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Impact tectonics; beyond the craters.

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Abstract:	This paper introduces a new set of five (5) hypotheses on how large-bolide (asteroid or comet) impacts on Earth are an integral but overlooked part of plate tectonic theory. The hypotheses reflect over a decade's research and characterization of impact-tectonic far-field (ITFF) crustal and lithospheric strains stemming from the two well-known and thoroughly characterized Chicxulub (~66 Ma) and Chesapeake (~35 Ma) impact craters on the North American plate. Impact-tectonics research has traditionally focused on cratering processes and near-crater strains whereas consideration is given here to the prospect of catastrophic, sudden upheavals occurring thousands of kilometers away from the crater upon impact from the imparted ground energy that dissipates both rapidly upon impact and then more slowly through time. The main problem with identifying and cataloguing suddenly versus uniformly imparted tectonic strains is that there is no basis to do so. That is, far-field, impact-generated secondary structures and plate reorganizations are not currently thought to stem from large impacts and are therefore not an integral part of plate-tectonic theory. This hampers our understanding of many enigmatic geological features and processes like diatremes, hot-spots, kimberlites, and epeirogenic uplifts that currently have no or little causative explanations in our current plate-tectonic paradigm. Remotely sensed Earth data are integrated and compiled in this paper to show that the Chicxulub impact likely resulted in major plate reorganization in its wake and has direct ties to epeirogenic uplifts of Laramide age in the North American plate. Moreover, similar crustal and lithospheric ITFF strains mapped for the Chicxulub impact are also seen scaled-down with respect to the Chesapeake impact in the Mid-Atlantic region of the Eastern USA. Computer-generated geometric models of the ITFF strains are developed and shared in order to advance our understanding of these processes that have recently come to light with the advent of computerized geographic information systems, global-positional-system and openly shared geospatial data.

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May 3, 2019

Cover letter

Dear *Geosciences Frontier* editorial staff,

Please accept this manuscript titled *Impact tectonics; beyond the craters* that details far-field, tectonic strains stemming from large, hypervelocity bolide strikes on Earth. It is a concept that is long overdue in geology, one that reignites the flames of catastrophism within a discipline founded on the guiding principles of uniformitarianism. This research article fits precisely into your mission of providing innovative, challenging concepts related to understanding lithospheric and mantle dynamics. This work was not possible before the advent of Global Positioning Systems (GPS) and Geographic Information Systems (GIS) that have evolved and proliferated over the past two decades. We are in the midst of an information bloom born out of the invention of personal computing, the Internet, and having unfettered, open-access to publicly share technical data. I stumbled upon this new outlook upon integrating the base-available geospatial data for the most thoroughly characterized continent (so far), which was not possible at the beginning of my career just over 30 years ago because we lacked the ability to look introspectively back on Earth as if peering through a telescope at another terrestrial planet or Moon. However with the advent and use of remote sensing, GPS, and GIS we can now see plate tectonics from a different perspective, and as I say in the paper, one that's not all uniformly staged. But knowing that paradigm shifts in science are normally slow, tedious processes constrained by the scientific method, I also hope that the aforementioned information revolution expedites this transition to what is recognized in evolutionary biology as punctuated equilibrium – a paradigm that transcends our oversimplified views of plate tectonics to allow for periodic upheavals of Earth's crust that modern humans simply have yet to experience because of the nature of deep time. Significant advancements in science can be made with an open mind and by imagining the implications and possibilities.

Sincerely,

Gregory C. Herman, PhD
email: Gregory.Herman@raritanval.edu

Highlights:

Large asteroid and comet impacts on Earth contribute to plate tectonic processes.

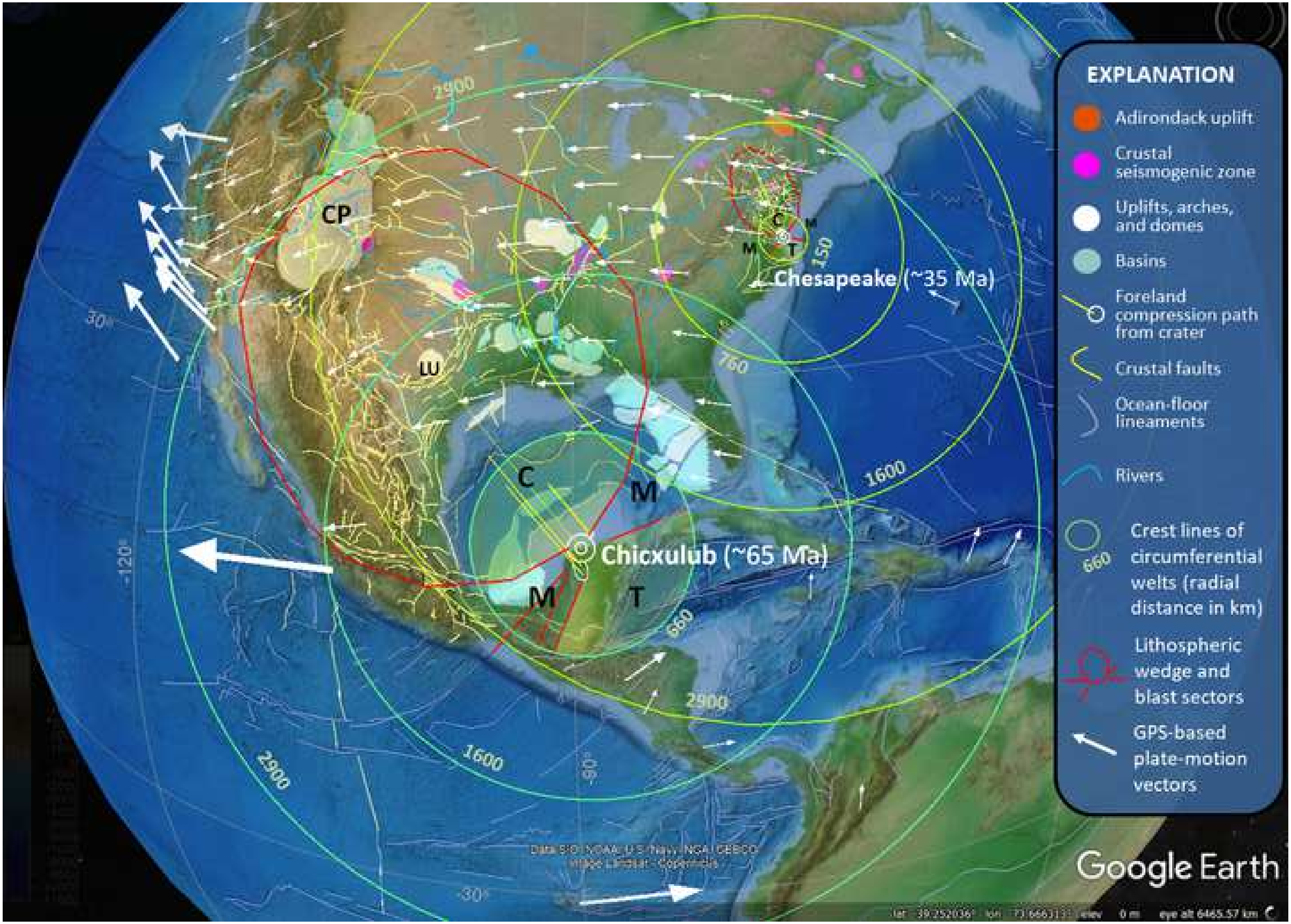
Suddenly imparted lithospheric and crustal strains occur at great distances from craters.

Impact-tectonic, far-field lithospheric strains reflect Earth's compositional layering.

Geological accounting of impact-tectonics strains has only begun.

Punctuated equilibrium serves as a guiding principle for plate tectonics.

Graphical Abstract



Title page

Impact tectonics; beyond the craters

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Manuscript

May 2019

Impact tectonics; beyond the craters

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1.0 Abstract

This paper introduces a new set of five (5) hypotheses on how large-bolide (asteroid or comet) impacts on Earth are an integral but overlooked part of plate tectonic theory. The hypotheses reflect over a decade's research and characterization of impact-tectonic far-field (ITFF) crustal and lithospheric strains stemming from the two well-known and thoroughly characterized Chicxulub (~66 Ma) and Chesapeake (~35 Ma) impact craters on the North American plate. Impact-tectonics research has traditionally focused on cratering processes and near-crater strains whereas consideration is given here to the prospect of catastrophic, sudden upheavals occurring thousands of kilometers away from the crater upon impact from the imparted ground energy that dissipates both rapidly upon impact and then more slowly through time. The main problem with identifying and cataloguing suddenly versus uniformly imparted tectonic strains is that there is no basis to do so. That is, far-field, impact-generated secondary structures and plate reorganizations are not currently thought to stem from large impacts and are therefore not an integral part of plate-tectonic theory. This hampers our understanding of many enigmatic geological features and processes like diatremes, hot-spots, kimberlites, and epeirogenic uplifts that currently have no or little causative explanations in our current plate-tectonic paradigm. Remotely sensed Earth data are integrated and compiled in this paper to show that the Chicxulub impact likely resulted in major plate reorganization in its wake and has direct ties to epeirogenic uplifts of Laramide age in the North American plate. Moreover, similar crustal and lithospheric ITFF strains mapped for the Chicxulub impact are also seen scaled-down with respect to the Chesapeake impact in the Mid-Atlantic region of the Eastern USA. Computer-generated geometric models of the ITFF strains are developed and shared in order to advance our understanding of these processes that have recently come to light with the advent of computerized geographic information systems, global-positional-system and openly shared geospatial data.

