Neotectonics of the New York Recess

MEETING PROCEEDINGS AND FIELD GUIDE FOR THE 2015 CONFERENCE
OF THE GEOLOGICAL ASSOCIATION OF NEW JERSEY

EDITED BY

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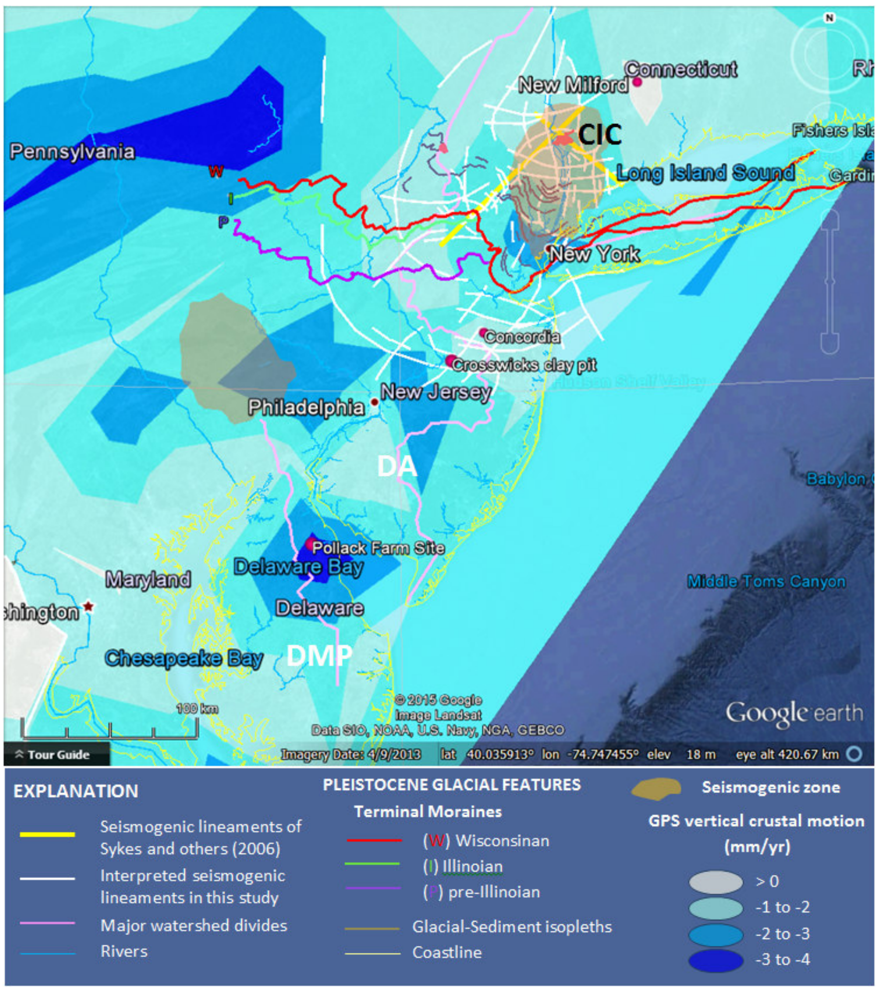

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Chapter 4. Neotectonics of the New York Recess, USA

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Abstract

The present-day (neo-) tectonic framework of the west central Atlantic continental margin centered on New Jersey is mapped using digital geophysical and geological data with Google Earth (GE). The incorporated data themes are available from our internet web site www.ganj.org/2015/data.html. These data include some samples of high-precision, laser-based (LiDAR) topographic surveys in the form of hill-shaded raster imagery that were used in conjunction with GE's aerial imagery to help portray our neotectonic setting. Other incorporated geological themes include 1) historical earthquake occurrences, some of which provide focal-mechanism solutions for the current state of crustal stress, 2) current crustal motions including long-term determinations of horizontal drift and vertical ground motion gained from ground-fixed and continuously monitored global-positioning-systems (GPS), 3) and regional geological themes portraying geological strata and trends of secondary tectonic structures including fold axes and major facture systems. These themes are used to gain a perspective on the latest brittle structures that may have originated in our current state of crustal stress, that are seen in outcrop or the shallow subsurface using geophysical methods, and that overprint older paleotectonic (ancient) structures. A simple set of chronostratigraphic groups are used that divide our regional strata into sections separated by major unconformities that are then used to summarize, review, and discuss structural features within each section with respect to their spatial distribution and kinematics. This systematic approach towards cataloguing our current geological setting results in the portrayal and definition of some newly recognized regional geological features and points to the need for a reappraisal of some older, classic interpretations of structural and tectonic stages that have impacted our region during the Mesozoic and Cenozoic eras. Although Mesozoic structures and their overprint of earlier Paleozoic and Proterozoic ones aren't neotectonic in nature, recognition of these older features in the various chronostratigraphic groups is important when considering the latest brittle structures occurring here that may have formed in our current state of crustal stress, or were reactivated in the relatively recent geological past because of their favorable orientations with respect to on-going Earth processes that incite brittle failure of the crust. Because of the geological complexity of this region, and the voluminous tectonic and structural data available for inclusion, it is impractical to cover all of the details involved in this process. Instead, an approach is taken where particular, detailed studies that best exemplify the end goals are integrated and illustrated to set the stage for further efforts along these lines.

Introduction

The theme for this year's GANJ conference and field trip is *Neotectonics of the New York Recess*. This is the first time in our organization's three decade long history that we have tackled the topic of our current tectonic setting. Perhaps it's because we sit on the eastern margin of the North American continent, a region of extreme human population and infrastructure that is generally considered to be tectonically passive by virtue of a lack widespread orogenic activity, and where only occasional, subtle glimpses of contemporary or historical tectonic activity occur. Or perhaps recent technological breakthroughs have led us to this point where precise and robust data sets are now available for the type of integration and comparison that enable characterization of the relatively subdued tectonic effects occurring here.

Only recently have Earth scientists gained free and open access to the kinds of universally uniform computer platforms and visualization software necessary to access, integrate, generate, and communicate the myriad data sets needed to characterize the subtle neotectonic aspects of a geologically complex region. With these tools and data, a vast number of spatially referenced geoscience themes are now easily compared and contrasted, allowing us to explore the more elusive links between our current states of crustal stress, current plate motions in 3D, and hence our current, or neotectonic, setting. These tools also provide the means by which to emphasize the distribution and nature of the youngest brittle structures in our region. This focus on brittle structures is simply because most common strain responses to imposed stresses on Earth's crust at land surface are elastically bending and fracturing. Earthquakes for example signal brittle-fracture response within the upper 20 km of our crust (Sykes and others, 2006). Widespread and pervasive tensile fractures associated with Mesozoic rifting distributed across broad swaths of the Appalachian foreland culminations and basins have control over the uneven and scalloped nature of our continental margin. Yet, superimposed on these Mesozoic tensile and transtentional features are younger brittle features that are commonly discordant with respect to all earlier finite-strain axes.

As presented in this chapter, integration of neotectonic aspects of this region noted in earlier chapters with the results of the above types of evaluation lends support to new tectonic interpretations, introduced here, that begin to shed light on some of the unexplained, relatively recent epeirogenic movements noted in our region. This chapter summarizes what is currently known about the neotectonic setting and structural framework of the Appalachian region centered about New Jersey, near geographic coordinate's 40^{o} N latitude and 74^{o} W longitude. This region happens to comprise the ill-defined junction between the central and northern Appalachians, including such prominent physiographic features as the Pennsylvania Salient, New York Recess, Salisbury Embayment, and the Adirondack Mountains (fig. 1). This small section of the continental land mass located on the North American plate (NAP) has been repeatedly tectonized by a series of well-constrained geological events associated with various convergent (mountain-building) and divergent (ocean building) tectonic events (fig. 3). Older, widely recognized events include the Grenville (Proterozoic), Taconic (early Paleozoic), Acadian (mid Paleozoic) and Alleghanian (late Paleozoic) orogenies, each of which contributed major tectonic components to our region. The Early Mesozoic Newark rift basin, the archetype rift basin and significant component in a continental-scale rift system that shredded the entire eastern continental seaboard of the NAP, spans New Jersey as well as parts of neighboring Pennsylvania and New York. With respect to more recent upheavals in our region, Woodworth (1932) and Davis (1963) both chronicled crustal arching and relatively abrupt changes in base level elevation that took place during Jurassic and Tertiary times that can now be placed into a neotectonic perspective.

This work benefits from a computerized, multi-variable analysis of the geology in our region that provides snapshots of our present day physical setting with respect to our current state of crustal stress and absolute crustal-plate movements. Complexities that arise with working with such large sets of geospatial data are addressed by grouping geological units into lithic groups (figures 1 and 2) and implementing a simple feature-accounting system reflecting our tectonic history in order to itemize and systematically compare strain features and effects (fig. 3). This allows a close examination of the different groups of brittle strain features and kinematics. When coupled with constraints stemming from work focused on lithospheric crustal responses to glacial and sedimentary loading of the continental margin, this work may help explain how and when our neotectonic stress regime switched polarity and evolved to where we are today. What certainly becomes clear from this process is a picture of our current neotectonic framework showing coincident and congruent breaks in crustal motion with clusters of recorded earthquakes. With further scrutiny, other tectonic controls can be evaluated with respect to measured plate motions, including lithospheric flexuring and local crustal failure stemming from a host of tectonic processes including erosion, denudation, sedimentation, and periodic advance and retreat of continental glaciers and marginal seas.

What has not been determined is the manner and/or source of the tectonic stresses on our region during the Tertiary period that resulted in late-stage, brittle shear fracturing and oblique wrenching of this region from east-central Pennsylvania through New Jersey and southern New York which increase in intensity towards the Chesapeake Bay impact site. Regional data indicate a post Newark-aged northward push into and through our region of that not only sheared the crust, possibly compacting it by as much as 10%, but also thickened and hence uplifted it, perhaps by as much as a few kilometers. These observations are placed into context with the working hypothesis that I published in an abstract almost ten years ago (Herman, 2006) that related large, hypervelocity bolide (asteroid or comet) impacts on Earth to geodynamic processes and measureable lithospheric strains.

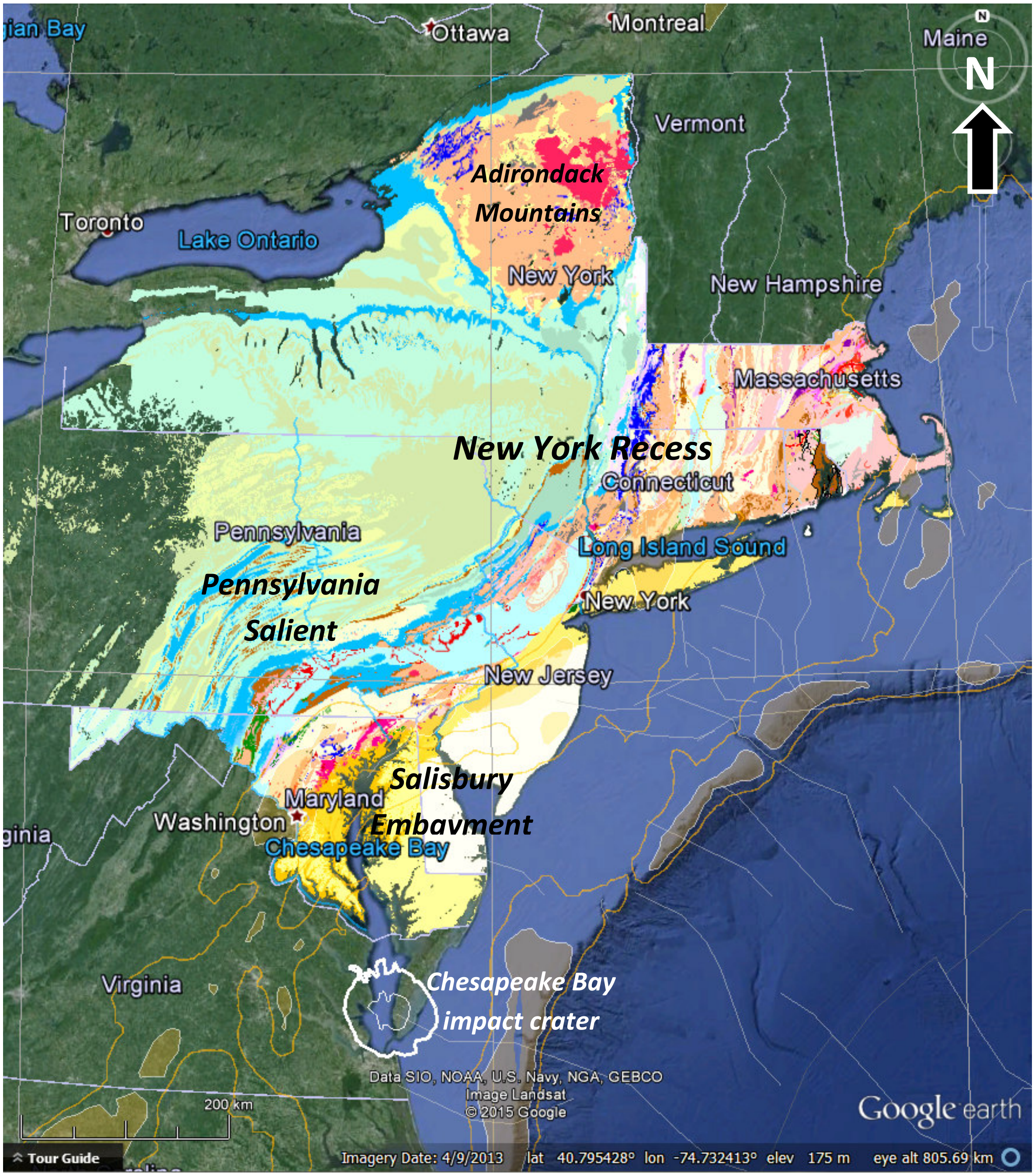


Figure 1. Integrated USGS geological themes covering parts of seven states, centered about New Jersey. Bouguer gravity isolines (Herman and others, 2013) and interpreted oceanic fractures covering the coastal and shelf areas are shown. The Cheseapeake impact crater, depicted by the white lines, are buried beneath ~3 km of sediment at the mouth of Chesapeake Bay. To allow tectonic analyses on a regional scale, and integrated geological base map was compiled using thirty-one (31) lithic groups to color the statewide themes. Each lithic group and its associated color is defined in figure 2.

	RGB	Unit
1	100 100 100	Amphibolite
2	250 30 80	Anorthosite
3	240 220 250	Argillite and hornfel
4	0 170 250	Carbonate
5	200 50 150	Conglomerate
6	250 220 100	Cretaceous sedimentary
7	250 180 180	Felsic intrusive and granofel
8	220 150 150	Felsic extrusive and metavolcanic
9	250 170 120	Gneiss and paragneiss
10	150 200 175	Graywacke
11	240 110 110	Intermediate intrusive
12	250 90 170	Intermediate extrusive
13	210 0 0	Jurassic plutonic
14	210 250 210	Jurassic sedimentary
15	250 170 0	Jurassic volcanic
16	0 0 250	Marble and calcareous metasedimentary
17	0 128 0	Mafic extrusive, metavolcanic, greenstone and serpentinite
18	255 0 130	Mafic intrusive
19	170 230 200	Mudstone and shale
20	220 180 250	Phyllite
21	190 210 150	Sandstone
22	250 230 200	Schist
23	220 250 150	Siltstone
24	230 200 250	Slate
25	235 235 190	Taconic allocthons and Jutland Formation
26	250 230 10	Tectonic breccia, mélange and mylonite
27	250 250 220	Tertiary sedimentary
28	170 250 250	Triassic sedimentary
29	160 80 0	Quartzite
30	255 255 135	Quaternary sediment
31	192 0 0	Ultramafic

Figure 2. Stratigraphic units and associated Red-Green-Blue (RGB) computer palette used for compling an integrated geological base map for regional tectonic compilation and interpretation of the NY Recess region, as presented in figure 1. Grouping units in this manner enables the integration of state-geology themes that are otherwise coded by formation and provide too much detail.

This chapter includes known details and processes that help us understand our neotectonic setting, but much is left to be desired. Written and photographic accounts of disrupted Late Mesozoic and Cenozoic coastal plan deposits are rare. Most clay pits and artificial outcrops are largely reclaimed and developed. Foreland penetrative crustal compaction of classic Appalachian foreland affinity are found sparingly in the Newark Supergroup where late-stage penetrate strains and reverse faulting point to a more recent brittle event that may correspond to some of the regional uplifts that have been chronicled in this region by workers over the past century. But detailed subsurface work in this region by many workers over the past few decades, occurring in both fractured bedrock and post-Jurassic strata of the coastal plain, have helped identify relatively young, igneous intrusives, brittle faults, and nearby bolide-impacts of considerable size that may share a linked tectonic heritage. For example, brittle strain effects of late Jurassic or Cretaceous crustal transtention in the New

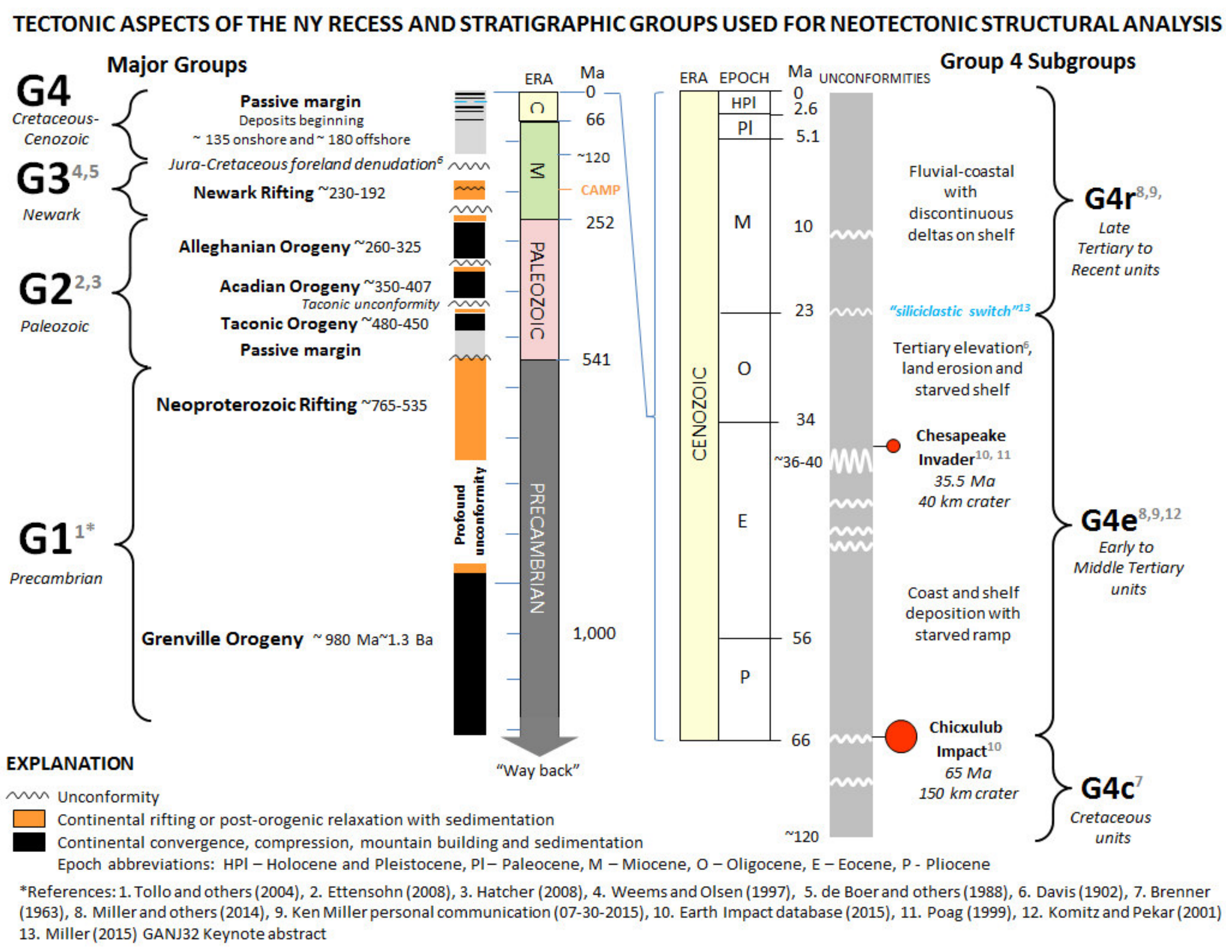


Figure 3. Chronostratigraphic groups used for a neotectonic structural analyses of NAP mid-Atlantic region. Two large-bolide impacts on the NAP during the Cenozoic are shown relative to time and stratigraphic aspects. References for the tectonic and stratigraphic aspects are footnoted after group names and abbreviations. Era and stage boundary ages are from www.stratigraphy.org.

Jersey highlands can now be seen clearly on modern, laser-derived base imagery to cross-cut and segment Musconetcong Mountain with discordant faults showing both normal and oblique slips (see Chapter 5, STOP 1). These trends appear to link with cross-strike fracture cutting Cretaceous coastal plain units, pointing to probable eastward- to northeastward-directed transtentional collapse of the New York Recess including part of the Early Cretaceous coastal plain. This region was subsequently compressed and elevated yet again, more than once, as indicated by the orientation of the current stress regime, and a brittle, non-coaxial overprint that subtlety affects all pre-Cretaceous bedrock in the region. Because late-stage, uplift events in this region are apparently sub-vertical or epeirogenic in nature from a geomorphological viewpoint, recent work of Herman and others (2013) in GANJ 30 becomes relevant for helping to explain Mesozoic crustal inversion, first outlined by Woodworth (1932), that probably stems from distributed thermal welting and emplacement of intrusive bodies of the Central Atlantic Magmatic Province (CAMP) along the eastern continental margin of the NAP. However, this fails to account for Cenozoic-aged tectonic disruptions that produced pronounced continental unconformities, such as the mid-Cenozoic one in the region of the NY Recess that temporally coincides with the arrival of the Chesapeake Invader (fig. 3 and Poag, 1999).

The following work is organized to show the un-interpreted graphic data first for review and consideration, before discussing ensuing interpretations. The methods of data integration, processing, and display are noted for the various themes, including current, crustal-plate motions, recorded earthquakes, and 3D vectors summarizing our current state of crustal stress. Aspects of other regional and global Bouguer gravity and aeromagnetic geophysical themes are included to help decipher and constrain the ensuing, interpreted tectonic trends. The various brittle geological features found in the region are then discussed using chronostratigraphy to systematically assess their occurrence, spatial distribution, and kinematic behaviors, beginning with the most recent ones and progressing backwards to relatively older ones. The results of this process leads us past conventional thinking to cautiously consider whether some of the neotectonic effects we see, particularly those that don’t fit current tectonic paradigms, could have formed as far-field brittle effects imparted by catastrophically large-bolide impacts on the NAP during the Cenozoic Era. In other words, can impact tectonics fill in current gaps in our tectonic history that conventional orogenic processes cannot fully explain? Can catastrophic impacts help explain documented, epeirogenic episodes of crustal compression and ’out-sequence’ orogenic structures like those reported in the Juniata Culmination of Pennsylvania (Herman, 1984)? These thoughts are not commonly held or entertained by the general geological community at this time, but they are bolstered by recent radiometric work conducted in Pennsylvania and northern New Jersey using Rhenium and Osmium (Re/Os) isotopic age dates obtained from sulfide-mineralized faults zones (Chapter 3; Mathur and other, 2015). All signs at this time point to a widespread episode of tectonic disruption in our region at the time of and immediately following the Chesapeake impact. But are there other, more plausible explanations? If one merely entertains the notion of tectonic catastrophism, then why not extend the plank farther and wrestle with the notions of what tectonic and geodynamic effects can (or do) stem from very large, extremely energetic bolide impacts such as Chicxulub, the one that hit the Gulf of Mexico at the dawn of the Cenozoic Era! Could the Chicxulub impact have subsequently altered global plate dynamics? Can the Chicxulub impact be responsible for the current state of crustal stress and NAP plate motions in places as far removed as New Jersey? At the end of this chapter and forum, I hope that we land securely on solid footing, where we can not only consider catastrophism in a neotectonic sense, but begin seeing it in a global sense. For if these hypotheses are tested and ring true, then they must blend seamlessly with uniformitarianism in order to fully account for the geodynamic processes observed around us.

Digital Geospatial Themes in a GE KMZ format

Over the past two decades digital-mapping systems and methods have arisen that provide extremely accurate measurements and visualization of grounded field positions and surface geologic structures. These also provide timed measurements of crustal-plate motions from over a decade of Global Positioning System (GPS) data. Terrain maps in some places are now measured with sub-meter precision using airborne laser mapping (LiDAR). This chapter reflects the use of such data and methods to integrate, interpret, and share geospatial data using this forum so that anyone can access and use them in the same environment in which they were organized. This allows one to place discrete, geology observations into context with the sequences of Appalachian tectonic events that shape our region.

As noted previously, this study is centered between the Adirondack Mountains of New York and the Chesapeake Bay as part of the Salisbury Embayment of Maryland and Delaware. Both raw and interpreted data are compiled, including preliminary tectonic interpretations of geological features over parts of New Jersey, Maryland, Delaware, Connecticut, Massachusetts, and the eastern parts of New York State and Pennsylvania (fig.1). This was done in order to place New Jersey and the New York City area into geospatial context within a broader region that shares geological processes and products. The figures represented herein that use Google Earth (GE) were generated using the data that are available from download from the GANJ web site. These databases are mostly reprocessed and packaged source themes from the US Geological Survey, the Geological Society of American (DNAG magnetic and gravity potential field data), the National Oceanic and Atmospheric Administration (NOAA) and the National Space and Aeronautical Administration (NASA), among others. The methods used to generate new data and interpretations are intertwined herein with descriptions of how each theme was accessed, processed and used for regional visualization.

