Early Cenozoic tectonic disruption of the Central Appalachians by the Chesapeake Invader.

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Abstract

Geological, geochronological, and geophysical data compiled and mapped for the Pennsylvania Salient and New York Recess show that this region was uplifted from tectonic compression in the Cenozoic period. We propose one phase of regional lithospheric compression in the Tertiary period stemming from the oblique bolide impact that produced the large crater now buried beneath the mouth of Chesapeake Bay, Maryland, USA (Poag and others, 1992; 1994, Koerbel and others, 1996; Poag, 1996; 1997, and 1999; Horton and others, 2005). The hypervelocity impactor likely descended along an oblique path coinciding with the axis of Chesapeake Bay along azimuth 347°. The impact compressed and thickened the Appalachian crust from brittle shear fracturing and faulting focused in a foreland compressional sector that is part of a circumferential blast pattern including large-wavelength but small amplitude lithospheric welts lying at great distances from the crater. The foreland compressional sector fans northward away and outward from the impact crater into the central Appalachian foreland where bedrock strains of Cenozoic age affect all older rocks and measurements of bulk crustal compaction reach 10%. Prior to recent discovery of the concealed crater, most of the tectonic effects interpreted in this region are thought to solely result from the suturing of tectonic plates during Paleozoic orogenesis. In contrast, we illustrate how this bolide impact contributed to the geological expression of the central Appalachian Mountains by overprinting the Paleozoic orogenic belt, a transtentional strain field imparted by Mesozoic continental rifting, and basal Tertiary strata of the Cenozoic coastal plain. The Chesapeake impact is therefore one of the latest of a series of causative tectonic agents contributing to the physiographic expression of the scalloped, passive margin.

Introduction

The cratering effects from large, hypervelocity asteroid, comet and meteorite (bolide) impacts on terrestrial planet and moon surfaces are visually apparent and well known. Numerous studies have shown that large, episodic bolide collisions with host bodies disrupt the atmosphere, obliterate the impactor, and leave telltale scars behind on the host's crust including not only complex craters, but near-field fracture fields lying close to the point of impact (Sharpton and Ward, 1990; Koerbel and Henkel, 2005). But there has been little consideration for, or tectonic accounting of, catastrophic, far-field crustal strains lying outboard of the crater at distances of hundreds to thousands of kilometers that directly stem from such large impact events. Moreover, there are only abstract concepts of any long-lasting geodynamic consequences to periodic large-bolide, impacts (Herman, 2006).

We show here that some of the compressive, brittle strains found in crust throughout the central Appalachian region, including the Pennsylvania Salient and bounding parts of the New York Recess, represent ground strains lying within a compressed sector situated in front of an oblique, hypervelocity bolide strike that produced the crater (Poag, 1999). The central rim of this Eocene-age (35.5 Ma) crater is about 85-kilometer diameter, and circumferential gravity anomalies beyond that are mapped at radial distances exceeding 150 km (fig. 1). The crater was discovered lying beneath a blanket of Cenozoic sediment shed off the flanking Appalachian Mountains and is shown here as having produced a regional, penetrative strain field including circumferential crustal welts to the impact point lying hundreds to thousands of kilometers distance away from the crater (figures 2 and 3). We incorporate potential-field geophysical data and structural kinematics in Paleozoic and Mesozoic bedrock in Pennsylvania and New Jersey and the Re-Os isotopic dating of Cenozoic-aged sulfide mineralization in the region (Mathur and others, 2008; 2015) to illustrate where the Chesapeake impact structurally compressed, thickened and elevated the central Appalachian crust foreland of this bolide strike that likely descended along a path coincident with Chesapeake Bay along azimuth ~347^{o} (fig. 1). Kinematic indicators from detailed structural analyses of bedrock are consistent with a Cenozoic-age tectonic northwest-directed push from the head of Chesapeake Bay that tightened the central Appalachian foreland fold-and-thrust belt, accentuated the scalloped Appalachian margin, and left Cenozoic igneous intrusions systematically aligned in its wake (figs. 3 and 5). These tectonic aspects overprint strain fields stemming from earlier Paleozoic orogenesis and Mesozoic rifting, the latter also having localized epeirogenic movements (Herman, 2015) associated with intrusive emplacement of the Central Atlantic Magmatic Province (CAMP) into the crust during breakup of Pangaea (Marzolli and others,1999; Herman and others, 2013).

Stratigraphic, structural, geophysical, and radiometric evidence.

We summarize below the regional stratigraphic succession, structural observations, and geophysical evidence including radiometric ages of brittle faulting and hydrothermal mineral growth in support of this far-field strain hypothesis. Figure 2 summarizes the tectono- stratigraphic groups for the New Jersey area in the central Appalachians covering Proterozoic through Cenozoic crustal rocks (Herman, 2015). An expanded Cenozoic section includes subunits separated by major unconformities developed on the central Appalachian margin of the North American tectonic plate (NAP) beginning with a prominent one at the Cretaceous-Tertiary boundary.

Figure 1, table 1, and figure 4 summarize radiometric ages obtained from outcropping or mined sulfide-mineralized fault breccia in both Paleozoic and Mesozoic bedrock that plot near an isochron of 35 Ma (figure 1 ; Mathur and others, 2015). This geochronology was obtained from sulfide-mineralized fault breccia having Os isotopic concentrations indicating upper-mantle to lower crustal depths of origin (Mathur and others, 2008). Early sulfide mineralization is also seen in extension veins of Mesozoic age like those commonly associated with calcite vein fill and hydrocarbon expulsion from the Newark rift basins (Parnell and Monson, 1995l; Herman, 2009). Early veins in foreland carbonate and siliciclastic rocks have sulfides with calcite and quartz intergrowths respectively that may stem from older Alleghanian orogenesis. But the earliest forms and varieties of vein sulfides including pyrite (with lesser chalco- and arenopyrite) are superseded by sulfide-cemented fault breccia (Mathur, 2008) returning a 29-point isochron indicting Eocene ages that closely match the impact age when considering measurement errors (table 1 and figure 4). Earlier vein sulfides do not return reliable Re-Os isochron because Re may not have reached closure temperature in pyrite (~300^{o} C; Brennan and others, 2000) during either the Mesozoic thermal pulse or any Mississippi-valley type, late-Paleozoic sulfide mineralization (Roden and Miller, 1989; Kohn and others, 1993; Blackmer and others, 1994; Smith and Faill, 1994; Smith, 2003). Fluid-inclusion analysis of sphalerite mineralization in Mesozoic rocks provides age estimates of a possible 155-167 Ma (Cretaceous) hydrothermal event in this region (Smith, 2003), however fluid inclusion temperatures from the Eocene fault breccia indicate a higher-temperature thermal event that exceeded 300^{o} C (Mathur and others. 2008). This Re-Os isotopic data clearly reflect an impact-driven epigenetic mineralization event in the central Appalachians having a deep lithospheric origin.

Outcrop-based finite-strain studies of Paleozoic rocks of the Appalachian Plateau through Mesozoic-aged bedrock of the Newark Supergroup also show, penetrative bulk compaction of rock-forming calcite grains approaching 10% within in a finite-strain field that fans northward out in front of Chesapeake Bay (figs 3 and 5). Bedrock in this region was subject to secondary crustal compaction that overprints both Alleghanian orogenic and Newark rift structures. The Tertiary disruption would likely have been a sudden push that translated and thickened the crust as part of a lithospheric wedge produced by impact. We portray the event in Google Earth (figs. 2-7) using an impactor of 10-km radius and a 30^{o} incidence to give this tectonic event geospatial perspective. Most reports of the Chesapeake

Invader cite a 3-5 km bolide based on the crater dimensions but this multi-ringed impact structure was probably more energetic than prior estimates cite. Circumferential, positive Bouger gravity anomalies clearly lie at 150-km radius from the point of impact (fig. 1), and although the angle of incidence of the oblique impact is poorly constrained, it may become more clear after a thorough compilation and review of other post-impact tectonic structures mapped in the central and southern Appalachians that must fall into the other, marginal and extensional strain sectors lying adjacent and in the wake of the crater respectively (figs. 3 and 5).

The regional stratigraphic succession and structural kinematics of Paleozoic rocks throughout the Pennsylvania Salient and New York Recess (fig. 2) indicate at least two episodes of post-CAMP tectonic inversion in the region (Herman, 2015; Merguerian, 2015). Latest-stage kinematic indicators in Paleozoic rocks at Bear Valley and Cove Valley in the Pennsylvania Valley & Ridge Province show consistent late-stage, sinistral-oblique slip kinematics in the Pennsylvania Salient that are congruent with this late, N-S tectonic push directed up Chesapeake Bay, with resultant structures fanning outward away from a compressed spine into the Appalachian foreland (figs. 3, 6, and 7). Mesozoic (Newark) transtentional structures affecting CAMP rocks are also reactivated and structurally inverted by this late compression that opened suitably oriented fractures (fig. 9) and imparted mechanical twins in calcite cemented tensile-transitional fractures mapped as joints and autoclastic fault breccia in Triassic rocks (figs. 10 and 11).

Steckler and others (1993) estimate a minimum of 3 km of denudation over the Newark basin and surrounding region based on fission-track analysis of zircons from both Proterozoic basement and Jurassic basalts. More recent estimates of up to 6 km of erosion in the piedmont are reportedly associated with late-stage intra-basin faulting (Withjack and others, 2013). Basal sections of the NJ Coastal Plain of Mesozoic age younger than the impact are likewise compressed, fractured, and locally folded (Herman and others, 2013; Herman, 2015; 2016). It is likely that this crustal disturbance also produced a pronounced, post-impact, mid-Tertiary unconformity in the region (fig. 2). Miocene and younger strata mostly lack any secondary tectonic structures except in areas in the Delaware coastal plain (Andres and Howard, 1998) in an area having some of the fastest rates of crustal subsidence (~3-4 mm/yr) based on ground-fixed GPS monitoring and reporting (Herman, 2016). The relatively rapid rate of current subsidence in the Pennsylvania culmination may reflect an inherited tectonic response to the Early Tertiary uplift (fig. 12). The pronounced, linear break in the historical GPS vertical-velocity field on the west side of the Pennsylvania salient (fig. 12) therefore probably signals current, continued and prolonged far-field crustal-strains that continue to operate today as inherited from this ancient event.

