Evaluation of John Boyd Thacher State Park
Albany County, New York

For its Merit in Meeting National Significance Criteria as a National Natural Landmark

Representing Cuestas and Hogbacks and Late Silurian – Devonian Periods in the Appalachian Plateau (Bio)Physiographic Province

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View northwest along the 100-foot cliff (Upper Manlius and Coeymans Formations) of the Helderberg Escarpment toward the Mohawk Valley. The broad lowland to the right (northeast) is the Hudson Valley (and glacial Lake Albany). Photo by D. DiQuinzio, National Park Service, September 2014.

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Executive Summary

A day trip to John Boyd Thacher State Park, in Albany County, NY, followed by thorough literary research, describes a remarkable site recommended for recognition as a National Natural Landmark. This site exemplifies the Helderberg Escarpment, a striking example of a cuesta, where a series of cliffs showcases Middle Paleozoic marine sedimentary rocks to form the western boundary of broad lowlands, the Hudson Valley to the east and the Mohawk Valley to the north. Exposure of these various sedimentary rocks and conspicuous fossils therein through the landform, and glaciation of this terrain allows a rich variety of physiographic features and habitats. Climate is humid and temperate, with winter extended by the northeastern facing cliffs. Primarily, then, Thacher park addresses "Cuestas and Hogbacks" and "Late Silurian through Devonian Period" history, two underrepresented themes in the Appalachian Plateaus biophysiographic province. Because Thacher is owned by the state of New York and operated as a park since acquisition in 1914, natural features are responsibly protected, maintained in good condition, and accessible to the public. Such ownership and land use favor recognition as a National Natural Landmark, a designation that would enjoy broad support by park officials and advocates.

Although Thacher does not directly provide fossil evidence to support the most compelling evolutionary themes of the Middle Paleozoic—the rise of vertebrates and the appearance of forests—as a key to understanding the stratigraphy of this interval in North America, the site is unparalleled. And it is a critical interval to understand; the Appalachian Mountains and their surroundings, i.e. most of eastern North America, are composed chiefly of rocks of this age. The 1700-foot stratigraphic section at Thacher exposes 14 different formations over an interval from the Late Ordovician (450 Ma) to the Middle Devonian (388 Ma) and is remarkably complete. These are the Upper Ordovician Schenectady Formation (shale and sandstone), the Upper Silurian Brayman Formation (shale, part of the Bertie Group) and Rondout Formation (dolostone), the uppermost Silurian-Lower Devonian Helderberg Group (with five formations, the Manlius Limestone, Coeymans Limestone, Kalkberg Limestone, New Scotland Shaly Limestone, and Becraft Limestone), the Lower Devonian Tristates Group (with three formations, the Oriskany Sandstone, Esopus Shale and Sandstone, and Schoharie Limestone and Sandstone), and the Middle Devonian Onondaga Formation and Union Springs Formation and Mount Marion Formation (lower part of the Hamilton Group). Although almost 40 million years of Middle Proterozoic history are recorded in Thacher's sediments, two unconformities within these 62 million represented years erase most of the Silurian record (20 m.y.) and introduce a gap in the Lower Devonian section at the Wallbridge Unconformity (3-5 my). Moreover, Thacher's section, its limestones in particular, is rich in invertebrate fossils, and the formations represent a variety of ancient depositional environments and lithologies. The cuesta complements this master section to allow attractive scenic vistas, guides park visitors through the stratigraphy, and creates a diversity of notable ecological environments, especially again, in association with the carbonates. This natural richness has long been recognized: the Helderbergs were critical formative grounds for nineteenth-century geology in North America.

Thacher compares favorably against its contemporaries that would also address themes of "Late Silurian and Devonian earth history", and "Cuestas and hogbacks" within the Appalachian Plateaus. In this (bio)physiographic province, neither of these themes is well represented in recognized National Natural Landmarks (NNL) despite this part of the country's richness in examples. Only one designated NNL site, Fall Brook Gorge (NY), addresses the Middle Paleozoic earth history theme. In Thacher's section of the province (Glaciated Allegheny Plateau) 5 other sites have been proposed: Chenango Valley State Park (NY), Chittenango Falls (NY), Letchworth Gorge (NY), Syracuse Meltwater Channels (NY), and Watkins Glen State Park (NY). World's End State Park (PA), on the Unglaciated Allegheny Plateau, would address the very end of this Middle Paleozoic interval. Thacher's Middle Paleozoic stratigraphy is thicker, captures more time, and is at least as fossil rich as compared to any of these other sites, proposed or established. Like Thacher, one designated NNL site, Buzzardroost Rock-Lynx Prairie-The Wilderness (OH), provides an important example of a cuesta in a critical transitional ecoregion, and a second proposed site, Tug Hill (NY), enhances similar ecological themes on a larger scale.

1 Introduction

1.1 Source of Site Proposal

John Boyd Thacher Park appears as an entry in the Baer et al. (1982) inventory of potential National Natural Landmarks of the Appalachian Plateaus biophysiographic province. In the inventory Thacher is classified under modern landforms (Group 1) as an example of river systems and lakes (Theme 8) and under natural history as addressing the Late Silurian and Devonian periods rise of vertebrates and the first forests (Theme 15). More recently, Chishti (2013) proposed the site as a potential National Natural Landmark as an example of a limestone escarpment with fossil beds within the Appalachian Ranges province, and also mentions Thacher's karst features and its historic stature as a place of geological importance. Here we consider Thacher to primarily address "Late Silurian and Devonian Periods" (Theme 15) and "Cuestas and Hogbacks" (Theme 2). Appropriate secondary themes might be "Sculpture of the Land" (Theme 6) or "Caves and Springs" (Theme 12), for the site's karstic features and "Eastern Deciduous Forests" (Theme 24) for remarkable diversity of ecological environments. See section 4.3 for a discussion of Thacher's theme designation. The site's historical status as a formative place of understanding in the geology of North America is significant, especially in comparison to its contemporaries (Section 10.) Finally, a theme gap analysis (Venti, 2015) supports that Thacher would address underrepresented themes in the Appalachian Plateaus biophysiographic province.

1.2 Evaluators

Dr. Nicholas L. Venti, Postdoctoral Researcher, Massachusetts Geological Survey, University of Massachusetts at Amherst. Dr. Venti is a paleoceanographer and (bio)stratigrapher by training, and works as a project manager and geologist on diverse applied studies that focus on the natural resources and hazards of Massachusetts and southern New England.

Dr. Charles Ver Straeten, Sedimentary Geologist and Curator of Sedimentary Rocks, New York State Museum and Geological Survey. Dr. Ver Straeten is largely focused on the Devonian Period across New York and the eastern U.S. He is an elected member of the International Subcommission on Devonian Stratigraphy and provided expertise for geology and paleontology exhibits at the newly opened (May 2017) John Boyd Thacher State Park Visitors Center.

Sarah C. Osgood, Undergraduate Student Geology Major, University of Massachusetts at Amherst. Ms. Osgood has been an indispensible asset to Massachusetts Geological Survey over the past year in service to a number of projects in various roles. With her versatility, passion, humor, and wit, she has a bright future as a geoscientist.

Alycia L. DiTroia, Master's Student in Geosciences, University of Massachusetts at Amherst. As an undergraduate, Ms. Ditroia served Massachusetts Geological Survey and the Geosciences Department diligently in the laboratory through an ambitious beach characterization study, which she presently pursues in an expanded scope as a graduate student.

1.3 Scope of Evaluation

Consistent with Thacher Park's location, this evaluation's study area is the Appalachian Plateaus biophysiographic province as recognized by the National Park Service. Nine sites selected for comparative analysis would address Thacher's primary themes of "Late Silurian and Devonian Periods" or "Cuestas and Hogbacks" and are found in the northeastern United States. Seven of Thacher's intraprovincial contemporaries occur within the Glaciated Allegheny Plaeau subprovince; two occur in the Unglaciated Allegheny Plateau subprovince. Eight of these contemporaries lie within the Northeast geographic region of the National Natural Landmarks program; one is found in the northern Midwest.

1.4 Preliminary Work and Acknowledgements

This evaluation is substantially improved by a number of individuals. We are grateful to our hosts, who facilitated a thorough and enthusiastic tour of the park on December 11, 2015: Maureen Curry, Park Supervisor; Nancy Engel, Director, Emma Treadwell Thacher Nature Center, John Boyd Thacher State Park; Thom Engel, Northeastern Cave Conservancy; Edward Stander, Structural Geologist, SUNY Cobleskill. Their knowledge and direction provide guidance for an initial site report (Venti, 2016), from which this full site evaluation builds. Local historian Timothy J. Albright, and Julie Lundgren, State Parks Ecologist, New York Natural Heritage Program provided additional materials and commentary incorporated into this report. Similarly, Deborah DiQuinzio, National Parks Service northeast regional National Natural Landmarks Program Coordinator, generously provided instruction, commentary, documents, photographs, and contacts throughout this process and her feedback greatly enriches the report. National Park Service sponsored travel to the field site, the initial site report, and this full evaluation.