This work used Microsoft's MS-Excel spreadsheet software to handle parametric data, and both ESRI's Arc-GIS and Google Earth (GE) to integrate and interpret the data. GIS was mostly used to conduct structural analysis of bedrock ridges exposed in high-resolution topographic maps (see Chapter 1). GE on the other hand, is a free, 4D global-visualization tool that is used both for viewing and interpreting the data, and for easily communicating the results. GE is a time-variant, virtual globe that works with geographic spatial coordinates and is a recognized standard for data sharing among the scientific and general community using the internet, including our GANJ web site. Most of the figures in this report were generated by capturing visual displays of various geospatial themes at various viewing scales directly from the computer-display screen. Therefore within this report, the term 'view scale' is used rather than the more common 'map scale', because the figures are simply graphics capture, or a 'screen grab' of a computer display when one is satisfied with the view. Representation of our current geological and geophysical state in this manner can be a risky task as the various geological units and geophysical data nomenclature are constantly in flux, and stem from varying periods of record and source scales, so each figure should be considered a static snapshot of the geodynamic processes that we dwell on. We are still learning the uses and limits of these technologies, which from my perspective, are getting better at an accelerated rate. Nevertheless, the visualized raw data serve to base new interpretations of how our region has evolved tectonically, and care is given to not only to outline the methods that have been employed, but also reference the source material and pertinent metadata for each theme that is needed to build a reliable foundation for the regional tectonic analyses.

Integrated USGS Geology using generalized lithic groups

Current statewide geological maps are compiled and distributed in a computerized format by the USGS for the entire United States by state, and for most of the world for hydrocarbon exploration[1]. These data are provided for download in various data formats, including those for GE as Keyhole Markup Language (KML) files or the compressed variety (KMZ files), as described in Chapter 1. The available USGS state-based KML files for Delaware, Maryland, New Jersey, Pennsylvania, New York, Connecticut, Massachusetts, and Rhode Island were manually reprocessed for generalization and use in conducting this regional, neotectonic structural evaluation. For example, rather than the default display mode based on individual geological formations as standardized by the USGS, this study includes a regional geology theme in a KMZ format that was customized for display using lithic groups. Data integration was done manually using Microsoft's freeware XML (extended mark-up Language) editor, XML Notepad 2007, as computer software that can read and display the KML folder structure, as well as allow addition of new folders with customized names of lithic groups that can receive groups of formations that were manually placed in each new folder using the primary rock type

[1] http://energy.usgs.gov/OilGas/AssessmentsData/WorldPetroleumAssessment.aspx

listed for each formation for each theme. Upon grouping adjoining themes in this manner, continuous patches of similar rocks or sediment visually emerge that aid in identifying tectonic structural discontinuities that correspond to folds and faults (figs. 6-9). Some mismatched stratigraphic units still occur along contiguous state boundaries (fig. 1) but many disappear from using this approach. Figure 2 details the 31 lithic groups that were used e to contrast certain lithologies that may lend clues into the occurrence of secondary structures by their fold and faulted patterns. A RGB color screen was worked out (fig. 2) to recombine each USGS state files including those for (fig. 1).

Current plate movement using ground-fixed Global Positioning Systems (GPS)

I began studying the neotectonics of this region in 2003 while conducting fracture-bedrock aquifer research for the NJGWS (Herman, 2005). Don Monteverde suggested in 2005 that I look into using ground-fixed receiving stations that use global-positioning-systems (GPS) technology to facilitate this work. At that time, NASA maintained an open-access internet portal through their Jet Propulsion Laboratory (JPL) that included almost 800 global stations where crustal movements were continuously being monitored (table 1), with most located on the NAP (Herman, 2006). The GPS includes a constellation of Earth satellites in geosynchronous orbits that are used for global navigation and precise geodetic position measurements. A GPS includes the navigation payloads that emit radio signals, receiving station on or close to the ground, the data links, and the associated command and control facilities operated and maintained by the US Department of Defense in conjunction with civil and commercial service providers. GPS provides determinations of three dimensional positions referenced to N-S, E-W, and UP-DOWN, with velocities along each position in mm/yr, and time records kept for about 95% of the time, for 24 hours a day, in all weather, and around the globe (Assistant Secretary of Defense, 2001). Daily positions are collected and analyzed by various organizations and institutions that then deliver these geodetic data to the California Institute of Technology under contract with NASA's Jet Propulsion (sideshow.jpl.nasa.gov/mbh/series.html, and to NOAA through their CORS (Continuously Operated Reference Stations) web portal with data covering the USA (geodesy.noaa.gov/CORS/). Record keeping began for some stations in 1989, with each station having come on line at various dates with unique types of data records, and sampled at varying frequencies. GPS time-series data for each receiver location are analyzed by various sources to determine short- and long-term positional changes of the station through time relative to a fixed, mathematical reference frame (calculated ellipsoids or spheroids). But reference frames and instrumentation are periodically modified and improved, and different adaptions evolve for use by international and national agencies and programs requiring standardized and robust data sets. Prior to September 6, 2011, CORS GPS data were compiled and released as long-term data using a reporting format standardized with NASA-JPL data that referred to an International

Terrestrial Reference Frame of 2008 using 2005 coordinates for the GRS80 ellipsoid. Since 2011, CORS data update new a new coordinate reference frame and are no longer available as tabular data sets using customized queries to simultaneously access data records for multiple stations. COPS data users must now access single records at a time and statistically process each data set to analyze long-term trends. We're currently investigating ways to automate this process at the NJGWS, but for now, the 2009 data are used for this work, and are only spot checked for validity with respect to variations of long-term trends over time. Table 1 provides a basic statistical summary of four different GPS data sets that used as part of this work. It shows that the number of global, ground-fixed receiving stations has increased by over 300% in a span of only 10 years. This table also includes a comparison of the formal positional and velocity errors for global data sets downloaded one decade apart. For more information on GPS and recent development in the technology see www.gps.gov/systems/gps/space/ and www.ngs.noaa.gov/CORS/coords.shtml.

Table 1. Basic statistical summary of four, ground-fixed GPS data sets used for analyzing and representing long-term crustal-plate motions. Rates of motion stated in mm/yr.

Data set	No.	Avg. X vel.	Avg. Y vel.	Avg Z vel.	Avg horiz. vel. (calc)	Avg. X vel. error (+-)	Avg. Y vel. error (+-)	Avg Z vel. error (+-)	X-vel. range	Y-vel. range	Z-vel. range
NASA 2005 GLOBAL	778	23.4	12.2	3.7	27.0	0.2	0.3	0.6	> -71.5 < 66.8	> -35.2 < 57.4	> -90.9 < 125.4
NASA 2015 GLOBAL	2485					0.2	0.2	0.7			
NOAA 2009 NY REGION	67	0.4	0.6	1.2	-	-	-	-	> -1.6 < 1.2	> -1.4 < 2.4	> -3.9 < 0.2
NOAA 2014 SPOT	7										

I suppose it was just good fortune that I visited the CORS web portal in 2009 and downloaded a data set covering this region before the aforementioned changes in CORS positional recording and data access policies took effect, as the use of these data are rapidly becoming more sophisticated and difficult to use because of growth and specialization of the industry. The 2009 data set includes records for 67 ground-fixed, GPS receiving stations in the region of the NY Recess (fig. 4). I used ESRI's ArcView's 3D Analysts GIS software to produce a simple triangular integrated network (TIN) surface map based on the interpolation of point values and showing areas with the same ground motion. Upward rates are positive and

Figure 4 *(Legend and explanation below figure on opposing page).* 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, princial axes of crustal compression reported from focal-mechanism solutions from well-constrained earthquakes, and some key structural analyses used for interpretations. Note the parabolic line connecting the seismic zones wrapping arond the rising Adirondack Mountains, which appear to act as a buttress that is resisting the slow, northwestward plate drift with rates that slowly increase NE up the spine of the Appalachian Mountains.

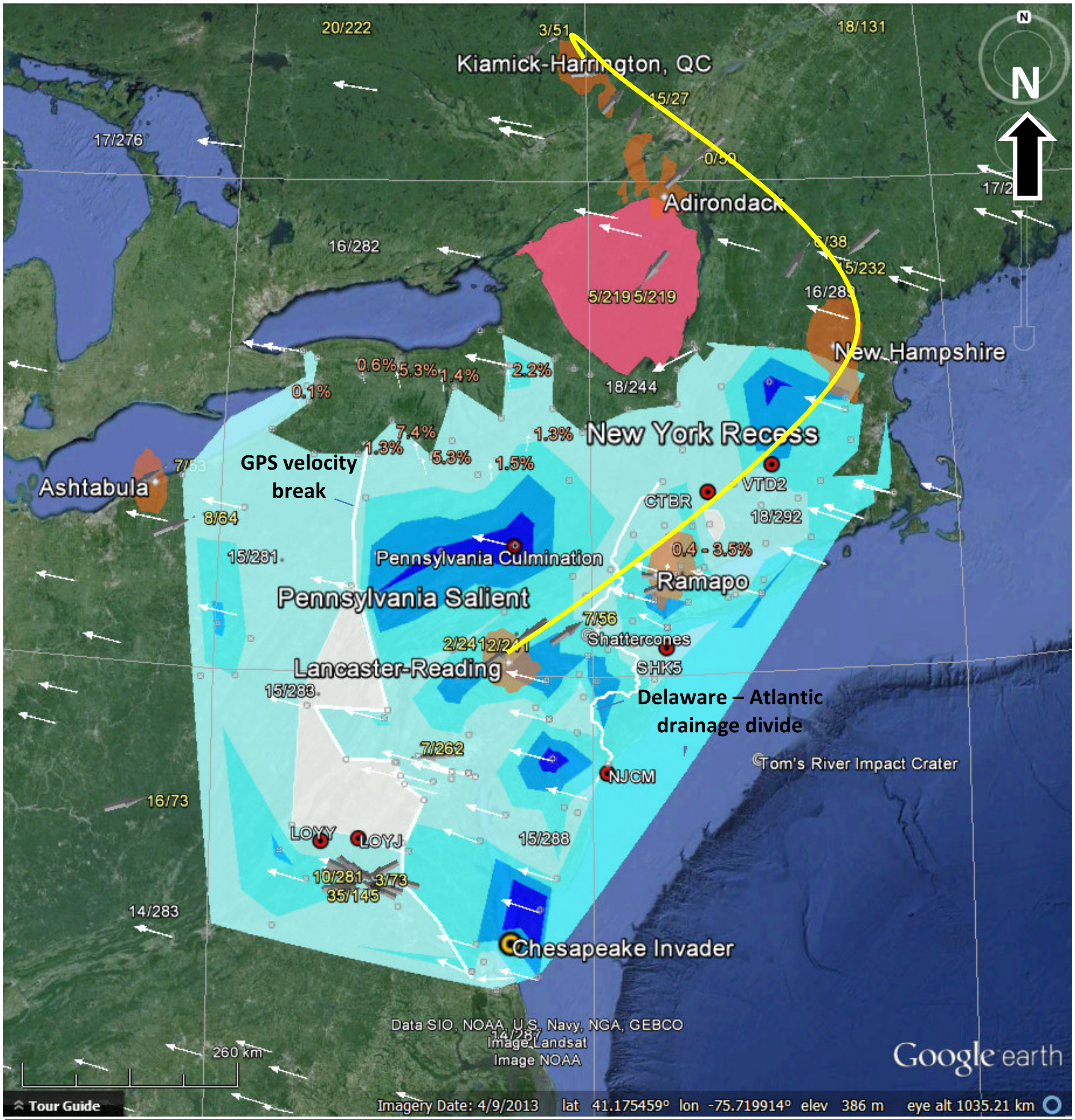
NASA-JPL[2] and NOAA-CORS[3] ground-fixed GPS data to capture 'long-term' horizontal and vertical crustal movement - The large white vectors show the horizontal component of current crustal motion in mm/yr based on NASA-JPL[2] global data downloaded in May 2015. Different stations came on line at different times and use different sampling rates. Some vectors include white labels showing magnitude (mm/yr) and bearing (azimuth 0-359^{o}). Current regional horizontal motion is to the WNW at rates that gradually increase from ~14 mm/yr at the Chesapeake Bay in the SW to ~16 mm/yr in the northast (NE) near the Adirondacks. The blue and white polygons comprise an equal-velocity surface capturing a snapshot of 'long-term' trends in vertical ground motion captured from NOAA's on-line data portal referred to as 'CORS'[3]. This surface was derived using the 151 ground-fixed CORS records located with the small, white, open circles. These time-series records also have varying record lengths and sampling rates. The polygons were generated as a GIS triangulated integrated network (TIN) with break lines set to the 5 velocity ranges detailed in the figure explanation below right. See text for more information on how long-term GPS-series data were obtained, plotted, statistically analyzed, and spot checked for accuracy.

Crustal seismogenic zones - Orange polygons represent the historical, crustal-seismogenic zones derived using a GIS grid of uniform cell size (50 km) to quantify the density of earthquake epicenters falling within a 1^{o} search radius from cell centers within a geographic range of latitude 90^{o} S to 90^{o} N and longitude 30^{o} E to 150^{o} W (Herman, 2006). Epicenter densities were derived for each cell from a GIS point shapefile of 27,852 earthquake epicenters with a magnitude 2.0 or greater, obtained from on-line earthquake records maintained by the USGS-NEIC, the New Jersey, Ohio, and Indiana geological surveys, and Harvard's Weston Observatoy (see text). A 2D polygon shapefile of seismogenic zones was generated from the gridded results where the density of earthquake epicenters exceeded 0.001 events per km^{2}.

Current, horizontal orientations of primary crustal compression - The thicker, gray, 3-dimensional vectors with yellow labels depict directions current orientation of the crustal stress regime by depicting the bearing and plunges of the principal-axes of crustal compression calculated from well-constrained earthquakes that give 'focal-mechansim solutions' that are reported on-line and in the literature (table 2).

Detailed structural analyses – Small white vectors with orange labels indicate penetrative tectonic compaction (%) of calcite grains that fan out beyond the Pennsyania Culimination and Paleozoic rocks into New Jersey Mesozoic rocks (Engelder, 1979; Lomando and Engelder, 1984). See text for details.

2. NASA's Jet Propulsion Laboratory (http://sideshow.jpl.nasa.gov/post/series.html.
3. NOAA's National Geodetic Survey's Continuously Operating Reference Station (CORS) network (www.ngs.noaa.gov/CORS)



EXPLANATION

- Rivers
- 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 (details explained on caption on opposing page). Plunge (0-90) and bearing (0-359) of axes shown with yellow annotation.

downward are negative with ranges of about 0 to 4 mm/yr. The TIN uses three break line values to separate four ranges of vertical ground motion as summarized in figure 4. It is important to note that this 2009 representation of vertical ground motion is only a snapshot of how Earth's surface was moving at that time in a 'long-term' sense, which translates into a period of about a decade for some stations, but only shorter periods of as little as two or three years for others (figs. 4 and 5). But as a theme used for neotectonic studies when viewed together with complimentary themes including regional watershed divides, hydrography, and earthquakes, we will see that the geometry of this TIN surface conforms to map trends of historical crustal seismicity as well as the current physiographic expression of our landscape. But because the NOAA data are not as defined and inclusive with respect to formal error reporting, an additional study was done using spot GPS locations around this region for individual records downloaded in 2014 to further assess the variations and limitations seen in these data sets. Figure 5 is a summary of scatter graphs depicting timed variations and oscillations in the vertical component of crustal motion for the seven CORS stations shown in figure 4. For all charts, the vertical rate is plotted on the Y-axis and time is plotted on the X-axis. All spot locations have a negative (downward-trending) motion values determined using linear-regression statistics in MS Excel (red straight lines in figs. 5 and 6). The Wilkes Barre (WIL1) station has one of the longest records in the region and is used to compare results with 5 other stations having overlapping records and to characterize yearly oscillations in vertical ground motion (fig. 6). Note the variable monitoring periods charted in figure 5. Also note that a plot of a seven-day moving average through the raw data accentuates periodic, oscillatory trends with more clarity. Figure 6 is used to show that in our region, yearly fluctuations of our land surface systematically vary on the order of about 10mm/yr owing to solar gravitational induction of annual Earth tides. Seeing such systematic variability in timed GPS signals is important when deriving and assessing longer term, derivative TIN surfaces for used in regional kinematic analysis. A close look at these data show that the TIN surface uses velocity break lines at 2mm intervals, or at about 20% of the value of the overall expected annual range in vertical ground motion that we experience here. Table 1 also shows that positional accuracies in the vertical dimension are the least precise of all GPS positional coordinates because of such surface oscillations. Nevertheless, as we will see below, the geometry of this TIN surface, derived using statistical linear regression of data reflecting periodic, systematic oscillations of our land surface does indeed conform to complimentary geospatial physiography, hydrography, and crustal seismicity.

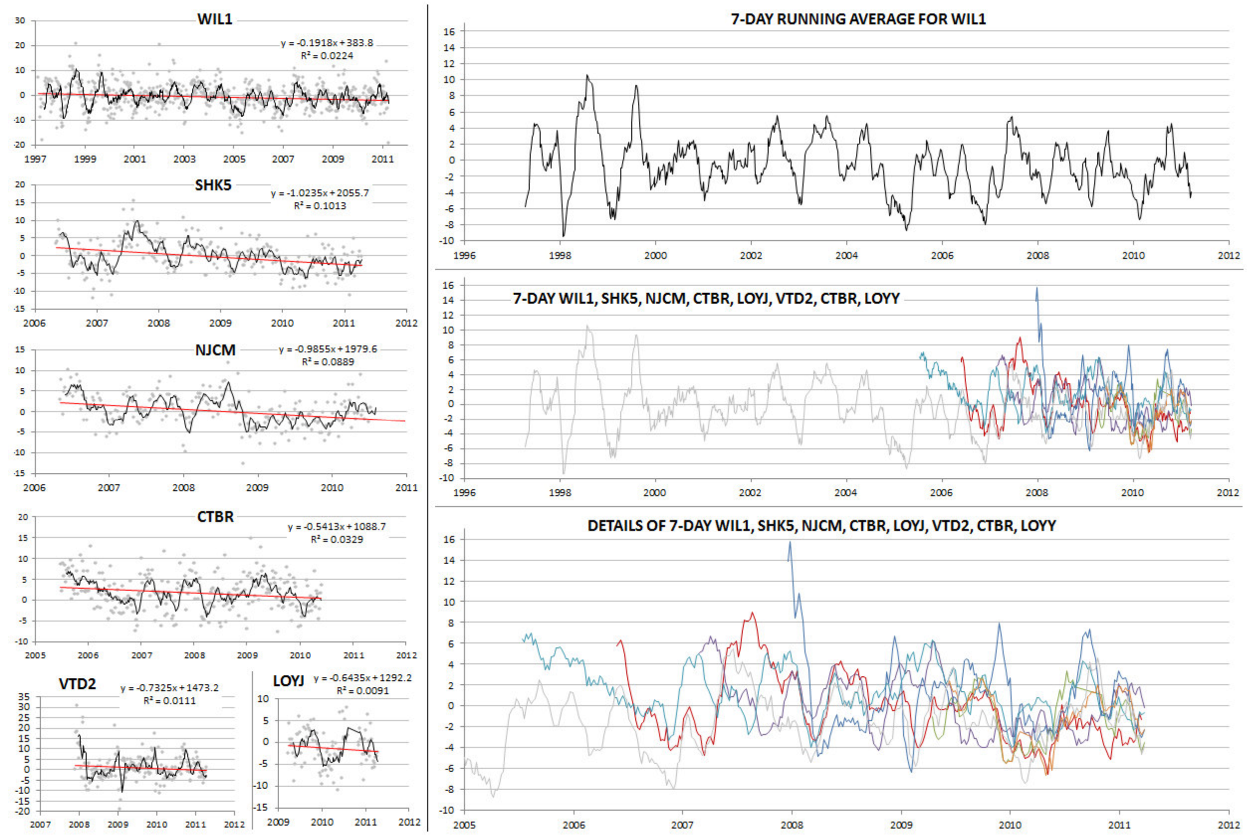


Figure 5. – Spot NOAA CORS data analysis showing unfiltered, filtered, and simple linear-regression lines summarizing data trends used to derive parametric data for the velocity axes.

Regional earthquake catalogs, crustal seismogenic zones, and depicting crustal compression

Five different sets of historical earthquake data are integrated into this work (figs. 4 and 6 to 8). The earthquake seismic zones named in figure 4 stem from the aforementioned, preliminary neotectonic assessment in this region (Herman, 2006). That work produced a GIS point theme using ESRI's (Environmental Systems Research Institute, Inc.) shapefile format with 28,139 earthquake events recorded from 1900 to 2005 between latitudes 39°N to 60°N and longitudes 46°W to 83°W. Of this total 26,625 included depth values and 27,852 are greater than or equal to magnitude 2. Most events were retrieved by a computer-based search from the USGS National Earthquake Information Center (NEIC) for the period of 1973 to 2001, but other instrumental and non-instrumental records were added from other earthquake catalogues maintained by Weston Observatory at Boston University and US States including New Jersey, Ohio, and Indiana. All records were combined and parsed to eliminate duplicate records. At this point is important to point out that earthquake magnitudes have been

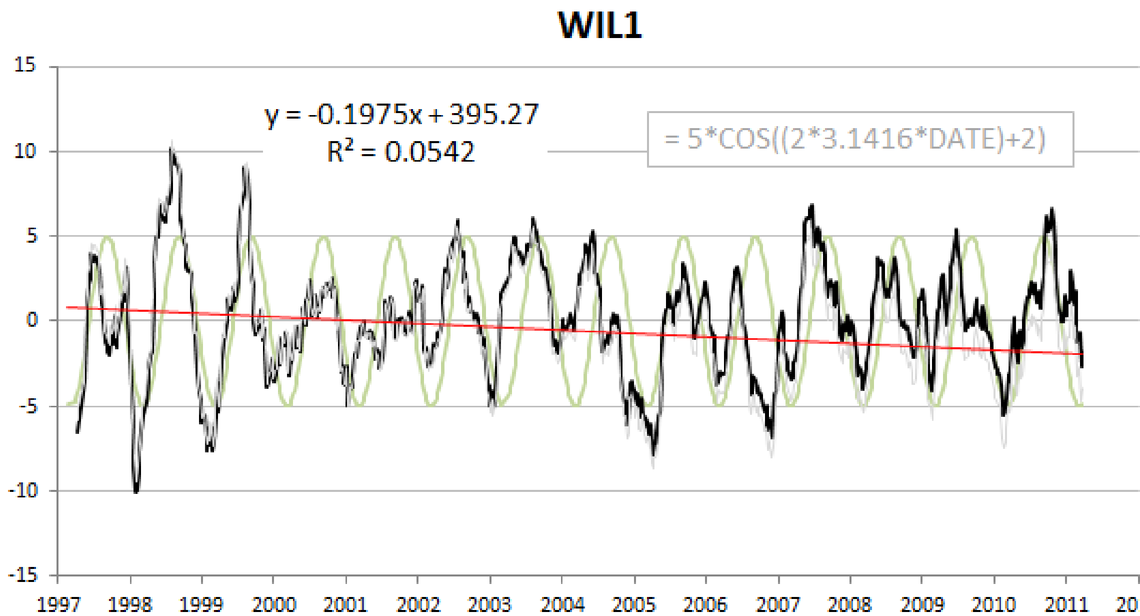
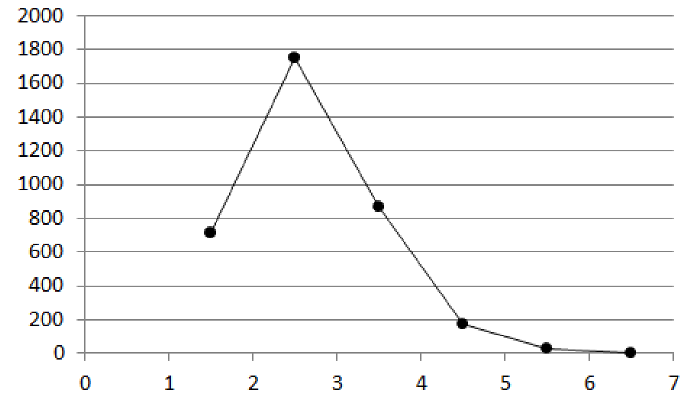


Figure 6. Fourteen years of vertical (Z-component) ground-position monitoring from Wilkes Barre, Pa station WIL1. Superimposed on the curve for the 7-day running average (thin, light-gray line) is the linear regression (red) line of the 7-day curve, an adjusted 7-day curve from removing the regional, sinking effect (regression value at time X) and a simple COSINE function showing a 31.7 nHz cycle manually fit to the data spread by trial and error. The COS function signals the amplitude variations stemming from solar-induced Earth tides with amplitudes in our region averaging about 5 mm/yr, and ranges in oscillatory motion of land surface of about 10 mm/yr. The largest range in 1998 occurred when our solar system was temporarily aligned in the Milky Way galactic plane as it crossed through during a 26,000-year periodic event (Meus, 1997).

historically defined in various manners, with the most recent, most quantitative form (Moment magnitude) having superseded the more familiar Richter magnitude value. Because of the relatively low-magnitude ranges of earthquakes in our region (fig. 7), most of the different magnitude values compiled over the historical record are comparable and only differ slightly when using magnitude classification schemes. For it's the larger and longer-period earthquake events above magnitude ~7 that the more modern methods are better formulated to assess (Aki, 1970). For this work, magnitudes were catalogued using the best methods available at that time, and we simply view then as representing systematic, logarithmic steps representing about a 30-fold increase in the amount of energy released per one-integer increase in magnitude (http://earthquake.usgs.gov/learn/topics/measure.php).