The late-stage penetrative tectonic compaction and wrenching reported in the Appalachian is modeled here as an fanned-shaped envelope whose basal geometry follows P-wave refraction paths that penetrate most deeply directly in front of the oblique impact, and diminish in intensity laterally (figs. 6 and 7). We hypothesize the return of a considerable amount of impact-generated ground energy at radial distance of about 2900 km from the crater, the same approximate radial distance to the core-mantle boundary, and therefore perhaps, a significant distance away from the crater where epeirogenic welting is pronounced as a result of constructively interfering far-field lithospheric strain responses, one of shear fracturing and rippling of Earth's crust at distances reflective of internal mineral-phase boundaries.

Discussion

Syntheses of late Cenozoic geological evolution of the middle Atlantic passive margin are provided by Poag and Sevon (1989) and Pazzaglia and others (2006). They report a deeply eroded early Tertiary Appalachian landscape of lower relief than today. Climate change, epeirogenic uplift, or rapid increase in the size of the Atlantic slope drainage basin, or some combination of all three factors, initiated the stripping of mature regolith in the middle Miocene and delivery to the Fall Zone. Increased sediment flux into the Baltimore Canyon trough (BCT), coupled with erosional unloading caused flexure of the margin with the Fall Zone located at the flexural hinge (Pazzaglia and Gardner, 2004). Continued Middle Tertiary flexural warping of the margin arched early Miocene terraces and contributes to the continued incision by the Susquehanna River channel. The incised Appalachian landscape now delivers an immature, heterolithic load to the Coastal Plain and shelf region that reflect both periodic, positive and negative, isostatic adjustment to the loading and removal of Quaternary continental glaciers and slow continental convergence on a passive margin. Erosion rates in Susquehanna River basin reportedly doubled from prior amounts immediately after the Chesapeake impact at ~ 35.5 Mya based on cosmogenic dating of the oldest river terraces and associated upland gravel at 36.1 + 7.3 Ma (Pazzaglia and others, 2006). Younger terraces yield dates of 19.8 +2.7 Ma and 14.4 +2.7 ka respectively. Campbell (1929) mapped the oldest gravels as mantling a doubly-plunging basement arch referred to as the Westchester anticline lying immediately foreland of Chesapeake Bay (fig. 5).

The inclusion of far-field, impact generated strains as part of the tectonic expression of the Appalachian Mountains addresses many, puzzling aspects of central Appalachia. For example, Herman (1984; 1985) reported complex tectonic structures in the Pennsylvania culmination that don't fit the model foreland fold-and-thrust belt paradigm following a 'break-forward' advance of stacked thrust sheets during orogenesis. Paleozoic beds are structurally tightened and elevated in the Juniata Culmination relative to flanking areas (fig. 3), and the manner in which the Pennsylvania crust was crumpled and compounded from thrust faulting is uncharacteristic and contains 'out of sequence' sections where beds subsequently pushed and raised along very steep reverse faults. Another noteworthy aspect of this work are conjugate planar microfractures (PMs) seen in strained Silurian quartzite occupying fold limbs across the width of the Pennsylvania culmination (fig. 14). These rocks are the basal section of the blind-thrusted 'roof' section that was under thrusted and mostly compacted by wedge faulting and folding during penetrative cleavage development in the associated finer-grained clastic and carbonate strata. The PMs in the Tuscarora resemble planar deformation features (PDFs) in quartz grains subject to shock metamorphism at pressures of ~10 to 30 Gpa (French, 1998; Lee and Leroux, 2015) but occur with less density (fig. 7). Because PDFs are shock barometers, more work is needed in order to understand if any of the conjugate PMs in the Juniata culmination result from tectonic orogeny, shock geodynamics, or both. Nevertheless, the out-of-sequence, tightened fault slices in the Juniata part of culmination (Herman, 1984; Sak and others, 2014) are sympathetic with other late-stage brittle shear strains reported at Cove Valley and Bear Valley (Nickelsen, 1987; 1996), where late wrench faulting on steep faults that are congruent with a late, N-S push centered directed from the head of Chesapeake Bay (fig. 5).

In the early 1980s when the Appalachian Tectonics Study Group[1] were interpreting root causes of salient curvature and crustal strains stemming from orogenesis, there was no knowledge of the Chesapeake impact crater, or for that matter, actual plate motions in the region that are now available from global positioning systems (Herman, 2015). Early attempts to reconcile curvature of secondary geological structures in the Pennsylvania Salient were only considered with respect to Alleghanian orogenesis and contradicted the simplest reconstruction of serial palinspastic sections that merged to a point at the head of Chesapeake Bay (Geiser, 1988; Hatcher and others, 1989). Attempts at deciphering the kinematic evolution of the Pennsylvania Salient using remnant thermal magnetization of beds involved in regional folding have proven uncertain (Cederquist and other, 2006). However, the aforementioned Re-Os radiometric evidence of widely distributed Lower Tertiary, brittle faulting associated with late-stage compaction in the Pennsylvania Salient and New York Recess substantiates the widespread, regional, far-field brittle strain field fanning outward in front the Chesapeake Bay impact crater for distances greater than 500 km through into foreland areas (Mathur and others, 2015; Herman 2015,).

Because such penetrative structures probably stem from the Chesapeake impact, then consideration should be extended to large impacts elsewhere and associated far-field strains that probably include the concentric lithospheric welts lying outboard of the crater at hundred to thousands of kilometers distances. In particular, the well-known Chicxulub crater appears to have similar far-field welts at ~660, ~1500, and ~2900 radii that are reflective of depths to major phase boundaries in Earth's interior (Herman, 2006) and represent the radial dispersion of ground energy following impact. This helps explain intracratonic epeirogenic movements and not only illustrates the likelihood of far-field strain effects occurring on Earth, but also points to the need for plate-tectonic theory to include such far-field impact-generated strains on other terrestrial planets. The introduction of periodic catastrophism into modern plate-tectonic theory would include such far-field lithospheric strains and any geodynamic fluxes, plate fragmentation episodes or adjustments caused by large, hypervelocity bolide impacts on terrestrial planets.

Historical interpretations of tectonic plate motions also lend credence to these impact-tectonic hypotheses. For example, at the dawn of the Cenozoic, shortly after the Chicxulub impact in the Gulf of Mexico, major plate reorganizations began that involved the North American, Eurasian, and African plates accompanied by major changes in the deep-ocean water circulation, permitting cold polar waters to move southward in the Atlantic Ocean basin (Klitgord and Schouten, 1986). Now, the North American tectonic plate and border plates in the Central American region move in concert about a hub containing the Chicxulub impact crater on the south rim of the Gulf of Mexico (Herman, 2005). Moreover, shortly after the Chesapeake impact oceanic sea-floor spreading halted west of Greenland and suddenly accelerated to the east by Iceland where it's currently focused in the North Atlantic region (Dore´ and others, 2015). Such corroborative evidence focuses consideration on how these two, known, large-bolide impacts on the NAP, at the beginning of and during the Cenozoic Era, have not only helped shape the crust, but continue to exert a dynamic neotectonic signature on our landscape that is so remarably remote to the causative agents. Ribiero (2002) postulated the need for considerations of external forces on our open, dynamic tectonic system, and finally over the past two decades we have ground-fixed, GPS instrumentation available to gauge actual plate motions to gain a realistic perspective on plate dynamics.

A plate-tectonic paradigm that includes far-field strain effects stemming directly from periodic and catastrophic bombardment by large bolides including intraplate crustal deformation and epeirogenesis simply makes sense. For now though, more work is needed to hypothesize and test models that integrate short- and long-term strain mechanisms that serve to dissipate pin-point energy fluxes, and the geometry of associated crustal and lithospheric strain fields. By definition, neotectonic strains are those that form in our current stress regime (Stewart and Hancock, 1994). In this context, do catastrophic impact strains qualify as a neotectonic features, or is that reserved to the more standard, uniformitarian viewpoints only? Regretfully, this work leaves many aspects of this neotectonic treatment and some conclusions unaddressed. For example, the scalloped, curved nature of our continental interior has been historically chronicled and debated for decades (Thomas, 1977; Marshak, 2004; Wise and Werner, 2004). The along-strike transition from the Pennsylvania salient in to the New York recess is perhaps the most studied and reported instance of a scalloped, passive margin that has historically been treated mostly as a byproduct of differential plate convergence with irregular docking of land masses at different places, times and directions as the orogenic suture closed. The evidence presented here supports the rather unheralded notion that much of our regional architecture, and especially the geometry of our scalloped margin, is more likely a product of continental rifting (Herman, 2014; 2015).

This work uses modern geospatial tools to help outline some new hypotheses to test both new and old ideas. We are encouraged by recent technological advances available with geographic information systems that facilitate the dynamic study and portrayal of Earth systems. Although considered tectonically passive with respect to currently active orogenic margins, the central Appalachian region has been steadily drifting as part of the NAP but punctuated with sudden tectonic upheavals that humanity has been fortunate to evade simply by our juvenile presence here. These conditions echo observations by Gould (2007) who characterized biological punctuated equilibrium through geologic time, which leads us to think that large, catastrophic impacts are causative agents for concurrent geological and biological revolutions on this terrestrial planet occupying the Goldilocks zone.

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Figure 1. Location map of nine of eleven (11) epithermal sulfide deposits in Pennsylvania and New Jersey (Mathur and others, 2015). Also shown are the locations of middle Eocene magmatism in West Virginia and Virginia (Southworth and others, 1993; Fulligar and Bottino. 1969, Tso and others, 2004), and the Tom's Canyon impact structure (Poag and Pope, 1988). The two base themes include an integrated, generalized, geological theme covering Maryland through New Jersey adapted from the USGS (Herman, 2015) and a Bouger Gravity anomaly map of Virginia (Snyder, 2005) showing rings of 100- and 150-km radii surrounding the Chesapeake impact crater. The presumed direction of bolide flight is from the SSE to NNW along the bright yellow line extending from the crater up the spine of Chesapeake Bay, corresponding to the primary direction of crustal compression resulting from a the oblique, hypervelocity strike. The light gray lines project from the crater outward like wheel spokes, one of which symmetrically bisects the Tom's Canyon impact structure and points to the probability of it having formed from a secondary spalled projectile with splashdown just beyond 300 km distance from the main crater.

Figure 2. Chronostratigraphic groups and subgroups used for tectonic structural analyses of the region (Herman, 2015). Two large-bolide impacts on the North American Plate during the Cenozoic are shown relative to time and stratigraphic aspects. References for the tectonic and stratigraphic aspects are footnoted after group names and abbreviations. Era and stage boundary ages from www.stratigraphy.org.