2 Characterization of Primary Natural (Geological) Features

2.1 Silurian and Devonian Periods

The Silurian and Devonian Periods together comprise the Middle Paleozoic Era, an interval of earth history characterized by high sea level, expansion of marine invertebrates, reef communities, fishes, and the emergence of the first land plants, insects, and by the end of the Devonian, four-legged animals on land. In early nineteenth century England, the (Upper Paleozoic) Coal Measures were found to occur stratigraphically above a series of sandstones and shales then referred to as the "Old Red Sandstone" (Dunbar, 1949). An English geologist, Roderick Murchison, studying graywackes below the Old Red Sandstone at the England-Wales border in the early 1830s, found distinctive fossils in these rocks and named the sequence Silurian after the Celtic Silures tribe (Murchison, 1839a,b). In 1836, Murchison and a colleague, Adam Sedgwick, began working on a sequence of gray fossiliferous rocks in Devonshire and Cornwall in southwestern England (Dunbar, 1949). There coral fossils intermediate in evolutionary position between those of the Silurian below and the Carboniferous above established the Devonian Period, named after county Devon, which the stratigraphers ultimately recognized as correlative to the Old Red Sandstone (Dunbar, 1949; Dineley, 1984; Stanley, 1999). Unfortunately, the 10,000-12,000-foot-thick Devonshire section of greywacke, slates, and limestones is deformed, so the type section for Europe is located in Germany's Rhine Valley (Dunbar, 1949). New York State's Devonian section, very thick and minimally disturbed, is more useful than both of these and provides the standard for North America (Dunbar, 1949).

Paleogeography in the Middle Paleozoic Era was very different than today. Laurentia (ancient North America) collided with Baltica (ancient Northern Europe) along the equator, and were separated by a shallow sea from ancient Siberia in the northern mid-latitudes (Scotese and Golonka, 1992; Domeier, 2016). The collision between Laurentia (or Laurussia) and Baltica, along with a microcontinent, Avalonia, historically referred to as the Acadian Orogeny, uplifted the Appalachian Mountains of North America, the Caledonide Mountains of Norway, the ranges along eastern Greenland, and the Scottish Highlands (Stanley, 1999; Rast, 1989). These mountains, and the basins that surrounded them, provide excellent records of the interval (e.g. Bayer, 1983; Milici and de Witt, 1988; see Section 3, "Distribution…"). To the south and east of Laurentia and ancient Russia, across the closing Iapetus Ocean, lay Gondwanaland, a supercontinent composed of ancient approximations of the other familiar land masses of the world (Scotese and Golonka, 1992). Gondwana stretched from ancient Northern China in the northern mid-latitudes to ancient South America, in the Antarctic (Scotese and Golonka, 1992). These Antarctic regions, ancient South America and ancient Africa, were periodically glaciated in the Late Devonian (e.g. Daemon and Contreiras, 1971; Caputo and Crowell, 1985; Boucot, 1988; Isaacson et al., 2008). Although convergence of the two major supercontinents caused progressive closure of the inland seaway, Iapetus, at times while the adjacent Rheic Ocean expanded (Domeier, 2016), global ocean circulation via the ancient Pacific, or Panthalassic Ocean, improved (Boucot, 1988).

Climate was generally warm (Frakes, 1992) and sea level generally high (e.g. Hallam, 1992; Haq and Schutter, 2008)—that is, between mass extinctions associated with cooling and drops in sea level during the latest Ordovician (Ghienne et al., 2014) and Late Devonian (Copper, 1986; Stanley, 1988; McGhee, 1989; 1996; Streel et al., 2000; Brezinski et al., 2008). These high sea levels allowed deposition in regional shallow seas throughout the world (Golonka, 2007, 2012), such that middle Paleozoic deposits can be found on every continent (Dineley, 1984; Isaacson et al., 2008; Clack, 2012). Sophisticated numerical models suggest that middle Paleozoic atmospheric oxygen levels were generally somewhat higher than today: as much as about 25%, but dropping to perhaps 13% during the Frasnian-Fammenian (Stages within the Devonian) mass extinction in the Late Devonian (Berner, 2006). A series of black shales from the Middle Devonian through the Devonian-Carboniferous boundary mark marine anoxia (Caplan and Bustin, 1999; Algeo et al., 1995). Referred to as the Hangenberg event, black shale beds at the Devonian-Carboniferous boundary even record low oxygen concentrations in freshwater environments (Marshall et al., 1999), and correspond to high turnover among vertebrate animals (Sallan and Coates, 2010). Oxygen levels did not recover to modern levels until the Late Paleozoic (Berner, 2006). Similarly, atmospheric carbon dioxide concentrations decreased from 0.05% to 0.03% through the middle Paleozoic, due to increased burial of carbon and silicate weathering (Algeo et al., 2001). With improved global ocean circulation, the global temperature gradient generally decreased to cool the low latitudes (Boucot, 1988). The Late Devonian was also a time of particularly high volcanic activity, second only to the Late Triassic (Ronov et al., 1980). Climatic changes of the Middle Paleozoic and their immediate causes, silicate weathering and carbon burial, are consistent with broader patterns of plants expanding into new habitats on land and mountain building during this interval, discussed in greater detail below.

Specificity of regional ecological environments peaked in Early Devonian times, replaced by more cosmopolitan taxa in the Late Devonian as the warmest environments were eliminated from the tropics and marine environments converged in the narrowing Iapetus Ocean (Boucot, 1988; Streel et al., 2000; Briggs and Crowther, 2001). Throughout the bulk of the interval, extensive and complex reefs composed of tabulate and stromatoporoid corals grew well into the mid-latitude ocean, as illustrated in eastern North America (Heckel and Witzke, 1979; Miller and Kent, 1988; Van der Voo, 1988; Stanley, 1999; Scotese, 2001; Copper, 2002). Many invertebrate groups diversified during the Middle Paleozoic Era: articulate brachiopods, bivalve mollusks, graptolites, ammonoids, and eurypterids (Stanley, 1999). Some ammonoids and eurypterids could move quickly through the water and filled ecological roles as predators (Stanley, 1999). In the Devonian, ammonoids evolved from *Bactritida* (Erben, 1960, 1964), a middle-late Paleozoic order of cephalopod intermediate in form between straight-shelled and coiled (e.g. modern nautiloids) forms. Although eurypterids first appear in the Ordovician (Lamsdell et al., 2015), the group reached its greatest diversity in the mid-Paleozoic (Late Silurian-Early Devonian), focused around (sub)tropical seas now preserved in North America and western Europe (Tetlie, 2007). Trilobite diversity, although volatile (Lieberman and Karim, 2010), declined from almost 20 families during the Silurian Period to only a handful by the end of the Devonian Period (Fortey and Owens, 1997). This decline apparently corresponds more closely with extrinsic factors such as climate and sea level versus intrinsic factors such as competition and adaptation (Abe and Lieberman, 2009).

2.1.1 *Vertebrate Evolution*

Vertebrates were represented primarily by fish during the Middle Paleozoic, although four-footed tetrapods crawled onto land by the Middle-Late Devonian Period (Clack, 2012). All major groups of modern fish first appeared during the Middle Paleozoic (Jarvik, 1980; Stanley, 1999). Jawless fish (agnathans) appear in the Early Paleozoic Era (Cambrian Period) and include conodonts (Donoghue and Aldridge, 2001), ostracoderms (both extinct), and the extant hagfish and lamprey groups (Sansom et al., 2001). Ostracoderms (Cope, 1889; now obsolete as a phylogenetic term), a group of jawless fish with armored heads and caudal (tail) fins, some with dorsal and even pectoral fins, are more closely related to gnathostomes (i.e. jawed vertebrates) than to other agnathan groups (Janvier, 2001). Of these, osteostracan, galeaspid, and pituriaspid groups (of ostracoderms) specifically share key similarities with gnathostomes: well-defined pectoral fins attached to an endoskeletal shoulder girdle, sclerotic rings (within the eye), ossified sclera (tough outer-eye covering), and cellular bone in both endo- and exoskeletons (Janvier, 1996, 2001).

In addition to the features of their ostracoderm ancestors listed above, gnathostomes would have also featured muscularized pectoral fins, two dorsal fins, an epicercal tail (upper lobe longer, tapering upward, with skeletal support along the top), and slit-shaped gill openings (Janvier, 1996, 2001). The jaw developed as a modification of frontal gill bars (Zangrel and Williams, 1975; Pough, et al., 2009; Compagnucci et al., 2013), presumably for increased respiratory function (Mallatt, 1996), as the earliest gnathostomes lacked teeth (Mallatt, 1996, Zhu et al., 2013). Nonetheless, occurrence of jaws in vertebrates seemingly corresponds to presence of an adaptive immune system, suggesting that these features evolved closely, arising perhaps to combat localized injuries and infections associated with a predatory lifestyle (Matsunaga and Rahman, 1998; Bleyzac et al., 2005). The earliest definitive fossil gnathostome, *Entelognathus primordilus,* found in a 419-Ma deposit in China, had a bony skeleton and toothless jaw (Zhu et al., 2013). The fossil provides the first example of Class *Placodermi* (McCoy, 1848), a group of extinct fish with jaws and armored heads, on the basis of its dermal skull roof (Zhu et al., 2013).