The earthquake GIS point theme assembled in 2005 was used with ESRI's cell-based modeling (GRID) program in the ArcView 3.2 GIS environment to calculate the density of earthquake epicenters lying within 1-degree square cells using a search radius of 50 miles from cell centers. A set of closed polygons were then generated that represent crustal seismogenic zones where grid density values were equal to or greater than 0.001 earthquakes per square

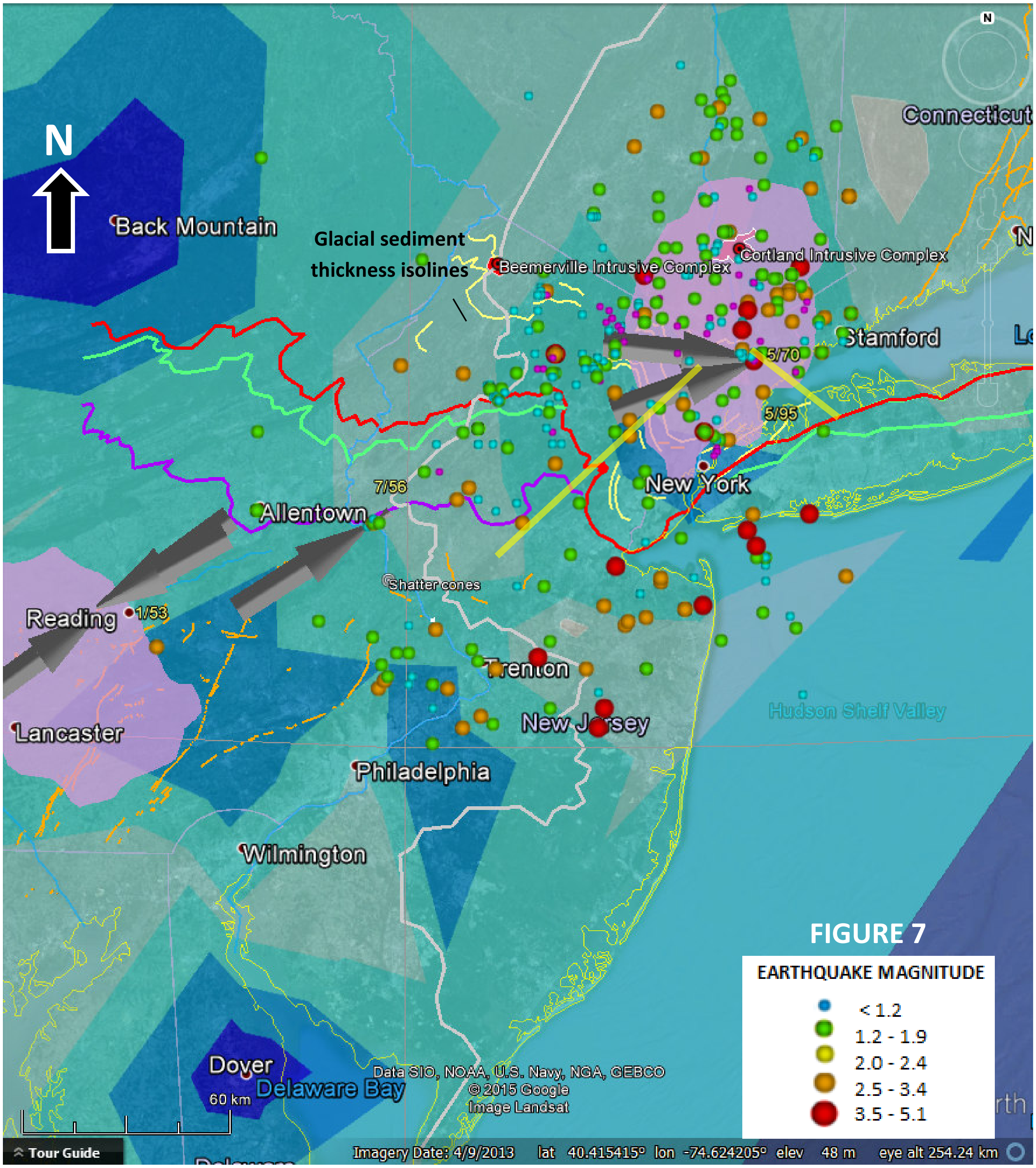
Figure 7. A scatter graph showing number of earthquakes grouped by the magnitude ranges showing in figure 10. This NEIC catalogue query includes over 3500 historical events recorded between LON 55W to 95W and LAT 30N to 50N. Most earthquakes in our region are in the 1-3 magnitude range.



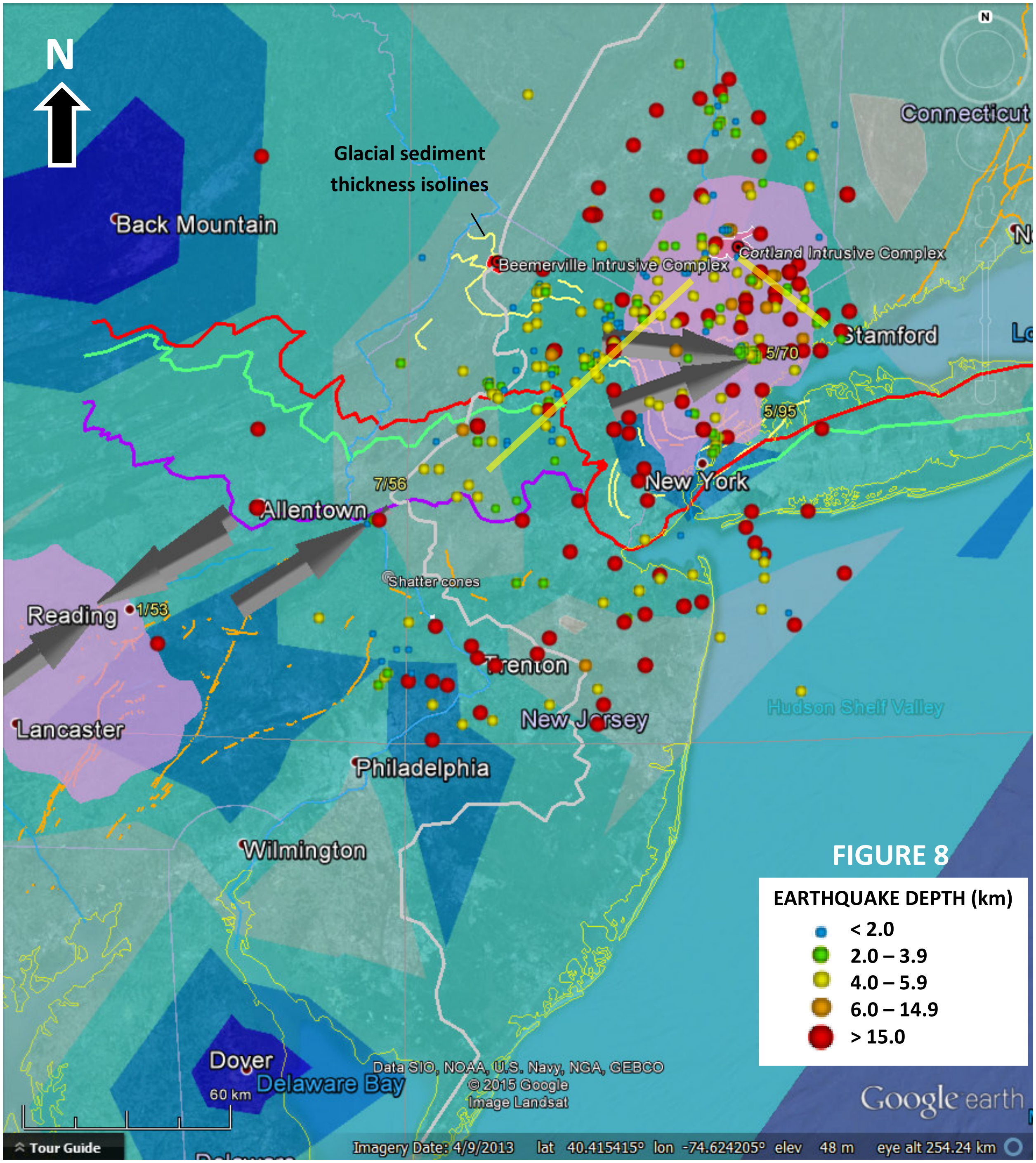
kilometer area. These values were derived at and symbolized using trial and error densities, search radii, and grid-cell sizes. This work was completed shortly before the work of Sykes and others (2006), the second of five data sources, that supersedes the earlier work by providing a more accurate, open-access earthquake catalogue covering the Philadelphia to New York region (figs. 8 and 9). But the aforementioned seismogenic zones are used here because they extend well beyond the geographic range of this newer catalog. A third earthquake catalog was obtained from the NEIC portal earlier this year by issuing a custom query for historical earthquakes lying within a region bounded by longitudes 55^{o} to 95^{o}W and latitudes 30^{o} to 50^{o}N (fig. 10). This query returned 3532 historical events that were subsequently parsed into folders holding point records of specific magnitude ranges as shown in figure 10 and tallied in figure 7.

Current crustal stress in our region using earthquake focal-mechanism solutions of principle stress axes (P-axes).

The remaining two data sources of earthquake parameters are listed in table 2 along with data from Sykes and others (2000) that detail locations, measurements, and reference sources for 45 principal axes of crustal compression (P-axes) found in our region that were derived by seismologists using analytic methods for some of the well-monitored earthquakes depicted in figure 10. The techniques surrounding the derivation of these data surpass the scope of this work, but simply state, the uneven manner in which energy is released during an earthquake indicates two possible planes of rupture, or fault planes that could have resulted in the observed energy release. By analyzing the various forms in resulting ground waves, directions, and travel times as received at various seismographic stations, the state of crustal stress that produced that energy release can be defined. The actual fault plane cannot be strictly determined, but is reduced to only a couple of geometric solutions predicated by rock mechanics. It is left to experienced professionals to determine which of two 'nodal' planes best characterizes a specific earthquake rupture based on many considerations, including field



Figures 8 and 9 (on opposite page with map legend). Locations of historical earthquakes (Sykes and others, 2006) shows ranges of magnitudes (fig. 7) and depths (fig. 8). The blue and gray polygons summarize the long-term vertical ground motion from the 2009 CORS data (fig. 4). Also shown are seismic zones (pink polygons), Jurassic dolerite dikes, Pleistocene terminal moraines and sediment-thickness contours (bright-yellow) and shorelines, rivers and streams from unpublished USGS hydrography (1:500,000 scale). Place names are default GE labels that appear when using a 60 km GE scale. The Beemerville and Cortland intrusive complexes are marked for reference. See text for further explanation of data sources. Straight yellow lines are seismogenic lineaments of Sykes and others (2006).



EXPLANATION

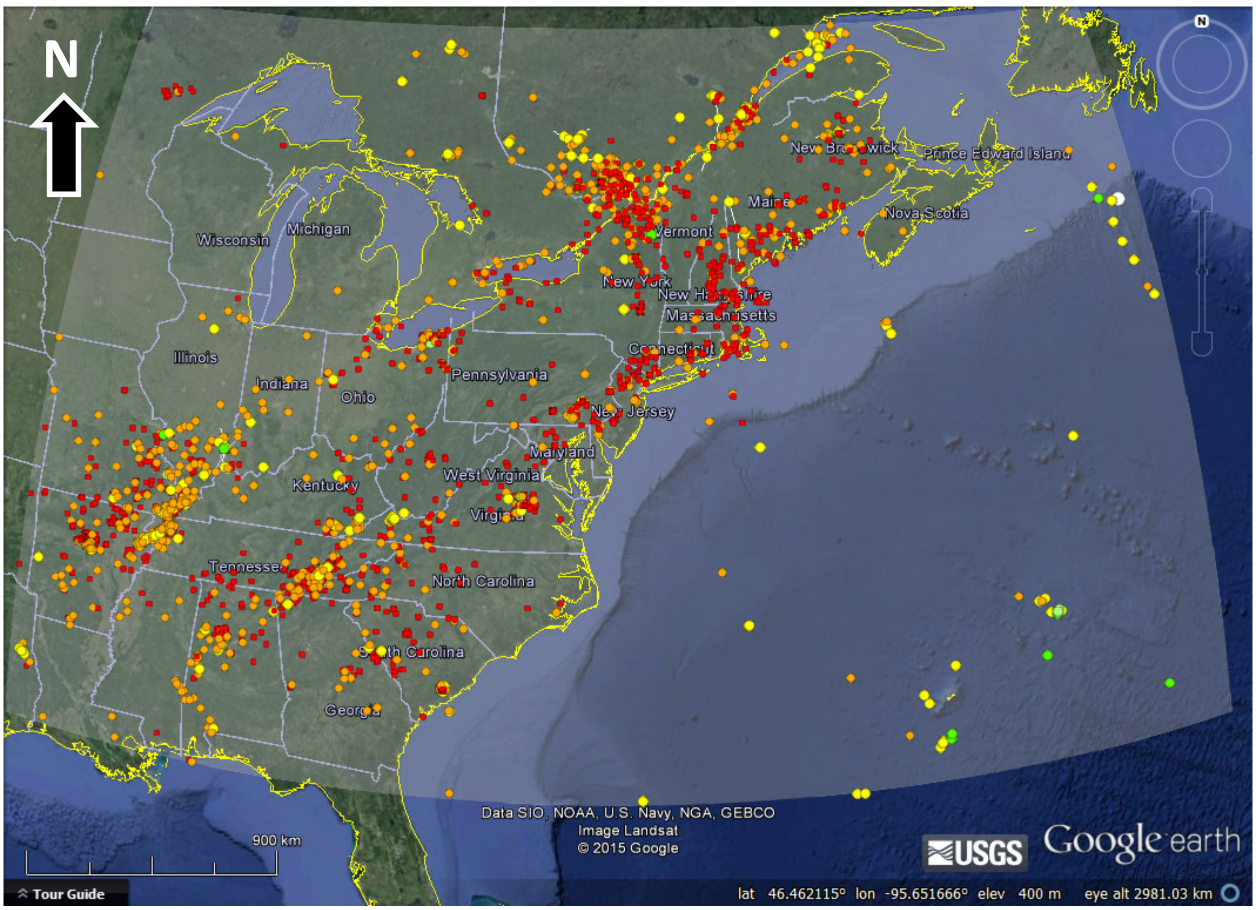
- Rivers
- Jurassic dolerite dikes
- Seismogenic lineament of Sykes and others (2006)

Pleistocene glacial terminal moraines

- Wisconsinan
- Illinoian
- Pre-Illinoian

- Delaware-Atlantic watersheds divide
- Historically active crustal seismic zone (see caption)
- Earthquake focal-mechanism P-axis solution

Accordingly, the parametric data in table 2 includes the locations and azimuthal bearing and plunge for each calculated P-axis derived for 28 earthquake events in the mid-Atlantic US region (table 3). These data were input into a KML-symbol-generating tool built by the NJGWS to geospatially plot and orient 3D object symbols in GE (Herman, 2013). The results summarized in figures 3, 8 and 9 show shaded, 3D gray vectors aligned along axes of principle crustal compression. Most of the P-axes in our immediate region plunge gently NE at angles less than 10^{o}, but some variability is seen in and near New Jersey were some axes point to the east, or plunge at shallow angles back to the SW (figs. 8 and 9). But one unexpected consequence of



Figures 10 (above). A NEIC search for historical earthquakes between Latitude's 30^{o} to 50^{o} N and Longitudes of 55 to 75^{o} W returned 3532 event records. The light-gray mask highlights the search area with the results displayed using ranges of magnitude detailed in the figure 11 legend.

Figure 11 (opposite page). Neotectonic interpretation of the NEIC earthquake data with respect to seismogenic zones and lineaments, and the horizontal component of NAP motion. The bright-yellow, polylines highlight patterns of crustal seismicity and are systematically distributed about the Adirondack shield. The light-blue polyline with opposing arrows notes a keel line separating structures plunging SW off the Adirondack uplift and NE off of the Pennsylvania culmination.

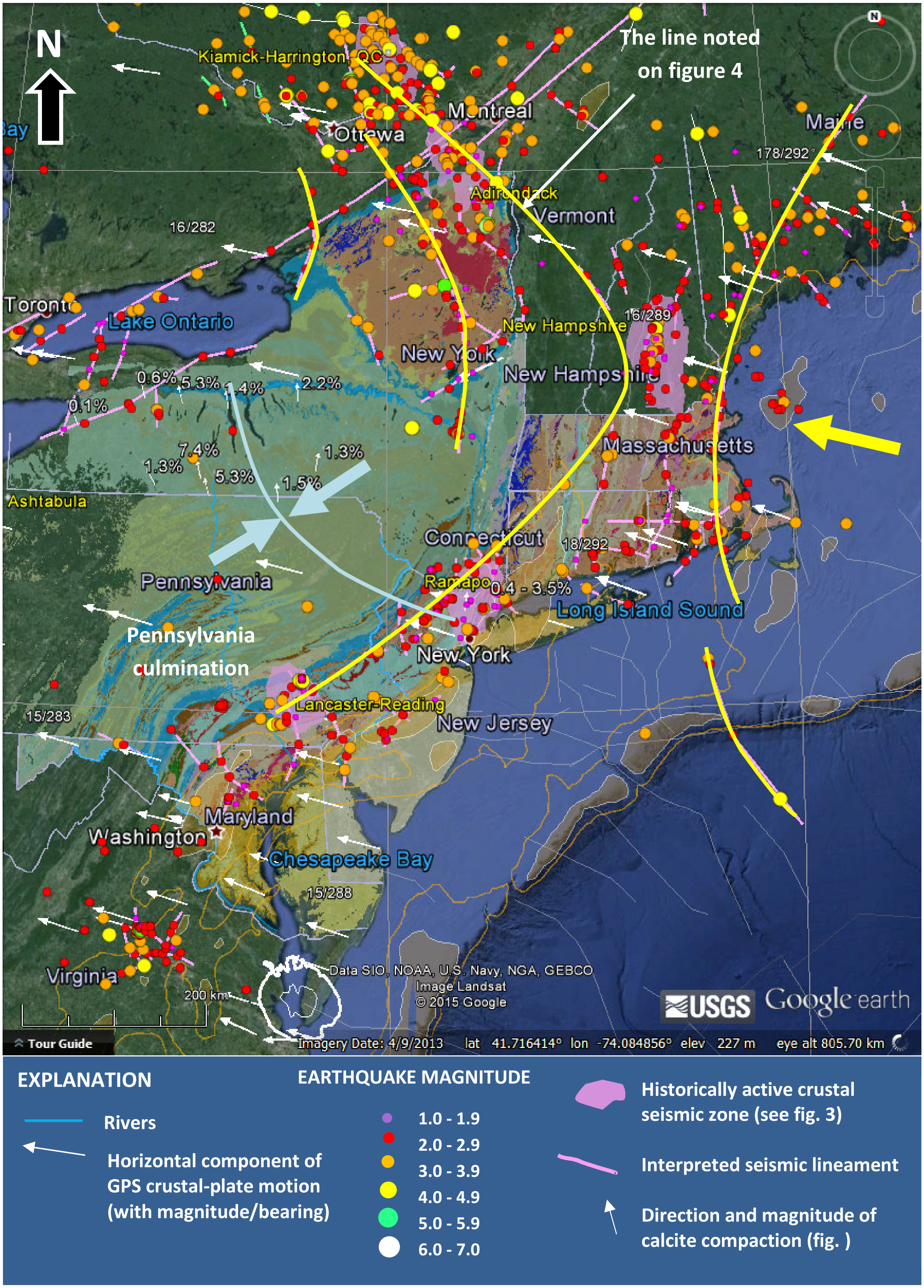

N
The line noted on figure 4
Kiamick-Harrington, QC
Montreal
Ottawa
Adirondack
Vermont
Maine
178/292
16/282
Toronto
Lake Ontario
New Hampshire
16/289
New York
New Hampshire
0.6%
5.3%
1.4%
2.2%
0.1%
7.4%
1.3%
1.3%
5.3%
1.5%
Massachusetts
Ashtabula
Connecticut
18/292
Pennsylvania
Ramapo
0.4 - 3.5%
Long Island Sound
Pennsylvania culmination
New York
15/283
Lancaster-Reading
New Jersey
Maryland
Washington
Chesapeake Bay
15/288
Virginia
200 km
Data SIO, NOAA, U.S. Navy, NGA, GEBCO
Image Landsat
© 2015 Google
USGS
Google earth
Tour Guide
Imagery Date: 4/9/2013 lat 41.716414° lon -74.084856° elev 227 m eye alt 805.70 km
EXPLANATION
Rivers
Horizontal component of GPS crustal-plate motion (with magnitude/bearing)
EARTHQUAKE MAGNITUDE
1.0 - 1.9
2.0 - 2.9
3.0 - 3.9
4.0 - 4.9
5.0 - 5.9
6.0 - 7.0
Historically active crustal seismic zone (see fig. 3)
Interpreted seismic lineament
Direction and magnitude of calcite compaction (fig.)

Table 2. Regional earthquake location and source parameters for focal-mechanism P-axes determinations .

ID	Longitude	Latitude	Depth	Trend	Plunge	Source*
1	-73.82	40.98	6	70	5	1985 Seeber and Dawers (1989)
2	-73.82	40.98	5	95	5	1985 Seeber and Dawers (1989)
3	-75.59	46.47	11	51	3	1990 Du and others (2003)
4	-73.46	45.20	12	50	0	1993 Du and others (2003)
5	-76.01	40.34	2	53	1	1994 Du and others (2003)
6	-76.05	40.34	2	241	2	1994 Du and others (2003)
7	-71.91	44.29	-6	38	6	1995 Du and others (2003)
8	-74.43	45.99	18	40	9	1996 Du and others (2003)
9	-71.35	44.18	7	232	15	1996 Du and others (2003)
10	-74.19	45.81	22	27	15	1997 Du and others (2003)
11	-69.91	47.67	5	102	20	1997 Du and others (2003)
12	-71.35	46.75	22	131	18	1997 Du and others (2003)
13	-80.39	41.50	2	64	8	1998 Du and others (2003)
14	-74.72	46.17	12	71	19	1998 Du and others (2003)
15	-66.39	49.65	18	118	18	1999 Du and others (2003)
16	-78.9	46.87	13	222	20	2000 Du and others (2003)
17	-74.25	43.95	8	219	5	2000 Du and others (2003)
18	-80.83	41.99	2	53	7	2001 Du and others (2003)
19	-73.510	44.650	15	252	30	2002 ISC-HRVD
20	-85.629	34.494	19.6	230	7	2003 ISC-NEIC
21	-86.968	33.203	5	146	74	2004 ISC-NEIC
22	-78.253	43.693	5	250	4	2004 ISC-NEIC
23	-85.796	39.594	6.1	273	0	2004 ISC-NEIC
24	-82.8	35.88	8	43	81	2005 ISC-NEIC
25	-77.287	39.184	5	262	7	2010 ISC-NEIC
26	-77.710	37.970	11	281	10	2011 ISC-NEIC
27	-77.933	37.936	6	104	9	2011 ISC-NEIC
28	-77.951	37.912	7.9	120	16	2011 ISC-NEIC
29	-77.948	37.825	0.1	92	5	2011 ISC-NEIC
30	-77.896	37.940	5	237	14	2011 ISC-NEIC
31	-77.814	37.903	4.9	145	35	2011 ISC-NEIC
32	-77.976	37.907	7.2	109	14	2011 ISC-NEIC
33	-77.932	37.950	3.4	114	5	2011 ISC-NEIC
34	-77.988	37.925	4.8	73	3	2011 ISC-NEIC
35	-77.993	37.935	3.8	107	18	2011 ISC-NEIC
36	-77.983	37.940	4.1	129	26	2011 ISC-NEIC
37	-77.951	37.946	3.1	144	30	2011 ISC-NEIC
38	-77.930	37.910	12	283	4	2011 ISC-NEIC
39	-73.699	44.513	11	92	7	2011 ISC-NEIC
40	-77.983	37.945	3.2	128	27	2012 ISC-NEIC
41	-77.984	37.913	2.9	74	48	2012 ISC-NEIC
42	-77.988	37.906	8.6	289	9	2012 ISC-NEIC
43	-87.1	32.83	12.7	230	10	2012 ISC-NEIC
44	-83.054	37.139	17.1	63	33	2012 ISC-NEIC
45	-80.836	38.642	9.2	73	16	2013 ISC-NEIC

using GE to plot these data arose from using the default placement setting in GE that clamps symbols to the ground. Each of the p-axis symbols uses a model built by positioning two 3D vectors pointing toward one another with the origin of the symbol in the center of the symbol (→•←). But when generated, each symbol was plot using the plunge value so that when it is clamped to the ground at the symbol center point, only the downward plunging half of the full symbol is revealed as the other half is masked beneath ground. This plotting effect reveals some very interesting pattern of historical seismicity, particular at the southern reaches of this region (fig. 3). These patterns merit further inspection and will be discussed in more detailed below.

When viewed collectively, these earthquake data define local and regional earthquake clusters, or swarms that commonly have a linear character that reflects systematic linkage of aligned fault segments comprising a fault system with individually segments active at different times. Historical seismic activity has been proposed to occur on old, ancient, deeply rooted faults such as the Ramapo fault in New Jersey (as detailed later) and appears to occur along linear trends that locally cut older Appalachian trends across-strike with fault systems such as the fault system that are detailed in STOP 1 of Chapter 5. But the geometric arrangement of seismogenic zones and linear trends seen in epicenter plots certainly display systematic distribution relative to the Adirondack Mountains (figs. 4, 8, 9 and 11). Patterns of historical crustal seismicity splay outward around this actively rising Proterozoic basement block as illustrated in figures 3, 8, 9 and 11. As the NAP slowly rotates about a hub that's more or less fixed on the Gulf of Mexico (Herman, 2006), the crust appears to be driving against a resistant Adirondack 'buttress' that is cored by deep-seated ultramafic igneous plutons (fig. 1). Other subsidiary seismic zones and lineaments in this part of the NAP point to other 'sticking areas' that are resisting plate rotation where similar, deeply seated igneous stock appear to pin the crust to the mantle. For example, the Cortland ultramafic intrusive complex of Late Ordovician age heads up, and may cause the Ramapo seismic zone (figs. 8 and 9). The lower arm of the parabolic fracture envelope extend from the Adirondack region SW through the Hudson Valley and the Ramapo seismic zone before dissipating somewhere past the Lancaster-Reading seismic zone (fig. 9). This arm parallels the Ramapo seismic line mapped by Sykes and others (2006) and plotted in figure 11. We can also use the various vectors of plate motion and the pattern of seismogenic responses to predict, oblique-slip motions on the varying old and new faults, and perhaps even examine seismic gaps more closely now. But with respect to the vertical-velocity field, we need to further account for both local and regional elastic strain effects in the crust stemming from erosion and sedimentary loading, glacial unloading, and probably anthropogenic loading, especially near the mouths of bays where humans tend to flock to and build up. Some of these aspects will be addressed in more detail below after some new tectonic representation are first presented that are based on highly detailed, laser-based surveys of land surface.