Figure 3. Google Earth screen capture summarizing structural elements of the U.S. Appalachian margin with respect to the Chesapeake impact crater (Poag, 1999). The crater resulted from a hypervelocity bolide several kilometers in diameter impacting the continental margin along a moderately inclined flight path descending from the SSE that resulted in a NNW-directed foreland push and crustal compaction within a crustal wedge that displaced Jurassic dolerite dikes and older crust. Some Appalachian anticlines (red) and synclines (blue) are compiled to emphasize the link between positive epeirogenic structures lying circumferential to the crater at the same radii like the Cincinnati Arch and the Adirondack Mountains. Note the locations of Nickelsen's Bear Valley (1987) and Cove Valley (1996) structural studies in the Pennsylvania Salient, and the Tom's River impact that's also of Eocene age (Poag, 1999). Circumferential rings of 150, 300, and 760 km are shown that emphasize hypothetical lithospheric welts.

Figure 4. Re-Os isochron plots of sulfide-mineral analytics for eight locations in Pennsylvania (fig. 1). Isotopic results from Lafayette Meadows (LM) also reflect the ~35 Ma isochron but are not plotted because the Re/Os ratios are significantly larger and the trends become difficult to view.

Figure 5. Screen capture of a GE display showing the Chesapeake impact crater with respect to the resulting crustal blast pattern, regional basement structure contours (feet) atop Precambrian basement (Rickard , 1973; Baranoski, 2013), CAMP dolerite dikes (Herman and others, 2015) deep basement faults of the Rome trough (deWitt, 1993), and linear traces of strong aeromagnetic positive amomolies seen in the global potential field data of Maus and others (2017). Crustal-compaction values gained from calcite-strain-guage data by Engelder (1979), Spang and Groshong (1981), Lomando and Engelder (1984), Craddock and others (1993), and Ong and others (2007). Green circles trace approximate crestlines of lithospheric arches lying circumferential to the crater shown at 300 and 760 kilometers radius from the crater that bracket interening troughs represented in profile in figure 6. Westminster arch (Campbell, 1929) is highlighted using yellow structural contours and a red, doubly plunging crestline.

Figure 6. Screen image of an AutoCAD model showing the upper half of an Earth-sized sphere sliced in half to illustrate major, interior phase boundaries in profile with respect to hypothetical, far-field impact strains. Shear fractures locally thicken the lithosphere by compressional wedging in the foreland owing to the obliquety of impact, and resonant seismic reflections produce long-wavelength surface ripples cresting at roughly 600 and 2900 km radius from the crater with estimated peak amplitude of 8 km. Profiles **a.** and **b.** depict a 20-km diameter sphere descending at an angle of 60^{o} toward Earth's surface. Profile **c.** shows details of a foreland lithospheric wedge occupying the compressed sector and bisected by the azimuth of the bolide flight path. The lower limit of crustal wedging is portrayed to conform to p-wave transmisson geometry that may vary in depth of penetration with impact angle and energy of the indentor. Shear fractures likely develop at acute angle to refracted P-wave paths that return impact energy to Earth's surface at about 2900-km distance from impact assuming a 660-km thick lithosphere. Compression, excavation, and indentation near the crater therefore gives way to foreland compression and uplift as illustrated with this model.

Figure 7. Oblique, SW view of the compressed crustal sector and lithoispherice wedge that is the foreland part of the radial blast pattern around the Chesapaeake crater. The foreland wedge is portayed

here together with a 5-km diameter bolide descending along a moderate angle from south to north. The primary path of crustal compression coincides with the azimuth of Chesapeake Bay and the maximim measured value of crustal compaction (%) in the foreland based on mechanically twinnned calcite (see refs in fig. 5). The compression axis bisects the Juniata Culmination and a foreland wedge of thickned crust through parts of the New York recess and Pennsylvania Salient. Also shown are locations of the Re-Os isotope data (Mathur and others, 2015), the Tom's River impact, and Eocene magmatism. Nickelsen's Bear Valley (date) and Cove Valley (date) kinematic studies straddle the culmination. C – compression, M – marginal, and E – extensional crustal sectors surroiunding the crater (white circular lines).

Figure 8. Photographs of complex transtentional structures of probable Mesozoic age with later (Cenozoic?) wrenching in upper Paleozoic strata at a coal mine from Bear Valley, Pa. (Nickelsen, 1963; location noted in fig. 1). Late-stage structural grabens (A) of probable Newark group (fig. 2; Herman, 2009) dip steeply west and have two sets of slickenlines (B) on graben-bounding faults. The earlier slickenlines indicate normal, dip-slip shearing during graben development, and later ones indicate compressional wrenching that is congruent to regional joints sets of sub-parallel strike (Engelder and others, 2001). Photo A from www.princeton.edu.

Figure 9. Optical BTV imagery collected in Early Mesozoic bedrock in New Jersey reveal late-stage, ~E-W-striking, reverse shear fractures that dip gently SE (circled), less so to the NW, that are among the most open and permeable conduits in these fractured aquifers. The schematic diagrams on the left illustrates a gently dipping plane cut by a borehole in wrapped and unwrapped versions of an optical-borehole image. The interpretation is conducted on the unwapped image. Note how early, mineralized fractures of steeper dip are sheared and offset in the image to the right along one of the moderatly dipping reverse shear planes. Well locations and details from Herman (2015). Depth units for the BTV imagery are feet below land surface.

Figure 10. Bedrock in the Trenton, NJ is structurally inverted by reverse shear fractures and faults striking about E-W that overprint and reactivate earlier tensile-transional fractures and faults developed from Newark rifting (Herman, 2009). The complex structural geometry in the region results in positive, transpressional flower structres that are deeply weathered and commonly masked at land surface. Note the location of core MW-20C at RACER-TRENTON where transtentional fault breccias healed with spar cailte are overprinted and twinned by tectonic compression (fig. 11).

Figure 11. Calcite-cemented autoclastic breccia in the Stockton Fromation retrieved at MW-20C by Haley-Aldrich, Inc. at he RACER-TRENTON site (fig. 9 and Herman, 2016).

Figure 12. GE display of the mid-Atlantic , continental and oceanic margin of the North American Plate (NAP), centered near 40^{o} latitude and -75^{o} longitude showing recent crustal motions determined using ground-fixed GPS receiving stations, crustal seismogenic zones, principal axes of crustal compression reported from focal-mechanism solutions from well-constrained earthquakes, and some key structural analyses used for interpretations (Herman, 2016). Note the parabolic line connecting the seismic zones wrapping around the rising Adirondack Mountains, which appear to act as a buttress in resisting the slow, northwestward plate drift with rates that slowly increase NE up the spine of the Appalachian Mountains. Also note the pronounced GPS-velocity break on the western side of the Pennsylvania Salient.

Figure 13. Photographs of strained Tuscarora quartzite in profile (ac tectonic plane normal to regional fold axes) from the Juniata Culimnation, Pennsylvania Salient (left; Herman, 1984) and shocked quartz crystals retrieved from core in Virginia (right - Horton and Izett, 2005).