2.0 Introduction

Plate tectonics is a unifying geological theory that evolves together with our ability to sense and characterize natural phenomena. Ribiero (2000) pointed out that Earth is an open, geodynamic system subject to external stimulation that current plate-tectonic theory simply doesn't account for. Empirical observation shows us that the perpetual, gradual tectonic shifts that we map and catalogue do not include causal mechanisms for enigmatic tectonic phenomenon like diatremes, hot-spots, kimberlites, and epeirogenic uplifts. With the advent and use of modern digital computing and remote sensing, clearer pictures are emerging on how geodynamic systems and plate tectonics work, and it isn't all uniformly staged. Of note here is how far-reaching, lithospheric strain fields are imparted to Earth from large-bolide (asteroid or comet) impacts that are an integral part of its tectonic history. But it remains sketchy how these strain fields formed, how they overprint earlier orogenic belts and influence subsequent geodynamic movements. The main problem with differentiating and partioning terrestrial strain features between those suddenly versus gradually formed is that there currently is no basis to do so. That is plate-tectonic theory currently doesn't factor in the energy absorbed from catastrophic, large-bolide impacts with the resulting momentum transfer and net strains. That's a big problem which hampers our understanding and characterization of many geological features that probably form suddenly as a result of large-bolide collisions occurring at hypervelocity speeds (>3 km/sec). This paper focuses principally on crustal and lithospheric strains seen using physiographic, geologic, and geophysical data. More consideration with respect to deep mantle strains and momentum changes resulting from impacts will be required.

Prior impact-tectonic research has focused principally on near-crater effects and crustal strains and little attention has been directed beyond the crater where far-field strains also occur. On Earth, It's vital to be able to identify and account for such widespread strain fields and long-lasting geodynamic consequences stemming from punctuated large-impact events versus those resulting directly from the constant and gradual processes currently addressed by plate tectonic theory. Our Moon is thought to have been spalled off Earth by collision with an extremely large extraterrestrial body early in the bombardment phase of our accretion history, but today, there is absolutely no accounting of any plate reorganizations or geodynamic changes resulting from any one of a large number of punctuated impact events reflected in geological time. Recast as a question, can the sudden excavation, compaction, and shearing of the lithosphere caused by oblique, hypervelocity bolide impacts raise mountains and form expansive basins at great distances beyond the crater in a geological instant?

3.0 The Chicxulub and Chesapeake Impact events

Impact-tectonics far-field (ITFF) strains are brought into focus here with respect to the Chicxulub (~65.0 Ma) and Chesapeake (~ 35.5 Ma) impact craters (fig. 1). The Earth impact database (2011) lists the diameter of the former as 150 km and the latter at 40 km. Both craters have been intensively studied and are portrayed here as having formed as a result of oblique, hypervelocity (>3 km/s) strikes from the southeast (SE) towards the northwest (NW) at 45^{o} incident angles (figs. 3 and 5). The impact angle for the Chicxulub event may have been as low as 25-30^{o} based on crater asymmetry, fern spikes and palynofloral extinctions across North America (Schultz and D'Honndt, 1996). However, determining the speed, obliquity, and direction of a bolide impact is fraught with uncertainty and is constrained only in the case of low-incident impacts (<30^{o}) that develop visual variation in form including oblong crater shapes and symmetric, distal ejecta blankets (Schultz and Gault, 1990). A 45^{o} incident angle is statistically the most probable one (Gault and Wedekind, 1978; Schultz and Gault, 1990; Ormo and others, 2013) and is used here for developing virtual geometric models of the various ITFF strain fields detailed below. Integrated geospatial data and computer-aided drafting (CAD) models are used to help show how enormous, brittle strain fields on Earth surround these large impact craters, and in the case of Chicxulub, change the course of plate dynamics (fig. 2).

The Chicxulub impact crater is world renowned owing to its catastrophic disruption of biological systems on Earth and division of geological time at the Cretaceous-Paleogene time boundary (K-Pg). Gulick and others (2013) provides a thorough review of the geological and geophysical characterization of this site. It was discovered and confirmed between 1970 to 1990 and is now recognized as one of Earth's youngest, multi-ring impact structures produced by multiple bolide impacts, including a very large one that produced the Chicxulub crater (170 km diameter) and several smaller ones resulting in the clustered aeromagnetic potential-field anomalies signaling multiple impact sites from a fragmented string of bolides . This 'event' is portrayed here to result from four, tightly clustered craters likely formed by the estimated 10 $\pm$ 4- kilometer-diameter Nemesis bolide (Alvarez and others, 1980), and three smaller ones with 1-km diameters.

The Chesapeake impact crater was discovered by the U.S. Geological Survey beginning in 1986 through deep coring efforts to establish an aquifer framework for the Chesapeake Bay area. The crater was confirmed and officially reported by 1992 and is currently tied for fifteenth place in the world with respect to the crater diameter (Poag and others, 1992; Powars and others, 1993; Earth Impact database, 2011). It has been reported as being the largest impact crater in the United States (Collins and Wunnerman, 2005) and the Earth's largest submarine peak-ring impact crater (Poag, 1997). At least one other smaller bolide impact of approximately the same age occurs about 340 km to the northeast of the Chesapeake crater (Poag, 1993) and with crater symmetry suggestive of a projectile fragment that was ejected downrange of the main impact (Mathur and others, 2015). It is highly probably that the Chesapeake impact was also an event involving more than one strike of a fragmented bolide. The trajectory of the oblique strike is uncertain, but portrayed here to be from the SE to the NW aligned up the axis of Chesapeake Bay, with the bay tributaries forking outward into the foreland from the primary compression path (fig. 6).

I first noticed ITFF strains imparted to the North American tectonic plate (NAP) after mapping neotectonic geospatial themes including historical seismicity and tectonic-plate motions using a geographic information system (GIS) when working at the New Jersey Geological Survey (Herman, 2006). The most apparent effects are seen from plotting ground-based global-positioning-systems data showing that tectonic plates surrounding the Chicxulub move in concert around the impact crater lying at the center of a strain-hardened hub (fig. 2). The NAP drifts horizontally at increasingly higher speeds moving away from the crater as part of a tectonic vortex that must have started whirling shortly after impact Eons ago! I was surprised to see such apparent, long-lasting geodynamic effects and remote epeirogenic crustal strains stemming from a bolide impact because catastrophic tectonic mechanisms are not reported in scientific literature. But that wasn't all. There are also circumferential patterns of intraplate crustal seismicity in the NAP lying about 1600 kilometers downrange of the Chicxulub craters (fig. 1), and horizontal velocity variations across the NAP show abrupt increases in plate velocity at 2900 km radial distance, or that corresponding to the radial depth to the Earth's core-mantle boundary (figs. 2 and 3). When circumscribing circles around the crater at those radii, it immediately became apparent that low-amplitude, far-field crustal welts and troughs also occur on the NAP that stem from the Chicxulub event that correspond spatially with many ill-explained seismogenic zones and epeirogenic uplifts including the Adirondacks and the Colorado Plateau. When evaluating similar welts stemming from the Chesapeake impact, the crest of its 2900 km welt, or crustal arch runs down the spine of the US Rocky Mountains and the Central American isthmus (fig. 1)!

Another ITFF strain feature stemming from hypervelocity, oblique bolide impacts is a thickened wedge of Earth situated downrange from the crater that is bilaterally disposed about a center line corresponding to the horizontal azimuth of the bolide's trajectory (fig. 5). The nature and physical extent of this feature is poorly understood owing to the lack of definition and recognition of this phenomenon. Many laboratory experiments have been conducted using oblique bullet-sized projectiles into Earth materials to investigate cratering phenomenon but the conditions surrounding hypervelocity events cannot be duplicated by humans in the laboratory (Schultz, 2015). From a structural viewpoint, when rock is subject to compression it fractures and shears with characteristic geometry following established criteria (Anderson, 2017; Labuz and Zang, 2012). Accordingly, an indenter compressing material at an oblique angle focuses compressive stress and strain downrange of the crater (fig. 5). This phenomenon was found by Stickle and Schultz (2012;2014) in laboratory tests using aluminum projectiles fired obliquely into plexiglass targets that resulted in mesoscopic, downward-descending structural damage zones that they termed 'tongues' in the compressed foreland sector with take-off angles parallel to projectile oblique trajectories. Immediately in front of the crater the crust and lithosphere are depressed and excavated from an impact-generated plunger effect, and in the case of the Chicxulub impact, the formation of the Gulf of Mexico. Owing to the geometry of compressive seismic waves, the depressed and excavated material near the crater leads to foreland contraction and tectonic uplift because p-wave compression paths follow concave-upward refraction paths that descend, flatten out, and then refract upward to intersect Earth's surface far beyond the crater (fig. 4). Textbook p-wave paths generated at Earth's surface are depicted as flatten near the base of the asthenosphere at about 660 km depth, and follow a return path upward to the surface nearly 3000 kilometers radial distance from an earthquake (fig. 4).