LiDAR- and aerial-photographic geological interpretations of tectonic structures

A series of regional structural interpretations of parts of northern New Jersey and eastern Bucks County, Pennsylvania were conducted at the NJWS during 2013 to 2015 because of the uncertainty of prior mapping and the new availability of high-precision, laser-based, topographic imaging referred to as LiDAR (see http://oceanservice.noaa.gov/facts/lidar.html), that includes derivative map products like grayshade, topographic relief maps showing bedrock ridges of relatively small relief that are absent from older maps and ortho-photo imagery (see Chapter 5 STOP 1). Currently, detailed, LiDAR surveys of New Jersey are available, but with varying coverage areas and spatial resolutions. The NJ Dept. of Environmental Protection (NJDEP) GIS group recently produced a statewide, standardized, LiDAR-based digital-elevation-model (DEM) and shaded-relief base theme having 15 m^2 cells for use in GIS. At this time, LiDAR data for New Jersey are not available on-line and are only released to the public after personal inquiry to the NJ State Dept. of Treasury[4]. In contrast, Pennsylvania maintains a user-friendly internet portal for distributing their LiDAR data and imagery through the Pennsylvania State Geospatial Data Clearinghouse (http://www.pasda.psu.edu/). For this study, LiDAR hill-shaded LiDAR imagery for areas of Buck's County Pennsylvania that are adjacent to 7-1/2' topographic quadrangles that were, and are currently being mapped by the NJGWS were captured on screen from display in a web browser and saved as separate raster images using a *.PNG file format. Each image was then manually registered in GE to result in a set of overlapping tiles that provide seamless coverage for mapping LiDAR-based bedrock features (fig. 12). These data were used as a basis for tracing bedrock ridges (tan lines on maps) and structural discontinuities from intrusive nonconformities (green contact lines) and other secondary structural features including faults (white lines) and the traces of fold hinges for both synclines (blue) and anticlines (red). Historical GE imagery was very helpful with these interpretations because syncline keels commonly contain a series of ponds or small water bodies' connected by streams running along the keel of the fold hinge. A scanned image of the geologic map of Buck's County, Pa. (Willard and others, 1950) was added to aid in the interpretation of structures that cross the Delaware River (figs. 12 and 15)

The New Jersey part of this work was done using ESRI's ArcGIS platform that provided proprietary access to the NJ LiDAR themes within the NJDEP. For this work, the various sets of LiDAR-based hill-shaded imagery were loaded into an ESRI ArcGIS project in order to trace noticeable bedrock ridges in areas having little sedimentary cover, and generate GIS shapefile themes of the various structural components (figs. 13-15). The same approach was used here, tracing and color-coding noticeable bedrock ridges, nonconformable lithic contacts, folds, and faults in conjunction with previous mapping, and thereby using detailed base imagery to augment the structural interpretation of our tectonic setting. Once a LiDAR theme was interpreted and finished for western (fig. 13) and eastern (fig. 14) parts of the state, they were

[4]https://njgin.state.nj.us/NJ_NJGINExplorer/jviewer.jsp?pg=lidar

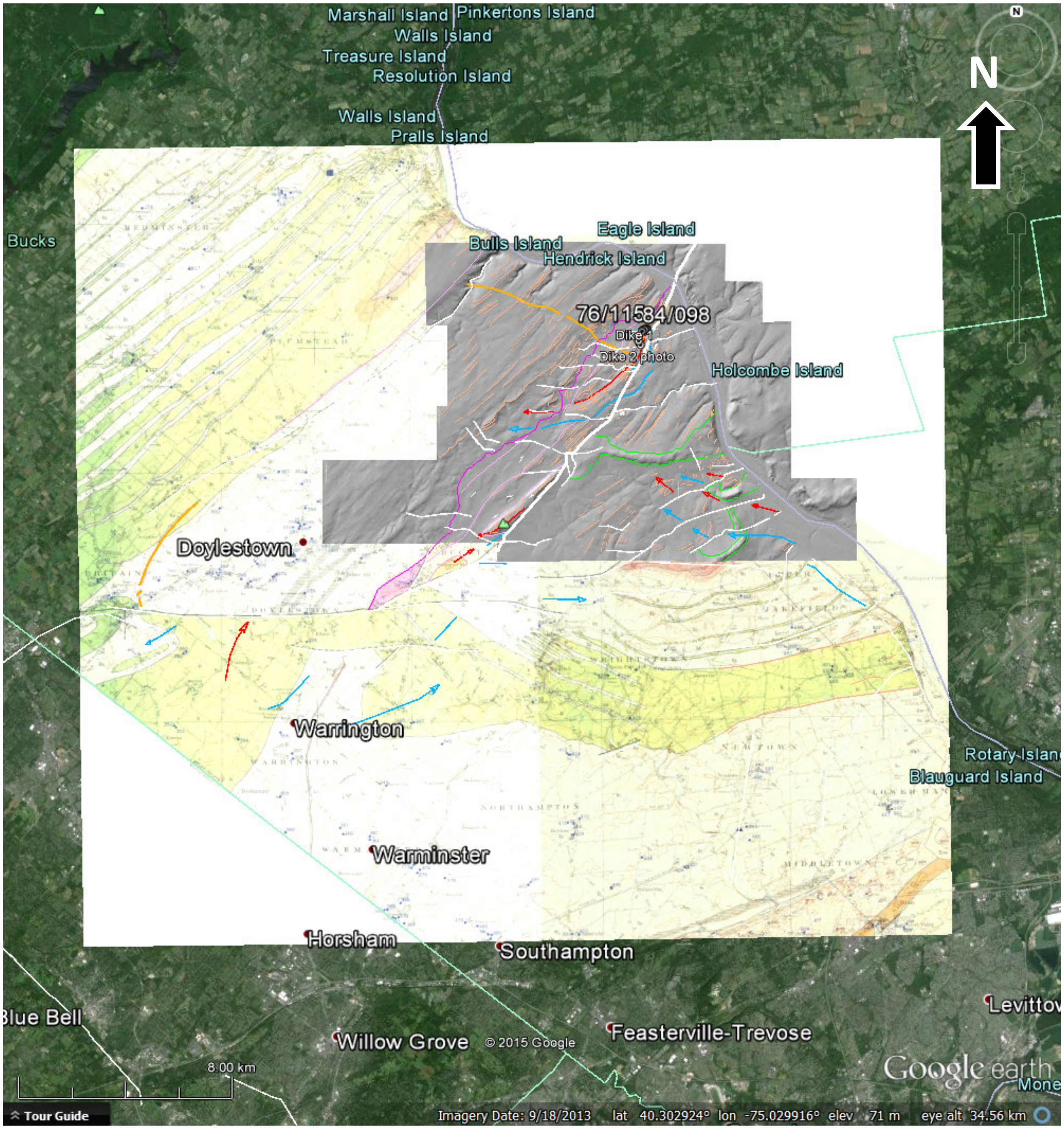


Figure 12. GE display of the Buck's County Geology compilation that is available for download from the GANJ web site. This KMZ file includes part of the Willard and others (1950) geological map of Bucks County, Pa. Large, (centered light-greenish image) and 9 gray LiDAR, hill-shaded images were screen captured from the PASDFA web site and manually tiled together to serve as a detailed base for resolving State-boundary issues stemming from earlier mapping in this area. Colored lines denote faults (white), Jurassic Dikes (orange), anticline axes (red), syncline axes (blue), and nonconformable contacts (green). This work is still in progress and the data files and interpretations are preliminary.

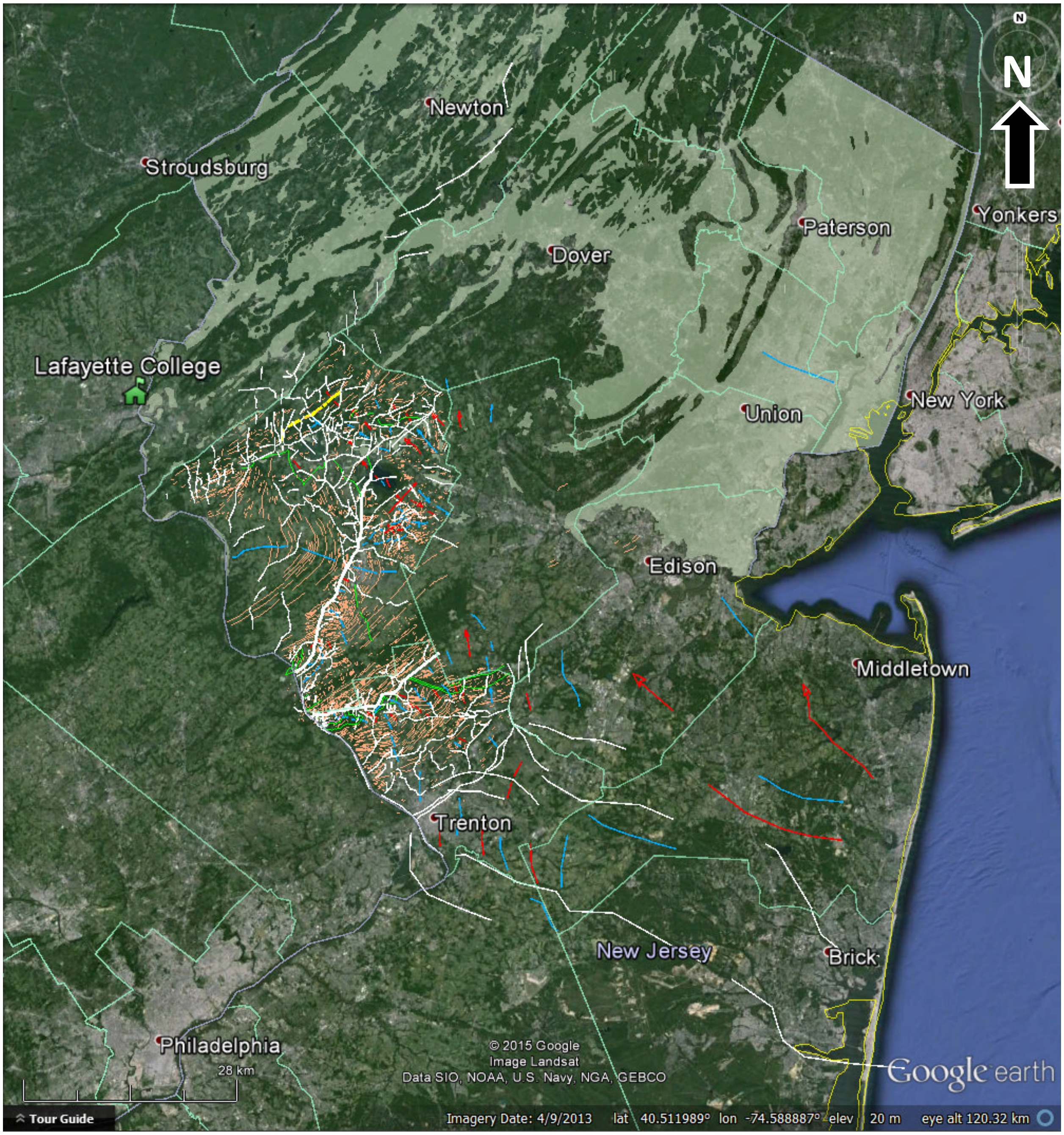


Figure 13. GE display of preliminary, LiDAR-based structural interpretation of western parts of New Jersey. The light green shaded area is a GE KMZ file based on NJ Geological Survey DGS96-1 showing areas of thick sedimentary cover that mask bedrock. Colored lines denote mapped and interpreted faults (white), anticline axes (red), syncline axes (blue) and nonconformable contacts (green). This work is still in progress and the data files and interpretations are preliminary.

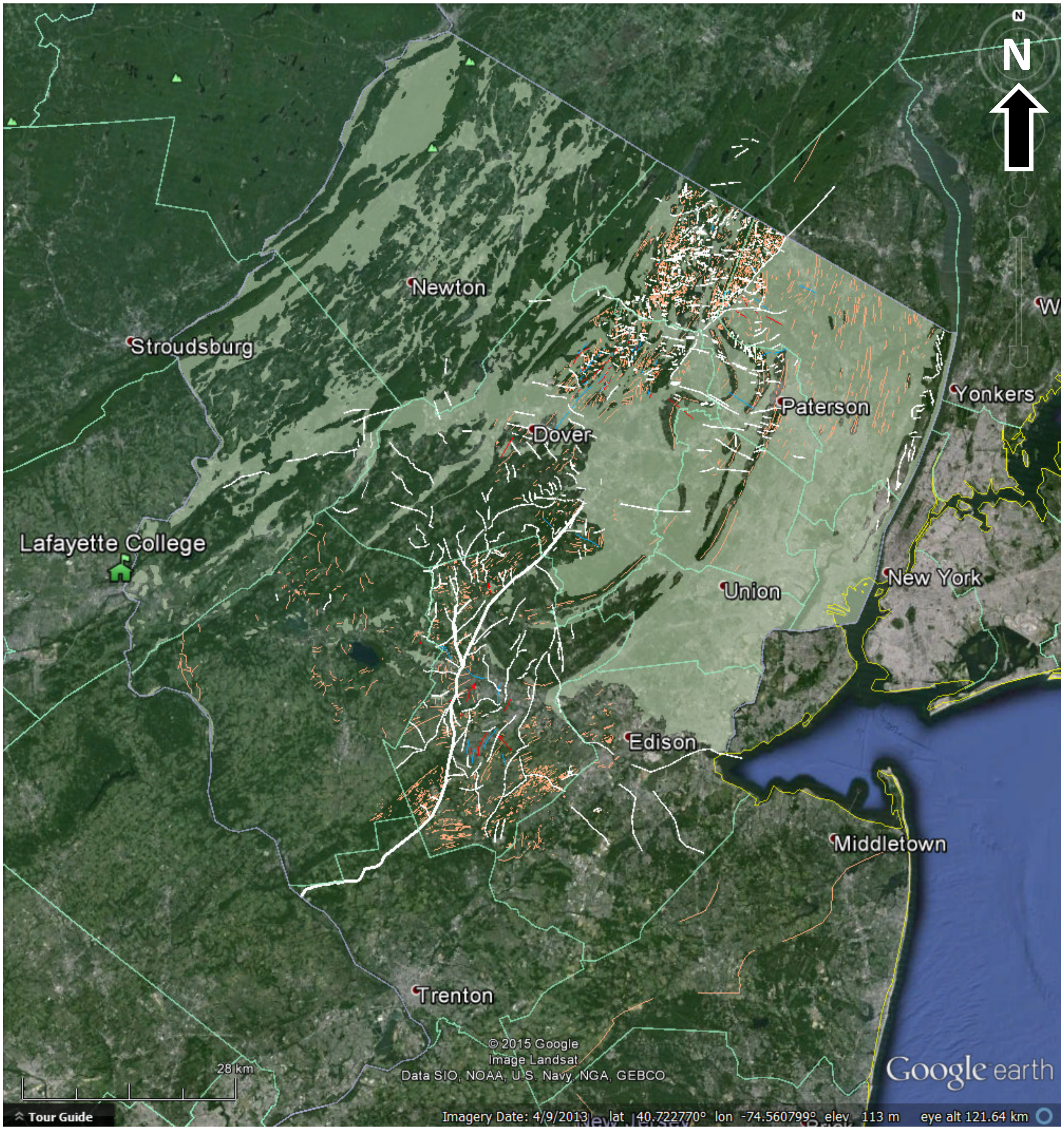


Figure 14. – GE display of preliminary, LiDAR-based structural interpretation of eastern parts of northern New Jersey. The light green shaded area is a GE KMZ file based on NJ Geological Survey DGS96-1 showing areas of thick sedimentary cover that mask bedrock. Colored lines denote mapped and interpreted faults (white), anticline axes (red), syncline axes (blue), and nonconformable contacts (green). This work is still in progress and the data files and interpretations are preliminary.

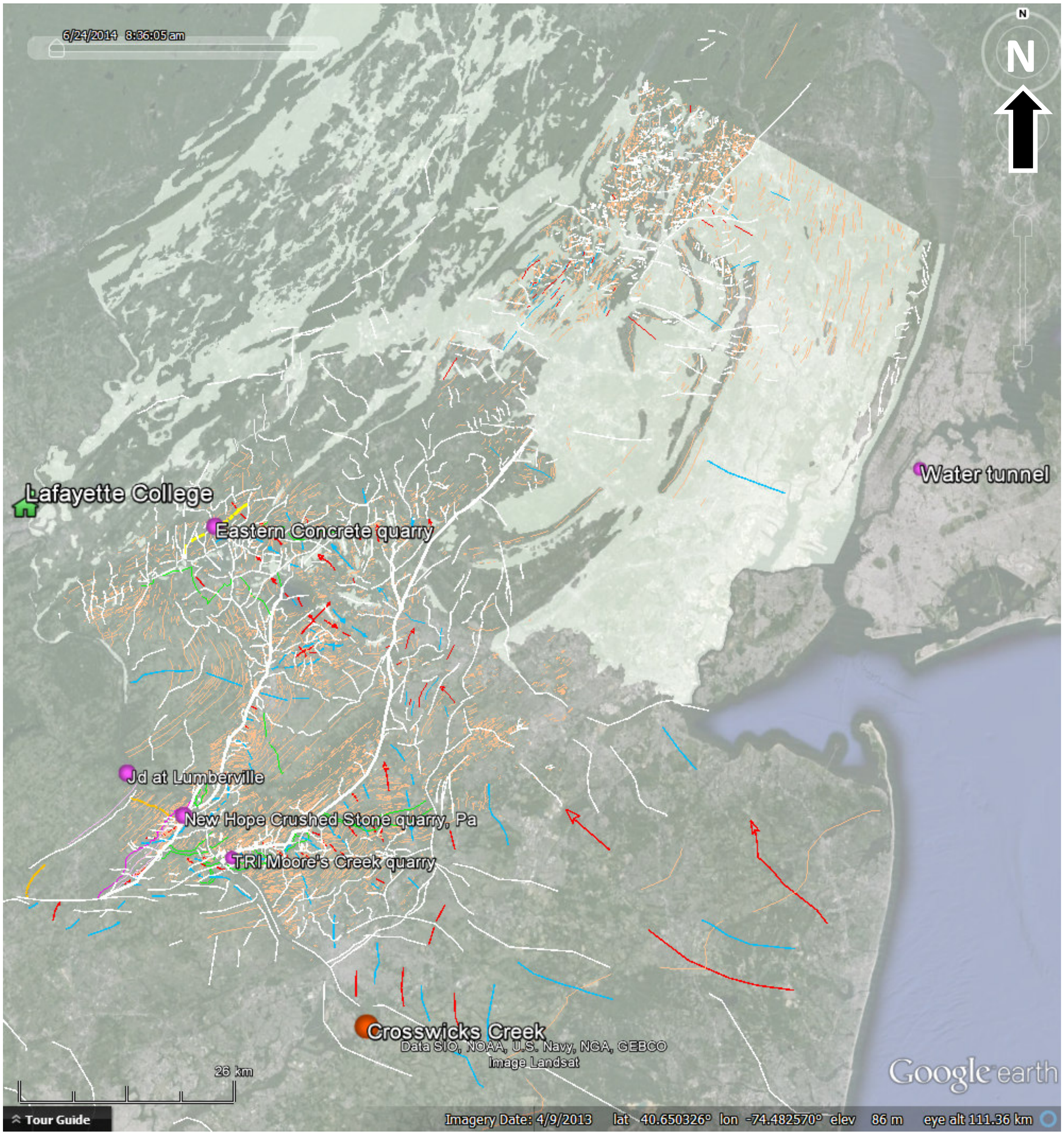


Figure 15. GE display of preliminary, LiDAR-based structural north-central New Jersey resulting from combining work for areas shown in figures 13 and 14. The light green shaded area is a GE KMZ file based on NJ Geological Survey DGS96-1 showing areas of thick sedimentary cover that mask bedrock. Colored lines denote mapped and interpreted faults (white), anticline axes (red), syncline axes (blue), and nonconformable contacts (green). This work is still in progress and the data files and interpretations are preliminary. Locations of the GANJ 32 field STOPS and some other points of interest are noted.

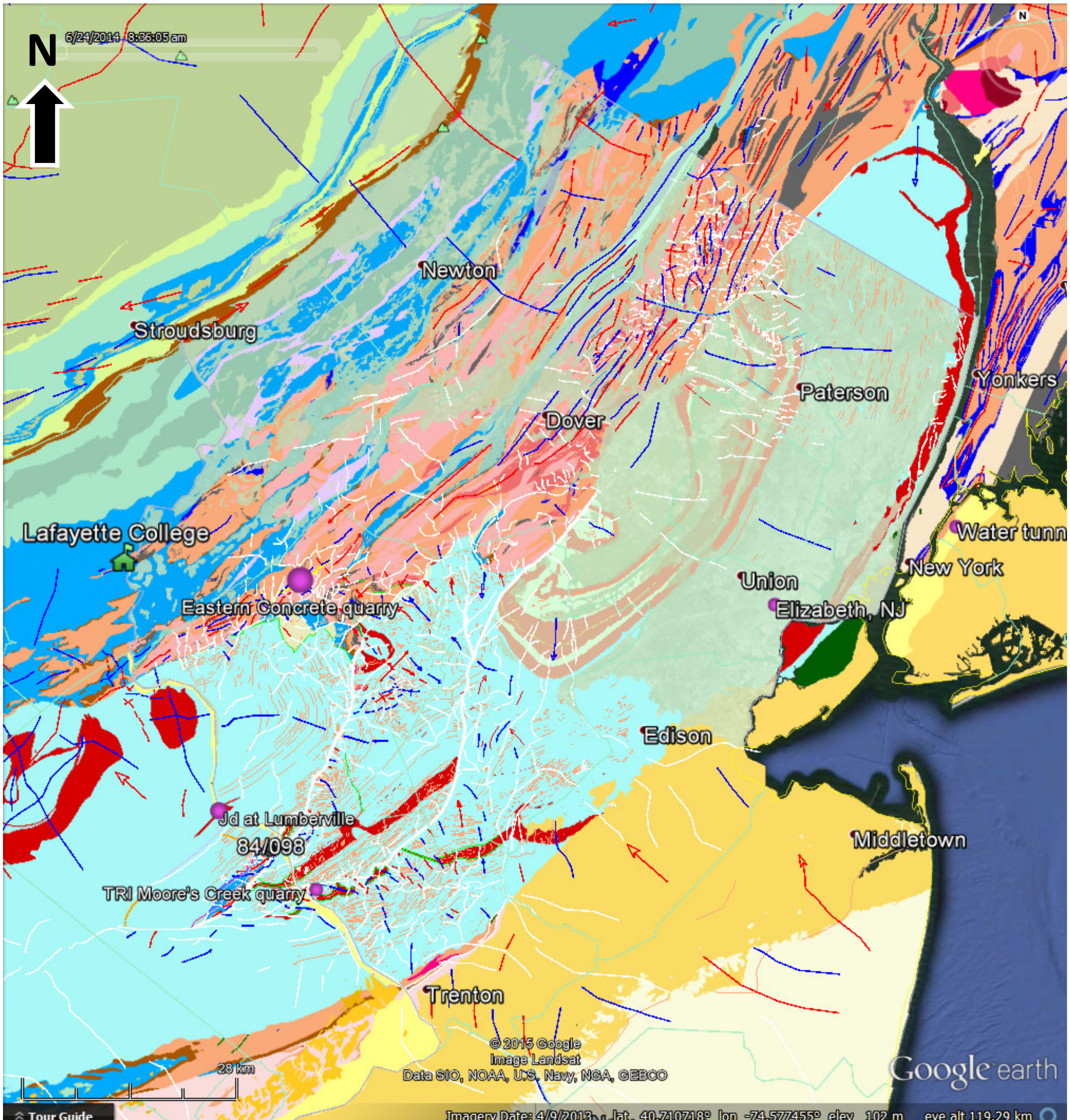


Figure 16. GE display of northern New Jersey and surrounding areas combining themes shown in figures 1 and 12 - 15. The legend for the lithic groups is shown on figure 2. Note the labels denoting the physiographic provinces and border faults along the NW edge of the Newark Basin, including the Ramapo fault. The Newark basin comprises most of the Piedmont province.

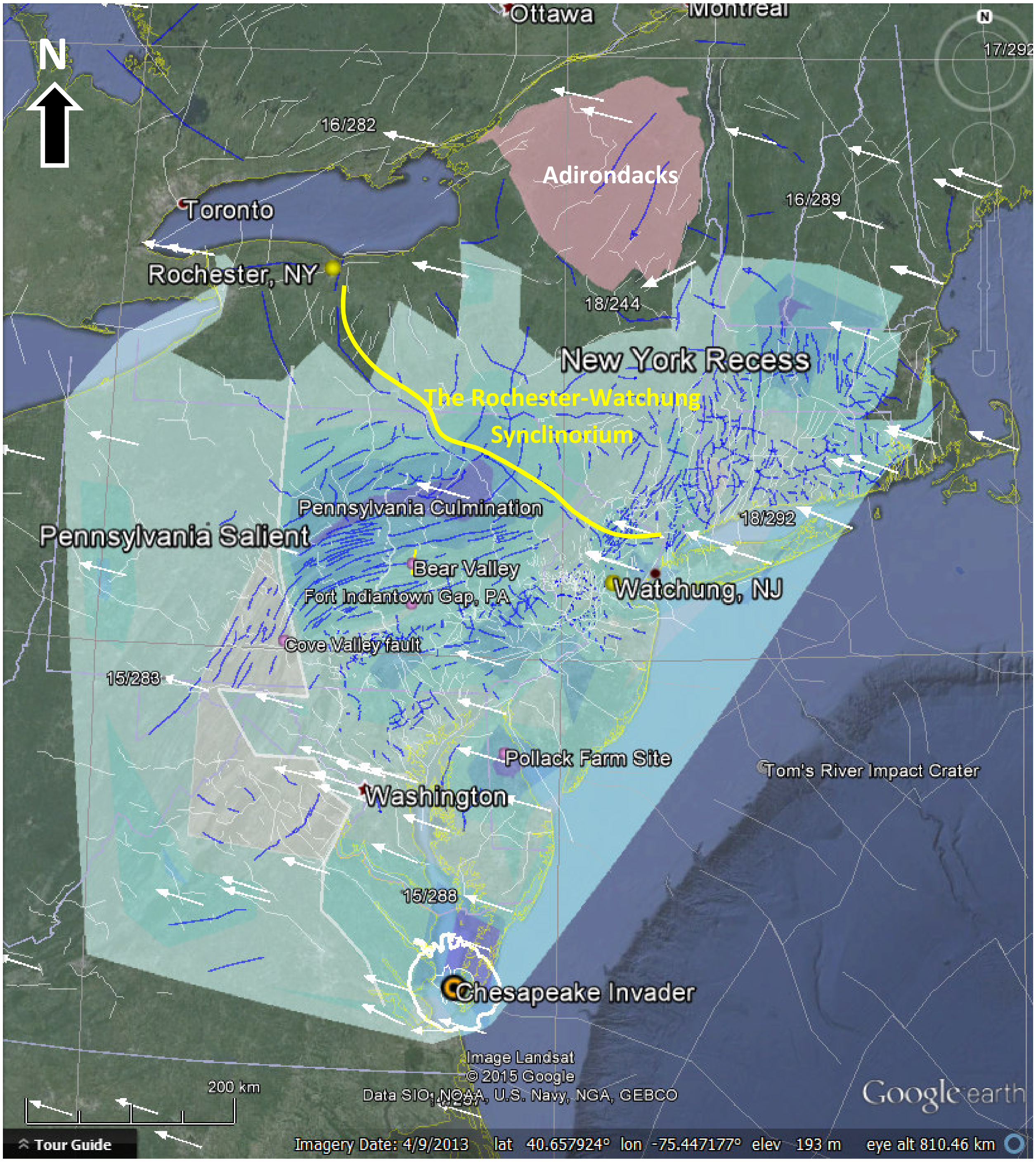


Figure 17. GE display showing aspects of the preliminary , regional neotectonic compilation in the region of the New York Recess showing traces of major fractures systems on and near land (white lines), interpreted oceanic transform faults (gray), current direction of horizontal plate drift, and syncline axes (blue lines) . Also noted is the Chesapeake Bay impact structure with the thicker white line noting the carter's outer rim, and other places referenced in the text.

converted to GE KML files, and then combined into a single theme for continued editing and refinement in GE (fig. 15). These themes are only preliminary bedrock interpretations that have yet to be reviewed and as such are provided through the GANJ web portal as open-file products that come with the caveat that they are still subject to revision and modification as they are in draft form and may be useful as a base for further work in adjacent areas lacking details or for whatever the user may have in mind.