Placoderms, many of which were predatory (Brett and Walker, 2002), were not only the most successful and diverse group of vertebrate in the Devonian Period (Carr, 1995a; Goujet, 2001); they evolve a number of remarkable features. Although placoderms have been traditionally understood to have evolved crushing plates extending from the jaw bones (e.g. Young, 2003), evidence has recently emerged that at least some members of the group evolved tooth-like structures (e.g., Johanson and Smith, 2005), or even true teeth as recognized by biomineral and organizational signatures (Rücklin et al., 2012). In Order *Antiarchi*, paired pelvic fins (i.e. hind limbs) are revealed by excellent preservation in the Early Devonian (413 Ma) Xitun Formation of Yunnan, China, (Zhu et al., 2012). Their presence in this early-evolved (Young, 2010) placoderm order suggests that hind limbs may have been widespread among the placoderm class (Zhu et al., 2012). Live birth, or viviparity, is first observed in Late Devonian (380 Ma) Australian Gogo Formation fossils of both *Arthrodira* (Long et al., 2009) and *Ptyctodontida* orders (Long et al., 2008), enabled by pelvic claspers (Ahlberg et al., 2009) that would have achieved the necessary internal fertilization. The first superpredator, of the Genus *Dunkleosteus* (Lehman, 1956), also of the placoderm Order *Arthrodira* (Westwood, 1891), appears frequently in Upper Devonian Ohio Shale and its stratigraphic equivalent, the Kettle Point Shale in Ontario (Carr and Hlavin, 2010). *Dunkleosteus terelli'*s jaw would have been the strongest of all fish and one of the most powerful of all animals: a large (6-meter-long, 1000-kilogram) individual might have applied over 4400 Newtons of force at the jaw tip, and over 5300 Newtons at the rear plates (Anderson and Westneat, 2007). Novel evolution of complex jaw mechanics allowed *Dunkleosteus* to rapidly suck in prey the way modern teleost fishes do (e.g., Westneat, 2006) and fragment it prior to ingestion (Miles, 1969).

Other gnathostome groups overtake placoderms following a series of mass extinctions in Late Devonian time (Carr, 1995). Unfortunately phylogenetic relationships between these groups and in relation to placoderms (Miles, 1973; Janvier, 1996; Davis et al., 2012) remain unclear due to lack of specimens (Coates and Sequeira, 2001) from extinct Class *Acanthodii* (Owen, 1846), sometimes referred to as spiny sharks. In contrast to placoderms, acanthodians were covered in scales versus dermal armoring, and had paired fins preceded by spines, but few specimens reveal endoskeletal details (Stanley, 1999; Coates and Sequeira, 2001). Mid-Ordovician and lowest Silurian occurrences of isolated scales attributed to this group would suggest acanthodians as the first gnathostomes (Smith and Sansom, 1997; Stanley, 1999). Morphological characteristics, too, would support that acanthodians represent an ancestral group with respect to extant *Chondrichthyes* (sharks, rays, ratfish) and *Osteichthyes* (bony fish and tetrapods) classes, *Placodermi* being further removed; however a dearth of fossils representing the acanthodian's earliest characters prevents confident conclusions (Davis et al., 2012). Recent discovery of bony-jawed placoderms, however, would suggest that *Osteichthyes* descended from that group (Zhu et al., 2013); *Chondrichthyes*, their own early evolution unclear (Coates and Sequeira, 2001), apparently resemble acanthodians more closely (Davis et al., 2012; Carole et al., 2016).

Chondrichthyes (Huxley, 1880; cartilaginous fish) are jawed vertebrates with a skeleton composed of a prismatic cartilage instead of bones (Moss, 1977), paired, generally non-retractile fins, electroreceptive sensors (Bullock et al., 1974), a spiral membranous fold, or spiral valve, in the intestines (Long and Walford, 2016, and others), and often placoid (tooth-like) scales (Long and Walford, 2016, and others). This Class is the first of the vertebrates to include taxa that survive to today in Order *Chimaeriformes* (Obruchev, 1953). Modern examples are chimaeras (or rat fish, elephant fish, spookfish, rabbit fish) of the subclass *Holocephali*, and Order *Elasmobranchii* (Bonaparte, 1838), i.e. Superorder *Selachimorpha*, the modern sharks, and Superorder *Batoidea* (rays, skates, and sawfish). Characteristic placoid (tooth-like) scales attributed to this group first appear in the fossil record as early as the Upper Silurian or even the Upper Ordovician (Lund and Grogan, 1997). Similarly, genomic molecular analysis of the most primitive Holocephalan, the elephant shark (Venkatesh et al., 2007), suggests this subclass emerged in Late Silurian time (Inoue et al., 2010). Although production of mineralized tissue was apparently more widespread in Paleozoic *Chondrichthyes* than in their modern counterparts, lack of mid-Paleozoic fossils obscures the group's early evolutionary history (Janvier, 1996; Lund and Grogan, 1997). Fossil-based evidence of the Class' emergence and mid-Paleozoic radiation consists strictly of isolated placoid scales until the earliest Devonian (Zangerl, 1981), when associated denticles (scales) first appear (Mader, 1986). Rare Devonian chondrichthyan endoskeletal fossils have been recovered from New Brunswick, Canada (Miller et al., 2003), South Africa (Maisey and Anderson, 2001), Bolivia (Janvier and Suarez-Riglos, 1996; Maisey, 2001), Antarctica and Australia (Young, 1982; Long and Young, 1995) and Germany (Heidtke and Krätschmer, 2001). Upper Paleozoic (Carboniferous and Permian Periods) fossils are more widespread (Schaeffer and Williams, 1977; Zangerl, 1981; Lund and Grogan, 1997; Coates and Sequiera, 2001).

Bony fish (Superclass *Osteichthyes*; Huxley, 1880) yields Class *Actinopterygii* (Klein, 1885; ray finned fish), and Class *Sarcopterygii* (Romer, 1955; lobe-finned fish). *Osteichthyes* generally feature an endoskeleton that incorporates true bone (Romer, 1985; Rafferty, 2008), a swim bladder, and three pairs of gill arches covered by a bony operculum (cover) (Romer, 1985). Although both osteichthyan classes are extant, which evolved first is unclear from earliest specimens (e.g. Janvier, 1978; Zhu and Schultze, 2001). Earliest (Late Silurian and Early Devonian) osteichthyan fossils (*Psarolepsis*) are sarcopterygerian based on the shoulder (Lu and Zhu, 2010; Zhu et al., 2009), but also contain primitive, non-osteichthyan features. Actinopterygians evolved fins supported by dermal bone radiating from the skeleton and are covered in ganoid (thick, non-overlapping) or leptoid (thin, overlapping) scales that grow through the life of the organism (Parenti and Weitzman, 2016, and others). Most (96%; Nelson, 2006) of modern fish belong to Infraclass *Teleostei* (Müller, 1845), a group of actinopterygians with intermuscular bones, and a heart with two arterial valves, but without muscles in the ventral aorta, though difficulty in applying these characteristics to fossils complicates their taxonomic assignment (Arratia, 2015). Many teleosts can protrude their jaws from their mouths, some in stunning examples of cranial kinesis (e.g. Westneat, 2006). Sarcopterygerians, e.g. lungfish, coelecanth, are recognized by their fleshy fins, pelvic and pectoral fins articulated like tetrapod limbs, and teeth with enamel (Romer, 1955; Nelson, 2006). Early taxa (e.g., Lu and Zhu, 2009; Zhu et al., 2009) were covered in complex cosmoid (Kardong, 1998) scales made of lamellar and vascular bone, keratin, and cosmoid bone, a material unique to this group (Meinke, 1984), but modern representatives have adopted elasmoid (heavily mineralized, overlapping) scales (e.g. Nelson, 2006).

From one group of sarcopterygians, the *Tetrapodomorpha* (Ahlberg, 1991a), the four-legged tetrapods would emerge (Ahlberg and Johanson, 1998). Tetrapods would have had limbs with digits, and would have been ultimately able to walk on land (Clack, 2012). Evolving a four-legged terrestrial animal from a fish required sweeping morphological changes. In tetrapodomorphs, in addition to expansion of lungs and devotion of skeletal muscles and support systems for air breathing, some bones in the back of the skull were replaced with muscles to produce a neck, the shoulder and pelvic girdles were reinforced to bear weight on strengthened limbs, and much of the dermal armoring was shed (Clack, 2012). As first observed in *Kenichthys* in the Early Devonian of China (Zhu and Ahlberg, 2004), Tetrapodomorphs, all aquatic, develop a choana, an excurrent nostril that appears as a hole in the roof of the mouth (Clack, 2012). The group also develops second paired radials in the limbs, homologous to the radius and ulna in the forelimbs and tibia and fibula in the hind limbs (Clack, 2012). This feature first appears in the basal group of tetrapodomorphs, the rhizodonts (e.g. Gregory, 1915, 1935; Davis et al., 2004), but becomes exemplified in the genus *Eusthenopteron* (Jarvik, 1980). Another tetrapodomorph, the genus *Livoniana*, recovered from the Frasnian (Late Devonian) of the Baltic region shows tetrapod-like features in an otherwise unusually specialized jaw, suggesting that this was a period of evolutionary radiation (Ahlberg et al., 2000).

Of the tetrapodomorphs, the *Elpistostegalia* (Genera *Panderichthys*, *Elpistostege*, and *Tiktaalik*; Ahlberg et al., 2000) fish are most closely related to tetrapods. Though no complete individuals have been recovered, the skull of *Elpistostege* features a tetrapod-like elongated snout and closely spaced eyes atop the head (Westoll, 1938; Schultze and Arsenault, 1985). *Panderichthys*, a substantial (1 meter long) fish, is better known, particularly from Baltic Frasnian deposits. Its skull featured a large spiracular chamber, where the middle ear would evolve (Brazeau and Ahlberg, 2006), and its *Elpistostege*-like eyes were set behind a brow (Vorobyeva and Schultze, 1991). *Tiktaalik* is known from a Late Devonian deposit in Arctic Canada (Daeschler et al., 2006). In addition to greater elongation of its snout versus other elpistostegalians, *Tiktaalik* had an early neck, having lost the extrascapular bones that join the head and shoulders in fish, as well as a functional wrist (Daeschler et al., 2006; Shubin et al., 2006).