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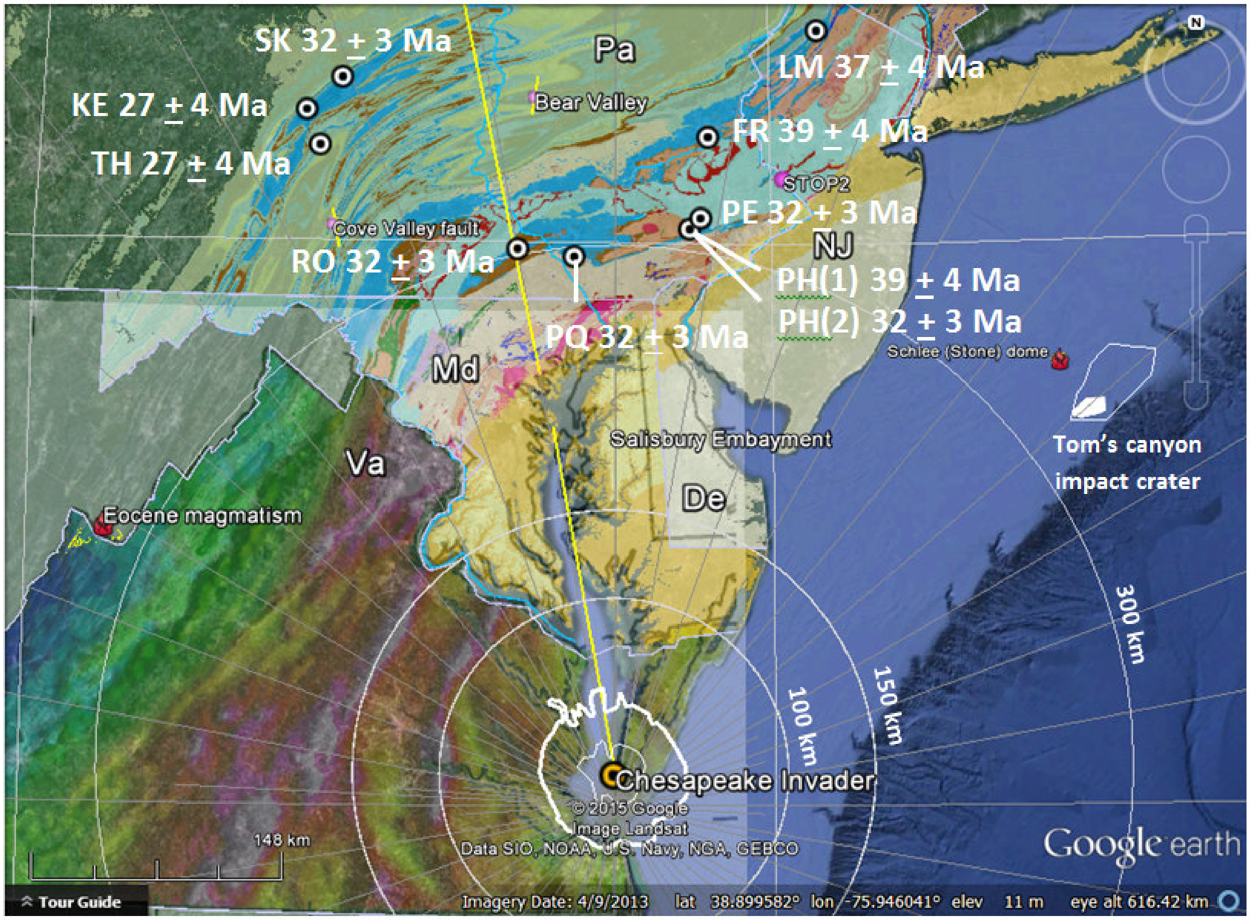
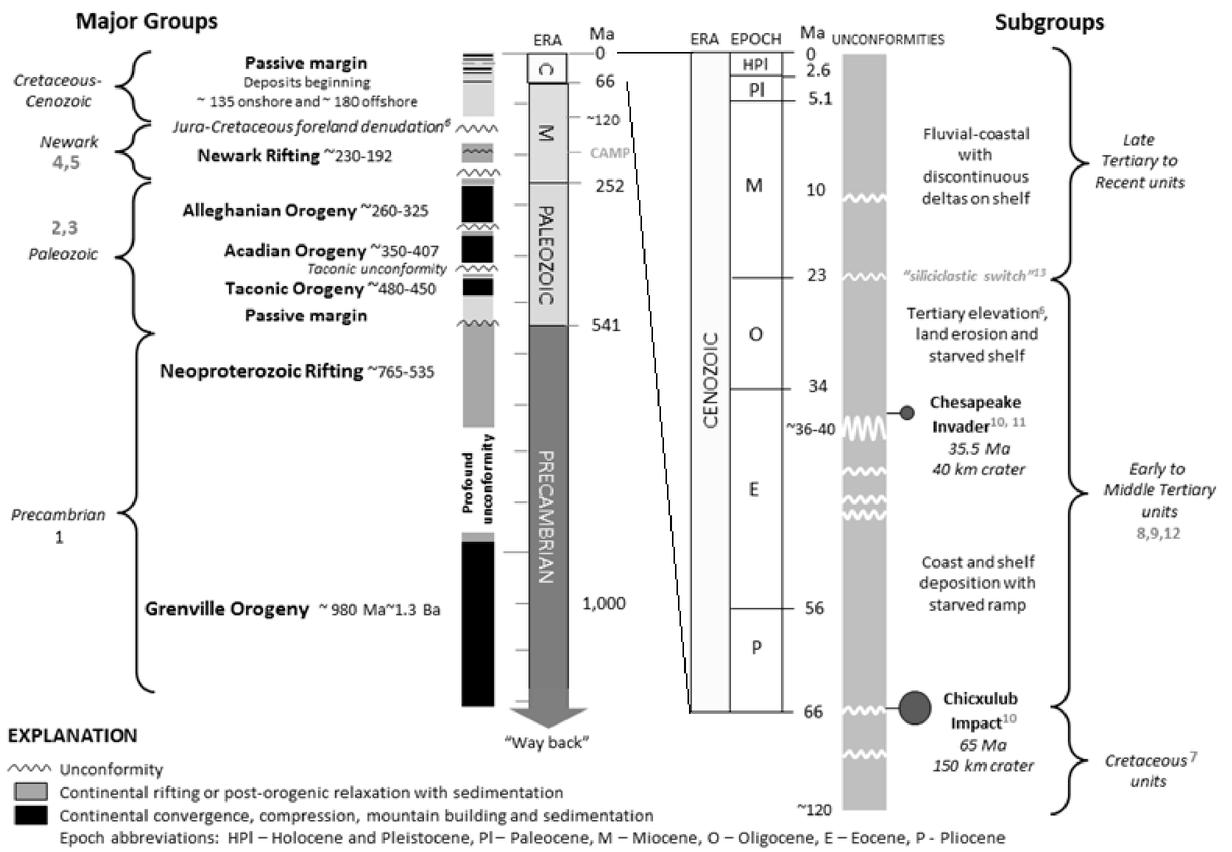
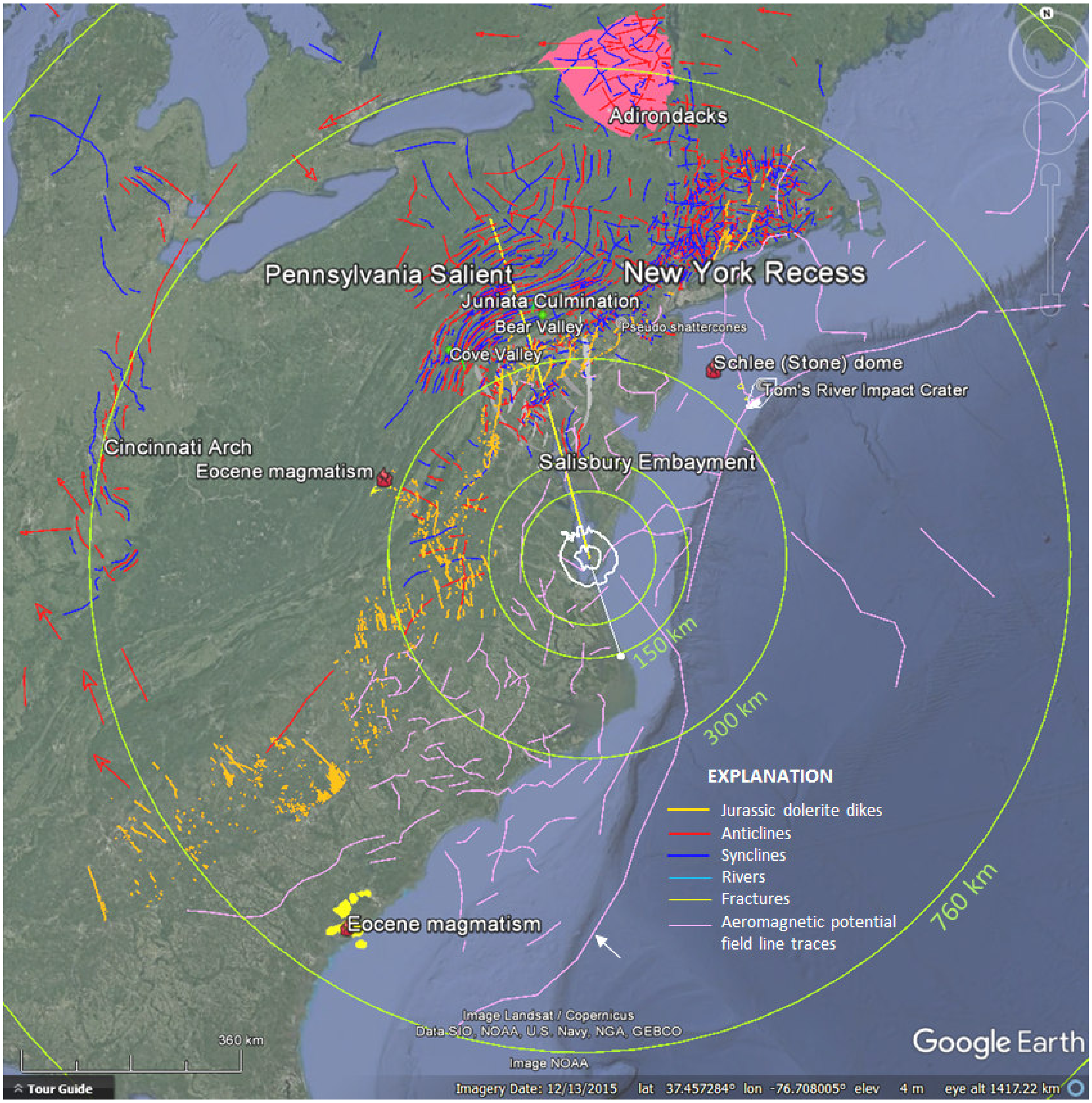


Figure 1.



*References: 1. Tollo and others (2004), 2. Ettensohn (2008), 3. Hatcher (2008), 4. Weems and Olsen (1997), 5. de Boer and others (1988), 6. Davis (1902), 7. Brenner (1963), 8. Miller and others (2014), 9. Ken Miller personal communication (07-30-2015), 10. Earth Impact database (2015), 11. Poag (1999), 12. Komitz and Pekar (2001) 13. Miller (2015) GANJ32 Keynote abstract

Figure 2.



Adirondacks
Pennsylvania Salient
New York Recess
Juniata Culmination
Bear Valley
Pseudo shattercones
Cove Valley
Schlee (Stone) dome
Tom's River Impact Crater
Cincinnati Arch
Eocene magmatism
Salisbury Embayment
150 km
300 km
760 km
EXPLANATION
Jurassic dolerite dikes
Anticlines
Synclines
Rivers
Fractures
Aeromagnetic potential
field line traces
Eocene magmatism
Image Landsat / Copernicus
Data SIO, NOAA, U.S. Navy, NGA, GEBCO
Image NOAA
360 km
Google Earth
Tour Guide
Imagery Date: 12/13/2015 lat 37.457284° lon -76.708005° elev 4 m eye alt 1417.22 km

Figure 3.

Table 1. Twenty-nine (29) Re-Os radiometric analyses from nine (9) mine, excavation, or core locations in Pennsylvania and New Jersey having Eocene-age sulfide mineralized fault breccia of hydrothermal origin.