The next step in the interpretation process was to take the LiDAR-based interpretations and compare them to the generalized, regional geological theme for further refinement. For this regional part of the structural analysis, the more prominent fracture traces (including faults) and fold axes were added to a new KMZ file with individual subfolders so that the interpretation could be augmented using GE imagery in combination with the USGS geology theme (fig. 17). The focus of the interpretation was one fracture systems that imparted structural discontinuity to older Appalachian grain, as well as cross-strike folds or flexures that were either added from published state geological maps, or were apparent with respect to the geological map pattern and landforms as seen in the historical photographic imagery within GE.

Data added from State geological maps within the region of study ranged in scale from 1:100,000 to 1:250,000. Many of the USGS GIS statewide geology themes include subthemes of digitized fault traces as part of the retrieved KML files, and these were incorporated as available. Other computer-based interpretation tools were used to constrain the directions and dips of some bedrock panels that define fold limbs. These software tools include the 3D GE and NOAA 3-point problem solving applications recently developed by the NJGWS as described and exemplified in Chapter 1. During interpretation, traces of major fracture systems, anticlines, and synclines were systematically organized into different subfolders in the KMZ file 2015_NJGWS_GANJ_32 GCH_NY_Recess Bedrock _Structure_Compilation.kmz that is available for download through the GANJ web site. Figures 16 through 19 show aspects of this regional structural synthesis with respect to part of the USGS geology theme, the ground-motion TIN (of fig. 3), and global geophysical, potential-field themes of Bouguer gravity and total magnetic field intensity that were compiled by different sources using a GE KMZ file format. These geophysical themes are very useful when used with GE theme-transparency settings to help constrain the form of interpreted regional structures. Note that major fracture systems are commonly mapped along surface-water drainage, and folds include an arrow head in many places indicating a probable direction of axial plunge. As a result, some unexpected regional-scale fold patterns emerged, such as a regional synclinorium that separates the Pocono Plateau from the Pennsylvania Culmination, referred to as the Rochester-Watchung Synclinorium. This major structural depression consists of a series of en echelon synclines stretching from Rochester NY through the Watchung syncline of NJ over a distance approaching 400 kilometers. This line appears to mark the current boundary between structures plunging SW off of the rising Adirondack shield, and NE off the eastern limb of the slowly subsiding Pennsylvania Culmination (fig. 17). This cross-strike trend appears common throughout the New Jersey, southern New York, and New England region, and lays sub-parallel to current, horizontal plate motions (fig. 17). Such features are candidate neotectonic structures as they appear to also conform to current plate motions and one of two statistical populations of current p-axes orientations in the region (fig. 18). Perhaps these broad, open folds and warps are a neotectonic strain response in the NAP as it continuously and slowly grinds over deep-seated, igneous intrusions that once pinned the crust to the mantle within the old Appalachians roots, and thereby resist current separation. These structures and such processes will be considered further in the concluding discussion.

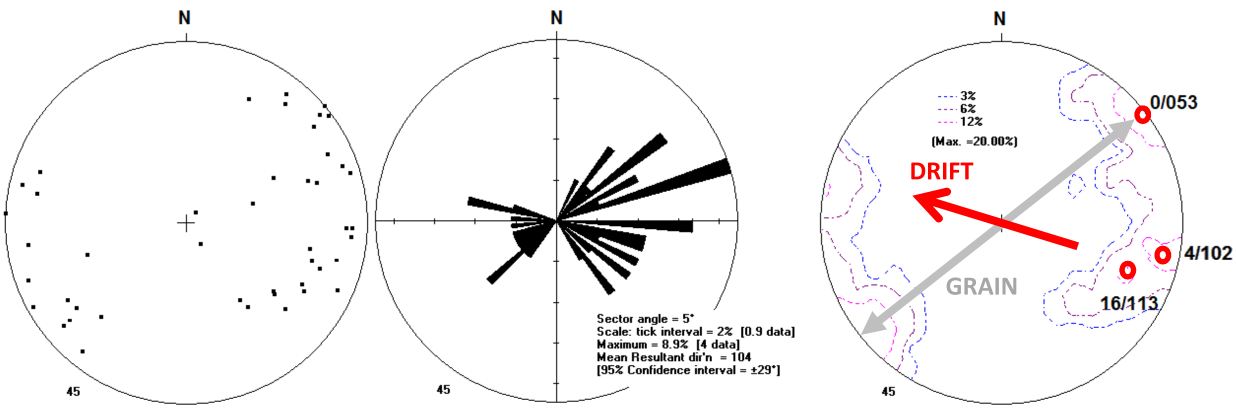


Figure 17. Lower-hemisphere, equal-angle plots of the 45 p-axes orientations compiled in table 2. Most current compression axes plunge eastward, and show three statistical 'maximums', one trending along the Appalachian tectonic grain (~053° azimuth), and two others that nearly oppose the current horizontal direction of plate drift (~287°).

Chronostratigraphic summary of tectonic stages and brittle structures in rock and sediment in the region of the New York Recess.

It is impractical for this chapter to thoroughly review and summarize all of the nuances stemming from the collective body of work detailing the different Appalachian structures in this region, not to mention the probability of their involvement in neotectonic activity. Rather, select studies are summarized that emphasize key concepts, or that include details pertinent to this report on the characteristic occurrences and distributions of known, probable, and possible neotectonic structures in our region. A systematic grouping of possible neotectonic features is done beginning with the least numerous and relatively youngest features before proceeding systematically backward through time and structural complexity using the chronostratigraphic units detailed in figure 3. Further discussion of the respective brittle, crustal strains is placed

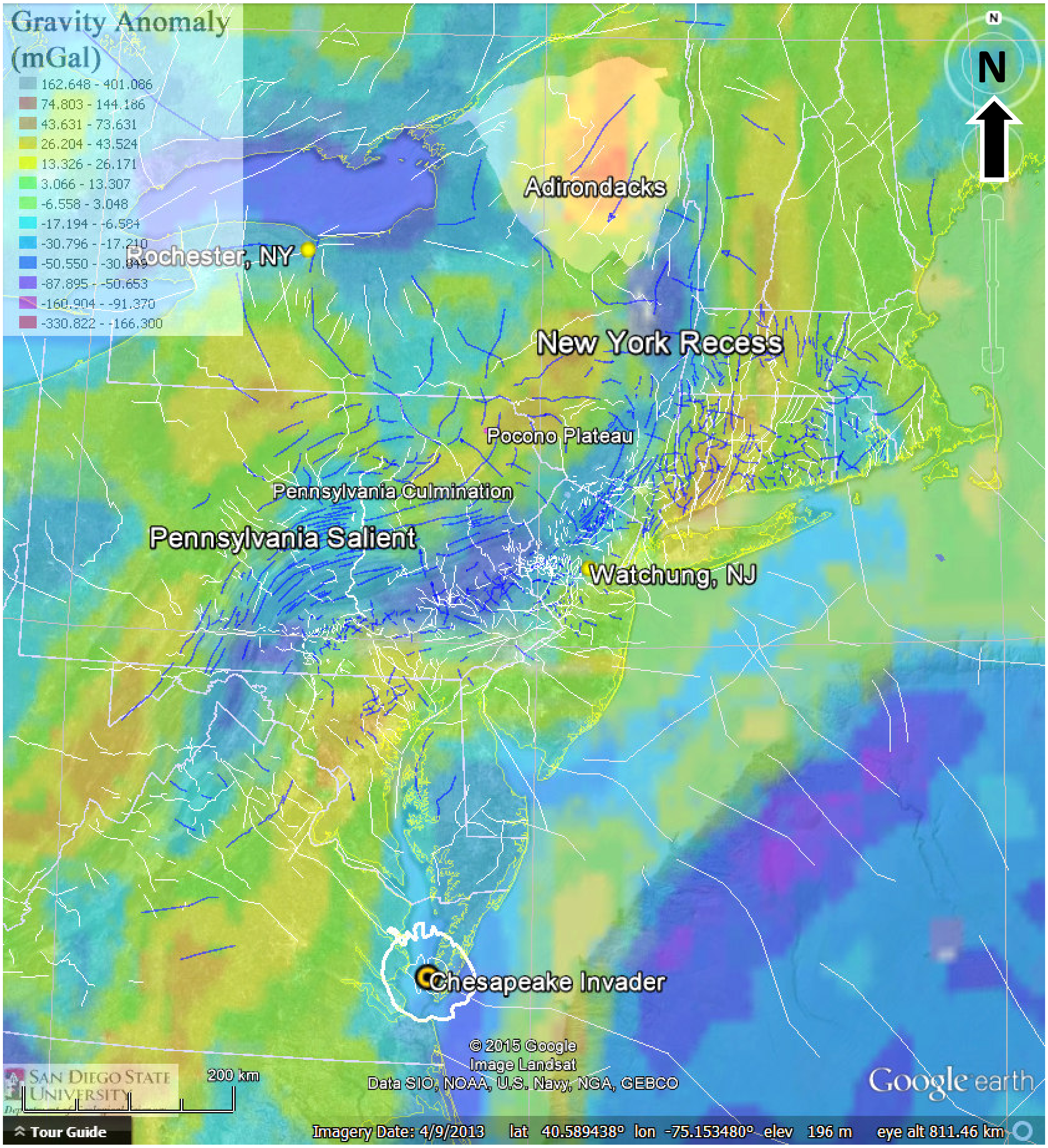


Figure 18. GE display showing the same interpreted geological structures noted in figure 17 with the GRACE Global Gravity Model 2 activated and set to about 60% transparency. For more information on this geospatial theme, please refer to:

Tapley, B., J. Ries, S. Bettadpur, D. Chambers, M. Cheng, F. Condi, B. Gunter, Z. Kang, P.Nagel, R. Pastor, T. Pekker, S.Poole, F. Wang, 2005, GGM02 - An improved Earth gravity field model from GRACE: Journal of Geodesy, http://www.csr.utexas.edu/grace/.

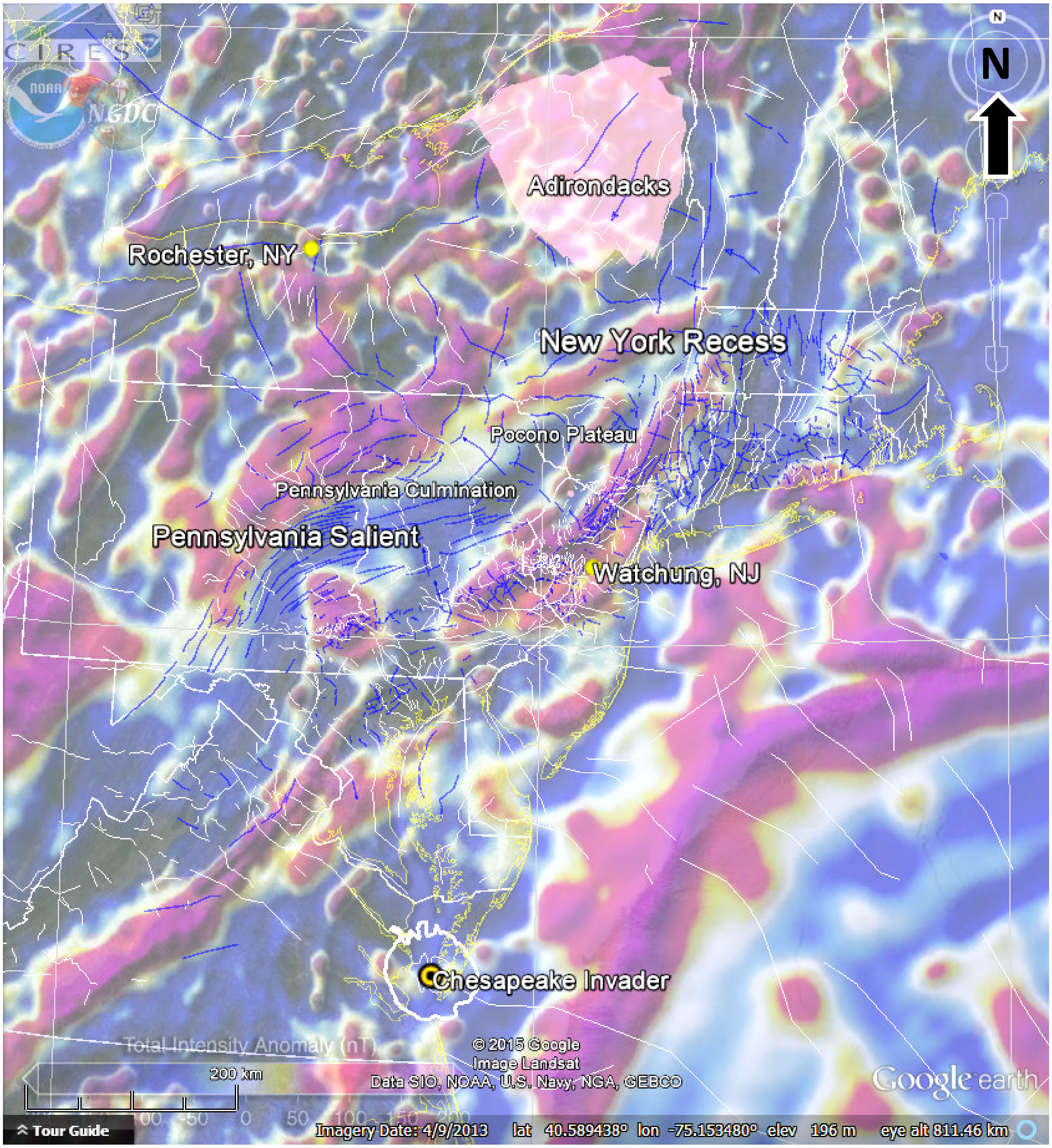


Figure 19. GE display showing the same interpreted geological structures noted in figure 17 with the Earth Magnetic Anomaly Grid EMAG2 activated and set to about 60% transparency. For more information on this geospatial theme, please refer to:

Maus, S., U. and 22 others, in review, EMAG2: A 2-arc-minute resolution Earth Magnetic Anomaly Grid compiled from satellite, airborne and marine magnetic measurements: http://geomag.org/info/Smaus/Doc/emag2.pdf. http://geomag.org/models/emag2.html

into context with hypothetical stressors and other critical, neotectonic considerations including glacio-isostasy, sedimentary loading and lithospheric flexure at the end of this report. For now, we progress backward through time and deeper into the lithic section to summarize what we currently know about known or suspected neotectonic structures occurring in this region.

Tectonic Group 4 Cretaceous and Cenozoic age (<120 Ma years)

As depicted in figures 3 and 20, a treatment of neotectonic structures in strata of Cenozoic age requires further use of subgroups that reflect the stratigraphy of the NJ coastal plain and nearby Atlantic shelf region, where the most complete sedimentary record is preserved. This primary grouping includes the glacial and pro-glacial detritus on land of Pleistocene age and the more recent Holocene alluvium (fig. 20). The Cenozoic Era into six epochs covers the past 66 Ma and is nearly halved at the Eocene-Oligocene boundary ~34 Ma, just above a pronounced unconformity found throughout the eastern margin of the NAP (fig. 20). There are a number of disturbances and sedimentary pulses both on land and in the costal and submarine stratigraphic record during this time, some of which must stem from the 'Tertiary elevation' of our region as previously noted. This uplift episode, or series of episodes, probably resulted in the rapid erosion of Appalachian cover, the amount of which is reserved later for late discussion and speculation. After the Oligocene, the seas returned and retreated onto the coastal plain of our continental margin many times (Pazzaglia and Gardner, 1994; Browning and others, 2008). Consequently, this stratigraphic record is complex but has been studied in detailed using drill core and multi-channel seismic reflection data throughout the mid-Atlantic region (for example, see Miller's keynote abstract and Metzger and others, 2000). As illustrated in figure 20, chronostratigraphic units are separated into groups that are bounded my major unconformities with both continental and submarine expression within strata deposited on the continental shelf. Focused consideration is given to a few records that show clear representations of stratigraphic and structural relationships pertinent to this neotectonic theme.

The description of this group is comparatively easy insofar as there has been no direct, confirmed, visual geological evidence of Quaternary to Late Tertiary geological faulting seen in the New Jersey, or the New York City area historically. There are isolated incidences where indirect evidence of Pleistocene sediment thickening across possible faults scarps (Stanford and others, 1997), or perhaps deposited and preferentially preserved along a reactivated Mesozoic fault (Herman and others, 2014), but the entire area has been mapped in detailed beginning around 1900 and there are no photographic reports or noted visual records of structural disruption of strata of this age. Owens and Minard (1979) report that a reorientation of Pliocene gravel of Late Pliocene age in the New Jersey Coastal Plain from south to southeast and speculated on a tectonic control, but they state that "no faults or folds have been detected in Cretaceous formations in the area to support his hypothesis". Late Pliocene to Pleistocene deposits offshore in this region have been extensively studies using high-resolution, seismic-reflection profiling like that of Metzger and others (2000), and there are also no know reports of visual, structural disruptions in subsurface records of this age strata, explicitly including the Cohansey Sand and Kirkwood Formation. The only indirect, subsurface interpretation invoking structural disruption of strata in the Coastal Plain of New Jersey is that of Sheridan and others (1991) from the southern part of the province where a deep seismic-reflection profile was run in an attempt to decipher upper crustal structures in the 2 to 6 km depth range. From this study they interpreted Mesozoic rift basins beneath Coastal Plain units based on horizontal velocity contrasts, and they depict in profile, half- and full-grabens from the line that have border faults cutting up section through most of the coastal plain units almost to the sediment-water

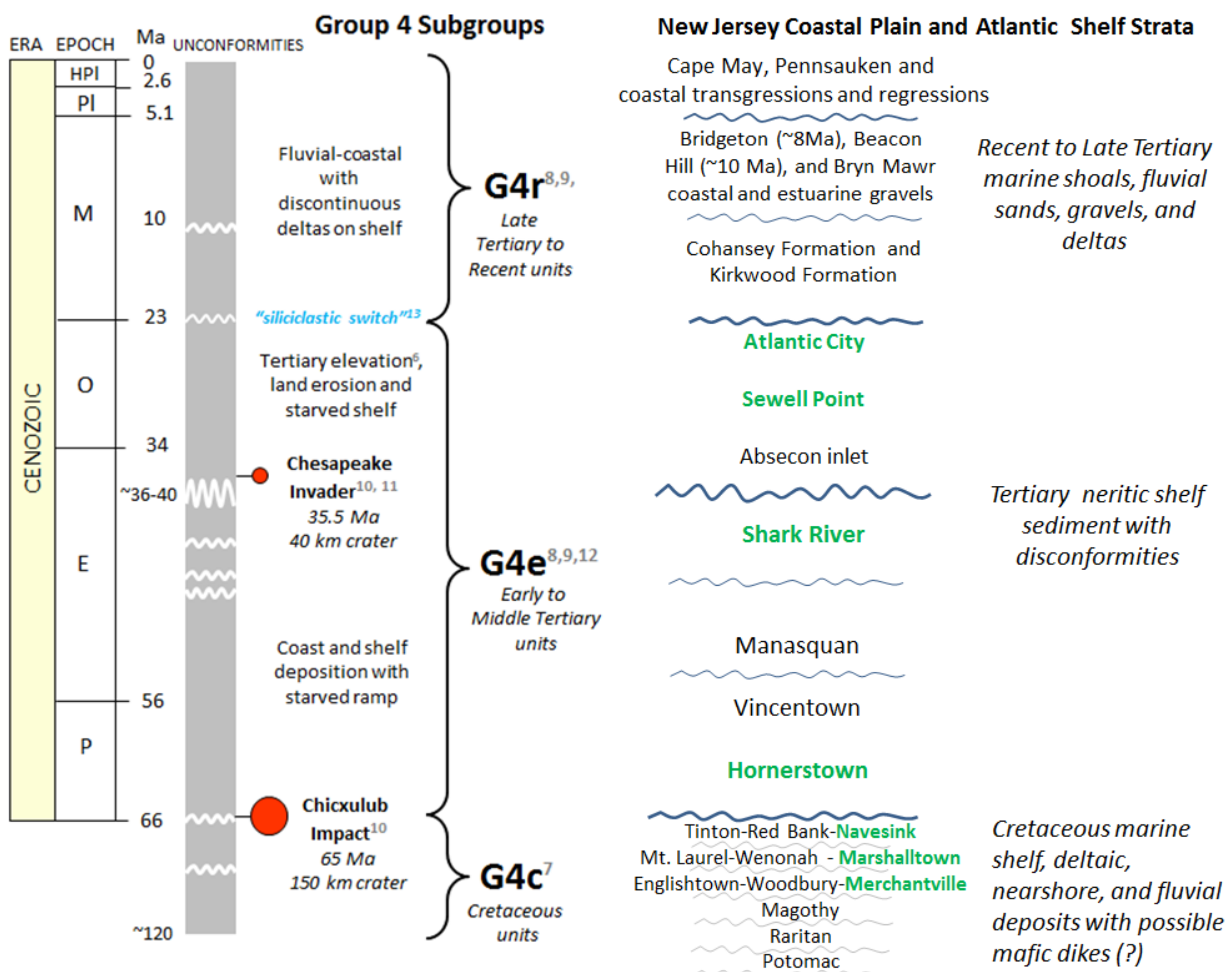


Figure 20. Chronostratigraphic tectonic subgroups for the Cenozoic Era with respect to strata of the New Jersey coastal plain and Atlantic continental shelf (fig. 3). Glauconitic formaitons are colored green.

interface. Offset on these faults is minimal; however the raw stacked records do not clearly show stratigraphic disruption, leaving these faults and their penetration of the coastal plain units as uncertain.

The lower –middle Miocene sequence in the coastal plain reflect a strong influence of riverine sources of sediment in contrast to subjacent marine strata (Browning and others, 2008). There is one well-documented site in this region where lower Miocene strata contain chaotic and folded beds with visible, brittle fractures and faults. It's noted in figures 17 and 23 as Pollack's Farm, and is situated across the Delaware River from New Jersey. Andres and Howard (1998) photographed fractures, joints, and faults in Lower Miocene strata here, but provided no orientation data. They attribute sedimentary disruption and some brittle fracturing to probable cryoturbation processes stemming from seasonal freezing in near periglacial climates, but state that some of these features appear to have formed in an extensional stress field, possibly related to reactivation of the nearby border fault zone associated with an inferred, buried Mesozoic rift basin, such as those reported by Sheridan and others (1998). However, they also note that some of the brittle features may have formed in response to erosion and unloading or weathering and mineralization processes. Ramsey (1998) also depicts sub-vertical fault here in cross section that repeatedly offset Lower Miocene strata along steeply dipping faults that terminate upward into blanketing Quaternary alluvium. So it is probable that brittle fracture and faults occur elsewhere in the region in strata of this age, but they remain elusive, and apparently spotty in their spatial distribution.

Crone and Wheeler (2000) summarized known occurrences of Quaternary faults, liquefaction features, and possible tectonic features in the Central and Eastern United States, east of the Rocky Mountain front. They report "in each case, paleoseismological fieldwork and other studies found no clear geological evidence of prehistoric earthquakes larger than the small or moderate shocks known historically". They included a review of reports pointing to the possibility of Quaternary tectonic activity based on pollen data, sea-level curves from tidal marshes, soft-sediment deformation observed in cored sediments from a glacial lake, and geomorphic observations. None of these provided evidence of sudden seismic slip as opposed to slow aseismic creep. Most are inconsistent with the orientation of the existing compressional stress field and the absence of significant post-Mesozoic slip. Nevertheless, modern geological and geophysical work have failed to directly demonstrate secondary tectonic structures in New Jersey or bordering parts of NYC and Pennsylvania for this group of strata.

Subgroup G4e – Early to Middle Tertiary (~23 - 66 Ma)

During the early Tertiary, the northern African plate boundary shifted from transtention to compression (Klitgord and Schouten, 1986), and our regional stress shift may have occurred during this time as well. There is a pronounced unconformity at the Cretaceous-Tertiary (K/T) boundary (fig. 20), and afterwards, the deepest water depths of the Cenozoic were attained in this region during the lower to lower middle Eocene (Browning and others, 1997). Land and coastal areas were elevated and eroded during this time (fig. 20), and the only coastal plain strata of Oligocene age in New Jersey are found in the subsurface in the southernmost area of the state (Miller, 2015). The New Jersey coastal plain strata contain other, pronounced unconformities within upper Eocene through Oligocene strata that were deposited in starved ramp and shelf environments (Miller, 2015). The pre-Miocene disconformity separating the Kirkwood Formation from subjacent Eocene strata in the NJ coastal plain is widely recognized in both outcrop and the subsurface as the longest hiatus in the northeast Atlantic continental margin, and resulted from a drop in sea level near the of Eocene time (Olsson and others, 1980). Moreover, seismic-reflection data in some areas of the shelf show pronounced channeling of a seaward-prograding wedge of sediment that was subsequently scoured by a down-slope erosional event that produced submarine canyons just above Eocene/Oligocene boundary (Miller and others, 1985). A subsequent, rapid rise in sea level began sometime during mid-Oligocene time but sedimentation rates remained slow then and the entire continental margin in the region was sediment-starved, not only of siliciclastic but also of pelagic carbonate (Browning and others, 1997). According to Malisnky and Barlett (1975), the stratigraphic sequences during this time to our north in Nova Scotia and Newfoundland are eroded on shore, and those offshore are the result of differential preservation with less than one half of Middle Eocene to Miocene time is represented, including 12 Ma hiatus separating Middle Eocene and Lower Oligocene units. Other, smaller-duration hiatuses separate Oligocene and Middle Miocene strata, as well as the Middle and Upper Miocene units to our north as well as here (fig. 20).