Tetrapods, the four-footed vertebrates, a monophyletic group, first appear in the Middle-Late Devonian (Clack, 2012). That is, body fossils of near-tetrapod (tetrapodomorph) fish and primitive tetrapods support the emergence of tetrapods in the Late Devonian (Clack, 1997), but a recently described Middle-Late Devonian trackway would advance that evolutionary narrative some 18 m.y. (Niedzwiedzki et al., 2010). The earliest tetrapod body fossils, *Obruchevichthys* of the Baltic (Ahlberg, 1991b) and *Elginerpeton* of Scotland (Ahlberg, 1991b; 1995) are late Frasnian (Late Devonian) in age. Limb construction in *Elginerpeton* would suggest that these earliest tetrapods were fully aquatic (Ahlberg, 1998). The earliest unequivocal tetrapod trackways are described from Poland and confidently dated to ~395 Ma (early Eifelian stage in the Middle Devonian) (Niedzwiedzki et al., 2010). The trackways imply an unexpectedly large animal relative to mid-Devonian sarcopterygians (Clack, 2012). The depositional environment, nearshore and lagoonal, would have supported vegetation to shelter the animals (Clack, 2012). Younger (probably Frasnian, i.e. Late Devonian) tetrapod trackways are described from the Genoa River of Australia (Warren and Wakefield, 1972) and the Valentia Shale Formation (Stössel, 1995) of West Ireland, Middle-Late Devonian in age (Williams et al., 1997; Clack, 2012). Furrows between the tracks suggest that these tetrapods' bodies dragged along the bottom in shallow water (Clack, 1997).

By the Late Devonian (Fammenian Stage), tetrapods achieved global distribution, spreading from Laurussia throughout Gondwana (Ahlberg et al., 2008). This early cosmopolitan distribution is consistent with a lifestyle that included a marine component (Thompson, 1980). But early tetrapods are associated with a variety of aquatic environments: marine (Lebedev and Clack, 1993), estuarine (Daeschler et al., 2006), marginal marine (Kurss, 1992; Luksevics and Zupins, 2004), and freshwater (Daeschler et al., 1994; Olsen and Larsen; Olsen, 1993; Larsen et al., 2008). Their occurrence in such varied aquatic environments suggests that tetrapods evolved to better exploit an aquatic environment and capitalize on the terrestrial realm (Clack, 2012), rather than by necessity in response to a drying climate as initially implied by the ubiquity of red sandstones of the period (e.g. Barrell, 1916; Lull, 1918) and proposed historically (Romer 1933, 1945, 1958). Three major developments remain mysterious: origin of limbs with digits, origin of walking, and origin of origin of terrestriality (Clack, 2012). In addition to Clack (2012), origins of tetrapod evolution are discussed by Thompson (1991, 1993), Daeschler and Shubin (1995), Clack (2005, 2006, 2007, 2009), and Coates et al. (2008).

2.1.2 *Plant Evolution*

Without a vegetated habitat, terrestrial environments would have offered little to tetrapods (Clack, 2012). On land, spores and cuticles resembling those of *bryophytes* provide evidence of early plants from the Ordovician (some 460 Ma) through the Silurian and into the Early Devonian (Edwards and Selden, 1993; Edwards and Wellman, 2001 and references therein). Beginning in the Silurian (some 430 Ma) *cryptospores*—spore-like structures thought to be the originators of non-vascular plants—decreased in diversity as *trilete* spores (spores that divide via meiosis, form a tetrad of cells, and are considered the originators of vascular plants), increased (Holland, 2015, and others; Gensel, 2008 and references therein). Both *cryptospores* and *trilete* spores, due to their size, gross morphology and wall structure, are believed to be direct ancestors of land plants (Holland, 2015, and others). In North America, *trilete* spores are known from as early as the Middle Cambrian Rogersville Shale from Tennessee, (Strother, 2000).

In Late Silurian (some 425 Ma) meso-fossils, *cryptospores* are found in-situ—that is, intact within the larger plant body—and connected to *rhyniophytes*, also referred to as *rhyniophytoids* (a leafless and rootless spore-bearing vascular plant) (Gensel, 2008). *Rhyniophytes* found within the Rhynie Chert of eastern Canada are the oldest known wetland biota preserved in-situ from the early Devonian (Tomescu and Rothwell, 2006). For these types of plants, the Rhynie Chert fails to provide evidence of any rooting sytems, or buried axes within the soils, (Gensel, 2001). The fossils provide insight into the Rhynie Chert as a wetland area in a hydrothermal basin with several habitats that include floodplains, ponds, lakes, and marsh-like areas. This same habitat is comparable to that of a Middle Devonian site, Gilboa, in New York State (Shear et al. 1984; Shear and Selden, 2001) (see Section 3, "Distribution…"). Close relatives to the modern crustaceans, called *Triops*, (the tadpole shrimp) and *Artemia*, the brine shrimp, are seen throughout the Rhynie, (Engel and Grimaldi, 2004). *Trilete* spores evolved from the *cryptospore* in the Late Silurian to Early Devonian and occur in *Cooksonia* species (the oldest known plant to have a stem), *rhyniophytoid taxa*, and other vascular plants (Gensel, 2008).

The *cooksonia* species provide a new perspective on the early stages of land colonization by complex organisms. Considered a "taxonomic wastebasket" or taxon whose only purpose is to classify organisms that do not fit anywhere else (Prothero, 2015), *Cooksonia,* a polysporangiophyte or plants with branches that terminate as spores, occurs within embryophyte macrofossils of the upper Wenlock Series in the Devilsbit Mountain district of County Tipperary, Ireland, in the middle Silurian (some 415 Ma) (Edwards & Feehan, 1980). The major expansion of these plants occurred in the Late Silurian. On Bathurst Island in the Canadian Arctic Archipelago, the lower Bathurst Island Beds contain the oldest fertile vascular plants of the North American continent (Basinger et al. 1996). The sporangium resembles that of *Cooksonia caledonica* in shape, but is much closer to *Zosterophyllum* (potential ancestor to Lycopsids) and is more complex than contemporary *Cooksonia* (Gensel, 2001). *Zosterophyllum* or *zosterophylls,* although abundant throughout the Palaeozoic, were not frequently seen in New York State (Edwards and Richardson, 2005). In southern Bolivia (Morel et al. 1995; Toro et al. 1997), three well-preserved specimens of *Cooksonia* were found in the Kirusillas Formation at Tarija, (Gensel, 2001). During its peak in abundance, the *Cooksonia* species correlates throughout the rock formations all the way to Vietnam (Janvier et al. 1987).

In addition to micro- and meso-fossils, small primitive plant megafossils appear throughout the Paleozoic (Edwards and Selden, 1993; Edwards Wellman, 2001 and references therein). *Lycopsids*, a group of primitive rooting vascular spore plants with a single vein per leaf, first appear in the Early Silurian, some 425 Ma (Rickards, 2000). Primitive horsetails, *Hyenia* and *Calamophyston*, have been found in Middle Devonian deposits (Edwards and Wellman, 2001). These horsetails are considered to be primitive spore-bearing plants. The evolutionary development of ferns is not exact. However the earliest ferns that have been identified are Late Devonian and related to the *zygopterid* ferns, as well as Fammennian (Late Devonian Stage) species of *Rhacophyston* (Edwards and Wellman, 2001 and references therein). *Rhacophyston* commonly grew in peaty swamps (Clack, 2012). They were capable of withstanding marshy wetland habitats (Greb et al. 2006). *Lycophytes* (club mosses), a contemporary, reached upwards of 36 meters, and are considered the largest land plants of the world at that point in time. In the Late Devonian, adjacent to horsetails and ferns, the first large trees and forests began to form (Prothero, 2006).

These forests that were slowly growing in size occurred in wet places, and even thought to be thick enough to house different habitats within them, (DiMichele and Hook, 1992). The majority of the plants growing during this time were in need of water and therefore inhabited areas along the coastlines, or in areas where flooding would occur (Hotton et al. 2001). Within these environments during the Middle Devonian, a variety of arthropods were living in the plant life. They included millipede-like arthropleurids, centipedes, scorpions, pseudoscorpions, mites, and large trigonotarbids (extinct, prehistoric arachnids) (Rolfe, 1980). Throughout much of the Middle Paleozoic, warm climate supported high plant diversity, widespread throughout wetland areas of the world (Streel et al., 2000, and references therein). During this interval a broad tropical region was inhabited exclusively by equatorial vegetation (Streel et al., 2000, and references therein). After an optimum in the Latest Frasnian, plant diversity decreased as cooler climates periodically restricted vegetation from the antarctic and cold-tolerant species inhabited tropical regions (Streel et al. 2000, and references therein).