No.	Sample #	County, State	Latitude	Longitude	Mineral	Re (ppb)	Os (ppt)	$^{187}Re/^{188}Os$	$^{187}Os/^{188}Os$
1	Thompson 1-1	Mifflin, Pa	40.515691	-78.039169	pyrite	2.30	19	1142 ± 103	0.53 ± 0.03
2	Roosevelt 1-2	Mifflin, Pa	39.987271	-76.690739	sphalerite	0.33	17	90 ± 8	0.29 ± 0.02
3	Keystone 2-1	Juniata, Pa	40.698547	-78.138857	galena	1.15	19	377 ± 34	0.21 ± 0.01
4	Keystone 2-2	Juniata, Pa	40.698547	-78.138857	sphalerite	3.03	18	833 ± 75	0.43 ± 0.03
5	Perkiomen 3-1	Montgomery, Pa	40.144176	-75.465042	pyrite	0.65	11	365 ± 33	0.41 ± 0.02
6	Perkiomen 3-2	Montgomery, Pa	40.144176	-75.465042	sphalerite	1.10	5	574 ± 52	0.47 ± 0.03
7	Perkiomen 3-3	Montgomery, Pa	40.144176	-75.465042	sphalerite	0.41	5	371 ± 33	0.41 ± 0.02
8	Perkiomen 3-4	Montgomery, Pa	40.144176	-75.465042	pyrite	1.08	3	1906 ± 172	0.23 ± 0.01
9	Perkiomen 3-5	Montgomery, Pa	40.144176	-75.465042	pyrite	0.20	5	224 ± 20	0.32 ± 0.02
10	Perkiomen 3-6	Montgomery, Pa	40.144176	-75.465042	sphalerite	1.24	30	203 ± 18	0.29 ± 0.02
11	Friedensville 4-1	Lehigh, Pa	40.562378	-75.413208	sphalerite	0.54	4	699 ± 63	0.71 ± 0.04
12	Friedensville 4-2	Lehigh, Pa	40.562378	-75.413208	sphalerite	0.31	15	118 ± 11	0.36 ± 0.02
13	Phoenixville 5-1	Chester, Pa	40.144176	-75.465042	sphalerite	0.76	5	849 ± 76	0.88 ± 0.05
14	Phoenixville 5-2	Chester, Pa	40.144176	-75.465042	sphalerite	0.82	2	894 ± 107	0.90 ± 0.07
15	Phoenixville 5-3	Chester, Pa	40.144176	-75.465042	galena	1.48	30	250 ± 23	0.32 ± 0.02
16	Phoenixville 5-4	Chester, Pa	40.144176	-75.465042	sphalerite	0.65	3	1049 ± 126	0.66 ± 0.06
17	Phoenixville 5-5	Chester, Pa	40.144176	-75.465042	galena	0.43	21	106 ± 10	0.29 ± 0.02
18	Phoenixville 5-6	Chester, Pa	40.144176	-75.465042	pyrite	0.50	7	2312 ± 208	0.91 ± 0.05
19	Pequa Gal 6-1	York, Pa	39.905383	-76.329648	galena	1.29	50	119 ± 11	0.29 ± 0.02
20	Pequa Gal 6-2	York, Pa	39.905383	-76.329648	galena	1.20	46	110 ± 10	0.27 ± 0.02
21	Little Juniata 7-1	Centre, Pa	40.832969	-77.966187	pyrite	0.500	19	1309 ± 118	0.850 ± 0.05
22	Little Juniata 7-2	Centre, Pa	40.832969	-77.966187	pyrite	0.543	24	1319 ± 119	0.870 ± 0.05
23	Skytop 8-1	Centre, Pa	40.832969	-77.966187	pyrite	2.82	20	760 ± 91	0.63 ± 0.04
24	Skytop 8-2	Centre, Pa	40.832969	-77.966187	pyrite	22.08	74	1169 ± 12	0.81 ± 0.04
25	Skytop 8-3	Centre, Pa	40.832969	-77.966187	pyrite	5.87	31	1002 ± 90	0.72 ± 0.04
26	Skytop 8-4	Centre, Pa	40.832969	-77.966187	pyrite	0.90	77	56 ± 4	0.19 ± 0.01
27	Skytop 8-5	Centre, Pa	40.832969	-77.966187	pyrite	2.81	26	548 ± 55	0.54 ± 0.01
28	Skytop 8-6	Centre, Pa	40.832969	-77.966187	pyrite	2.63	20	760 ± 76	0.64 ± 0.04
29	Lafayette 9-1	Sussex, NJ	41.094354	-74.668517	sphalerite	3.32	5	9004 ± 540	6.4 ± 0.38

Notes: Samples were obtained from subsurface specimens collected during historic mining operations and donated to the Carnegie Pittsburgh Pa. Institute (sample series 1 through 6) or more recently from excavated or cored bedrock. A single location is provided for each sample series that is based on historical records of curated samples or more recent field work. The Lafayette, NJ sample was obtained by Frank Markowitz, Richard Dalton, and Danial Dombroski of the NJ Geological Survey (NJGS) in the 1970's and archived at the NJGWS at 29 Arctic Parkway, Ewing, NJ.

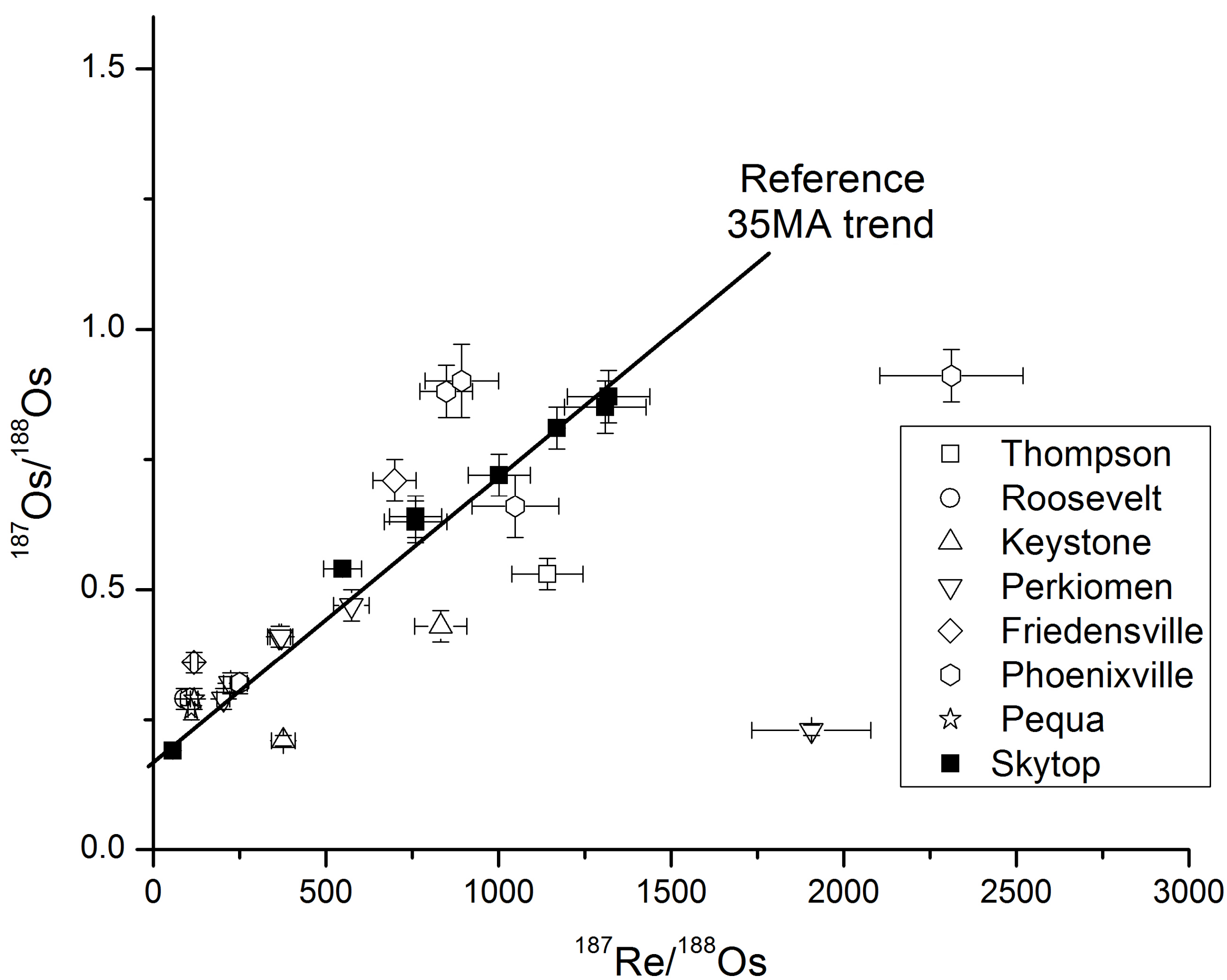
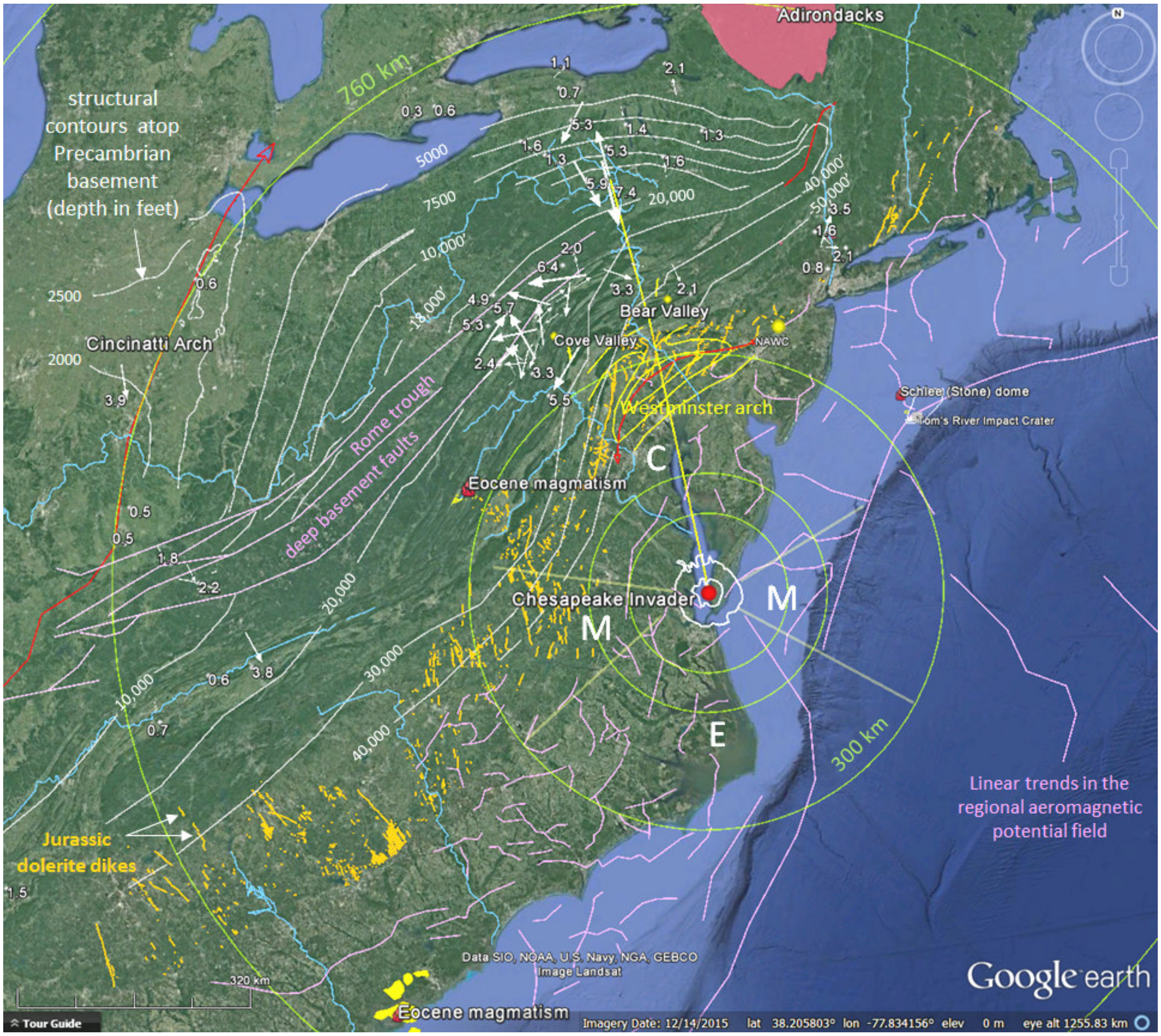
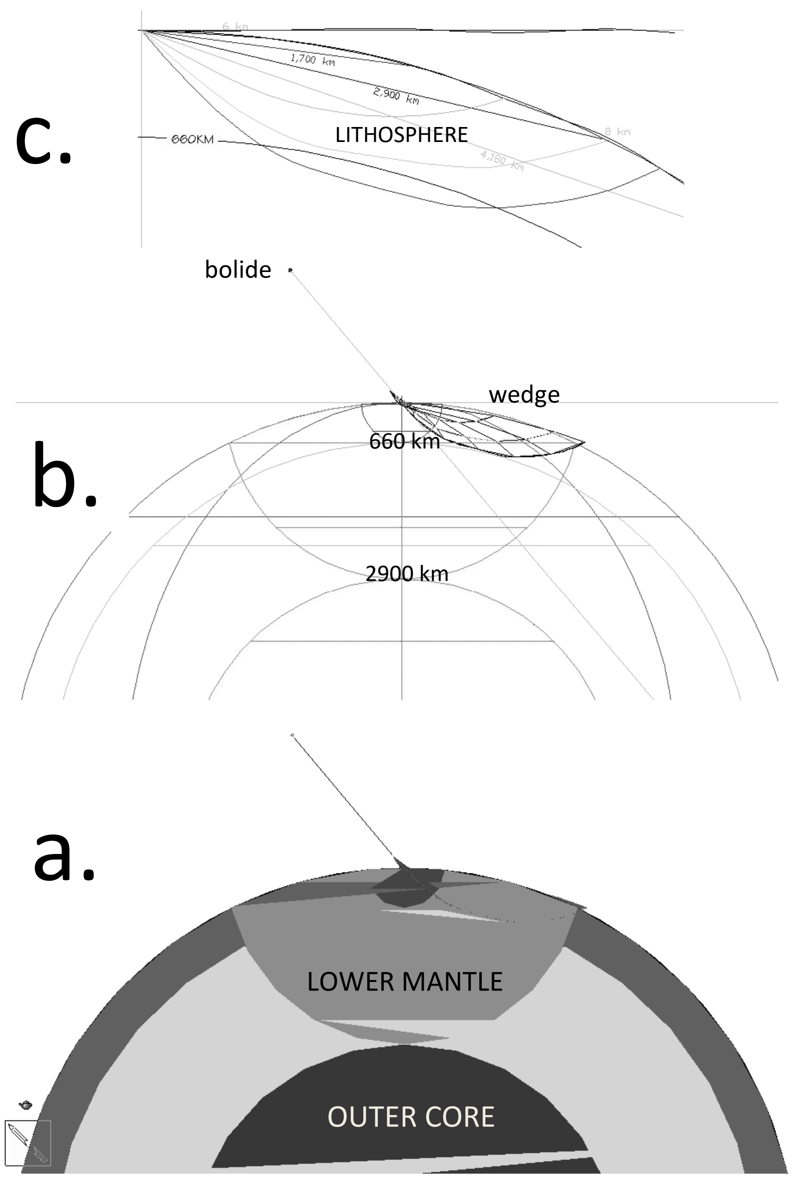