The only reported occurrence of brittle structures found in the Early- to Middle-Tertiary strata in New Jersey are localized, strangely-disrupted sandstone beds in the Vincentown Formation of Late Paleocene age, where thin beds of lithified, coarse sand are impregnated with limonite and appear to be rolled up and folded (fig. 21). However, these distortions may not be tectonic as they may stem from diagenetic alterations (Peter Sugarman, personal communication, November, 13, 2014). More exposures of these and-or other similar beds of this age are needed in order to better assess the nature of these secondary structures. Nevertheless, measured fracture orientations and possible fold axes in the unit are included on figure 21 to demonstrate that the trend of the apparent folding in this unit is nearly orthogonal to the current horizontal component of plate drift.

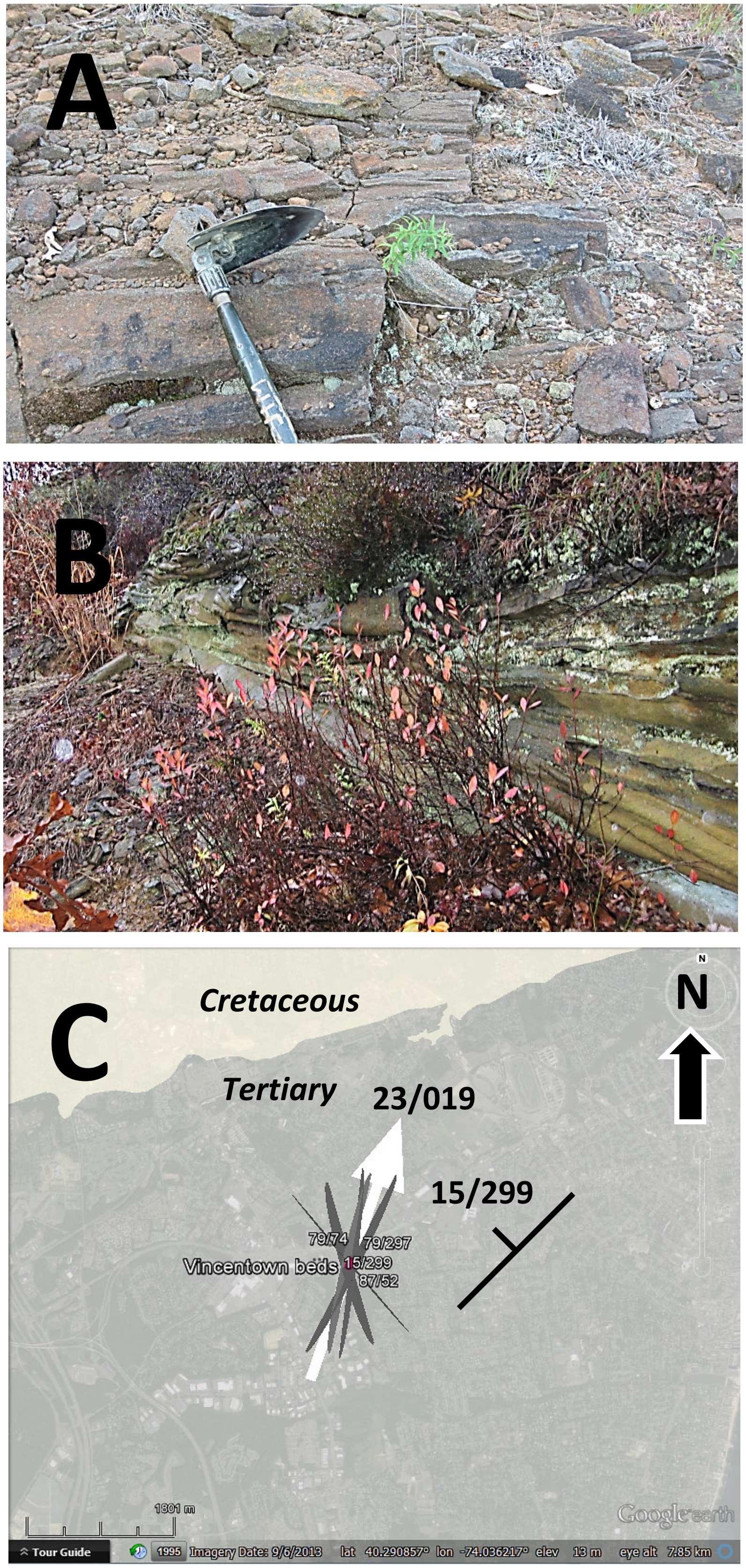


Figure 21. Photographs (A and B) and GE plot (C) of potential, secondary tecotnic structres in the Vincentown Formation of Early Tertiary age (fig. 20). (A – SE view and B NE view) GPS site coordinates are ~LAT 40.157 LON -74.657. The contorted, Fe-cemented sandstone beds are apparently rolled up and folded with a possible plunge/trend of ~23/019). Fracture planes (3D gray ellipses) strike parallel and across beds oriented ~15/299 (dip /dip azimuth). See text for further discussion.

Subgroup G4c - Cretaceous (~ 66 to 120 Ma)

Secondary structures cutting steeply dipping Cretaceous strata in the New Jersey Coastal Plain (fig. 22) have been mapped as cross-strike discontinuities (fig. 23). Old reports such as Ries and others (1904) also note structural disruption in Cretaceous clay, including small faults, iron-oxide veining, folding, and warping of these units in our region. They point out that tilting and folding of these units exert an “important influence of the form and extent of the outcropping beds”, but “faulting is rarely seen”. Dombroski (1987) noted fracturing, slickensided shearing and disturbed zones in the Cretaceous Woodbury Clay as part of a hydrogeological assessment of the Woodbury-Merchantville confining layer. I have also seen steeply dipping, slickensided, and pyrite-mineralized small faults cutting Cretaceous clay many years ago, but at the time was unappreciative of the tectonic implications, and unprepared to measure and record specific structural and locational information. The Cretaceous units of the Coastal Plain have been structurally disrupted, and today’s drainage patterns reflect rather subtle tectonic structural controls that are generally poorly understood, but are generally attributed to large-scale warping of the crystalline basement underlying the coastal plain (Owens and others,1986). Much more evidence of Cretaceous and Cenozoic tectonic structures occurs further south along the Appalachian margin beginning near Virginia and Maryland (York and Oliver, 1976).

Figure 22. Photos of steeply dipping beds (A) and faulted Cretaceous strata (B) described in NJGWS permanent notes from the Crosswick Creek clay pit circa 1956. This was noted as possibly stemming from soft-sediment slumping and sliding of beds into an old stream channel. But structural disruption of innner Coastal Plain strata has been reported in the Woodbury Clay, the Navesink Formaiton, Englishtown, and Raritan Formations that is probably tectonic is origin.

The New England Seamount Chain formed just to the east of this region about 70 to 124 Mya during active continental rifting as basin growth accelerated in the North Atlantic to the east of Canada and west of Greenland (Duncan, 1984). At this time, our region was probably being stretched in a northeastwardly direction (fig. 24) , as indicated by the latest-stage extension fractures cutting early Jurassic strata in our region along cross-strike trends of ~160^{o} to 180^{o} that we will cover in more detail below.

The set of oceanic transform faults referred to as Kelvin-Cornwall displacement (Drake and Woodward, 1963) coincides with the New England seamount chain (fig. 24) that is an integral structural component in stretching this part of the evolving NAP northeastward as spreading propagated northward along the Appalachian margin. The cross-strike secondary structures that cut Cretaceous units of the NJ Coastal Plain (fig. 23) display right-lateral and normal-slip components (Klewsaat and Gates, 1994) that are the same displacement noted along the Kelvin-Cornwall displacement. The zero (0) mGal Bouguer gravity anomaly exemplifies this stretch (fig. 24) if we assume that its current expression along the NAP's Atlantic margin reflects segmented CAMP bodies that were emplaced during the Jurassic and subsequently stretched during the Cretaceous (Herman and others, 2013).

Tectonic Group 3 - Newark (~120-260 Ma)

The rift-basin setting of the Newark basin is well known, and different sets of tensile brittle structures are systematically distributed, oriented, and arranged with respect to one another in Early Mesozoic strata (fig. 25, and Herman, 1997; 2005; 2013). Fractures generally strike parallel to nearby, mapped faults with steep dip angles (~60^{o} to vertical). They are densest near border faults that parallel the Appalachian grain (S1 of fig. 25) and large intrabasinal faults such as the Flemington and Hopewell (S2 of figs. 24 and 25, also see chapter 5, STOP 2). These three groups of extension fractures and faults developed with an upward, helical twist in strike through strata and time (fig. 26). The oldest (S1) fractures occur in the oldest strata and locally show signs of stratigraphic compaction, indicating that they formed early in the depositional history of the basin (Herman, 2001). Fractures of intermediate strike cluster about N10^{o} -N20^{o}E and are among the most widespread and pervasive joints in the region. These fractures probably formed during an accelerated phase of crustal extension and concurrent igneous intrusion of CAMP bodies as the crust was being rapidly pulled apart (Herman and others, 2013). Jurassic dolerite dike swarms in Pennsylvania bearing this strike penetrate far into the Appalachian foreland where they bound the eastern side of the Pennsylvania Culmination and coincide in trend with an intermediate reach of the Susquehanna River (fig. 27). The youngest set of extension fractures (S3) strike across the Appalachian grain and overprints and locally offset earlier structures (fig. 25). These fractures are also recognized in the NJ Highlands (Chapter 5 STOP 1) as well as the NYC area in Proterozoic and Paleozoic

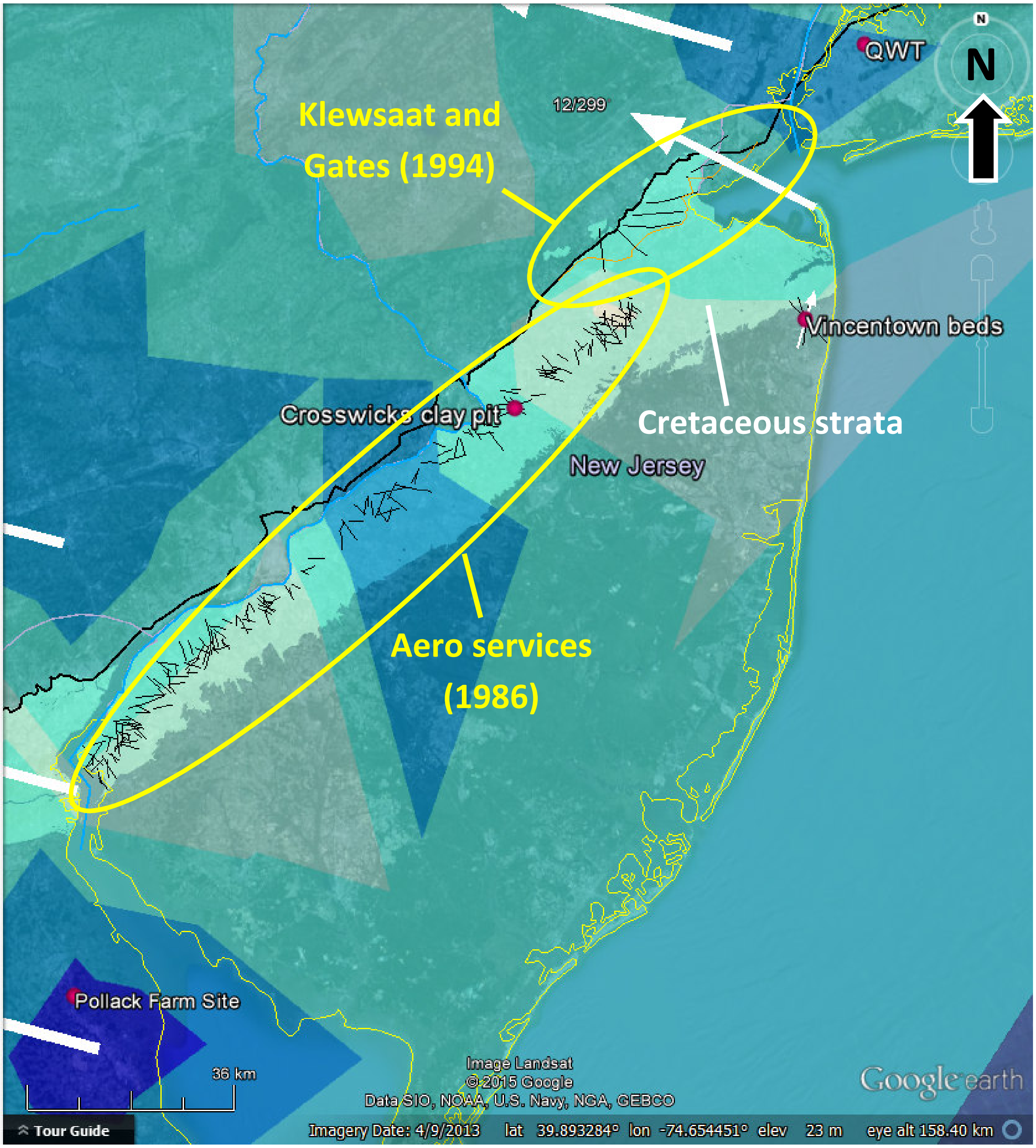


Figure 23. GE map centered on outcropping Cretaceous strata in New Jersey showing the TIN velocity surface (fig. 3), mapped topographic linements in the Woodbury Formation (Aero Services, 1986), concealed faults offsetting the buried extension of the Palisades Sill (Klewsaat and Gates, 1994), and other locations where apparently disrupted strata are reported in the NJ Coastal Plain (see text for further discussion) . QWT – Queen's Water Tunnel.

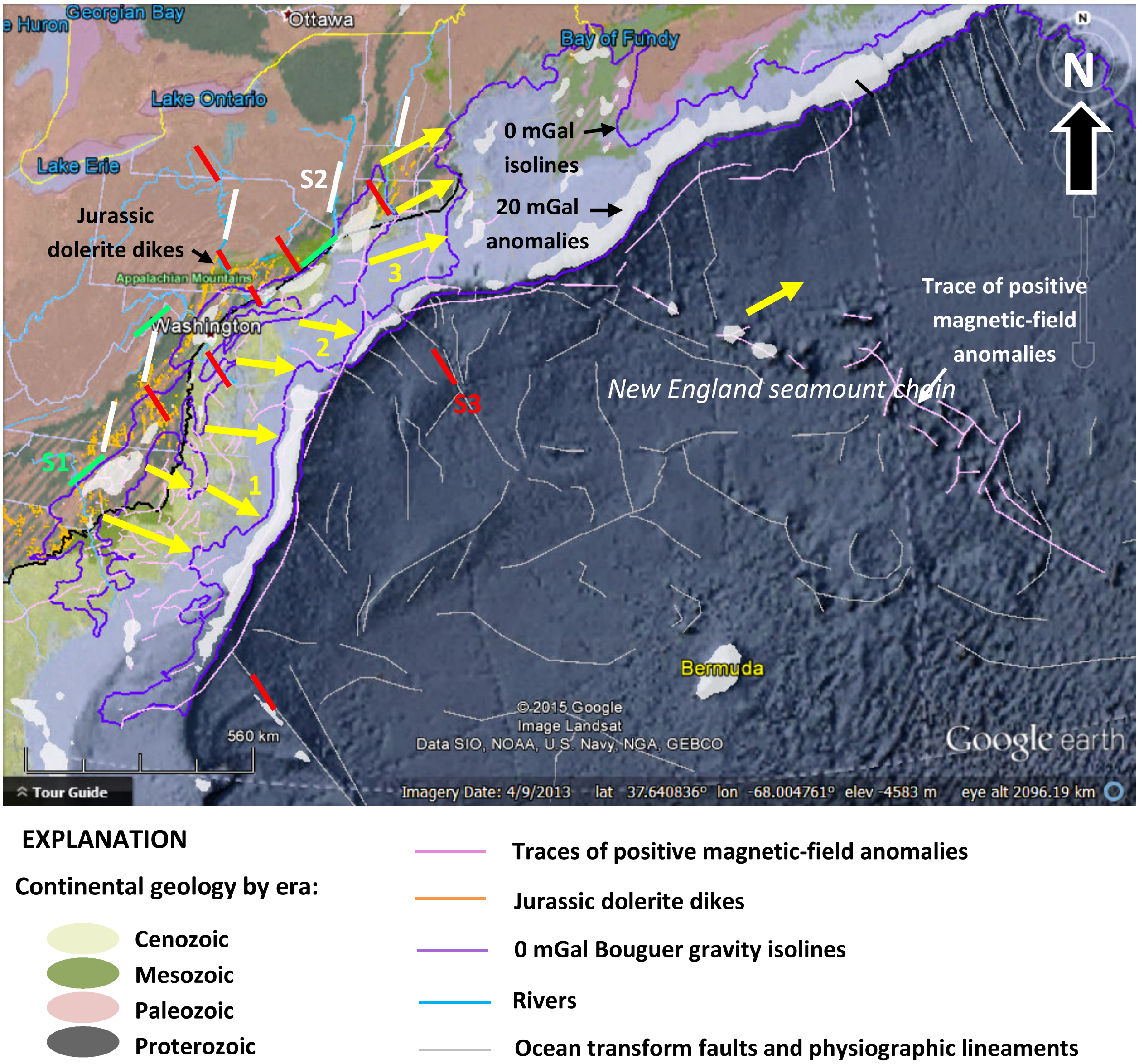


Figure 24. GE map centered between the Appalachian Mountains and Bermuda with yellow arrows highlighting three, incremental stretching directions (1 – 3) of the NAP continental margin based on overlapping tectonic extension fractures identified in Mesozoic rocks of New Jersey (Herman, 2009) and assuming that the 0 mGal Bouguer gravity isolines (purple polylines) along the continental margin were once joined prior to continental rifting (Herman and others, 2013). A semi-transparent base image shows continental geology by Era and grayshade sea-floor physiography[5]. These three proposed stetches during the Mesozoic correpsond to steeply dipping fracture sets highlighted using thick, colored lines aligned parallel (S1), oblique (S2), and almost normal (S3) to the NAP continental margin, and account for the trends of Jurassic dikes and major river segemnts.

[5]http://www.impacttectonics.org/KMLZs/GCH%20Impact%20Tectonics%2001-2015.kmz

rocks (Merguerian 2015; Chapter 2 of this volume). Together they reflect a systematic counter-clockwise rotation of the finite-stretching direction of our continental margin during Mesozoic rifting. This fracture record therefore also records the systematic rotation of the NAP Atlantic margin as it was being incrementally stretched apart, opened, and filled by growing oceanic crust (Herman, 2009). The latest-stage fracture geometry found in the Newark Basins is also seen in the Cretaceous strata detailed above and in crystalline basement as we see in Chapter 5, STOP 1. These structural systems form rhombohedral-shaped fault slices and blocks that dip moderately to steeply SE-E that are bounded by both SE-E (synthetic) and NW-N (antithetic) dipping extension structures that worked together to accommodate bulk stretching and sagging of crustal rocks (for example see Chapter 5, STOPS 1 and 3). Now that the systematic nature of these brittle rift structures is recognized, not only on the basis of structural geometry but also

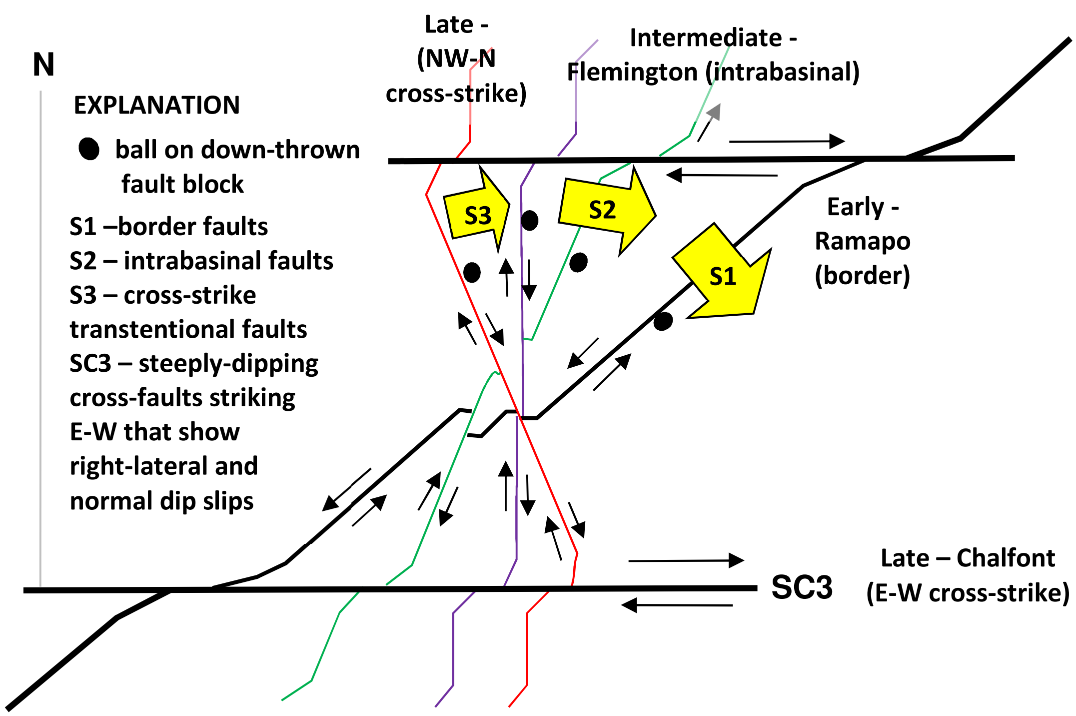


Figure 25. A schematic diagram illustrating how brittle rift-related structures mapped in the Newark Basin and surrounding region are oriented, overlap and interact. S1 (oldest) through S3 (youngest) sets of extension fractures (joints) and brittle faults fall within three sectors, have variable spatial distributions and densities in the basin, but consistently show the same orientations and structural interactions. S3C faults are complimentary to S3 fractures and may be coeval. The fracture and faults systems worked together to stretch and drop crustal blocks downward towards the southeast to northeast during rifting of the continental margin through time. The horizontal component of oblique slip is shown as arrows indicating observed slip directions on cross-strike, moderately- to steeply dipping fault planes.

with respect to kinematic indicators and secondary minerals infilling fracture interstices, we need to reappraise the nature of other brittle fractures (joints) mapped in the Appalachian foreland owing to the probability that the intense stretching phase resulting in S2 brittle structures probably reached well into the Pennsylvania Salient (fig. 27). Fractures systems of this strike are mapped in the Allegheny Plateau of New York and Pennsylvania that are currently thought to stem from Alleghanian orogenesis (Engelder and Geiser, 1985 among many others). But these fractures show congruency with both the Jurassic dikes, and subparallel reaches of the Susquehanna River and it's likely that many of these fracture systems, as well as other relatively late foreland strains reported in Pennsylvania will be reinterpreted to stem from Mesozoic and perhaps even Cenozoic strains. For example, a detailed structural analysis of late-stage Alleghanian structures at Bear Valley, Pennsylvania (Nickelsen, 1987) includes late-stage graben development consistent with S2-phase Mesozoic stretching. Moreover, the latest deformation phase reported there is oblique, foreland-directed slip found with slickensided shear planes showing sinistral wrenching of graben-bounding faults (fig. 28). Therefore, it's possible that prior, classic structural interpretations of the structural stages seen at the surface in Paleozoic strata of the Appalachian foreland needs reinterpretation, because two of the latest structural stages appear to post-date Paleozoic orogenesis in the Central Appalachian foreland. This point will be discussed further below with respect to the older tectonic structural groups.