With changes in climate during the Middle and Late Devonian, drier weather made way for taller and bushier plants and the beginning of progymnosperms, plants ancentral to gymnosperms, but still spore-bearing (Clack, 2012). Early Devonian (Pragian Stage) assemblages, as evidenced by the Posogchong flora from China, illustrate advancement in taxa and increased phylogenetic diversity of vascular plants (Shougang and Jinzhuang, 2013). With the basic development of ferns, progymnosperms, the beginning of the diversification of seed plants can be seen (Beck, 1960). This taxonomic connection is illustrated through a fossil specimen that shared characteristics between the wood of *Callixylon* and the leafy branch system of *Archaeopteris*, considered the first “true” tree (Beck, 1960). Hydrasperms or “lyginospterids,” are also considered pre-seed bearing plants that were likely to form into seed bearing plants. These progynosperms were thought to retain spore-like pollen with proximal germination (Crane et al., 2004). By the end of the Devonian, the landscape became more diverse, with both wetter and drier climates supporting vegetation (Algeo et al. 1995; Algeo et al. 2001; Algeo and Scheckler 1998).

2.2 Cuestas (and Hogbacks)

A cuesta is a type of asymmetrical hill with one gradually sloping side and one steeply sloping side, or escarpment, that form a distinctively shaped ridge (National Park Service, 1990; Cuesta, 2016). This simple definition describes only a topographic form without structural implications, as endorsed by Veatch (1906). However, a structural component is commonly included in the definition (Howell, 1957) “A cuesta is a structural plain, so tilted that it has a perceptibly sloping surface” (Hill, 1896). In also referring to dip-slopes and strata, the National Park Service definition (National Park Service, 1990) would agree with the inclusion of a structural component. Cuestas differ from hogbacks and homoclinal ridges (characterized by strata dipping in the same direction) simply by the angle of their dip slopes, cuestas being more asymmetrical with a gently angled dip slope (Cotton, 1885).

Cuestas form after the angled uplift of layered strata and subsequent erosion of these layers into an asymmetrical ridge. The ridge is capped by the most resistant strata which also forms the back of the gently sloping side. The strata that once overlaid this capstone have become eroded sediment that fill the valleys to either side (Goudie, 2013). But not too much sediment, or else the cuesta would not be expressed as a landform. For example, where sandstones provide resistant caprocks, the resulting sliprock (i.e. bedrock) slopes are weathering-limited such that loose debris is removed faster than it is produced (Carson and Kirkby, 1972). Although weathering of resistant caprocks may form sliprock surfaces or weathering pits, undercutting of the resistant caprock by sapping of weaker underlying lithologies is the dominant erosion mechanism and the cuesta profile is cut laterally (Howard, 1970, Howard and Kochel, 1988). (Even where layered rocks are covered in sediment, continuity between contacts of eroding layered rocks can explain the development of stair-step patterns in bedrock-controlled drainages (i.e. watersheds) (Perne et al., 2017), as in the Midwestern United States (see Section 3, "Distribution…").) As the dip angle of stratified (layered) rocks approaches horizontal, increasing volumes of rock must be eroded and transported away to maintain the cuesta landform (Howard and Kochel, 1988). Especially in very shallowly dipping rocks, promontories develop between drainages, but in these places surface area exposure increases to accelerate weathering and thus reduces the profiles of these feratures (Lange, 1959, Howard and Kochel, 1988). Finally, the structural features responsible for cuestas need not be layered rocks alone: faults and fractures can also enhance topography through weathering to form cuestas (Doelling, 1985; Howard and Kochel, 1988). For example, extension (pulling apart) created a persistent horst-and-graben (down-dropped blocks between relatively elevated ones) topography in the Needles section of Canyonlands National Park (McGill and Stromquist, 1975).

3 Distribution of Primary Natural (Geological) Features

3.1 Silurian and Devonian Periods

Middle Paleozoic deposits can be found on every continent (Dineley, 1984; Cloutier and Lelievre, 1998; Isaacson et al., 2008; Clack, 2012). High sea levels afforded deposition in regional shallow seas throughout the world (Golonka, 2007, 2012). Gogo, for example, in northern Western Australia, was a tropical reef in Devonian times, and has yielded many important fish fossils (Long, 2006). Spectacular invertebrate fossils: trilobites (Fortey and Chatterton, 2003; Klug et al., 2009), cephalopods (Töneböhn, 1991; Klug et al., 2008) and arthropods (Alberti, 1969; 1982) have been recovered from Morocco, formerly a subtropical (Golonka, 2012) shallow marine environment. Miguasha, or Escuminac Bay in eastern Canada, preserves a Devonian coastal brackish to marine environment. Its fossils have provided so much insight into near-tetrapod elpisostegalian fish and their contemporaries (Schultze and Cloutier, 1996; Cloutier, 1996) that it has been designated a World Heritage Center (http://whc.unesco.org/en/list/686). Carbonate platform deposits of this interval are widespread in the northern continents, at that time in (sub)tropical paleopositions (Wilson, 1975; Heckel and Witzke, 1979; Dineley, 1984), with notable examples found in northwest Australia (Playford and Lowry, 1966), southern Morocco (Burchette, 1981), northern Alberta, Canada, the eastern United States, theArdene-Eifel area in Germany, Belgium (Tsien, 1977, 1979), Siberia in Russia, and Pakistan (Stauffer, 1968). In South America, the Paraná basin records the middle Paleozoic antarctic (Lange and Petri, 1967; Daemon et al., 1967; Zalan et al., 1987), a distinctly cooler biotic realm (Boucot, 1988, and references therein). This region, dominated by burrowing bivalves, was largely unaffected by the Late Devonian Frasnian-Famennian extinction (Boucot, 1988; Stanley, 1999).

The mountains that formed during the Acadian Orogeny, an episode of tectonic collision between Laurentia and Avalonia during the mid Paleozoic, and the basins that surrounded them, provide excellent records of the interval in their sediments (Allen and Friend, 1968; Ziegler, 1981; Bayer, 1983; Ettensohn, 1985; Faill, 1985; Milici and de Witt, 1988; Cloutier and Lelièvre, 1998; Ver Straeten, 2010). In North America sediments shed from the Acadian Orogeny fill the Catskill Delta to form the Appalachian Plateau (Woodrow and Sevon, 1985). In northern Europe, although corresponding large-scale deposition of Caledonide material in the North Sea did not occur until the Late Paleozoic (Zeigler, 1981; Soper et al., 1987), the Silurian and Devonian Old Red Sandstone fills three major basins in Great Britain (Barclay et al., 2005). The Orcadian Basin (Orkneys, Shetlands, northern Scotland) contains excellent lacustrine (lake) deposits with fish fossils (Dineley and Metcalf, 1999). In Midland Valley

(Scotland) conglomerates and finer sediments were deposited in a number of discrete sub-basins and preserve important primitive plant fossils (Cleal and Thomas, 1995). The Anglo-Welsh basin (South Wales) provides early fish and vascular (veined) plant fossils (Cleal and Thomas, 1995; Dineley and Metcalf, 1999). Similarly, Early Devonian tectonic activity in ancient South China (Wang et al., 1990; Rong et al., 2003; Liao and Ruan, 2003) allowed the 2000-meter-thick Cuifengshan series (Xing-xue and Chong-yang, 1978) in Yunnan, China. The various (sub)tropical marine facies of the depositional series includes the Xitun Formation and yields key fish (e.g. Zhu et al., 2001, 2012) and primitive plant (e.g. Yang and Li, 2009; Xue, 2009, 2012; Hao and Xue, 2013) fossils, as well as various invertebrates. As Dineley (1984) discusses, additional notable deep-water deposits of this interval around the world include basins in central Europe (Krebs, 1979), the Pyrenees (Tucker, 1974), the North America Rocky Mountain region (Churkin, 1974), the Canadian Arctic (Kerr, 1982), the Ural Mountains between Europe and Asia (Brievel et al., 1968; Read and Watson, 1975), Central Asia (Zonenshain, 1973), in far eastern Russia and Alaska, over much of South America, South Africa, and in eastern Australia (Cas et al., 1981).

The eastern United States offers excellent Middle Paleozoic deposits, too. Minimally disturbed Silurian and Devonian marine sedimentary rocks surround Michigan Basin (Fisher et al., 1988 and references therein) and Illinois Basin (Collison et al., 1988 and references therein), and outcrop in northeastern Iowa (Bayer, 1983). In this part of the country extensive stromatoporoid-tabulate reefs colonized the ancient shelf of Laurentia, the ring around Michigan Basin a barrier complex (Ingels, 1963; Mesolella, 1978; Whiteley et al., 2002). To the southeast, a deepening marine basin was centered in southeastern New York and northeastern Pennsylvania (Barrell, 1913; Woodrow and Sevon, 1985). Sediments shed from the uplifted areas to the east filled the Catskill Delta (Woodrow and Sevon, 1985) to comprise the modern Appalachian Plateau from central Kentucky to the Mohawk River Valley in central New York (Milici and de Witt, 1988 and references therein). At its center in northeastern Pennsylvania, these sediments approach 10,000 feet in thickness (Barrell, 1913). In New England, the roots of the Acadian mountains are highly deformed metamorphosed sedimentary and igneous rocks of this age and older from small terranes and island arcs (small land masses) sandwiched between the northeastern Appalachians and the Avalon Terrane (along the coast) during the Taconian and Acadian orogenies (Zen et al., 1983; Ostberg, 1985; Rast, 1989; Lyons et al., 1997). Less severely deformed Middle Paleozoic sequences were folded and thrusted into the Valley and Ridge Province in the Central and Southern Appalachians from central Alabama to central Pennsylvania, largely during the Late Paleozoic Alleghanian Orogeny (Rast, 1989, and references therein).