4.0 Absorbed ground energy

But at what threshold value of energy flux do geodynamic changes on Earth result from such events? The total energy involved in plate tectonics at any given moment should immediately increase by the ground energy absorbed by Earth upon collision with a large, hypervelocity bolide. That is, if the total energy spent moving all of the tectonics plates at any given second in time suddenly increases by the ground energy imparted by an impact, then using the abbreviation PTE for plate-tectonic energy:

EQ. 2 PTE_2 (Post-impact) = PTE_1 (Pre-impact) + the total impact ground energy (IGE_T)

A recent estimate of the annual energy output (or total work done) by plate tectonics on Earth is on the order of 10^{19} joules, with 60% thought to be expended though earthquake seismicity (Swedan, 2013). That's about ~10^{12} joules of work per second that Earth expends in moving its surface plates around. By comparison, the ground energy absorbed by a terrestrial planet from large bolides of the size responsible for the Chesapeake and Chicxulub craters is on the order of 10^{22} to 10^{18} joules using seismic efficiencies on the order of 10^{-2} to 10^{-6} (table 1; Shultz and Gault, 1975; Meschede and others, 2011). That's at least a million (10^{9}) times more energy suddenly being introduced into the plate-tectonic equation from a large impact. Elliot (1976) estimated the gravitational energy expended to emplace the largest thrust sheet in the Northern Rocky Mountains of Alberta Canada at about 10^{19} joules. In other words, there is more than enough ground energy introduced suddenly to terra firma from large-bolide impacts than it takes to raise mountains like the North American Rockies. That is not to say that catastrophic impact events are solely responsible for a mountain's majestic architecture, just that impact tectonics may be one causative agent of a set including ordinary tectonic orogenesis.

5.0 Impact-tectonic (IT) far-field strain hypotheses

5.1 Based on these findings, five (5) hypotheses are formally introduced here respect to the ITFF theme:

1) Large bolides with diameters over 1 kilometer that impact terrestrial planets produce widespread brittle strain fields in the lithosphere from the dissipation of imparted ground energy that extends outward beyond the crater for thousands of kilometers, and are therefore classified here as *far-field strains* versus those occurring near the crater. The threshold distance between distant versus close strains has not yet been fixed, but on Earth may lie at a radial distance approximating the 660-km depth to the subsurface seismic discontinuity at the base of asthenosphere between the upper and lower mantle (figs. 2 and 3) which plays an important role in the dynamic state of the Earth's interior.
2) Oblique, hypervelocity impacts on terrestrial planets have circumferential blast patterns around the main crater (fig.) where:
   a) The lithosphere is compacted, sheared, and thickened within a foreland sector lying downrange of the crater and bilaterally disposed about the bolide trajectory. These foreland strains include lithospheric wedging portrayed here with basal geometry following refraction paths of compressional seismic waves (p-waves) that fan out into the foreland.
   b) The lithosphere is extended and is stretched up range of an oblique impact in a hinterland sector opposing the foreland. Magma can be generated here through decompression melting and development of hot spots and aseismic ridges. This sector is referred to as the "forbidden zone" in impact cratering studies (Gault and Wedekind, 1978) owing to its characteristic lack of ejecta from low-incident impacts (<45^{o}).

c) Bi-lateral, medial sectors in the lithosphere fill gaps in the blast pattern between the foreland and hinterland sectors. These medial sectors likely involve lesser volumes of magmatism and a variety of mixed-mode faults. Variations in the geometry of a specific blast pattern are likely predicated by variations in both the physical nature of the projectile and target, impact obliquity and speed. Experimentation is needed in order to characterize these variations. These sectors have been shown experimentally to contain distal, symmetric ejecta blankets resembling butterfly-wings especially from impacts at very-low incidence angles ($<10^{o}$; Gault and Wedekind 1978).

3) ITFF strains include circumferential welting at radial distances of thousands of kilometers beyond the crater where primary seismic reflections from the impact are returned to Earth's surface off deep, interior phase boundaries (figs. 3-5). Associated mantle creep or brittle flexural lithospheric responses contributing to the development and timing of these welts hasn't been firmly constrained yet.
4) ITFF strains overprint and can perturb inherited tectonic processes on regional and sometimes global scales (fig. 3). On terrestrial planets like Earth having continuous and gradual plate tectonic shifts, very large-impacts can directly influence subsequent plate motions, but the threshold energy values between those having pronounced versus subtle or no geodynamic effects has yet to be determined.
5) The strain rates and geodynamic perturbations in plate movement occur rapidly upon impact and dissipate at decaying rates moderated by the propagation velocities of seismic waves and mantle creep. Whether periodic sudden increases in magma generation and plate motions ensue immediately upon impact and slowly dissipate through time in a systematic manner has not been generally considered or characterized with mathematical or virtual models.

5.2 ITFF Strain partitioning

If we consider how to partition impact-induced ground strains occurring in the crust, lithosphere, and asthenosphere between the various melting, ductile and brittle strain responses, then the dissipation of introduced ground energy can be partitioned between fluid, (melt), plastic (crystal plasticity) , and brittle (fracture and fault) strains:

EQ. 3 $IGE_T = IGE_M$ (melting) + IGE_D (ductile strains) + IGE_B (brittle strains)

Melt production includes all terrestrial material directly melted by conductive heating or friction, the latter of which includes pseudotachylyte formed along shear planes that may sole and be distributed within impact-generated lithospheric wedges. The ductile strains include any permanent bulk compaction and folding. Bulk compaction accounts for any penetrative, permanent solid recrystallization, reduction in porosity or increase in material density as a result of crystal plasticity and shock metamorphism. Folding strains include the buckling and flexures directly stemming from impact stresses. I am unaware of any scientific experimentation or reports of the amount of work done or energy spent from folding geological material. The set of ductile strain mechanisms for dissipating IGE is therefore:

EQ. 4 $IGE_D = IGE_M$ (melting) + IGE_C (bulk compaction) + IGE_F (folding)

It is unclear if brittle strain responses to suddenly imposed shear stresses occur in the upper asthenosphere because of high strain rates, or if they do occur, what their depth limit is and how their development and spatial distribution is influenced by varying the impact criteria listed in table 2. This topic certainly merits more consideration and testing, but analog tests using physical models is hampered by the difficulty of mimicking the projectile velocity, or the physical conditions producing planetary layering, or the time needed to dissipate the energy flux. The brittle strains are portioned into those commonly seen at Earth's surface. They include brittle fracturing (no interstitial fault slip) and the three principal fault types exhibiting dominantly normal, reverse, and transform fault slips:

EQ. 5 $IGE_B = IGE_BF$ (fracturing) IGE_BR (reverse faulting) + IGE_BN (normal faulting) + IGE_BT (transform faulting).

The total accounting of impact-induced ground energy therefore includes a set of seven possible strain responses:

EQ 6. $IGE_T = IGE_M$ (melting) + IGE_C (bulk compaction) + IGE_DF (folding) + IGE_BF (fracturing) + IGE_BR (reverse faulting) + IGE_BN (normal faulting) + IGE_BT (transform faulting)

6.0 Computer models

Soon after discovering the mapped ITFF strains surrounding the Chicxulub impact I began using computer-aided drafting systems to build virtual, three-dimensional (3D) globes of Earth including its seismological layering to visualize and examine the structural and geophysical controls on the observed strain fields (figure 3 and table 1). Early models used AutoCAD R14 software (Herman, 2006) but progress was slow as little is known or reported about impact-related geodynamics or far-field strain mechanisms. Since then I have been using SketchUp Pro CAD software to develop ITFF strain models because the program output is compatible with Google Earth (GE), one of today's most robust and universally employed virtual globes that provides seamless integration of complimentary geological and geophysical data sets to visualize and test the modelling results (figs. 1 and 6). This approach has facilitated the search for other large impacts on Earth but progress is hampered by the lack of recognition or confirmation of other large craters, many of which are undiscovered or unconfirmed as they too lay buried deep beneath younger sedimentary blankets like the aforementioned that evaded discovery for a very long time. Large craters also probably lie concealed beneath thick ice sheets or at the bottom of the seas making confirmation difficult in either case. The current Earth Impact Database (2011) has only one confirmed impact mapped in the oceanic realm which emphasizes how nascent of view we have on these processes. Nevertheless, at the time I concluded my Master's thesis that focused on 'orogenic' structures in the Pennsylvania Salient (Herman, 1984) I was unaware of the concurrent discovery of the Chesapeake Invader (Powers and others, 1993; Poag, 1999). Since then, from working in in adjacent regions of Pennsylvania, New Jersey and New York, there is ample evidence of brittle structural overprinting including sulfide-mineralized faults and veins in the central Mid-Atlantic continental region within lower Tertiary and older bedrock with probable tectonic ties to the Chesapeake crater (Mathur and others, 2015; Herman and others, 2015). Any geodynamic consequences arising from the

Chesapeake impact are not apparent like those stemming from Chicxulub, but both impacts show similar lithospheric foreland contraction, uplift, and welting (figs. 1 and).