Reference
35MA trend
Thompson
Roosevelt
Keystone
Perkiomen
Friedensville
Phoenixville
Pequa
Skytop
0.0
0.5
1.0
1.5
0
500
1000
1500
2000
2500
3000
$^{187}Os/^{188}Os$
$^{187}Re/^{188}Os$

Figure 4.



Adirondacks
760 km
structural contours atop Precambrian basement (depth in feet)
5000
7500
10,000'
20,000
2500
2000
Cincinatti Arch
Bear Valley
Cove Valley
NAWC
Westminster arch
Schiee (Stone) dome
Rome trough
deep basement faults
Eocene magmatism
C
Chesapeake Invader
M
M
E
300 km
Linear trends in the regional aeromagnetic potential field
Jurassic dolerite dikes
20,000
30,000
40,000
10,000
Data SIO, NOAA, U.S. Navy, NGA, GEBCO
Image Landsat
Google earth
Eocene magmatism
Imagery Date: 12/14/2015 lat 38.205803° lon -77.834156° elev 0 m eye alt 1255.83 km

Figure 5.



c.
1,700 km
2,900 km
660KM
LITHOSPHERE
bolide
wedge
b.
660 km
2900 km
a.
LOWER MANTLE
OUTER CORE

Figure 6.

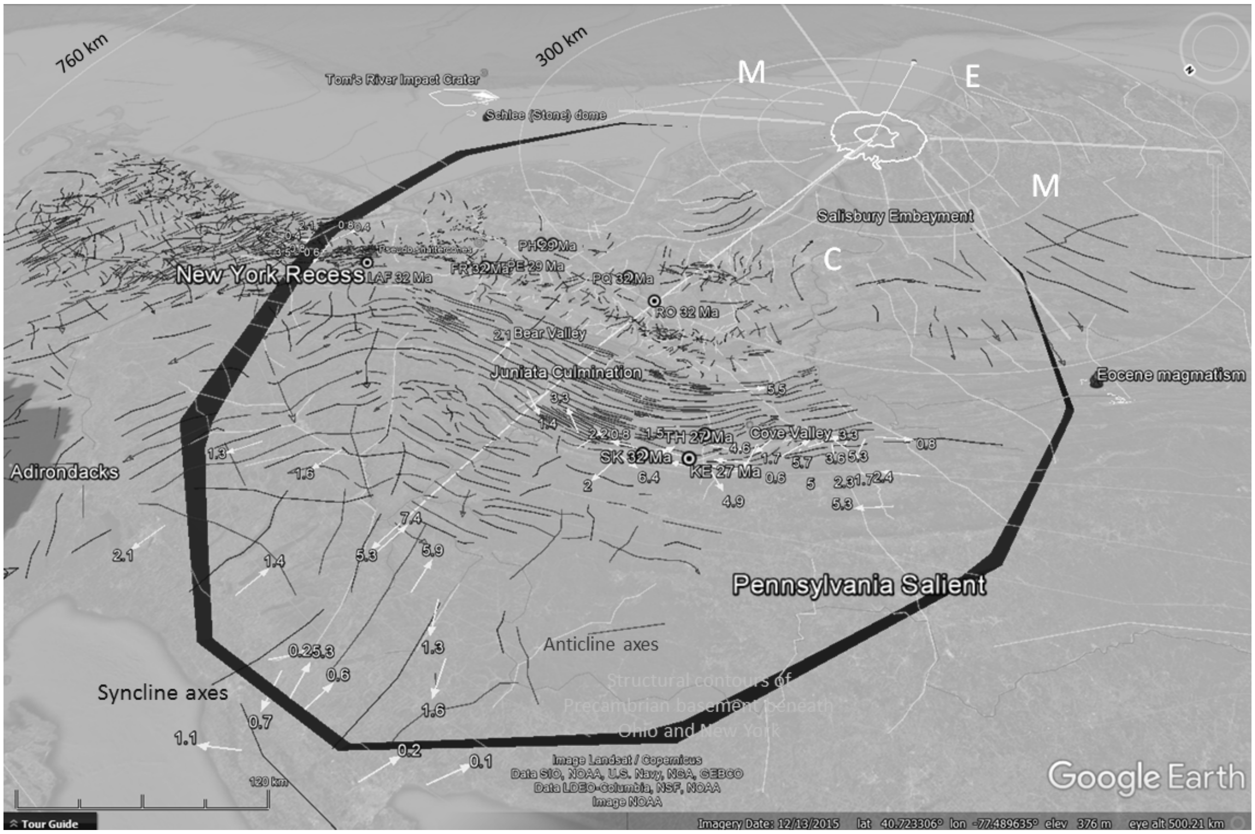

760 km
300 km
Tom's River Impact Crater
Schlee (Stone) dome
M
E
M
Salisbury Embayment
C
New York Recess
Bear Valley
Juniata Culmination
Eocene magmatism
Cove Valley
Adirondacks
Pennsylvania Salient
Anticline axes
Syncline axes
Structural contours of Precambrian basement beneath Ohio and New York
Google Earth

Figure 7.