The smaller and more widespread and abundant invertebrates generally make the best chronostratigraphic indicators. During this interval, graptolites, chitinozoans (Paleozoic marine microfossils of unknown taxonomic affinity), and brachiopods, in particular, provide primary means to date and correlate relative ages of Middle Paleozoic deposits. Ammonoids, where available, provide excellent means to correlate across space and time due to their rapid evolution and broad geographic distribution (Becker and Kullman, 1996). In the Silurian, nearshore environments (preserved in the United States) were dominated by brachiopods of the genus *Lingula* with lesser amounts of various bivalve mollusks and brachiopods of the order *Rhynchonellida*; continental shelves by the brachiopods of the genus *Eocoelia* followed by brachiopods of the orders *Strophomenida* and *Orthida* and trilobites and crinoids; deeper offshore environments by brachiopods of the genus *Pentamerus* and family *Atrypidae* with lesser amounts of gastropods, bivalves, and brachiopods of the superfamily *Orthacea* (Ziegler, 1965; Zeigler et al., 1968; Bretsky, 1969). In the Devonian, bivalve mollusks and the brachiopod genus *Camarotoechia* (of the order *Rhynchonellida*) dominate an assemblage in the near-shore marine environment that is again supported by lesser amounts of various *Rhynchonellids* (Copper, 1966), with bivalve mollusks of the genus *Cypricardella* prominent during the Late Devonian (Sutton et al., 1966; Bretsky, 1969). Dominant members of Early Devonian continental shelf assemblages, brachiopods of the order *Strophomenida* (Copper, 1966), with lesser *Orthida*, trilobites and crinoids (Bretsky, 1969) were overtaken in the Late Devonian by brachiopods of orders *Orthida* and *Productida* (Sutton et al., 1966). Farther offshore the *Atrypid*- and *Pentamerid*-dominated assemblages of the Silurian continued through the Early Devonian (Copper, 1966), but the Late Devonian saw bryozoans joining *Atrypid* brachiopods as most prolific.

The Catskill Delta yields not only a master stratigraphic section for the Devonian of North America, but impressive fossils that illustrate evolutionary trajectories of the high-profile vertebrate group (Linsley, 1994; Cloutier and Lelievre, 1998; Whiteley et al., 2002) and vegetated terrestrial environments (Sevon, 1985; Banks et al., 1985). For example, the Upper Devonian Cleveland Shale represents a relatively deep platform during that time (Ehlers et al., 1951; Collison et al., 1988) that hosts 40 species of vertebrates (Hlavin, 1973; Williams, 1990; Cloutier and Lelievre, 1998), and also yields brachiopods, bivalves, gastropods, cephalopods, crinoids, and eurypterids (Hlavin, 1976). Its placoderm fossils are particularly impressive (Carr, 1991; 1994; 1995b; 1996), and account for over half of the vertebrate species (Cloutier and Lelievre, 1998). Tetrapod fossils are described from the Upper Devonian (Famennian Stage) Catskill Formation in northern central Pennsylvania (Daeschler et al., 1994) and at Red Hill, also in this area of the state (Daeschler and Cressler, 1997, Murphy, 2006). Gilboa, in eastern New York, preserves a complex Middle Devonian forest ecosystem (Goldring, 1924, 1927; Banks et al., 1985; Stein et al., 2012) and its invertebrates (Shear et al., 1984; Shear and Selden, 2001). Red Hill, at the top of the Devonian section, preserves a spectacularly diverse terrestrial ecosystem, with 13 species of vertebrates, tetrapods among them, arthropods, and a complex forest ecosystem (Daeschler and Cressler, 1997, Murphy, 2006). Other locations in this Catskill coastal plain of eastern New York notable for plant fossils include the base of Brown Mountain along Schoharie Creek, a quarry in Cairo, South Mountain at the Schoharie-Greene County line, a Pond Eddy quarry, and Cannonsville Reservoir (Banks et al., 1985).

New York State alone hosts a number of remarkable Middle Paleozoic fossil beds and localities (Whiteley et al., 2002). After a final early Silurian tectophase (episode of mountain building) of the Taconic Orogeny produced a wedge of clastic sediment collectively referred to as the Queenston Delta (Ettensohn and Brett, 1998), Silurian sediments across New York are primarily dolostones deposited originally as limestones on a stable continental platform (Whiteley et al., 2002). The middle Silurian Maplewood Shale of the Lower Clinton Group contains abundant microfossils: acritarchs (diverse, unrelated, ancient microfossils), algal resting cysts, and early plant spores (Whiteley et al., 2002). Within reef mounds in Niagara County at the upper boundary of the Irondequoit Limestone (also middle Silurian), pockets of greenish shale yield abundant trilobite fossils: large genera *Bumastus*, *Illaenoides*, and *Diacalymene*, as well as *Cheirurus* sp. and *Scutellum rochesterense* (Whiteley et al, 2002). Perhaps the most notable Silurian unit in North America with respect to its fossils is the Rochester Shale, which outcrops in western New York (Whiteley et al., 2002). More than 200 invertebrate species have been recovered from this unit, including 80 bryozoan species and 20 trilobite species (Whiteley et al., 2002). One particular clay-rich dolostone bed near the base of the Goat Island Formation in western New York yields well-preserved soft-bodied organisms: algae, worms, and graptolites (LoDuca, 1995; Whiteley et al., 2002). A bed in the upper portion of this unit contains chert nodules that beautifully preserve sponge spicules, brachiopods, and trilobites in Niagara County and near Ancaster, Ontario (Whiteley et al., 2002). The Upper Silurian Vernon Formation contains dolostone beds that yield jawless armored fish (Whiteley et al., 2002). The Bertie Dolostone (Upper Silurian) contains extraordinary eurypterids—the state fossil of New York is a eurypterid, *Eurypterus remipes*—along with some of the oldest examples of plant macrofossils (Whiteley et al., 2002).

Devonian deposits in New York begin with the Helderberg Group in eastern New York. In the skeletal Coeymans Limestone are abundant fossils: crinoids, ossicles, various brachiopods, corals, the cystoid *Lepocrinites* (Goldring, 1933; Whiteley et al., 2002). The Port Jervis Formation, the highest formation of the group, outcrops near the border with New Jersey where a locality known as “Trilobite Mountain” yields an abundance of *Phalangeocephalus dentatus* and other trilobite fossils (Whiteley et al., 2002). The Early Devonian Glenerie Limestone of the Tristates Group preserves an abundance of diverse assemblages of brachiopods, snails, and trilobites in eastern New York (Whiteley et al., 2002). Higher in the Tristates Group, the basal contact of the Schoharie (Carlisle Center Member) Sandstone on the Esopus

Shale preserves trace fossils including *Cruziana*, V-shaped scratch marks attributed to trilobite furrowing, exposed at cuts along U.S. Route 20 near Cherry Valley in Otsego County (Miller and Rehmer, 1979; Whiteley et al., 2002). At the top of the Early Devonian section, exquisitely preserved brachiopods, cephalopods, corals, and trilobites weather out of the former Rickard Hill member (now only a facies; Ver Straeten and Brett, 2006) of the Schoharie Formation in Schoharie Valley and near Albany (Goldring, 1943; Whiteley et al., 2002).

At the base of the Middle Devonian section, the Edgecliff Member of the Onondaga Formation is coral rich with small- to medium-scale reefs and solitary rugose corals and abundant crinoids; shaly beds interfingering this limestone have yielded spectacular trilobites (Whiteley et al., 2002). Above the Edgecliff lies the Nedrow Member, rich in solitary rugose and tabulate corals, brachiopods and trilobites (Whiteley et al., 2002). At the top of the Onondaga Limestone in central and western New York, abundant fish teeth and bones mark the Seneca Member (Whiteley et al., 2002). Above the Onondaga, the Hamilton Group's rich fossil assemblages have been studied since the time of James Hall (mid 1800s) (Whiteley et al., 2002). Unusual brachiopods, trilobites, crinoids, and other invertebrates of warm-water affinity dominate the Stony Hollow Member of the Union Springs Formation (Whiteley et al., 2002). The Cherry Valley Limestone in central New York, composed of styliolinids, small, conical pelagic (far from shore and the bottom) organisms, and cephalopods, also hosts abundant early goniatitic ammonoids (Whiteley et al., 2002). A thin shale and limestone bed in the overlying Oatka Creek (Chittenango) shale hosts a rich and diverse fauna across the state, referred to as the Halihan Hill bed (Griffing and Ver Straeten, 1991; Whiteley et al., 2002). Its coral-rich assemblage in the Hudson Valley region is replaced westward by a diverse fauna of brachiopods, bryozoans, bivalves, and others (Griffing and Ver Straeten, 1991; Whiteley et al., 2002). Wood scraps are found in the Chittenango Shale Member of the Oatka Creek Formation (Whiteley et al., 2002), while Gilboa, in eastern New York, preserves a Middle Devonian forest (Goldring, 1924, 1927; Banks et al., 1985; Stein et al., 2012) and its invertebrates (Shear et al., 1984; Shear and Selden, 2001). Higher up in the Oatka Creek Formation, exceptional brachiopods and mollusks are preserved in the Bridgeport Member, the Solsville Sandstone, and the Pecksport Shale (Whiteley et al., 2002). Above the Marcellus subgroup, diverse faunas reappear in central and western New York in the Skaneateles Formation, with more trilobites than the Halihan Hill bed (Whiteley et al., 2002). Within the Ludlowville Formation, the Wanakah Member gray shales host exceptional fossil richness: in western New York over 200 species of corals, brachiopods, bryozoans, crinoids, trilobites, etc. are reported (Whiteley et al., 2002). Amadeus Grabau (1898-1899) refers to muddy limestone beds therein as the "trilobite beds" (Whiteley et al., 2002). The Jaycox Member, at the top of the Ludlowville in western New York, hosts a notably diverse fossil assemblage: over 100 species of brachiopods, bryozoans, crinoids, mollusks, and trilobites (Whiteley et al., 2002). At the top of the Hamilton Group is the Moscow Formation, a widespread skeletal limestone at its base composed of crinoids and favositid (tabulate) and rugose corals (Whiteley et al., 2002). In western New York, the Menteth Limestone (of the Moscow) hosts silicified (preserved in silica precipitate) fossils that include organisms in early growth stages (Beecher, 1893) and the lower Moscow yields many of the largest trilobite specimens (Whiteley et al., 2002). The Kashong Shale, the member just above the Menteth Limestone, hosts abundant trace fossils as well as exceptionally well-preserved brachiopod bivalve, crinoid, bryozoans, and trilobite fossils (Whiteley et al., 2002). The Restof beds, within this member, yield prolific crinoids, blastoids (Paleozoic stemmed echinoderms that look like hickory nuts), and trilobites (Whiteley et al., 2002). At the top of the Hamilton Group, the Windham Shale contains a number of fossil-rich beds at regular intervals that illustrate the general high diversity of the Hamilton Group (Whiteley et al., 2002).