After constructing spheres of radii equaling the main compositional phase boundaries in Earth's interior (fig. 3), a foreland wedge was next constructed to envelope a volume of the lithosphere and asthenosphere where contraction and thickening occurs downrange of the oblique strike within the compressed blast sector (fig.5). This wedge is modelled to have a concave upward; spoon-shaped base that likely corresponds to pseudotachylyte shear planes following p-wave refraction geometry (fig. 5). The sole geometry is modeled to flatten out in the case of Chicxulub near the base of the asthenosphere at about 660-km depth. The fan was built by copying the primary path, duplicating, and scaling them laterally using the cosine of successive, 10^{o} radial sectors symmetrically disposed about the principal axis of compression through a 160^{o} range across the foreland (figs. 5 and 6):

EQ 1. Length of the p-wave refraction path (L_p) = COS (α) where α = acute angle between the wedge symmetry axis and the generated p-wave arc (fig.)

The model wedge was built to show crustal depression and excavation immediately downrange of the crater but contraction and thickening beyond a crossover point where the sole fault flattens, then continues upward downrange to return shock energy to the planetary surface. This geometric transition corresponds to crustal arching and epeirogenic uplift as seen in Llano Texas and Westchester Pennsylvania with respect to the Chicxulub and Chesapeake impacts (figs. 1 and 6). The sudden, brittle, contractional strain responses in the foreland sector would dissipate at some distance from the crater, modelled here for a 45^{o} take-off angle to resurface at about 3000-km radial distance in a direction downrange and with diminishing length and depth fanning outward toward the hinterland (figs .5 and 6). As built, the Chicxulub wedge reaches a width of about 2500 km, roughly spanning the distance from the Gulf of California in the West to the New Madrid seismic zone in the NAP interior to the East.

The crustal welts were constructed using a model polyline that deviates from a spherical surface because flexural arches and troughs are placed at the observed radial distances from impact (fig. 4A). The model polyline was repeatedly duplicated and rotated about the crater in 10^{o} sectors to assemble the spines of a 3D mesh surface (fig. 4B). These welts are modeled in a preliminary sense here with amplitudes on the order of 15 km such that elevation ranges between adjacent crests and troughs reach up to 30 kilometers (fig. 4). The 2900 kilometer circumferential uplift around the crater is the most prominent of the ITFF welts where calculated earthquakes stemming from impact exceed Richter magnitude 9 or 10 just minutes after impact (table 1) and unlike anything experienced by humans in recorded history.

A final modelling component depicted in figure 5 reflects a preliminary attempt at manually fitting elliptical fault planes to surface or near-surface fault traces that are symmetrically disposed about the impact site at the continental scale (fig. 1). These fault traces include oceanic submarine spreading ridges and other concealed faults that bound subsurface basins and domes as revealed through geological and geophysical studies (fig. 1). Seismic elastodynamic theory equates the energy released on a fault surface to its physical area (Aki, 1972) and it is therefore possible to mathematical account for the absorbed and dissipated ITFF brittle ground strains stemming from large-impact events using a similar, more rigorous approach. This task remains, but this preliminary model raises some very interesting geometric aspects that merit further study. The fault pattern depicted here mimics material-failure patterns induced with uniaxial stress tests, and with differential scaling may prove to be applicable to other ITFF strain fields stemming from oblique impacts on terrestrial planets. With the SketchUp-Google Earth software compatibility one can instantaneously duplicate, scale, rotate, stretch and place such models virtually anywhere else on Earth, Mars, or the Moon (at this time) to assess their relevance in other cases. The models developed and represented here are currently available for download at www.impacttectonics.org/models/Chicxulub.html.

7.0 Summary

Because of the advent and rise of digital geospatial computing and from having access to openly shared geospatial data to decipher complex global geological systems like GPS-based plate motions and historical crustal seismicity, we are now see overwhelming evidence of impact-tectonic signatures that overprint and perturb plate tectonic processes. But accepting an altered tectonic paradigm to allow for punctuated strains to be recognized and mapped amidst those stemming from otherwise uniform tectonic processes requires having the categorical folders to place them in. Deciphering ITFF strains normally thought to stem from tectonic orogenies now becomes part of the detective process when deciphering compound structures. A more thorough accounting of ITFF effects should prove to be an integral part of plate-tectonic theory.

Recorded human history only reflects time when plate tectonics has operated at the gradual rates that we characterize using uniformitarian principles. Relatively constant horizontal motions on the order of millimeters to centimeters per year are the standard course stemming from empirical observations. But catastrophic, instantaneous propagation of seismic waves radiating outward away from a large-impact sites are difficult to fathom because they can hypothetically raise mountains suddenly when terra firma gets rung like a bell and its carpet gets rumpled and welted. We have not experienced this as humans and our established viewpoints reflect our geologically brief existence. If we theoretically recognize the potential of impact tectonics to suddenly impart widespread tectonic revolutions as part of plate-tectonic theory we then become aligned with Gold and Etheredge's (1977) punctuated equilibrium as a more inclusive guiding principle of plate-tectonic theory, one that directly reflects our discretization of time. As Gould (1987) wisely stated "if we equate uniformity with the truth and relegate the empirical claims of catastrophism to the hush-hush unthinkable of theology, then we enshrine one narrow version of geological process as true *a priori*, and we lose the possibility of weighing reasonable alternatives."

8.0 Acknowledgements

This work reflects my interaction with and influences from many people throughout my career. I was first introduced to geology 40 years ago by an older boss whose name I sadly can't remember when we were working away from our central-Ohio base near Glacial National Park as contract industrial laborers at an aluminum refinery. Off-hour day trips into the park changed the direction of my life as I have since strived to understand how mountains rise. In that respect I was fortunate for my early training at Ohio University under the tutelage of

Damian Nance, Gene Heine, Roy Mapes, Randy Steinen, Jeff Smith, and Tom Worsley. Damian especially stoked my interest in structural geology and global tectonics. A senior studies seminar taught by Damian and Tom opened my eyes to the 'big picture' and the exciting realization that geology is a relatively new and imperfect science with many unexplored frontiers. Peter Geiser at the University of Connecticut soon after provided the next level of formalized training in structural geology, and together with his brother Jim, introduced me to advanced structural concepts and modern computing applications in geological sciences. While there, I was also fortunate to participate in the Appalachian tectonic studies group, an informal group of structural geologists whose focus at that time was deciphering fold-thrust belt complexities in the Appalachian Mountains. This group met once a year over am 18-year period and it was there I had the opportunity to meet and interact with Nick Nickelsen, Terry Engelder, Don Wise, Bill Dunne, Gill Wiswall, Charlie Onasch, Steve Wojtal, Jerry Bartholomew, Frank Pazzaglia, Mary Beth Gray and many others. But it was my 32-year career at the New Jersey Geological Survey (NJGS) under the umbrella of the NJ Dept. of Environmental Protection that I first became immersed in bedrock field mapping, then geographic-information systems, and finally fractured-bedrock-aquifer research. Under the direction of State Geologists Haig Kasabach and Karl Muessig in successive administrations I was able to conduct the field and laboratory work leading to this discovery of events occurring on the North American tectonic plate. However, the resulting excitement was then tempered by the realization (and directives) in the midst of my career that I could not commit to an academic pursuit on civil service time. Nevertheless, my continued interest in this topic slowed but nevertheless continued during off hours and gained support from a couple of friends and colleagues who I hereby acknowledge and wholeheartedly thank for helping me through that time. Manny Charles has always supported this effort. We met at the NJGS, shared a mutual interest in structural geology, and I remember fondly when he handed me a hardcopy of *The Chesapeake Invader* by Wiley Poag in the early 1980's at the office. My MSc thesis dealt with unravelling foreland structures of Pennsylvania but I concluded that work without understanding many aspects of the driving factors. But soon after and upon discovery of the deeply buried crater under the mouth of Chesapeake Bay, many major pieces of the regional puzzle began falling systematically into

place, and Manny has been my primary sounding board through all of it. On the other hand, my friend and career-long mapping partner Don Monteverde (NJGS) provided key insights in the field but critical viewpoints on the emerging hypothesis that I also benefited from, because this work will undoubtedly be likewise challenged by the rigors of peer-review and scientific debate. Other former colleagues at the NJGS that I also acknowledge for having a hand in this work include Butch Grossman, Mike Serfes, Steve Spayd, John Curran, Dick Dalton, Mark French, Mike Gagliano, John Dooley, Bob Canace, Pete Sugarman, Scott Stanford, Ron Witte, and Gregg Steidl. I also thank J. Mark Zdepski, a long-time local friend and fellow geologists for listening to me rant and rave for many years about the lack of understanding and appreciation of impact-tectonic effects in the general geological community. Mark had a world-physiography map hanging in his office that helped spark my imagination and formulate some of the ideas behind these impact-tectonic hypotheses. Only a few years ago while attending the annual field conference of Pennsylvania geologists, Gail Blackmer suggested that I contact Ryan Mathur at Juniata College about his work on impact-generated sulfide-mineralized veins that he was obtaining radiometric ages for within the Pennsylvania fold-and-thrust belts. That was greatly appreciated as Ryan filled a critical gap in the hypotheses by obtaining absolute age dates on post-impact, far-field tectonic structures that independently confirmed my hypothesis. This personal contact has grown to include insights supplied by Barry Scheetz and Duff Gold from Penn State University which has been very rewarding. Lastly I thank Heidi Sue for making our home my comfort zone and sharing in my dreams.