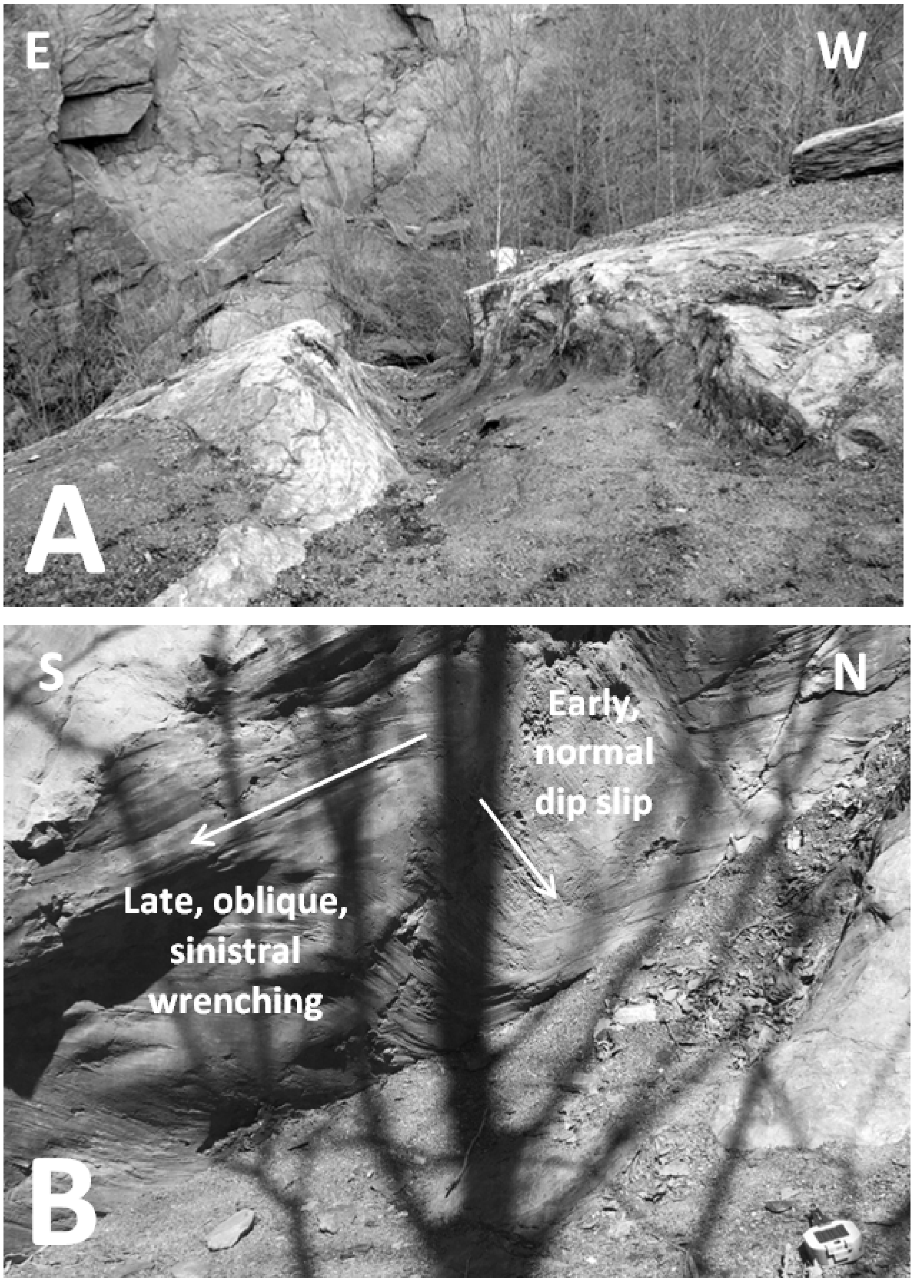
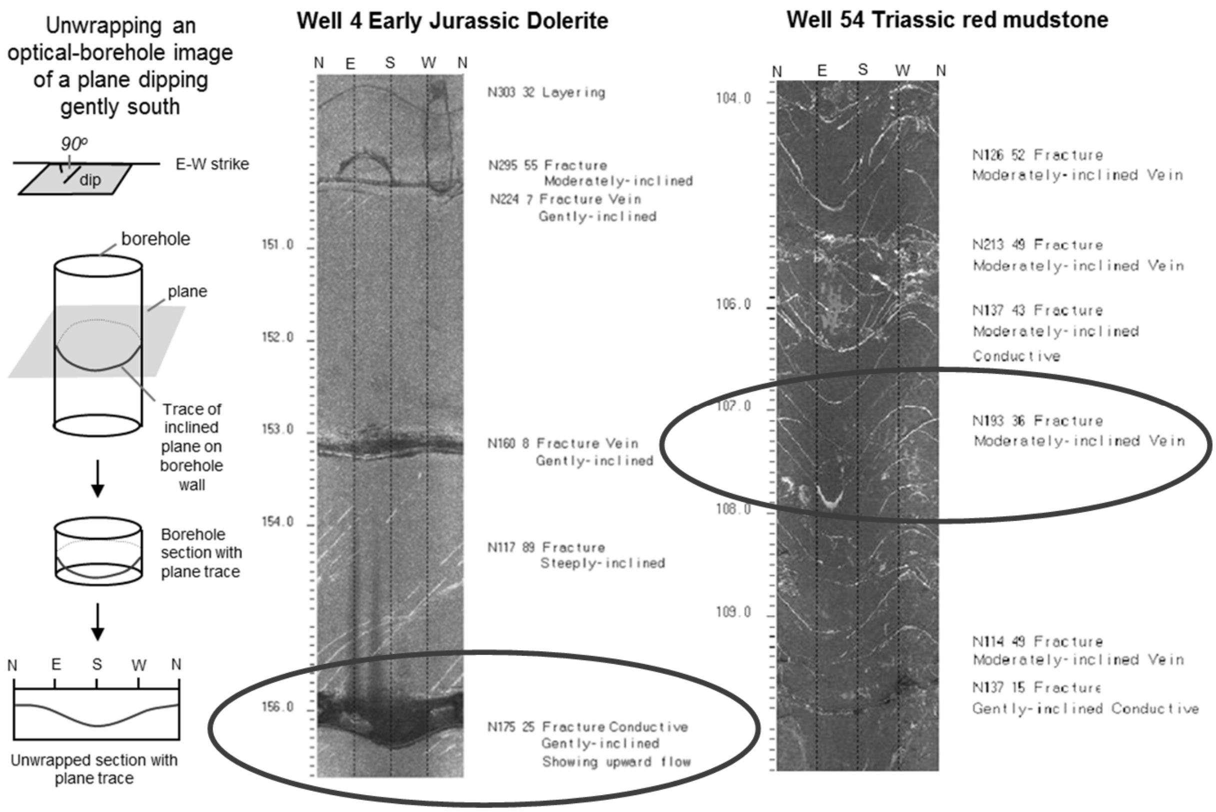

E
W
A
S
N
Early,
normal
dip slip
Late, oblique,
sinistral
wrenching
B

Figure 8.



Unwrapping an optical-borehole image of a plane dipping gently south
90°
dip
E-W strike
borehole
plane
Trace of inclined plane on borehole wall
Borehole section with plane trace
N E S W N
Unwrapped section with plane trace
Well 4 Early Jurassic Dolerite
N E S W N
151.0
152.0
153.0
154.0
156.0
N303 32 Layering
N295 55 Fracture Moderately-inclined
N224 7 Fracture Vein Gently-inclined
N160 8 Fracture Vein Gently-inclined
N117 89 Fracture Steeply-inclined
N175 25 Fracture Conductive Gently-inclined Showing upward flow
Well 54 Triassic red mudstone
N E S W N
104.0
106.0
107.0
108.0
109.0
N126 52 Fracture Moderately-inclined Vein
N213 49 Fracture Moderately-inclined Vein
N137 43 Fracture Moderately-inclined Conductive
N193 36 Fracture Moderately-inclined Vein
N114 49 Fracture Moderately-inclined Vein
N137 15 Fracture Gently-inclined Conductive

Figure 9.

Combined GM-RACER and NAWC Hydrogeological Framework

West Trenton Township, Mercer County, New Jersey

Profile view of stratigraphic intervals penetrated by BTV records

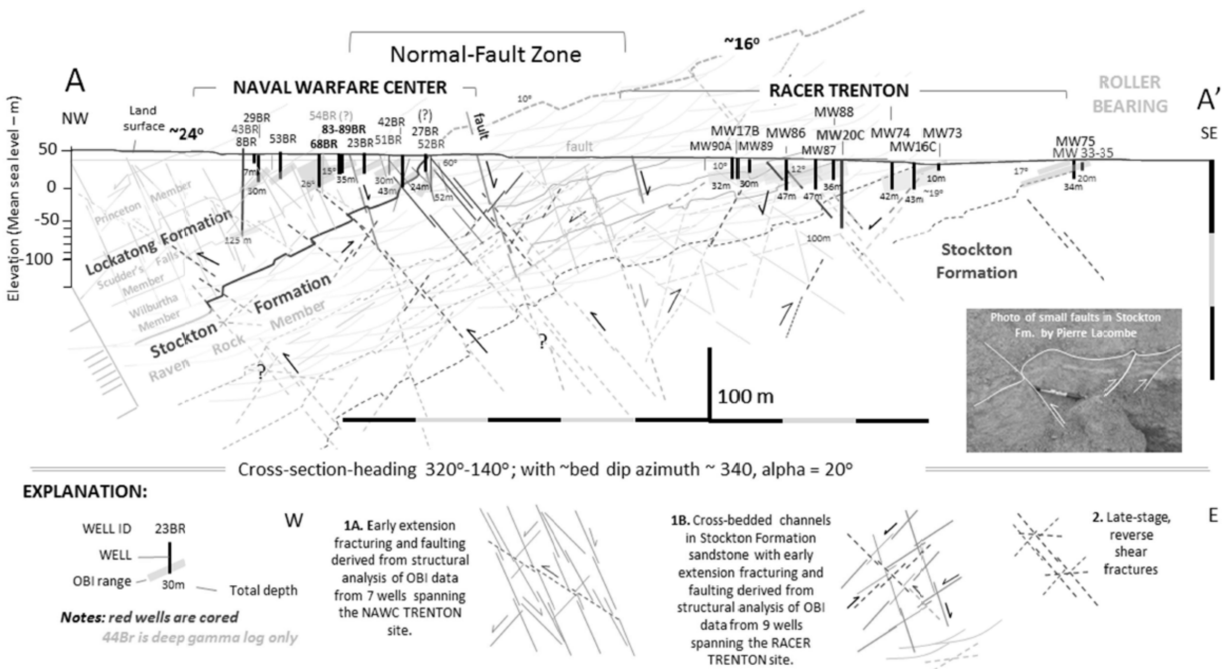


Figure 10.