Up to 2 km of Upper Devonian strata outcrop in the southern tier of New York State, deposited during an interval of deepening of the Appalachian Basin. (Isachsen et al., 2000; Whiteley et al., 2002). Due to dysoxic (oxygen-deficient) or anoxic conditions, the basal Geneseo Shale hosts few fossils, though driftwood fragments, the ammonoid predecessor goniatites, nautiloids, and conodonts are common in some intervals (Whiteley et al., 2002). Moreover, an extinction in the latest Middle Devonian had decimated trilobite and rugose coral populations (Whiteley et al., 2002). Catskill Delta sediments build a thick sandy and silty section through the Frasnian Stage in the Sonyea and West Falls Groups (Whiteley et al., 2002). These are also generally poor in fossils, although some silty beds contain coquinas (shelly hash) of brachiopods and bivalves (Whiteley et al., 2002). In the Late Devonian, the basin depocenter shifts southward (Sevon and Woodrow, 1985; Whiteley et al., 2002), and though an uppermost Devonian (Famennian) section is preserved in southwestern New York and Pennsylvania, much of the Famennian section is eroded from the south-central portion of the state (Rickard, 1975). Finally, non-marine facies preserved in eastern New York, deposited along a Catskill coastal plain during the Middle and Late Devonian, provide insight into terrestrial environments (Sevon, 1985), such as the forest at Gilboa.

3.2 Cuestas (and Hogbacks)

Noteworthy cuestas around the world include landforms in the UK, United States and France. The United Kingdom's famous cuestas are composed of Jurassic and Cretaceous marine sediments. The Cretaceous White Horse Hills of Wiltshire, known for the historical carving of a horse into the side of the hills, are also an exemplary set of chalk cuestas traversed by a trail system and visible to the public (Wiltshire, 2016). The Cotswold Hills are a much larger set of cuestas, spanning 60 miles from the Dorset coast to Yorkshire coast (Gloucestershire, 2016), and therefore represent the vast stratigraphy of the Jurassic period. The Burgundy region of France lends itself to good wine production due to the high proportions of calcium carbonate that compose the soil there - eroded from surrounding Jurassic limestone scarps (Guyett, 2013). The escarpments of Côte d'Or were formed during thrusting events of the Alpine Orogeny, resulting in a 30° dip slope angle (Guyett, 2013).

In North America, many noteworthy cuestas are associated with gently dipping sedimentary rocks. On the Colorado Plateau, the Grand Staircase and Mogollon Rim form spectacular examples of cuestas (Foos, 1999a). The Grand Staircase is formed by over 10,000 feet of Permian-to-Tertiary (some 200 million years) of sedimentary rocks gently dipping to the north exposed over a distance of some 50 km (King, 1977; Foos, 1999b). Resistant rock layers of various colors form the steeply sloping cliff faces of the cuesta along the Utah-Arizona border (King, 1977; Foos, 1999b). At the Mogollon Rim or Escarpment, the southern edge of the Colorado Plateau, the Permian Kaibab Limestone forms a capstone at the top of 200-500 m of relief to the basin-and-range province to the south across eastern central Arizona (Holm, 2001). Some combination of faulting (Hunt, 1956, McKee and McKee, 1972; Reynolds, 1988) and erosion (Pierce et al., 1979; Young, 1979; Lucchita, 1984; Holm, 2001) apparently formed the escarpment. In Texas, shallowly dipping sedimentary rocks form a stair-step topography in the Hill Country (Stricklin et al., 1972; Barker and Ardis, 1996) and Edwards Plateau (Barnes, 1992) of Central Texas (Wilcox et al., 2007), and to the south, the Bordas Scarp forms a relatively young caliche (carbonate-cemented soil) cuesta (Sellards et al., 1933) in the Reynosa Formation (Trowbridge, 1924) that extends across the border into Mexico (Johnston, 1963). In the northeast, middle Paleozoic marine sediments across a broad region—New York through Ontario—form the Niagara Cuesta which slopes gradually to the east and west (e.g. Dunbar, 1949).

4 Natural Features in Consideration

At Thacher Park, the Helderberg Escarpment dominates the landscape as a cuesta, where shallowly dipping beds form a series of cliffs that offer impressive vistas. Above the Great (Hudson River) Valley to the east the Taconic Range in Massachusetts and Vermont appear (www.nysparks.com/parks/128/details.aspx, 2016). To the north, across the Mohawk Valley, the Adirondack Mountains of New York are visible (www.nysparks.com/parks/128/details.aspx, 2016). Thacher's Paleozoic formations reveal a rich and beautifully preserved Late Ordovician through Middle Devonian marine sequence (Goldring, 1933). Easily accessible via roads and walking paths, this impressive view and abundance of conspicuous marine fossils in Late Silurian-Early Devonian units (especially in the Helderberg Group) have made a popular destination for naturalists since the earliest days of geology in North America (Torrey, 1935). Glaciation of this region and subsequent ice retreat, some 16,000 years ago, exposed fresh bedrock along the gently sloping tops of the cuesta and enriched the landscape with more subtle features, such as Thompson's Lake, and ice-contact and meltwater deposits of Glacial Lake Albany in the valley below (Dyke and Prest, 1987; Engel, 2015a). Under a Modern humid climate, sinks, glens, caves, and karstic patterns develop in the southward dipping (~1°) (Goldring, 1935; Stander, 2015) Paleozoic sequence as groundwater winds its way northeastward down the cliff (Cuomo and Harvey, 2013a). Finally, Thacher's geologic configuration allows great ecological diversity: 14 different sedimentary units provide a full spectrum of soil nutrient and pH conditions, and caves and cliffs provide rare ecological habitats. In total the park hosts hundreds of plant and animal species, many of which might not otherwise occur in the region if not for this diversity of habitats (Cuomo and Harvey, 2013b; Engel, 2015b).

4.1 Geological Features

4.1.1 *Description*

John Boyd Thacher State Park, in the Helderberg hills of Albany County, New York, has a rich geologic history, and represents a seminal region in the history of North American geological and paleontological studies since early in the 19th century. The rocks of the park comprise over 1700 feet/520 meters of Late Ordovician to Middle Devonian strata (ca. 450-388 million years ago) (Figs. Thacher, cross section; Thacher, stratigraphy). These strata are encountered through the landscape of Thacher Park, which consists of a series of plateaus and cliffs that form a cuesta above the broad Hudson River Valley below (Figs. Cuesta, block diagram, southeast vista; Thacher, cross section, NNL boundary). Each surface of this cuesta, created as the Hudson River drainage carved through a thick Paleozoic marine sequence centered in eastern Pennsylvania and extending through the Appalachians (Dunbar, 1949; Milici and de Witt, Jr., 1988; Isachsen et al., 2000), offers special features. Thacher State Park's cliff and Indian Ladder trails guide visitors through alternating hard and soft stratigraphic layers that form the most dramatic facets of the cuesta (Fig. Indian Ladder, trail).

The Helderberg Group (Manlius, Coeymans, Kalkberg, New Scotland, and Becraft Formations) is the central focus of the stratigraphy at Thacher (Figs. Thacher, cross section, stratigraphy). The contact between the Early Devonian Coeymans Limestone and Kalkberg Formation, a siliceous and shaly limestone that weathers more easily than the Coeymans, forms the capstone of a striking 100-foot cliff on which the main park offices and facilities are built (see cover photo) (Fig. Escarpment, facilities) (Goldring, 1933). This surface, subtly pocked with broad, shallow doline depressions (Engel, 2015), offers vistas across the broad Hudson River valley over New York's capital region and the Berkshires and Taconic Range beyond and to the north across the Mohawk Valley to the Adirondacks (www.nysparks.com/parks/128/details.aspx, 2016) (Fig. Facilities, overlook). The basins below would have provided a primary drainage route for the northeast and Southern Great Lakes region during early deglaciation, before the Saint Lawrence drainage opened between 12,000 and 11,000 years ago (Dyke and Prest, 1987; Engel 2015a). Subtle glacial features associated with this outflow, dammed at Glacial Lake Albany, can be seen (and imagined) from the cliff in the valleys below (Fig. Glacial Lake Albany).