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Figure 1. Hypothetical, far-field crustal strain fields mapped around two large impact craters on the North American tectonic plate (NAP). Lithospheric faults and welts were also imparted to Earth by the oblique bolide impacts that formed the Chicxulub (~65 Ma) and Chesapeake (35 Ma) craters. These are dissipative strain responses to suddenly imparted ground energy and extend for thousands of kilometers beyond the craters. Circumferential blast patterns drawn around each crater indicate strain sectors dominated by compression (C) and reverse faulting, tension (T) and normal faulting, or mixed-mode (M) stresses and faulting within lateral sectors. The foreland is compressed and thickened in a lithospheric wedge downrange of the crater where compressive shear is focused and refracted back to the surface at great distances. The lithosphere is stretched and sheared with transform faults in the wake of each impact where igneous activity is common, and mixed-modes of crustal faulting occurs. Crustal seismogenic zones inside 90^{o}N to 90^{o}S latitudes and 30^{o}E to 150^{o}W longitudes mapped from the US Geological Survey National Earthquake Information Center event query (Herman, 2006). Basins and uplifts mapped from Ewing and Lopez (1991) and Li (2006). LU – Llano uplift. CP – Colorado Plateau. ETOPO1 surface base theme from Amante and Eakins (2008).

Figure 2. A.) An orthographic map projection of Earth centered on -90^{o} Longitude and 20^{o}Latitude near the Chicxulub crater on the South shore of the Gulf of Mexico showing how tectonic plates currently spin about the crater. The red arrows are a selected few, stylized motion vectors pointing in the direction of horizontal drift based on historical GPS-monitoring of tectonic-plate motions. Actual motions are depicted to scale in figure 1. Tectonic plate boundaries show that the crust is fractured into small plates to the South, and rings drawn around the crater at 600, 1700, 2900, and 3800 km radii represent crest lines of circumferential welts. **B).** A plot of the horizontal component of plate velocity versus distance from the crater for GPS stations located on the North American Plate (NAP) show a velocity boundary at about 2900 km radial distance, the same distance as the depth to the core-mantle boundary (table 1). AP – Atlantic plate, PP – Pacific Plate, COP – Cocos plate, CAP – Caribbean plate, SAP – South American plate.

Figure 3. Earth profile illustrating the interior layering of Earth and the parameters used to calculate impact-related ground energy (Table 2) and construct CAD models of the IT far-field strain effects. The mean radius of Earth reportedly varies and is often listed as 6371 km. The value of 6370 is used here to simply the model. Note the light-gray spherical traces stacked below the impact point representing the traces of spherical reflections having the same radii as the phase boundaries.

Figure 4. A.) Profile diagram of Earth' near-surface geometry of p-wave refraction paths resulting from various take-off angles, and a model surface line used to construct crustal welts that likely have deep-seated origins stemming from refracted and reflected ground energy suddenly imparted by large bolide impacts. **B.)** A 3-dimensional (3D) mesh was generated using AutoCAD R14 by duplicating and rotating the model surface line to construct equuidimensional sectors comprised of simple line segments connecting equally-spaced vertices. The mesh potrays the mapped circumferential crustal welts relative to the impact catrers.

Figure 5. Various parallel views (TOP – A & B, LEFT –C. and ISOMETRIC – D.) of a 3D SketchUp Pro model of Earth IT far-field strain effects stemming from the Chicxulub impact event. The model is oriented with the crater at the model center (coordinates 0,0,0) and the y-axis aligned downrange of the impact. Earth's respective layers are rendered semi-transparent to show geospatial geometry of the strain effects and reflection geometry. The 3D pink ellipses (top views) represent early efforts at fitting 3D fault planes symmetrically distributed about the impact to help account for fault-realted ITFF strains.

Figure 6. A regional map of hypothetical ITFF strain fields associated with the Chesapeake crater. Note the traces of the crustal welts stemming from the Chicxulub (CX) and the constructive overlapping and spatial alignment of the 760-km and CX2900 arches with the Adirondack uplift and bulging of the continental shelf. ETOPO1 surface base theme from Amante and Eakins (2008).

Figure 7. Four GE views of the hypothetical ITFF strain fields stemming from the Chicxulub and Chesapeake impact events with respect to **A.)** the ETOPO1 theme (Amante and Eakins, 2008), **B.)** Whole-Earth gravity (Sandwell and Smith, 2009), **C.)** Whole-Earth aeromagnetics (Maus and others, under review), and **D.)** Continental geology by Era (http://www.impacttectonics.org/Earth/Geology_KML.html).

Figure 1

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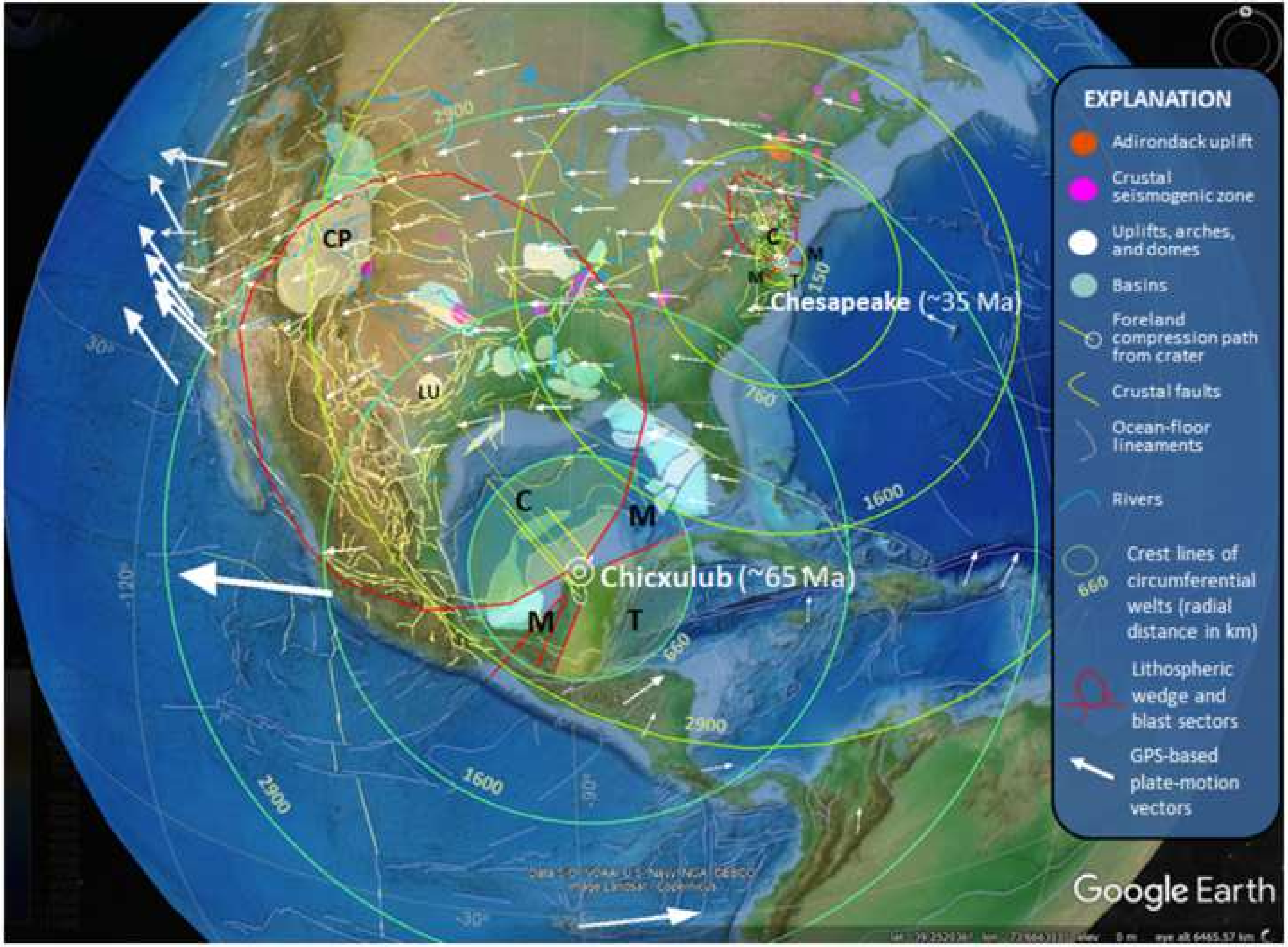

