Cenozoic igneous rocks, in shade. After Hunt (1956).

Figure 2: Great Unconformity Near Baker's Bridge, Colorado. The Baker's Bridge Granite (~ 1.72 Ga, or 1.72 billion years of age) is overlain by the Upper Devonian Elbert Formation (~ 380 Ma). Author's photo.

Figure 3: Tilted rock sections along CO-550 in the western San Juan Mountains (part of the Rocky Mountains). Author's photo.

Figure 4: Faulted and folded Uncompahgre Formation south of Silverton, Colorado, along the route of Durango-Silverton Narrow Gauge Railroad. Author's photo.

Figure 5: Roadcut along CO-550 in the western San Juan Mountains, showing evidence of shock metamorphism in the exposed rock units. Author's photo.

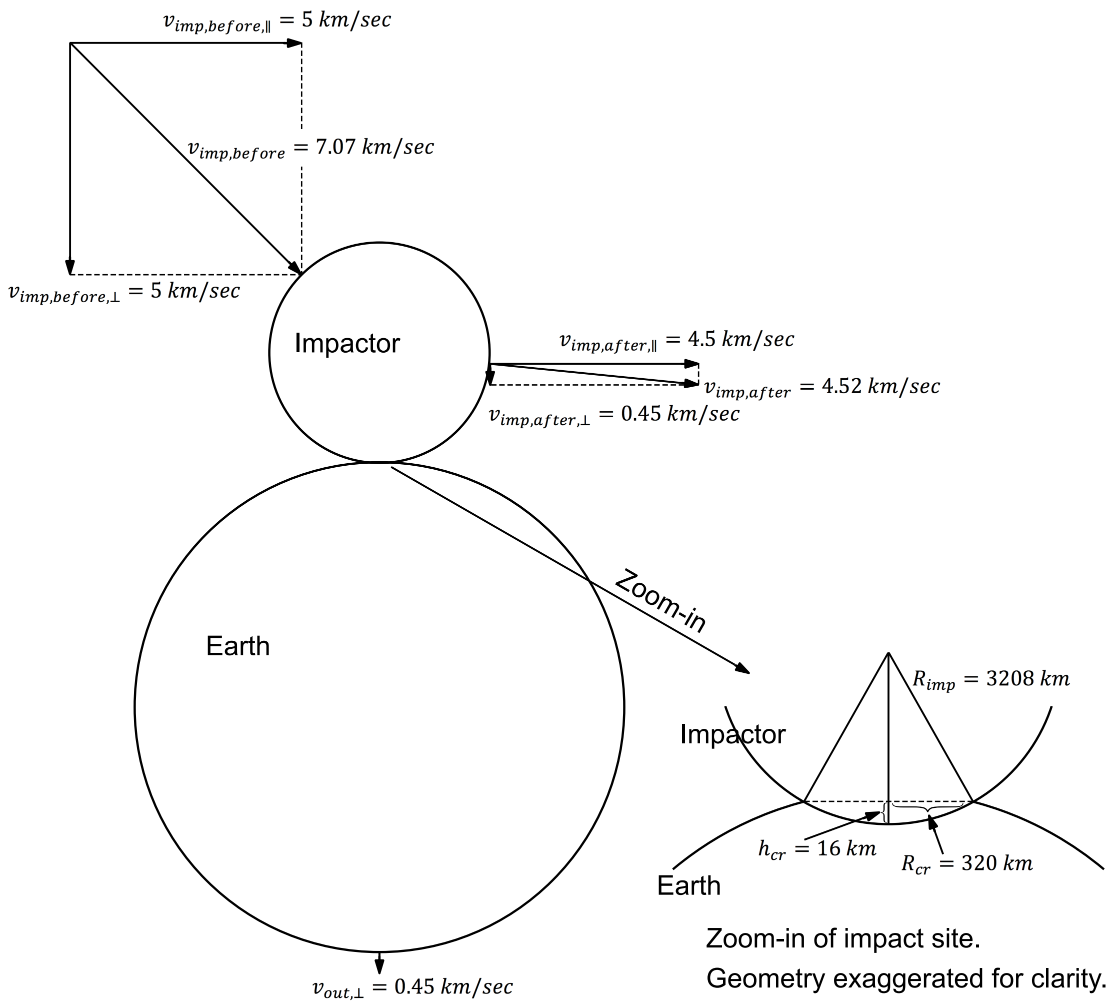

Figure 6: Schematics of the Impact Event. Earth's orbital and spin motion not shown in the figure, and not included in the impact calculation.

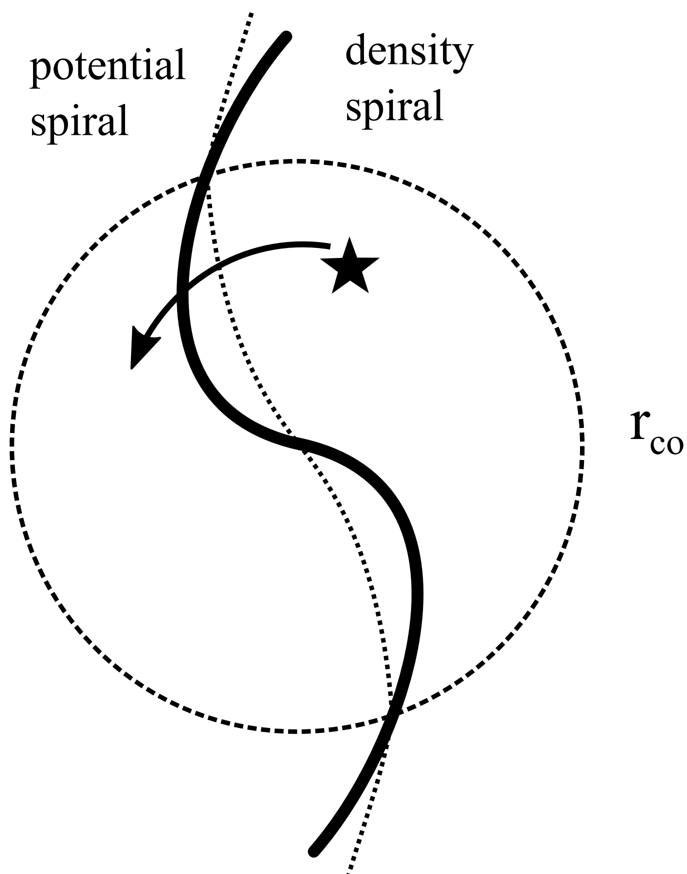

Figure 7: Potential (dashed) and density (solid) spirals in a disk galaxy possessing intrinsic density wave mode of spiral type. The position of a typical star (such as our Sun) inside the corotation radius (r_{co}, where the density wave and the orbiting stars rotate with the same angular speed) is also marked. The Sun overtakes the spiral density wave periodically in its orbital motion around the center of the Milky Way (after Zhang 2017).