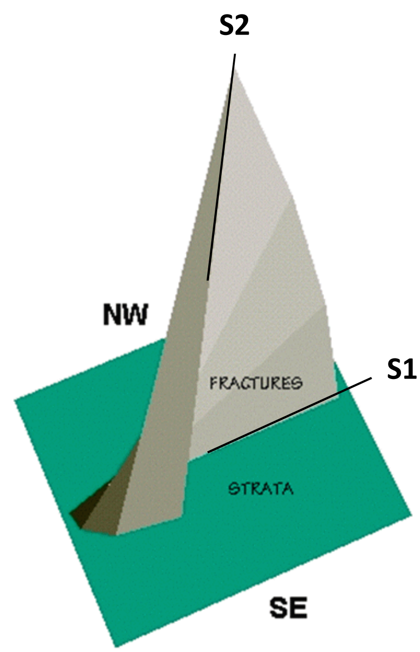
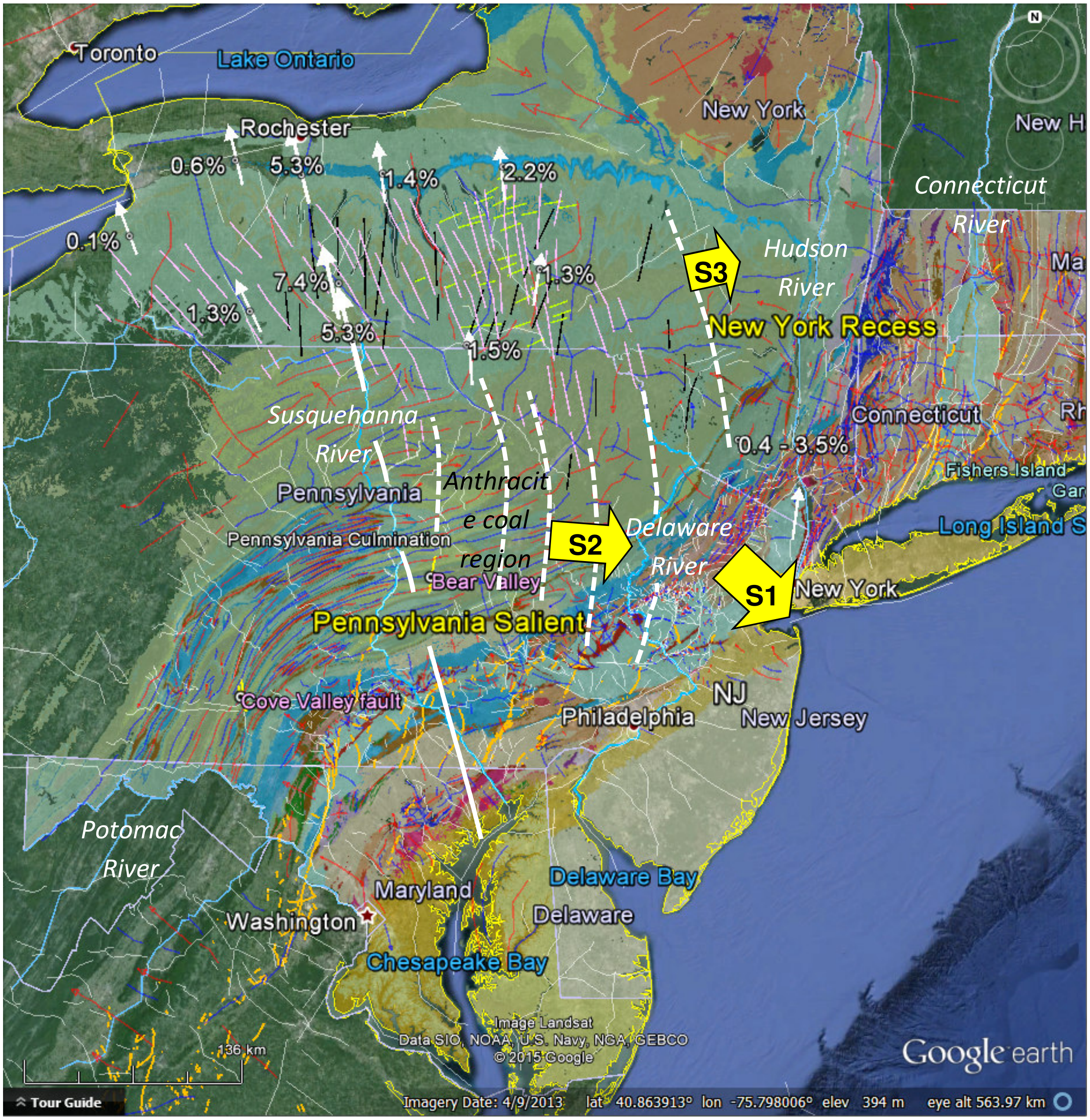


Figure 26. 3D diagram illustrating that extension fractures (joints) in the Newark basin are systematically arranged in the straigrpahic section with an upward, helical twist that reflects incremental rotation of the reigonal stetching direction from SE to E through the Meosozic. Strata mostly dip gently NW. The oldest srata commonly aligned paralell to the Appalachain grain (S1) whereas younger ones (S2 and S3) cut across it.

The Newark Basin Ramapo and border faults

Perhaps the most renowned fault that was active during the Mesozoic and has been appraised with respect to neotectonic activity is the Ramapo fault (Crone and Wheeler, 2000). This fault is one a series of linked faults that form the province boundary between the Ramapo-Hudson Highlands to the NW and the Piedmont to the SE (fig. 16). Originally thought to be a potentially active fault, or fault system, the Ramapo fault has probably been active to some degree throughout the entire Phanerozoic.



EXPLANATION

Rivers

Jurassic dolerite dikes

Major fracture systems

Appalachian Plateau joint sets

Youngest

Intermediate

Oldest

Fold axial traces

Anticline

Syncline

Figure 27. GE map showing regional joint sets of intermediate age on the Appalachian Plateau align with Jurassic dolerite dikes, river systems, and directions of regional stretching during the Mesozoic (thick yellow arrows labeled S1-S3). Joints sets adapted from Engelder and Geiser (1980) and Hancock and Engelder (1989). Note locations of the Cove Valley fault and Bear Valley. White arrows show directions and magnitudes of horizontal compaction measured in calcite grains in Paleozoic AND Mesozoic rocks (Engelder, 1979; Lomando and Engelder, 1984). The white line extending from Chesapeake Bay to the 7.4% value trends ~azimuth 347°.

The fault was a focus of research in the 1970's because it's a prominent, major fault occurring at a province boundary with historical crustal seismicity recorded near its map trace during a time requiring regional assessments of seismic risk for siting nuclear-power generating stations (Aggarwal and Sykes, 1978). Crone and Wheeler (2000), provide a thorough review of the historical reports of low-grade crustal seismicity in the area of the Ramapo fault both from map and profile perspectives. They cite several lines of reasoning disfavoring any significant, current activity on this fault. Detailed structural analyses of rock fabric at several locations showed mostly late- stage normal and oblique slips (Burton and Ratcliffe, 1985; Ratcliffe, 1980, 1982a; Ratcliffe and others, 1990) that are inconsistent with the existing, east–northeast-trending,

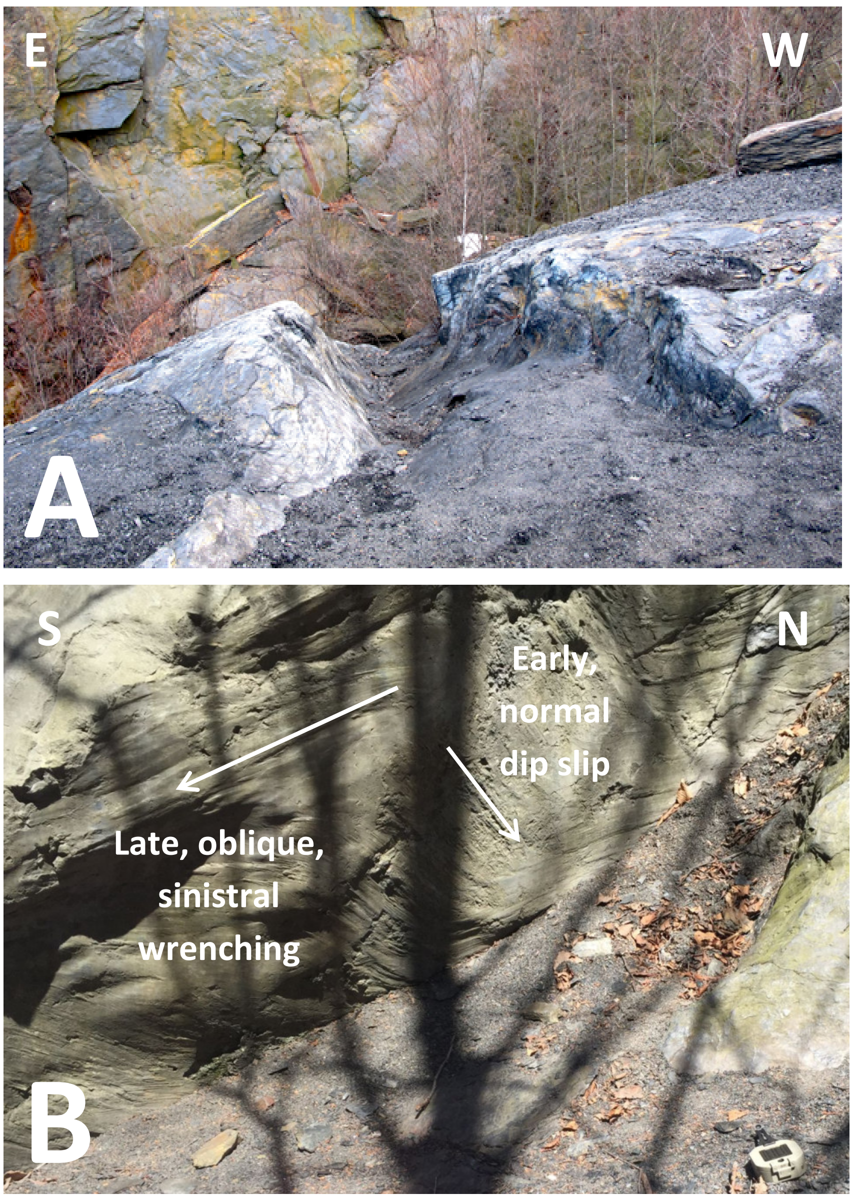


Figure 28. Photographs of probable Mesozoic and possible Cenozoic structures in upper Paleozoic strata at a coal mine in Bear Valley, Pa. (location noted in fig. 27). Late-stage structural grabens (A) of Newark S2 fault strike (fig. 25) dip steeply west and have two sets of slickenlines (B) on graben-bounding faults. The earlier slickenlines indicate normal, dip-slip shearing during graben development, and later ones indicate transcurrent wrenching (Nickelsen, 1963) that is also reported northward to the edge of the Appalachian plateau on regional joints sets of sub-prallel strike(Engleder and others, 2001). Photo a courtesy of www.princeton.edu.

contractional stress field (fig. 3). Also, Stone and Ratcliffe (1984) trenched the up dip projection of the Ramapo fault at two localities with both investigations finding no evidence of quaternary tectonic faulting. As Crone and Wheeler (2000) summarize, “No available arguments or evidence can preclude the possibility of occasional small earthquakes on the Ramapo fault or other strands of the fault system, or of rarer large earthquakes whose geologic record has not been recognized. Nonetheless, there is no clear evidence of quaternary tectonic faulting on the fault system aside from the small earthquakes scattered within and outside the Ramapo fault system”.

Other geological features that may indicate neotectonic structural reactivation or overprinting of Newark structures

There are only a few reports detailing relatively young, brittle strains that overprint Newark structures. A couple stem from outcrop evidence whereas many others have been emerging from the deployment of borehole-televiewer (BTV) cameras that capture oriented photographic images of the borehole walls and that are used to interpret subsurface water-bearing features within different strata (fig. 29; Herman and Curran, 2010). Lucas and others (1998) were the first to map and report compressional overprinting of Newark strata in the Jacksonwald syncline where foreland-type folding occurs with penetrative structures and shearing indicating “shortening at a high angle to the border fault”, that strikes about E-W there (fig. 30). Since then, there have been only a few, relatively recent reports of compressive overprinting or potential neotectonic reactivation of Newark structures, including the structural overprint of the discordant, compressional folds found along E-W striking segments of the Hopewell fault system as reported in Chapter 5, STOP 2. A more recent report of possible neotectonic reactivation of Newark structures stems from optical BTV records of Triassic mudstone from Elizabeth, New Jersey (Herman and others, 2015). The BTV data show apparent evidence of oblique slip on steeply dipping S1 (border-fault parallel) extension fractures, based on the offset of sub-horizontal veins that are probably relatively young, sub horizontal gypsum veins found in this part of the basin, and that have been cited as being the youngest, mineralized veins set in basin strata (El Tabakh and others, 1998). The Elizabeth report shows how older, S1 extension fractures of Newark age are favorably aligned to slip in our contemporary, compressional stress field.

One isolated patch of Late Pleistocene, very-fine grained alluvium bearing charcoal was recently uncovered along the trace of the Flemington fault that may signal relatively recent tectonic movement (Herman and others, 2012). This unusual deposit sits atop soft red shale and butts up against the fault, thereby inviting speculation of structural control of Quaternary age, but it could also be the result of selective preservation in a depositional trough. There is no fracturing in this silty clay bed, and therefore this one point of observation doesn't provide enough information to verify neotectonic activity. However, subsurface evidence of late-stage reactivation and shearing of Mesozoic and older bedrock is rather common in optical BTV images like those shown in figure 28. These records stem from fractured-bedrock aquifer subsurface investigations throughout northern New Jersey in Mesozoic through Proterozoic

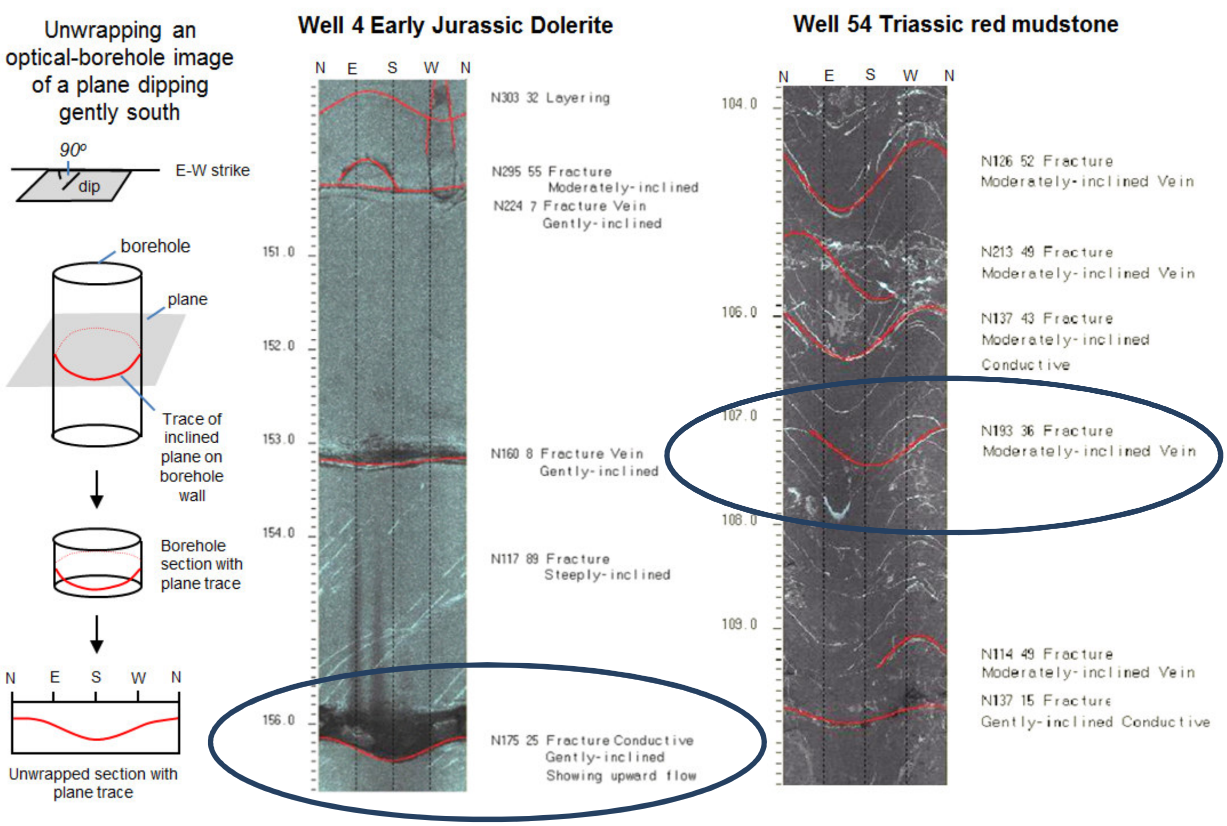


Figure 29. Optical BTV imagery collected in fractured-bedrock aquifers in New Jersey commonly show late-stage, ~E-W-striking, reverse shear fractures that dip gently SE (circled), less so to the NW, that are among the most open and permeable fracture conduits in the region. The schematic diagrams on the left illustrates how a gently dipping plane that is cut but a borehole appears in an unwrapped, optical-borehole image that is 'flattened' for interpretation. Note how early, inerlzied (S1) fractures are sheared and offset in the image to the right along one of these shear planes. The locations of these two wells are noted in figure 29. Depth units for the BTV imagery are feet below land surface.

bedrock and show sporadically distributed, late-stage, brittle, reverse shear planes that commonly strike ~E-W (fig. 28). These features are among the among the most open, permeable fracture systems in the area.

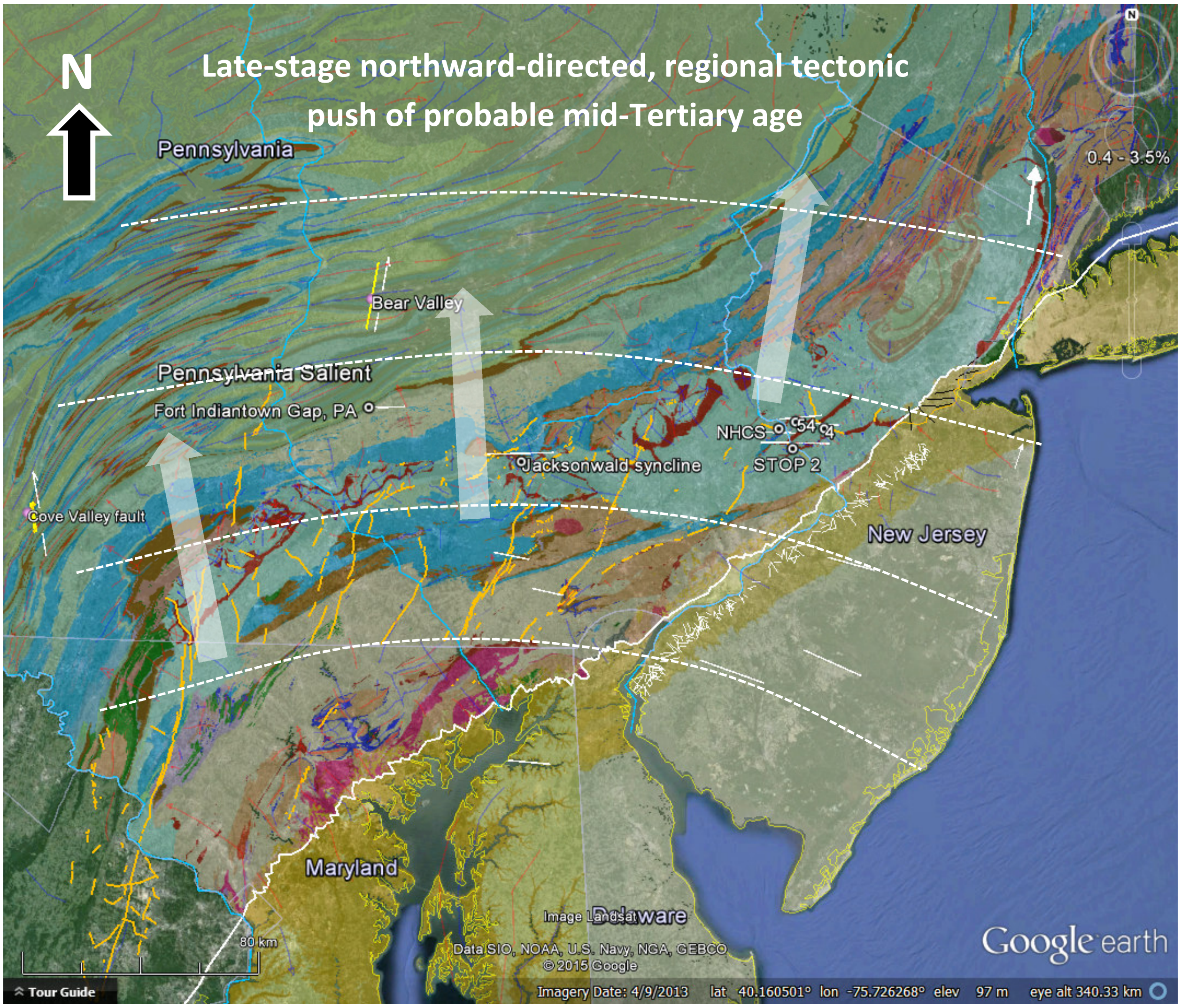


Figure 30. GE map showing the radial distribution of late-stage, probable Tertiary compressional push resulting in a north-directed, compressional, structrual overprinting of this region. The systematic orienntation of these late-stage features fans in an arcuate, convex manner above upper reaches of the Chesapeake Bay. This push laterally compacted both Palezoic and Mesozoic bedrock by a few percent, imparted mineralized shear fractures that cross-cut and offset earlier structres, and now are among the most, open, permeable features seen in the subsurface (fig. 28). NHCS-New Hope Crushed Stone quarry, locations labeled 4 and 54 refer to well records of Herman and Curran (2013). Key to geological units on figure 2.

Tectonic Groups G2 (Paleozoic >260 Ma) and G1 (Proterozoic >~765)

These two groups are covered together because we are just beginning to understand how to view the commonly mapped structures in basement rocks of the Highlands and cover rocks of the Valley and Ridge provinces with respect to both Mesozoic and Cenozoic strains. The sequence of pre-Mesozoic tectonics events in our region is diverse and complex. The summary in figure 3 provides no tectonic and structural details surrounding the series of orogenic pulses that helped form our Appalachian highlands, lowlands, and plateaus. To this point, a few key studies of classic Appalachian structural chronology and studies of foreland penetrative strains are reported in this region, and figure into this neotectonic survey, and are discussed and reevaluated with respect to some newly emerging map patterns and tectonic concepts.

As reported in Chapter 2, Merguerian (2015) provides a retrospective of his work in identifying the different sets of brittle discontinuities cutting Proterozoic basement and Paleozoic cover rocks in the New York City (NYC) area. He denotes these as Groups A to E, with the latter two, D and E showing good evidence of post-Paleozoic movements. His Group D fractures strike NNE parallel to Herman's (2007) S2 tensional fractures and they both dip steeply with predominately normal dip-slip kinematic indicators. They also share the same zeolite-to-calcite epithermal mineral assemblages infilling fracture interstices and coating fault surfaces (Chapter 2, fig. 11 and Chapter 5, fig. 30). Similarly, the latest NW-NNW striking (Group E) structures in NYC parallel the S3 Newark structures (noted above, that overprint and reactivate older ones (fig. 25). The 'E-S3' fractures show the largest post-metamorphic movements of both dextral and sinistral oblique slips (Baskerville, 1982; Merguerian and Sanders, 1996; Merguerian and Sanders, 1997). Dextral separations are measurably larger in the range of 100-200 m whereas the sinistral movements are reported on the order of centimeters (Merguerian, 2015). The Mosholu fault is one of the largest northwest-striking faults in the New York City area with a map throw of about 35 m of dextral slip (Baskerville, 1992). The interpretation of its recent tectonic uplift is suggestive but not yet conclusive. However, as Merguerian (2015) points out, sinistral slip along these systems is more probable in the present-day stress field (figs. 8 and 9). Seeber and Dawers (1989) also favor interpretation having dextral-slip movements on cross-strike structures of 'E-~S3' orientation resulting from Mesozoic rifting.

Richard Nickelsen (1963, 1987) chronicled the relative sequence of brittle strain events in the Appalachian Valley and Ridge province Pennsylvania, and his work figures prominently into this neotenic evaluation. It was demonstrated above that his latest two phases of structural deformation in the foreland corresponds with the intermediate 'D orS2', extensive Mesozoic stretch seen in this region as CAMP bodies rose from beneath the emerging proto-continental margins to feed massive sills and volcanic flows (Herman and others, 2013). The latest, sinistral wrench slips on the graben-bounding faults in the anthracite coal measures also agrees kinematically with more recent work that he conducted on the western flank of the Pennsylvania culmination, marked as the Cove Valley fault in figures 17 and 27 (Nickelsen, 1996). This is another area where sinistral wrenching occurs on latest-stage structures in the Appalachian foreland. He described these late-stage faults as having brecciated Silurian quartzite, but elusive in outcrop “because the surfaces are never slickensided or slickenlined. Proof of their existence rests in finding truncation of previous structures and the unique, brittle, fracture surfaces” … “that are coated with thin layers of extremely angular breccia that does not show evidence of progressing toward a finer cataclasite”. In other words, this episode of rock fracturing doesn’t appear to have been part of a progressive continuum, but more of a solitary episodic overprint. Additionally, this fault and other nearby similarly aligned cross faults offset rock ridges and locally coincide with limonite mines, some of which have reported hydrothermal pyrite. These are critical observations in light of other detailed microstructural studies of the foreland section by Engelder (1979) and Lomando and Engelder (1984) using techniques pioneered by Groshong (1972) of microscopically measuring twinned calcite grains to resolve principal axes of compressive tectonic shortening, and gauge the magnitude of penetrative, bulk, lateral compaction. This work shows foreland, penetrative shortening of Paleozoic AND Mesozoic rocks approaching 8% along a medial line roughly coinciding with the right side of the Pennsylvania culmination and intermediate north-south stretches of the Susquehanna River running along ~347^{o} azimuth (fig. 27). The strain field dies out laterally with diminishing strains fanning outward towards Lake Erie to the west and Long Island, NY to the east.

Geiser and Engelder (1983) postulated that two compressive pushes seen in the Pennsylvania salient, referred to as “Lackawanna” and “Main” phases were discreet tectonic episodes, perhaps separated by millions of years. A very interesting aspect of their work is they also note a very rapid strain rate for the latest push that reportedly happened is less than 1 million years. Gray and Mitra (1993) recognized five stages of foreland brittle tectonism in the Pennsylvania salient (Stages A-E) including three compressive phases that are probably Alleghanian followed by two post-Alleghanian trends. As seen before, stage 4 (D) conjugate extension faults are grouped with late-thrust faults and associated slickensides and gash veins, POST-folding crenulation cleavages, and finally veining and fracturing of stage 5 (E). They report that the three, earliest stages were continuous, but not necessarily the latter two. The more recent detailed structural analyses of penetrative strain and shortening directions in the Pennsylvania culmination by Saks and others (2014) also points to two phases of non-coaxial strain, with mean orientations of the early-stage of azimuth ~336 +16.3 and the later one along ~343^{o}. This latter one deviates less than 5^{o} azimuth from the ~347^{o} (NNE) axis of maximum shortening occurring along the east side of culmination (fig. 27).

Gwinn (1970) reintroduced the Pennsylvania culmination as the 'Juniata Culmination' and noted that both Nickelsen (1963) and Wise (in Nickelsen 1963) and Rodgers (1964) speculated that it may be partly a product of post Appalachian basement uplift transverse to trends of Paleozoic folding, although evidence of basement involvement is lacking. Blackmer and others (1994) used fluid inclusion geothermometry in the region and found initial rapid burial and unroofing during the Late-Permian through Early Jurassic that they attributed to flexure and rebound of the foreland to erosional loading and unloading of the Alleghanian thrust sheets. An episode of little to no unroofing (Middle-Jurassic-late Oligocene) possibly began with inception of drift at the Atlantic continental margin. Then, an episode of rapid unroofing over the full width of the basin occurred from the Miocene to the present. The driving mechanism for this renewed unroofing was not identified. Despite the earlier speculations of Davis (1902) and the more recent ones noted above, a popular consensus is that most tectonic structures in the Pennsylvania salient reflect Late Paleozoic orogenesis. As demonstrated herein, the latter viewpoint seems improbable as both Mesozoic and Cenozoic uplifts probably occurred here. With respect to just how many happened, and when they happened, and if they happened during our current, compressional state of crustal stress is the focus of the following discussion.