Figure 2

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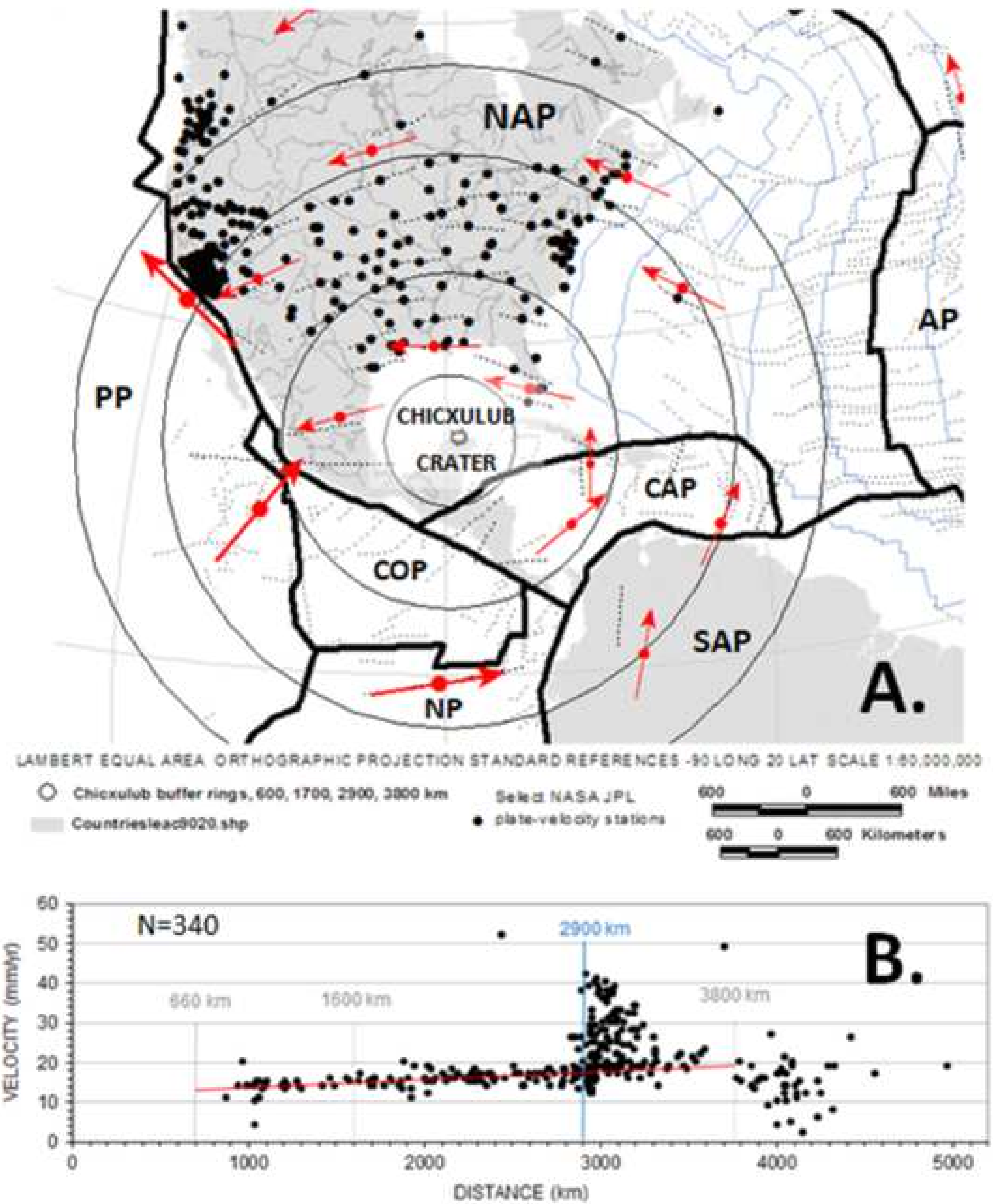

Figure 3

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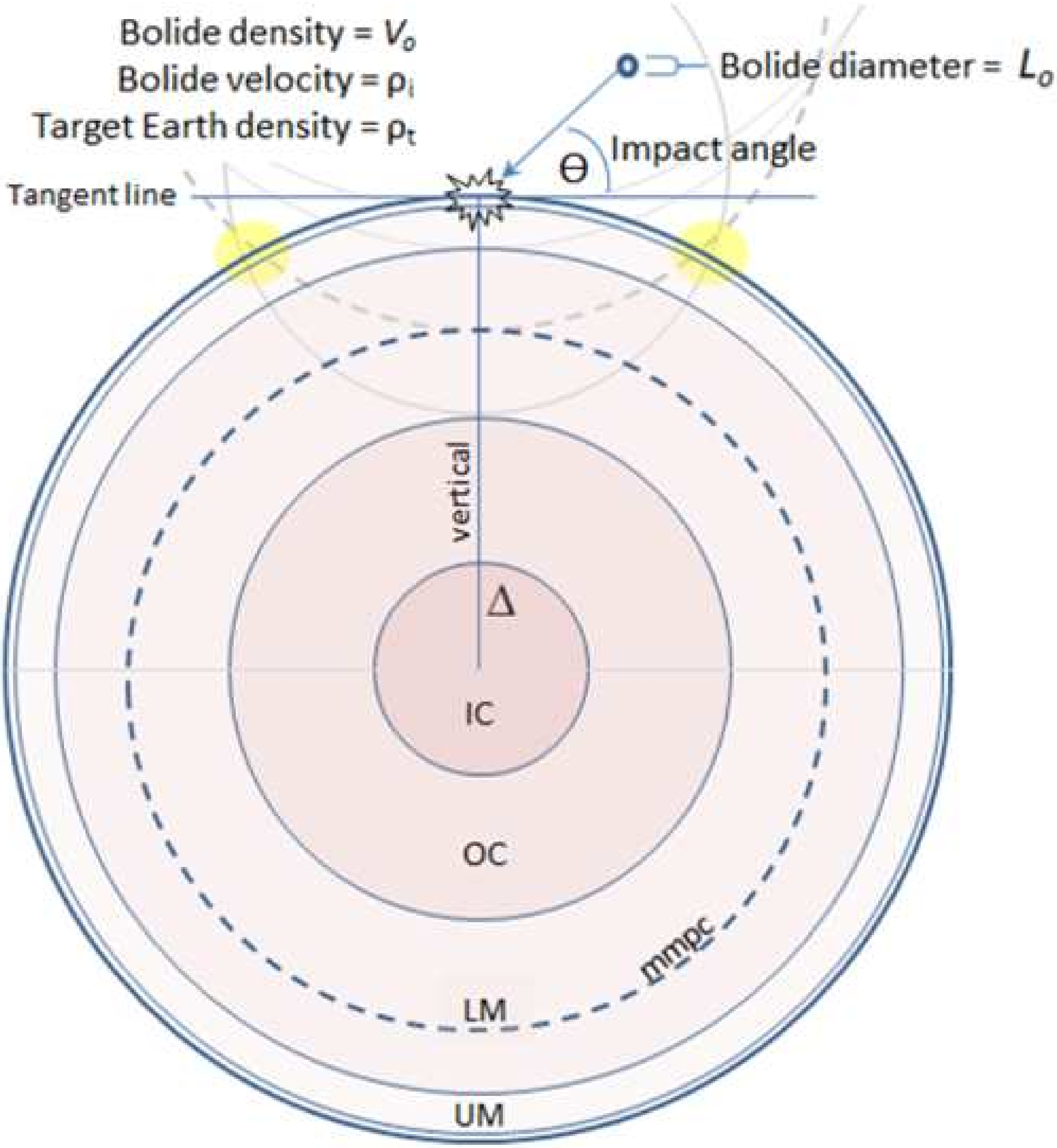

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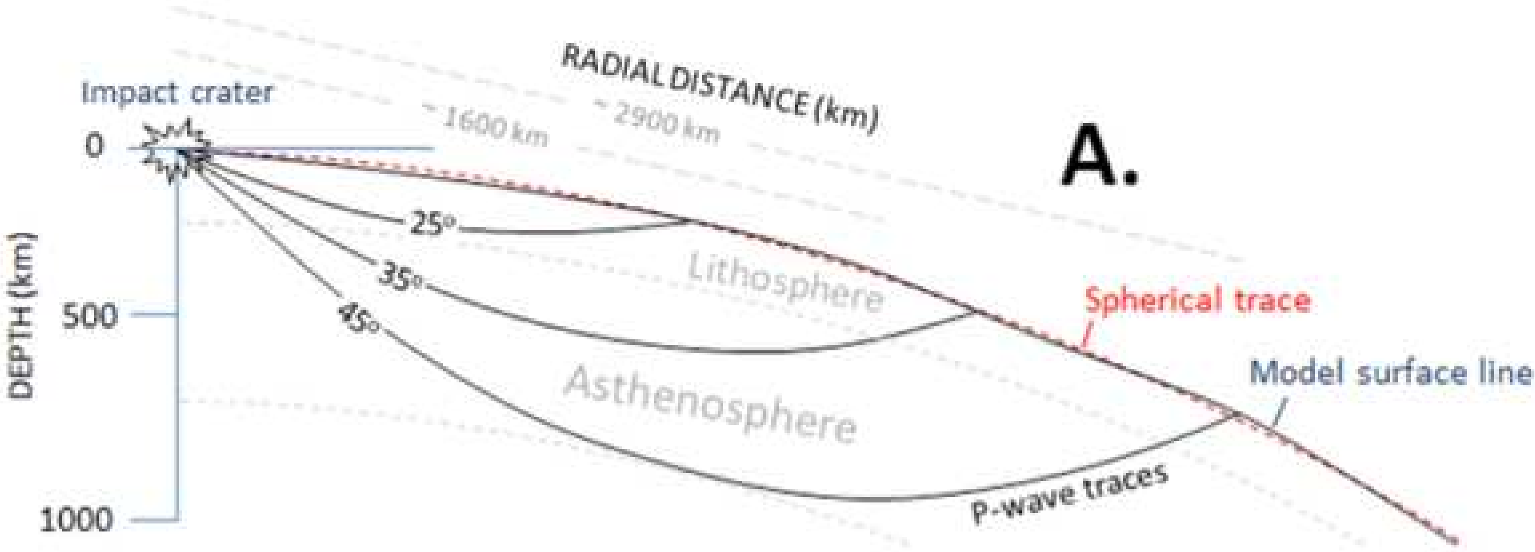