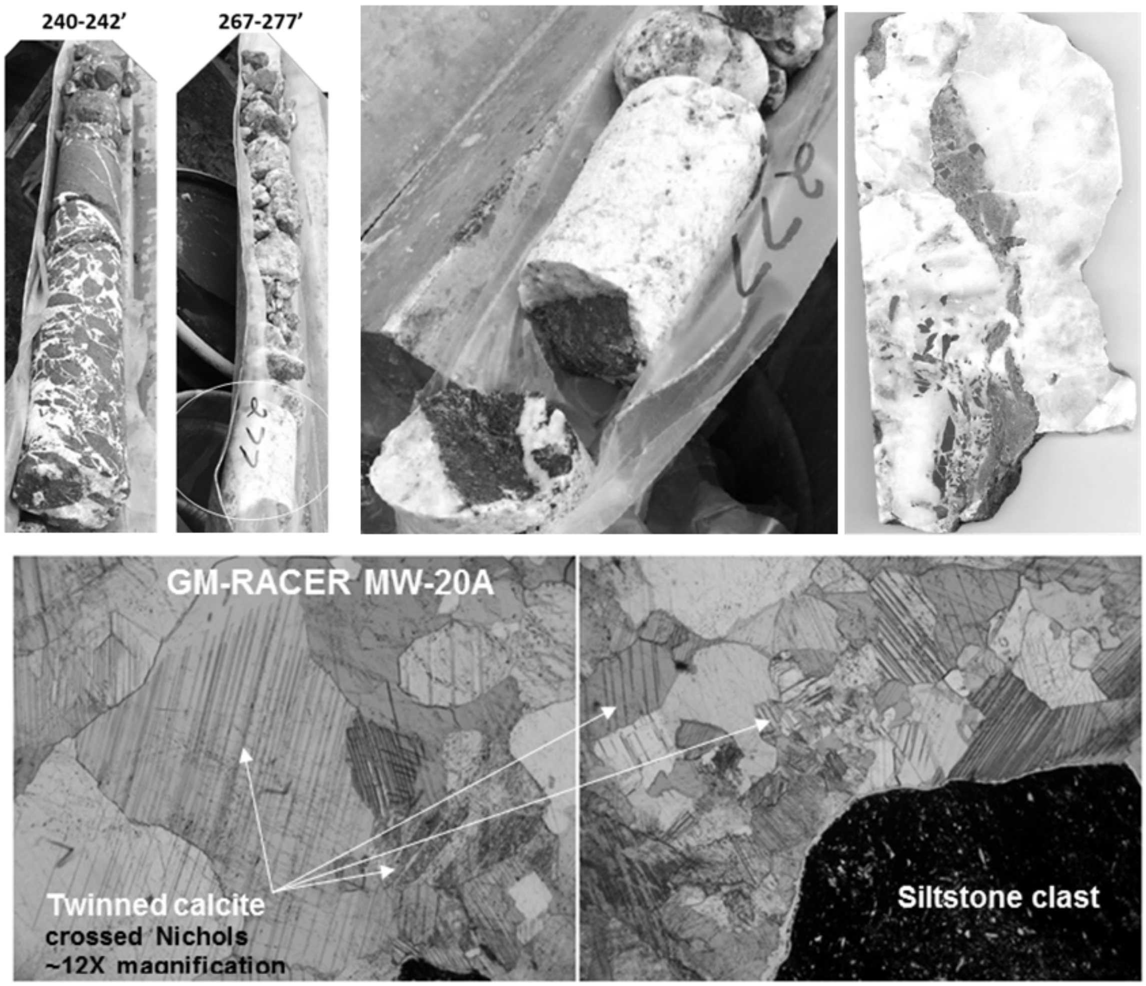
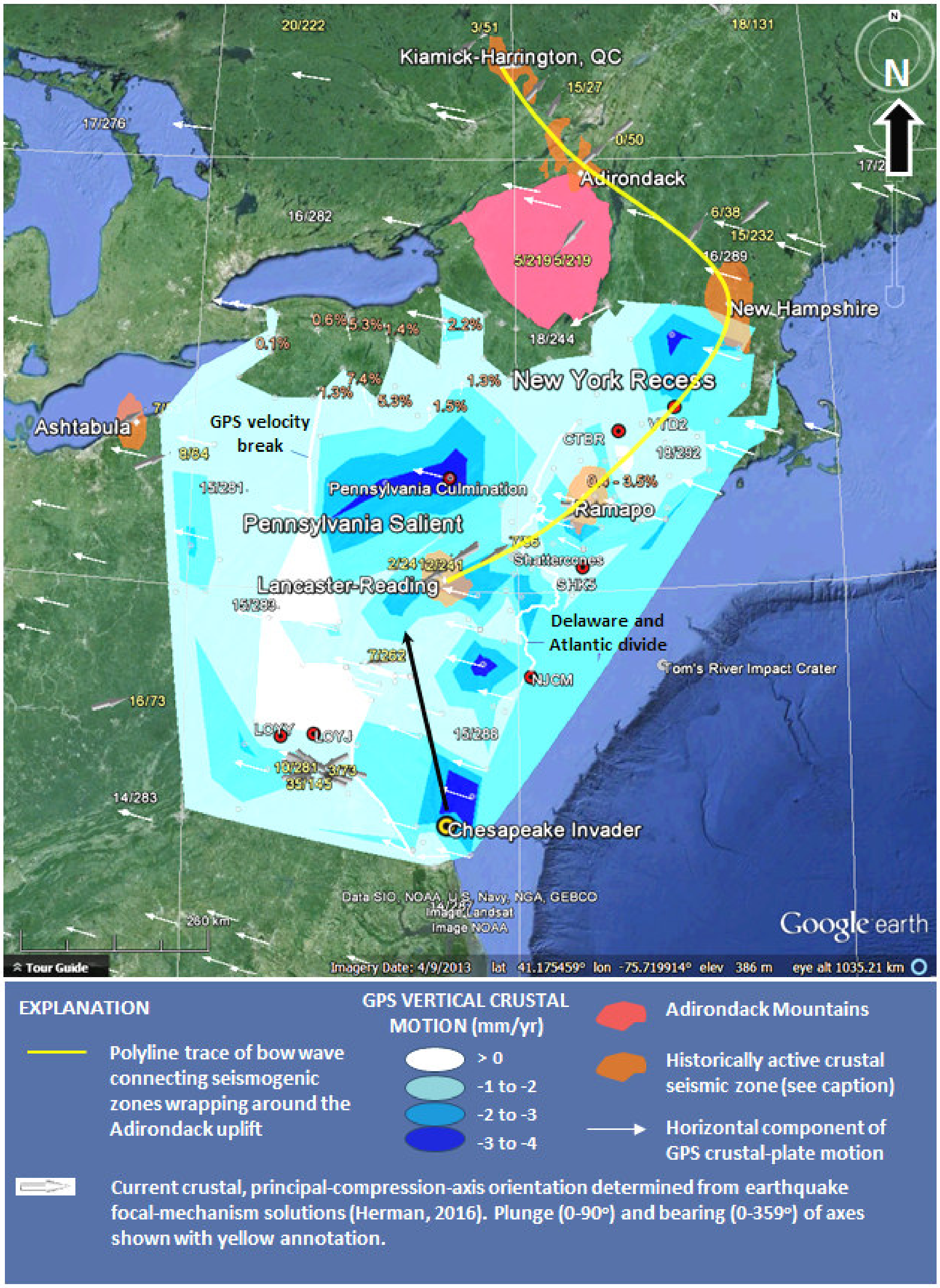

240-242’
267-277’
GM-RACER MW-20A
Twinned calcite
crossed Nichols
~12X magnification
Siltstone clast

Figure 11.



Kiamick-Harrington, QC
Adirondack
New Hampshire
New York Recess
Ashtabula
GPS velocity break
Pennsylvania Culmination
Pennsylvania Salient
Ramapo
Shattercones
Lancaster-Reading
Delaware and Atlantic divide
Tom's River Impact Crater
Chesapeake Invader
EXPLANATION
Polyline trace of bow wave connecting seismogenic zones wrapping around the Adirondack uplift
GPS VERTICAL CRUSTAL MOTION (mm/yr)
> 0
-1 to -2
-2 to -3
-3 to -4
Adirondack Mountains
Historically active crustal seismic zone (see caption)
Horizontal component of GPS crustal-plate motion
Current crustal, principal-compression-axis orientation determined from earthquake focal-mechanism solutions (Herman, 2016). Plunge (0-90°) and bearing (0-359°) of axes shown with yellow annotation.

Figure 12.

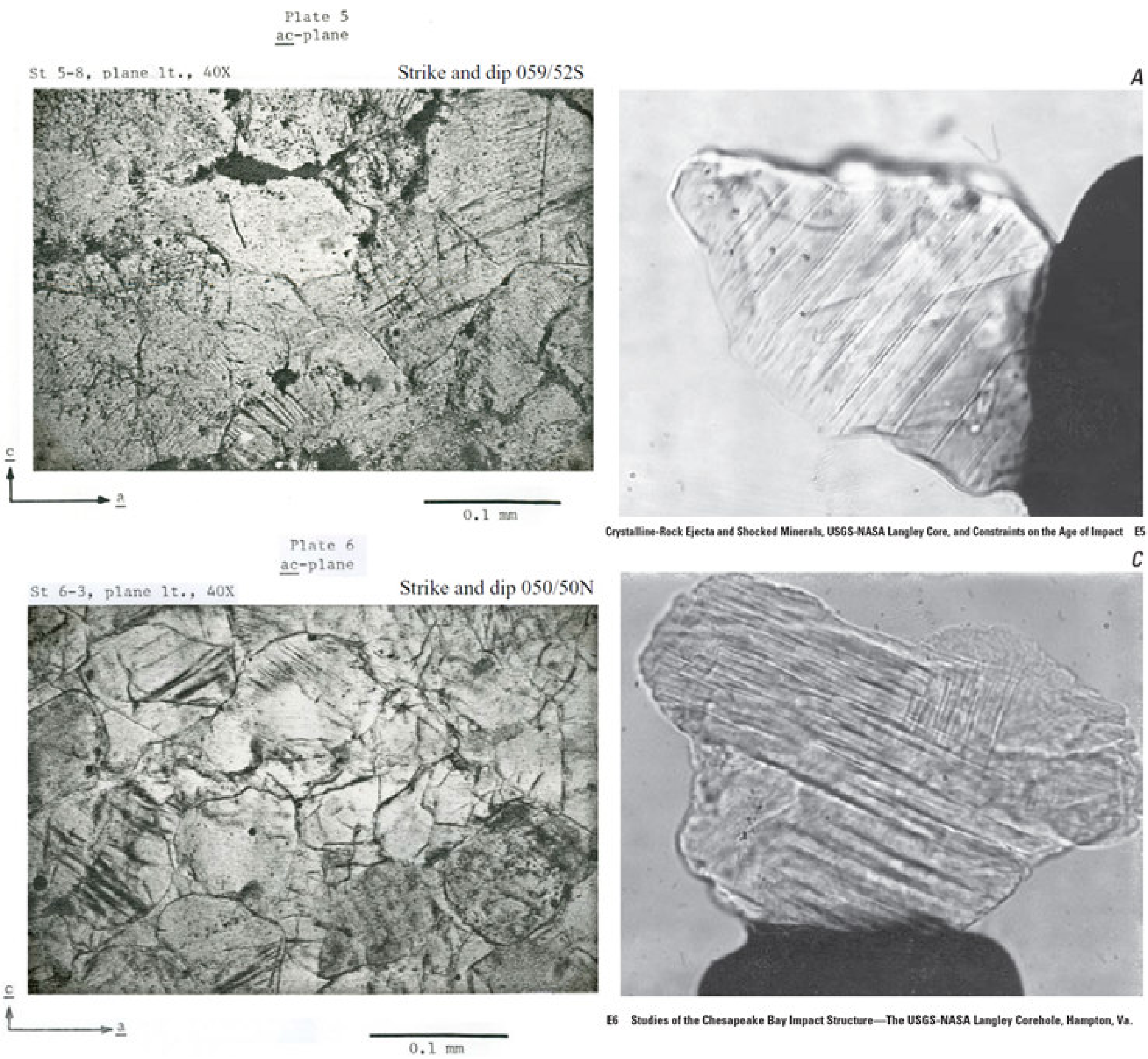


Plate 5
ac-plane
St 5-8, plane lt., 40X
Strike and dip 059/52S
c
a
0.1 mm
A
Crystalline-Rock Ejecta and Shocked Minerals, USGS-NASA Langley Core, and Constraints on the Age of Impact E5
Plate 6
ac-plane
St 6-3, plane lt., 40X
Strike and dip 050/50N
c
a
0.1 mm
C
E6 Studies of the Chesapeake Bay Impact Structure—The USGS-NASA Langley Corehole, Hampton, Va.

Figure 13.