Discussion

Some key points are summarized below from this work that leads to a reinterpretation of the late-stage neotectonic events affecting our region:

1) Actual plate drift determined using ground-fixed GPS systems show increasing horizontal velocities progressing northeastward up the Appalachian grain from Chesapeake Bay at ~ 13 mm/yr into southern New England at ~17 mm/yr. Actual vertical motions of the crust oscillate on the order of 10-20 mm/yr, but in the region south of Adirondack Mountains through the Hudson Valley and New Jersey, the continental crust is slowly sinking at rates approaching 4 mm/yr except in an area lying west of the Pennsylvania culmination and other small, isolated spots that are rising very slowly with rates of less than 1 mm/yr (figs. 4, 8, 9, 17 and 23). A pronounced, NNW-trending, linear break in vertical crustal motion is seen bounding the west side of the Pennsylvania culmination that is mirrored to the east where the Delaware River watershed is separated from the Atlantic watershed by a topographic divide that zig zags from south to north up through New Jersey into New York, mimicking the river's course (fig. 4). These two velocity breaks bracket the Pennsylvania culmination, where the largest areas are sinking the fastest, and they both verge southward towards Chesapeake Bay (fig. 4).

2) The east-central continental margin of the NAP is seismically active with patterns of historical seismicity showing remarkable congruency with not only GPS-derived estimates of actual crustal motions, but also with major physiographic features including surface water drainage patterns and regional watershed boundaries (figs 4,8,9, and 11). A careful look at the historical seismicity in this region also shows that seismogenic zones preferentially occur where deep-seated igneous plutons are present, including ultramafic plutons of the Adirondacks (fig. 11) and of the Cortland intrusive complex in the Ramapo seismic zone (fig. 9). These areas appear as crustal sticking points that resist drift and leading to accumulated elastic strain and consequential, periodic seismic releases. The GPS plate motions at this scale show southward crustal deflection around the Adirondack Mountains (figs 11 and 17). The systematic, arcuate patterns of crustal seismicity bowing around and opening westward behind the Adirondacks have a symmetric, but reflected counterpart lying generally conforming in alignment to the New England coastline (fig. 11). This latter lineament opens eastward and runs southward from Maine through Long Island Sound, trending about normal to the direction of current horizontal plate drift. The closest P-axes solutions plotted in this region are near Stamford, CT with some easterly trends that also oppose the current direction of plate drift (figs. 8 and 9).

3) The intermediate stage of crustal rifting during the Mesozoic (D-S2 above) is regionally pervasive, and part of a strain continuum that likely stretched the entire Appalachian margin and well into the continental interior. This is supported by kimberlites of Mesozoic age occurring on west-side of the Pennsylvania culmination and in southwest Pennsylvania (Bikerman and others, 1997; Parrish and Lavin, 1982).

4) Right-lateral displacements are noted along the ~E-W striking Kelvin-Cornwall transform fault marked by the New England seamount chain, that links to ~E-W, late-stage transtensional fault components displaying the same kinematics and that cut the continental margin through New Jersey where they involve complementary sets of N-S to NNE, cross-strike normal faults having right-lateral-oblique slip components.

5) Late-stage penetrative tectonic compaction and wrenching strains are found in the Appalachian foreland not only in Paleozoic rocks but also Mesozoic rocks of the NY-NJ Piedmont, and therefore, the tectonic event responsible for these strains must be, at least in part, Cenozoic, and probably mid-Tertiary in age; strata older than the mid-Tertiary unconformity (~40-36 Mya; figure 20) contain visible, mapped structures whereas younger strata generally do not. The only exceptions are where structurally disrupted Miocene sediments in the Delaware coastal plain occur in a small area coinciding with the fastest rates of GPS-based subsidence (~3-4 mm/yr; Pollack Farm fig.

17 and 23). Late-stage kinematic indicators at Bear Valley and Cove Valley shows consistent sinistral-oblique slip kinematics, and when considering the late N-S directed push found in the central part of the Appalachian foreland, the Newark basin and the NJ Coastal Plain (fig. 30) it appears that an episodic, rapid tectonic push occurred during the mid-Tertiary period, resulting in crustal uplift and the pronounced, mid-Tertiary unconformity in this region (fig. 20). This push seems to have originated near the head of Chesapeake Bay as measured from compressive strains that systematically dissipate laterally away from maximum strain axis running along a medial line up the right side of the Pennsylvania culmination and coinciding with intermediate stretches of the Susquehanna River (fig. 2). The relatively rapid rate of current subsidence in the Pennsylvania culmination is probably a continuing, neotectonic response to a Tertiary uplift event lying foreland of the Chesapeake Bay as revealed by the aforementioned, observed breaks in the GPS vertical-velocity field, the radiometric age work detailed in Chapter 3 (Mathur and others, 2015), and pressure- and temperature-dependent fluid inclusion work in the region by Blackmer and others (1994).

6) The distributions and orientations of the various p-axes measurements plotted in figure 31 show varying stress regimes with respect to the Appalachian Mountain chain. For example, foreland and west of the Appalachian Mountain belt, stress axes in more interior regions of the NAP consistently plunge gently northeastward along a bearing that fans slightly from 53^{o} to 73^{o}. When these trends are projected SW up-plunge, they verge to the southwest somewhere in the lower Mississippi River Valley. Another regime is seen plunging southward off the rising Canadian Shield (fig. 31). An interesting break in orientation of these P-axes solutions also occur across the Saint Lawrence Seaway that developed along a historically active seismogenic zone (fig. 10) and an ancient fault system of at least Mesozoic age (Tremblay and Lemieux, 2001; Mazzotti and others, 2004). Another region occurs along the continental margin where two principal directions of current crustal compression are resolved, one of similar trends seen in the Appalachian foreland (gently plunging NE) and another that nearly opposes current plate drift (fig. 31). This implies that the more interior, aseismic parts of the NAP have remnant compressive stresses nearly aligned parallel to the Appalachian Mountains, and that were deflected backward by rising areas to the north, whereas coastal areas near the continent-ocean boundary have a variable stress regime that is evolving to reflect current plate drift. This raises the question as to the nature of the old, remnant stress field of the continental interior that points southwestward and north of the Gulf of Mexico. Could the Chicxulub impact have triggered subsequent plate reorganization and reversed not only the polarity of the stress regime, but also the rotation of our plate (Herman, 2009)?

7) The sets of cross-strike fold axe depicting late-stage folding, warping, and in essence, crenulation of older Appalachian structures along trends paralleling current plate drift are intriguing but perplexing. As for the proposed Rochester-Watchung synclinorium (figs. 11 and 17), the nature and timing of these structures need more study. In a simple sense, one would anticipate seeing a structural trough situated between two structural culminations; the Adirondacks to the north and the Pennsylvania to the south. Definition of the Watchung synclinorium and other, similarly trending, en-echelon fold structures crossing the New York Recess (fig. 17) is based on an visual analysis of the systematic irregularities expressed as patterns seen in regional and local geological and physiographic features, and they are probably slowly growing neotectonic accommodation features reflecting progressively increasing strain rates in a direction trending NE up the Appalachian Mountain chain because of increasing drift rates. It is interesting to note that the cross-strike pattern, paralleling Merguerian (2015) latest-stage brittle structures in NYC, is apparently limited in distribution, occurring only north of the Rochester-Watchung synclinorium, with this pattern only continuing southward along continental-oceanic marginal areas of the piedmont and coastal areas.

In a general sense, tectonics encompasses all geological processes which control the structure and properties of the Earth's crust, and its evolution through time, in particular, with respect to mountain building. Therefore, in addition to considering our current, actual plate movements and historical seismicity records collected over such a brief time, many other geological processes bear on our current states of crustal stress and the resulting patterns of our crustal seismicity. In a similar sense that we see the variable, oscillatory motion of Earth's vertical ground motion, oscillatory, lower-frequency regional variations must also occur in response to long-period isostatic adjustments stemming from growth and retreat of continental ice sheets and encroachment and withdrawal of marginal seas. These longer-wavelength and longer-period lithospheric flexures and crustal adjustments probably take place over the course of tens of thousands to millions of years' time and exceed the capabilities of day-to-day GPS monitoring. These processes however cannot possibly be gauged solely through inspection of historical plate motions and seismicity records, but also rely on other geomorphological, sedimentological-stratigraphic, and geochemical processes that merit further consideration in more thorough neotectonic treatment that one day will exceed the scope of this work.

Because the GPS-derived rates of vertical plate motion align with apparent trends in the historical seismogenic patterns, especially with respect to the distribution of large, ultramafic plutons, then subsequent snapshots of the vertical-velocity field should show localized variations with time, but the longer trends should persist given the lack of any catastrophic, regional energy flux that would perturb our on-going, relatively uniform, plate drift. A few spot

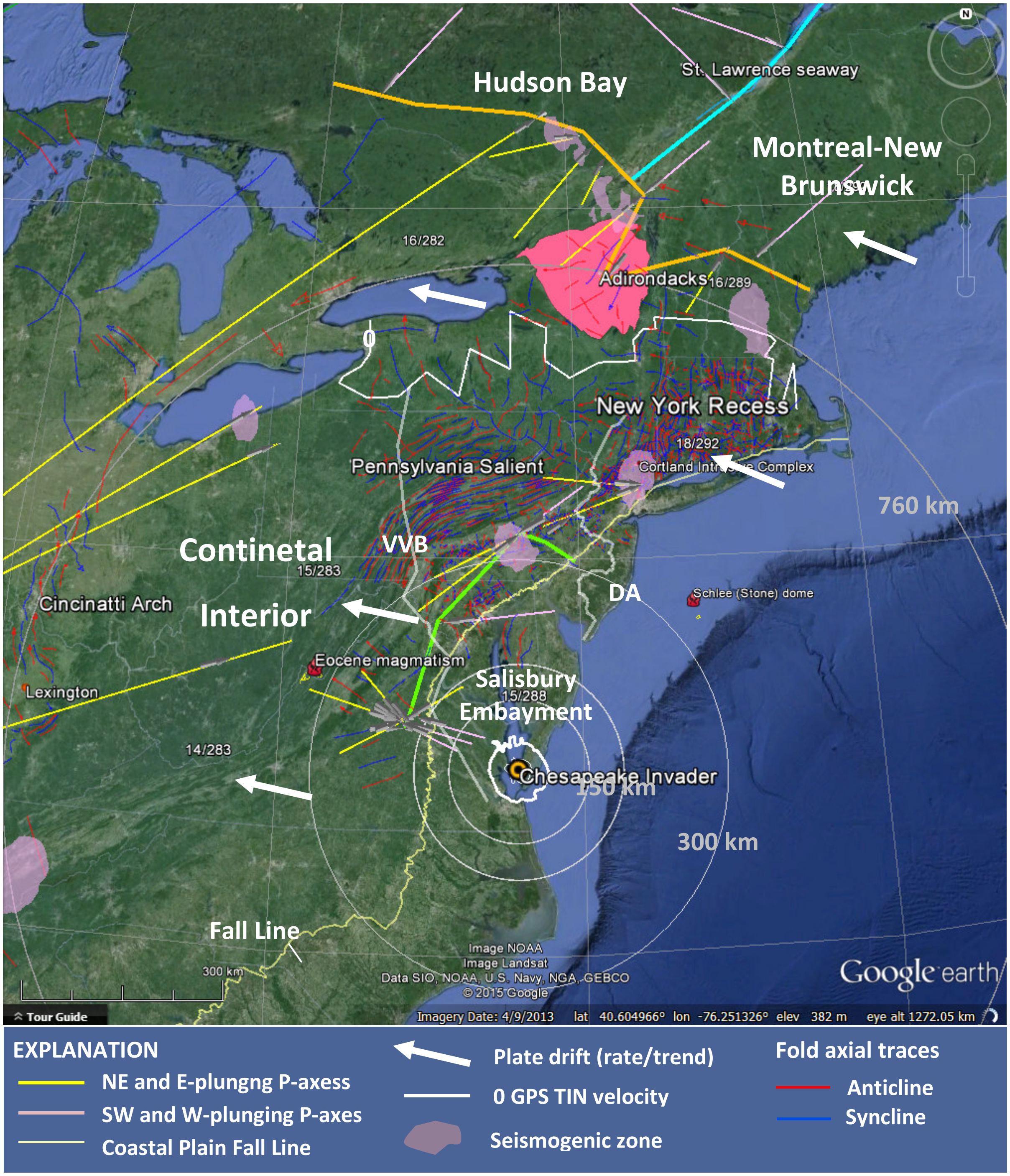


Figure 31. GE map showing stress-regimes (defined where P-axes display different trends and plunges), pronounced breaks in the TIN surface of vertical-crustal motion, the Delaware-Atlantic drainage divide (DA), the Coastal Plain boundary, compiled fold axes, and the Chesapeake impacts crater with concentric rings at varying radii. Colored straight lines emphasize plunge directions of compiled P-axes whereas colored (green, orange, and light-blue) polylines define stress regimes including the Hudson Bay, Montreal-New Brunswick, Salisbury Embayment, and Continetal Interior. The Pennsylvnia Salient NY Recess resemble the Continetal Interior but are evolving near the Fall Line. Rate of plate dirft in mm/yr.

checks of the vertical GPS rates in 2014 closely match the long-term values used to generate the TIN velocity surface, and the 2009 TIN surface is the best snapshot of vertical-plate motions that we currently have. As previously mentioned, plans are underway at the NJGWS to develop methods of automating computer retrievals of newer CORS data at successive, regular time intervals to facilitate further study of crustal dynamics, and one-day perhaps, be able to animate dynamic fluctuation of the surface over time. But for now, these results are encouraging, because the GPS rates of crustal subsidence in this regional generally agree with estimated rates of crustal erosion and denudation arrived independently. Specifically, Pazzaglia and others (2006) provide a synthesis of late Cenozoic deformation of the middle Atlantic passive margin. 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. 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. Erosion rates vary across the Appalachian landscape depending on local relief, rock type, and proximity to the fall zone along the NW edge of the coastal plain, but current erosion rates of about ~ 5 to 10 mm/yr are estimated using present-day solute loads. Rates may have peaked at ~80-100 mm/yr during Quaternary periglacial erosion (Pazzaglia and others, 2009). Stanford and others (2002) derived much lower, long-term denudation rates of denudation rates of ~ 0.01 mm/yr from Late Tertiary to recent times for a 2800 km2 section of the U.S. Atlantic Coastal Plain and Piedmont. This work used reconstructed topography at five different times from the late Miocene to the present based on mapping of fluvial strata, colluvium, and marginal-marine deposits that are constrained with radiocarbon dates, palynostratigraphy, and correlation to adjacent glacial and marine units. These rates are reported as agreeing with other denudation rates found in similar regions, but as pointed out, local erosional rates can clearly vary widely, over at least two orders of magnitude depending upon the setting. Additional work relating observed GPS trends with local geomorphological variations is needed and may prove very useful in the future. With respect to Pazzaglia and others (2009) work, one additional, critical piece of information supports the hypothesis that this region contains far-field crustal strains imparted by the Chesapeake Invader (Poag, 1999). They report that erosion rates in Susquehanna River basin doubled from prior amounts immediately after the Chesapeake impact at ~ 35.5 Mya. This work is based on cosmogenic dating of the oldest river terraces and associated upland gravel at 36.1 + 7.3 Ma (Pazzaglia and others, 2009). Younger terraces yield averages dates of 19.8 +2.7 Ma and 14.4 +2.7 ka respectively. This last point brings us to a few concluding remarks and thoughts.

In more than one way, GANJ 32 provides closure on many, puzzling aspects of my work in the central Appalachians over the past 30 years. In 1981-82 during the time when I was helping unravel the geological complexities of the Pennsylvania culmination with Dr. Peter Geiser at the University of Connecticut (Herman, 1984; 1985), I found some unusual tectonic structures in the culmination that didn't quite fit the model paradigm of foreland fold-and-thrust belt that develops with an ideal 'break-forward' advance of stacked thrust sheets, one-at-a-time, transported northwestward from Alleghanian plate convergence. Rather, the manner with which the Pennsylvania crust was crumpled and compounded from thrust faulting was uncharacteristically 'out of sequence' in the most tightly compacted areas that appear to have been selectively raised by a quick, uncharacteristic tectonic push. Moreover, from attempting to palinspatically reconstruct the Pennsylvania Valley and Ridge province using a set of serial, balanced cross section line traces across the salient to estimate crustal shortening and pre-orogenic spatial positions, the serial reconstructions merged toward a point at the head of Chesapeake Bay. At the time, we simply thought "how strange"', and "orogenic thrust belts shouldn't do that", so we temporarily stopped that aspect of the work then, which was subsequently included in later work by Geiser (1988).

Another curious aspect of my MS work in the Pennsylvania culmination is that conjugate, deformation lamellae were petrographically seen in each oriented sample of ridge-forming Silurian quartzite collected across the width of the culmination. I noted this curiosity at the time (Herman, 1985), and was assured then, and over the following decades by many structural experts working in the region, that these were not uncommon, and that they probably are ordinary, brittle orogenic strain mechanisms. The problem is that I haven't seen them reported elsewhere in this arrangement in other orogenic settings, but they do occur as such near crustal impact craters , albeit with much higher concentrations and grain densities near the crater. Quartz deformation lamellae by definition are sharply defined crystal defects, or glassy, extremely narrow (~1 Um) bands that only form at high orogenic stresses of 110-200 Mpa in quartz (Blenkinskop and Rutter, 2014). Similar microstructures referred to as basal quartz, planar deformation features/lamellae (PDFs) also occurs in many silicates that have been shocked by terrestrial bolide impacts, and are best represented in quartz and feldspar. Apparently, their orientation is sensitive to pressure, and is a shock barometer at pressures between 15 and 35 GPa (Lee and Leroux, 2015), or values approximately an order of magnitude higher than those cited above for orogenic lamellae. Clearly, more work is needed in order to understand if these conjugate deformation lamellae in the culmination result from standard orogenic process or shock geodynamics. But cross-section representation of the out-of-sequence, tightened fault slices (Herman, 1984; Sak and others, 2012) are identical to those portrayed near the Cove Valley fault by Nickelsen (1989), where late stage, wrench faults like this belie a late, N-S push centered along the spine of Chesapeake Bay. Also at this time, everyone working on Appalachian structural chronology in the region, including the Appalachian Tectonics Study Group[6] were interpreting root causes for observed effects without any knowledge of the nearby Chesapeake impact crater (Poag, 1999), or for that matter, actual plate motions. This was at the advent of computerized mapping and satellite-based Earth imaging and monitoring of Earth's surface and geosystems. I began conducting neotectonic studies in this region just after the crater's discovery while working at the NJGWS and finishing a PhD at Rutgers, New Brunswick on the crustal structure of pre-Cretaceous bedrock in New Jersey (Herman, 1997). When first accessing and plotting the NASA GPS plate-motion data I was struck (no pun intended) by the manner in which the North and central American plates rotated in concert around the Gulf of Mexico, and the approximate location of the recently discovered Chicxulub impact crater lying off the tip of Mexico's Yucatan peninsula. This crustal impact structure is an order of magnitude larger than the Chesapeake crater (www.passc.net/EarthImpactDatabase/index.html) and is temporally associated with the Mesozoic-Cenozoic geological revolution across the K/T boundary (fig. 3). It soon became clear to me that these sites of such massive energy fluxes somehow factored into current plate structures and geodynamics (Herman, 2006). But the hypothesis needed refinement and testing, and it thereafter became my hobby (www.impacttectonics.org) rather than my job, the latter of which focused on fractured-bedrock hydrogeology. Now, one-decade later, this GANJ meeting provides the opportunity to fill in some details that have puzzled me for nearly three decades and allow me to help report corroborating evidence in the form of absolute, radiometric age dates indicating a widespread, regional, far-field brittle strain field fanning outward in front the Chesapeake Bay impact crater for distances greater than 500 km away through foreland areas of Pennsylvania and New Jersey (Chapter 3, Mathur and others, 2015). When combined with the abstract notion of the aforementioned Chicxulub effects, I sincerely hope that this work helps advance some anemic aspects of plate tectonic theory that currently lacks any consideration of large, hypervelocity impacts on Earth. From my, and some others perspectives (Ribiero, 2002) these effects are real and measurable and will prove one day as a factor into a more complete, robust plate-tectonic paradigm, one that includes intraplate crustal deformation and epeirogenesis stemming directly from periodic and catastrophic bombardment by large bolides. For now though, it is important to understand the need for more work in examining magnitudes of ground-energy generated by such events, both short- and long-term strain mechanisms serving to dissipate the energy fluxes, and the geometry of associated crustal and mantle strain fields. Also, according to the definition prefaced in this book, neotectonic strains are those that form in our current stress regime. If proven correct, does a catastrophic event qualify as a neotectonic feature, or is that reserved to the more accepted, standard, uniformitarian viewpoints only?

[6]http://www.impacttectonics.org/ATSG/

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; Wise and Werner, 2004; Marshak, 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 a product of continental rifting, for it’s much easier to tear earth material apart with tension that assemble it through compression, The Mohr circle shows how siliceous crustal material do not sustain tension for long and fail quickly in comparison to compression strain responses. Consequently, tensional strains should be distributed over wide regions in comparison to compressional fold-and-thrust belts.

There have also been many studies conducted of plate dynamics in this region of the NAP that lends credence to the impact-tectonic aspects of these 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 that and resulted in major changes in the deep water circulation, permitting cold polar waters to move southward in the Atlantic Ocean basin (Klitgord and Schouten, 1986). Similarly, 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). There are many such corroborative lines of evidence supporting this concept that almost forces serious consideration of how these two, known, large-bolide impacts on the NAP, at the beginning of and during the Cenozoic Era, have not only helped shaped the crust, but continue to exert a dynamic neotectonic signature on our landscape that is so remote to the causative agents. But as this work puts forth new hypotheses, new tools and sophisticated means are being developed that will help us gain new perspectives on these problems. Overall, I am very encouraged by the rate at which technical advances along these lines are developing, and although our region is comparatively passive in a tectonic sense with respect convergent or transcurrent plate margins, this part of the NAP in the region of the New York Recess is demonstrably active and passive only in regard to lacking a nearby, major plate boundary. For it continuously drifts and cracks, and rises and sinks as part of a larger set of spinning and shifting lithospheric plates on a planet that we call home.

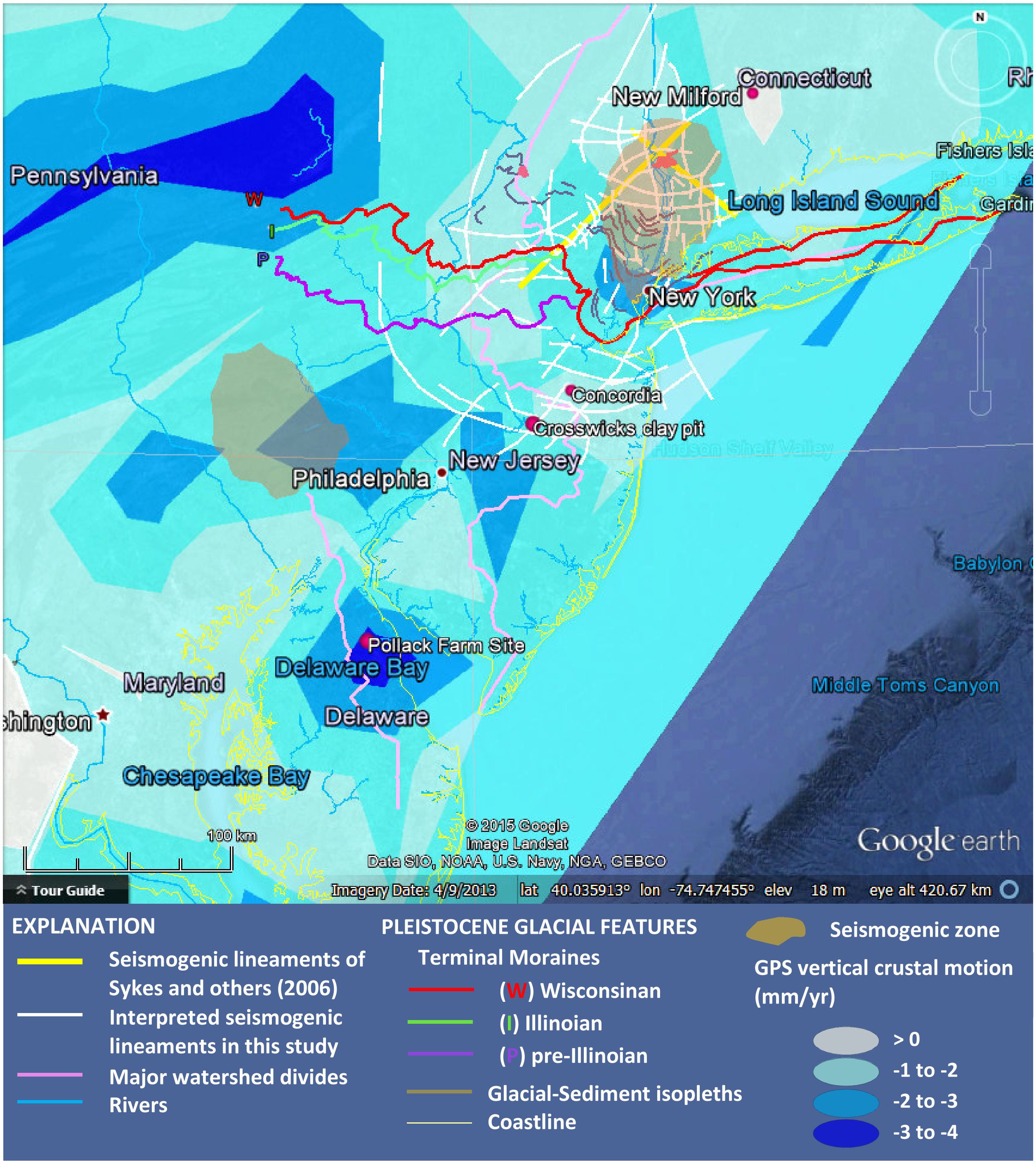


Figure 32. GE map showing interpreted sesimogenic lineaments of Sykes and and others (2006) in relation to others proposed here (white, thick, lines). Also shown are glacial sedimentary lines (see Chapter 1, exrercise 2), the TIN surface of vertical-crustal motion, sesimogenic zones, major watershed divides separating Delaware River and Atlantic drainages (DA), and bisecting the Del-Mar peninsula (DMP) divide (DA). Note the conformance of the TIN velocity break lines wi the interpreted sesimogenic linemanets and zones and their sptial arrangment reltaive to the Cortland Intruive Complex (CIC). Small areas showing positve crustal movemnts in Connecticut (New Milford) and New Jersey (Concordia) are highlighted.

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