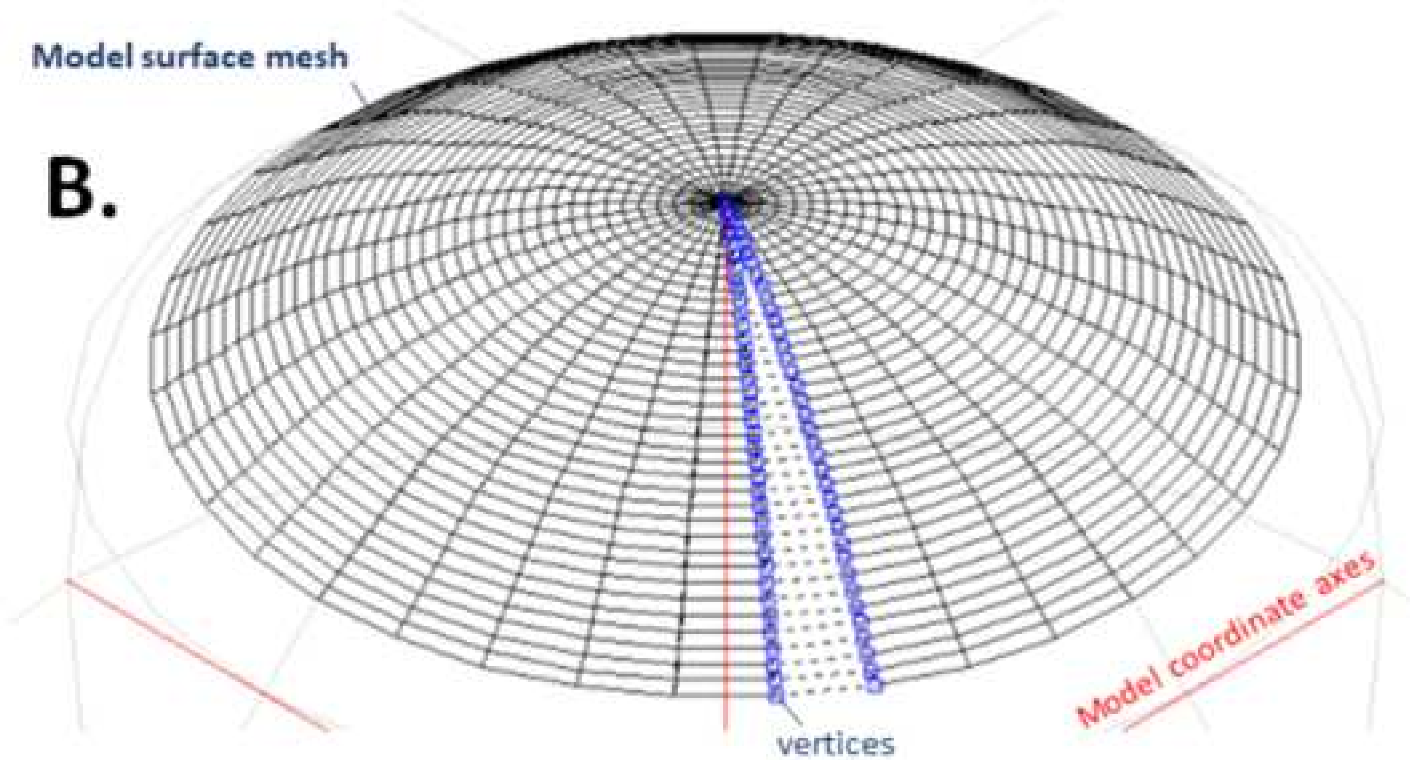

Figure 5

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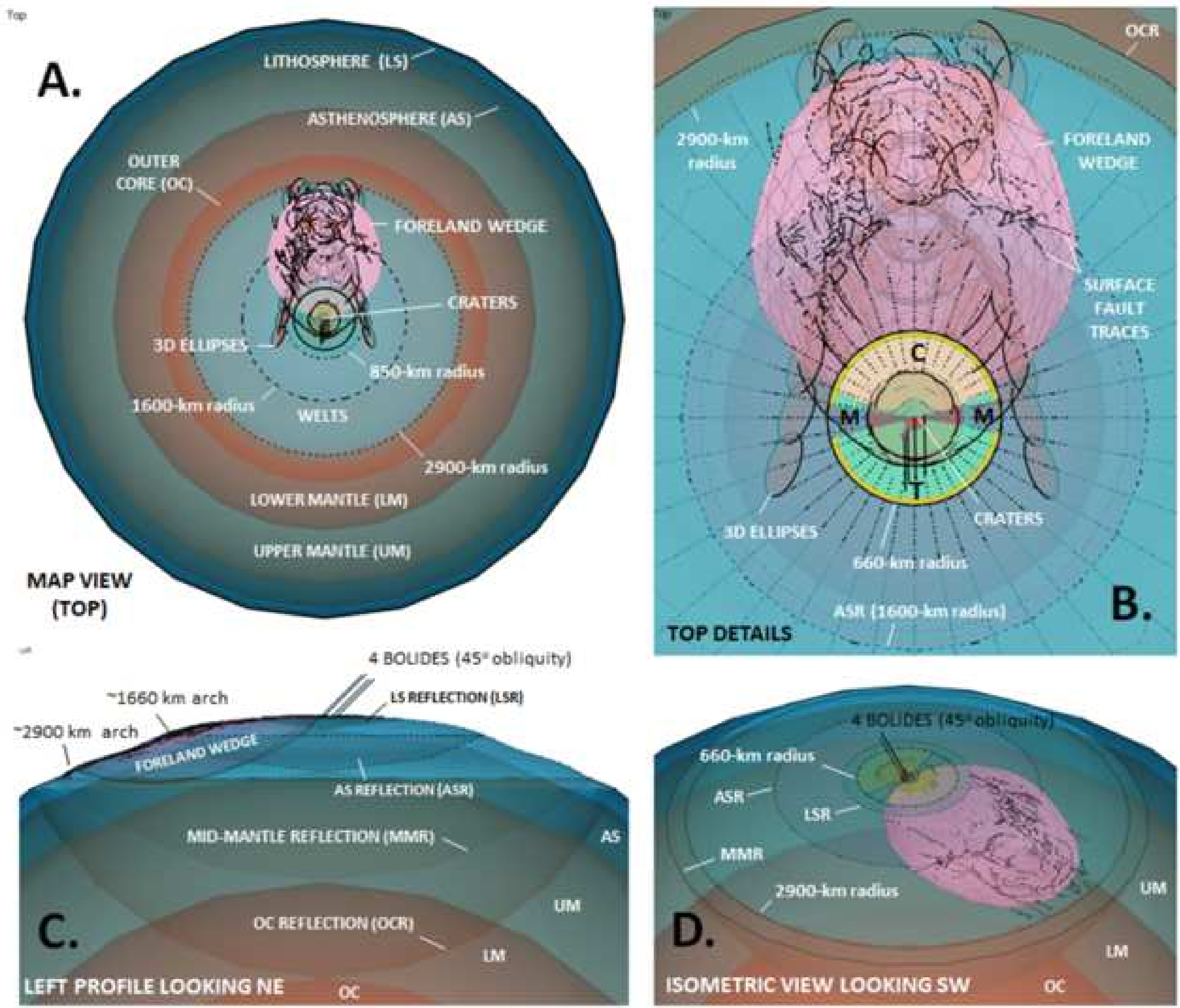

Figure 6

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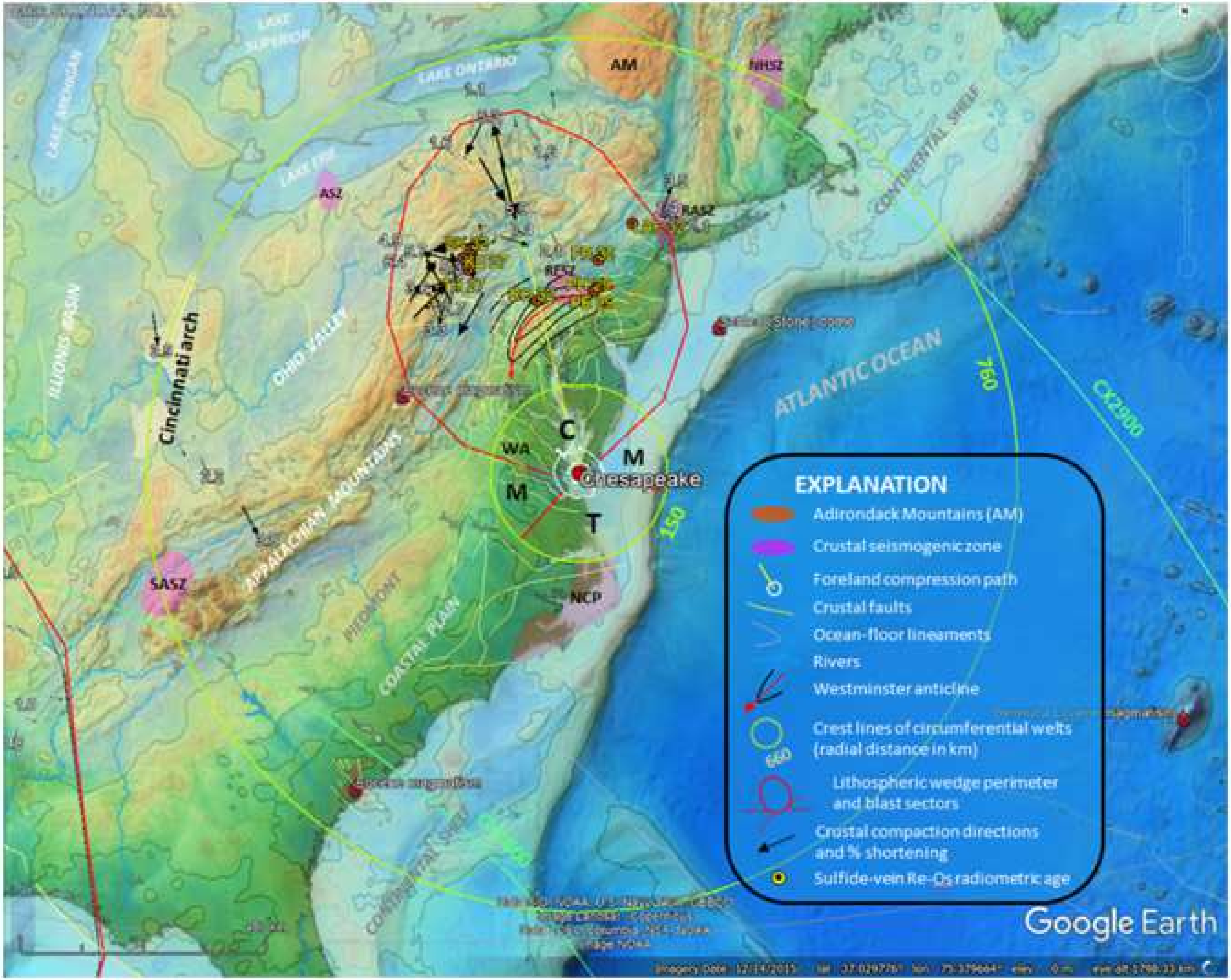

Figure 7

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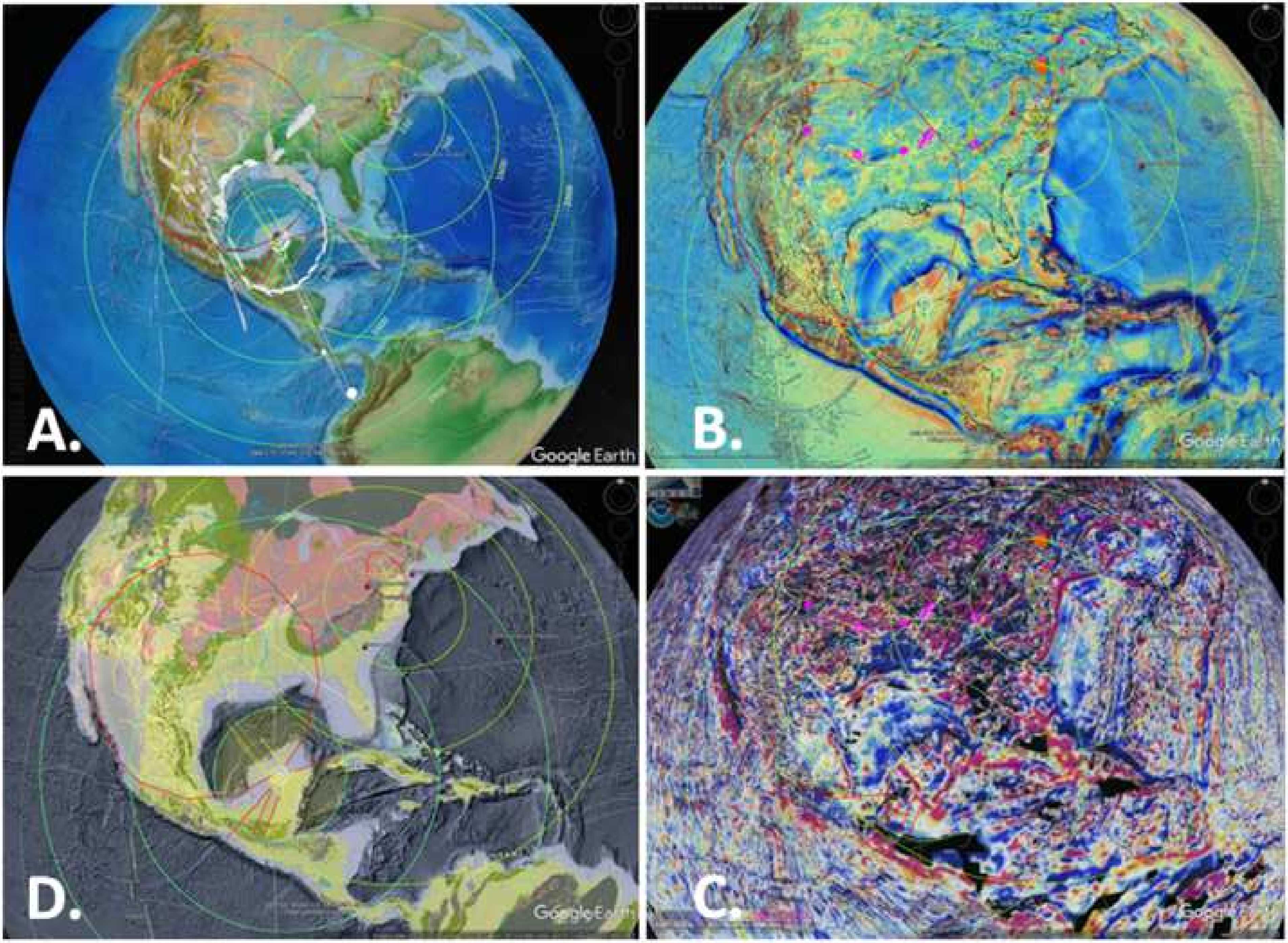

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Table 1. Spherical dimensions used to construct Earth IT models

Geometric sphere	Radius (km)	Radial depth from surface (km)
Earth mean (R_E)	6370*	0
Lithosphere	6170	200
Upper (UM) -lower (LM) mantle boundary	5710	660
Mid-mantle mineral phase change (mmpc)	4770	1600
Outer core (OC) radius	3400	2930
Inner core (IC) radius	1440	4930

 Click here to access/download;Table;table 2.tif

Table 2. Velocity, trajectory, and sizing parameters used to calculate crater diameters and the ground energy imparted into Earth by large-bolide impacts. All calculations used a projectile density of 3000 kg/m³ (dense rock); and a sedimentary target density of 2500 kg/m³. All values except ground energy estimates calculated online at http://www.lpl.arizona.edu/impacteffects/ (Collins and others, 2005).

Projectile Diameter (km)	12 (Chicxulub size)				5 (Chesapeake size)				1			
Impact velocity (km/sec)	30		15		30		15		30		15	
Bolide kinetic energy (BKE) before atmospheric entry (joules)	1.2×10^{24}		3.1×10^{23}		8.8×10^{22}		2.2×10^{22}		7.1×10^{20}		1.8×10^{20}	
Impact Angle (degrees from horizontal)	75	25	75	25	75	25	75	25	75	25	75	25
Final Crater Diameter (km)	193	141	137	85	89	65	63	46	22	16	15	11
Richter-scale earthquake magnitude at 2900 km distance from the crater	10.3	10.1	9.9	9.9	9.5	9.5	9.5	9.1	8.1	8.1	7.7	7.7
Impact-induced ground energy (~1 to 10% BKE; joules)	$\sim 1 \times 10^{23}$				$\sim 1 \times 10^{21}$				$\sim 1 \times 10^{19}$			
Time lag for seismic shaking to begin at 2900 km distance from the crater (minutes)	9.7											