Thirty-seven feet of fossiliferous Coeymans Limestone and 52 feet of fossiliferous Late Silurian Manlius limestone, with lesser amounts of Rondout Dolostone (Rondout Group) and Kalkberg Formation (overlying) comprise the 100-foot cliff face (Rickard, 1962), accessible via Indian Ladder trail (New York State Office of Parks, Recreation, and Historic Preservation, 2013) (Figs. Escarpment, 100-foot; Manlius, Indian Ladder; Thacher, stratigraphy). Due to the excellent exposure provided by the cliff, a number of near-shore and shallow-marine fossils and sedimentary features can be seen in these units (Goldring, 1933). Mudcracks (Fig. Manlius, mud cracks), reef-building *Stromatopora* sponges, bacterial thrombolites (layered mounds built by bacteria) (Fig. Manlius, thrombolite), *Tentaculites*, an abundant centimeter-scale conical shell with brachiopod-like features (Fig. Manlius, fossils), and *Leperditia*, an ostracode (sand-sized crustaceans) (Fig. Manlius, fossils), indicate that the laminated (finely layered)

(Fig. Manlius, thin-bedded limestone) Manlius Limestone was deposited in a high-salinity, near-shore environment, perhaps a tidal flat (Goldring, 1933; Whiteley et al., 2002).

This shallowest marine environment deepens during the Early Devonian as indicated by abundant, low-diversity fossil assemblages in the Coeymans Limestone above (Goldring, 1933; Dunbar, 1949; Milici and deWitt, Jr, 1988; Isachsen et al., 2000) (Fig. Coeymans, fossils). Brachiopods *Seiberella* or *Gypidula coeymanensis*, *Uncinulus mutabilis*, and *Atrypa reticularis* (Figs. Coeymans, brachiopods, fossils), and various crinoids (Figs. Coeymans, crinoids, fossils) are common throughout the unit, *Meristella laevis* fossils are less abundant, and *Stropheodonta varistriata* and *Camarotoechia semiplicata* fossils can be found in the Manlius transition zone (Goldring, 1933) (Fig. Manlius, limestone). A head coral with hexagonal prismatic chambers, *Favosites helderbergiae*, trilobites, and a pelecypod (bivalve mollusc) are less common (Goldring, 1933) (Figs. Coeymans, coral, fossils).

Water flows over and through the cliff. At the base of the 100-foot cliff, an underground stream emerges at Fool's Cave (Fig. Karst, Fools Cave). Minelot Creek, and Outlet Creek to the northwest, cut into the Coeymans Limestone to flow over the cliff in thin, ephemeral streams, Minelot Falls and Outlet Creek Falls (Figs. Falls, Minelot dry, Minelot flowing, Minelot Creek). When these are flowing, the sound of rushing water fills the valley (Albright and Ten Eyck, 2011). Because the Rondout Formation (Late Silurian) below is more dolomitic (and thus, less soluble) than the Manlius Limestone, dissolution of the Manlius provides an outlet for karst-flowing waters (Goldring, 1933; Ver Straeten, 2015) (Figs. Karst, outlet; Thacher, cross section, stratigraphy).

In total eight springs in or near Thacher Park illustrate that the lower Helderberg (lower Kalkberg, Coeymans, Manlius) limestones and Rondout Dolostone behave as a single karstic unit (Engel, 2017). In addition to the springs at the base of Minelot and Outlet Falls (Fool's Cave (350 m))(Figs. Karst, Fools Cave, outlet) are Eft Cave and Novemberkill Cave, audible running water at Yellow Rocks, and Natures Way Cave, just outside the park boundary (Engel, 2017). Of the 40 caves in Thacher Park (DeBolt, 2015), the most impressive are hosted in this karstic unit. Notable examples include Giant's Castle, or the Bridal Chamber (Fig. Karst, Bridal Chamber), a dead-end cave, Tory Spy Cave, a shelter cave (Fig. Karst, shelter cave), and the longest, Hailes Cave (Fig. Hailes, interior), initially surveyed at 2800 feet (854 m) (Albright and Ten Eyck, 2011) and more recently surveyed at 3854 feet (1175 m) (Engel, 2017).

A steep slope below the base of the 100-foot cliff cuts through the Late Silurian Rondout Formation (Rondout Group) and Brayman Shale (Bertie/Salina Group), and the Late Ordovician Indian Ladder and Schenectady formations (Prosser and Rowe, 1899; Ruedemann, 1930; Goldring, 1935) (Figs. Thacher, bedrock, cross section, stratigraphy). Here the Late Silurian Formations rest unconformably (separated by some 20 m.y.) on the Queenston Delta sediments (Late Ordovician Martinsburg Group (see Isachsen et al., 2000)) shed from the Taconic Orogeny (Fig. Thacher, stratigraphy). In Thacher Park, the Rondout Formation is thinly bedded, non-fossiliferous, and only four feet thick (Goldring, 1933). Although the Rondout is less soluble than the Manlius, this lower unit is softer, and thus poorly exposed at Thacher Park, buried in talus (fallen rock) and glacial drift in most places (Goldring, 1933). The Late Silurian Brayman Shale is only about a foot thick here, exposed as easily weathered, green or gray and pyrite-rich at the base of Outlet and Minelot Creek Falls (Goldring, 1933) (Fig. Karst, Fools Cave). The thick (350') siliciclastic (shale, siltstone, and sandstone) units below the Rondout Formation (Fig. Thacher, cross section, stratigraphy) offer few fossils, but despite generally poor exposure, the park contains good outcrops, especially of the Indian Ladder beds of the Schenectady Shale and Sandstone in the ravine below (east of) Indian Ladder trail (Goldring, 1933). Although fossils of bryozoan *Hallpora onealli*, brachiopods *Rafinesquina ulrichi*, and *Dalmanella multisecta*, and trilobite *Cryptolithus bellulus* deserve mention for occurring exclusively in the vicinity of Thacher within this portion of the stratigraphic section (Goldring, 1933) (Fig. Schenectady Formation, Indian Ladder beds fossils), the Indian Ladder beds are otherwise generally consistent with the Schenectady Formation below (Fig. Schenectady Formation, fossils).

Traveling southwest, away from the primary escarpment, and up in the stratigraphy and in elevation, the Early Devonian Kalkberg, New Scotland, and Becraft Formations (limestones predominantly of the Helderberg Group) provide less conspicuous topographic relief (Goldring, 1935) (Figs. Cuesta, block diagram; Thacher, bedrock, NNL boundary). A 49-foot-thick section of fossiliferous Kalkberg Limestone forms a low terrace above the Coeymans Limestone (Rickard, 1962) (Fig. Kalkberg, terrace). Exposures above Hailes Cave generously yield bryozoa, crinoids, various brachiopods, and corals (Goldring, 1933) (Fig. Kalkberg, fossils). Less conspicuous but commonly more fossiliferous, the New Scotland Formation forms gentle slopes above this terrace (Goldring, 1933, 1935). Exposures of the 66-foot section (Rickard, 1962) in the park's stream beds yield various brachiopods and gastropods (Goldring, 1933) (Figs. New Scotland, fossils, trilobite fossils; Thacher, bedrock, stratigraphy). Most conspicuous of the three units, the Becraft Formation crops out as low ledges of massive, pure limestone (Goldring, 1935). The twelve-foot section (Rickard, 1952) contains crinoid and various brachiopods (Fig. Becraft, fossils), truncated at the top by the Wallbridge Unconformity, a surface of non-deposition and/or erosion, widespread across the Northern Appalachian Plateau representing 3-5 million years of history (Goldring, 1933, 1935) (Figure Thacher, stratigraphy). In places this surface weathers to form a limestone pavement characterized by a clint and grike pattern, where dissolution along joints (large-scale fractures) forms sharp troughs (grikes) between intact slabs (clints) of ground surface (e.g. Fig. Karst, pavement). This texture is generally restricted to relatively undisturbed limestones exposed by stripping of unconsolidated surface sediments, often by glaciers.

The section resumes up and to the southwest (Fig. Thacher, bedrock) with the largely siliciclastic Early Devonian Tri-States Group, the Oriskany Sandstone, Esopus Shale and Sandstone and Schoharie Formation, collectively (Goldring, 1935) (Figs. Thacher, cross section, stratigraphy). This package of sediment corresponds to the first phase of the Acadian Orogeny and thus the beginning of the Catskill Delta. The Oriskany Sandstone represents a shoreline facies deposited as the ocean advanced over the ancient land surface (Goldring, 1933; Isachsen, 2000). Outcrops of the Oriskany Sandstone are more widespread than its thin (1'-2') section might predict, and contain robust brachiopods, gastropods, and worm burrows (Goldring, 1933) (Figs. Oriskany, fossils; Thacher, bedrock, stratigraphy). Most of the Tri-States Group consists of the Esopus Shale above (Isachsen et al., 2000), which is 100 feet thick in the Helderberg region (Prosser and Rowe, 1899; Fisher et al., 1970; Rehmer, 1976) (Fig. Thacher, stratigraphy), and largely barren of fossils except for rooster-tail shaped worm burrows (Goldring, 1933) (Fig. Esopus, fossils). Where present, the Schoharie Formation, the uppermost formation within the group, is up to 23 feet thick in Thacher Park (Johnsen, 1957) (Fig. Thacher, stratigraphy). In the Schoharie –Helderberg area, over 100 species of fossils have been described in this impure siliceous limestone (Goldring, 1933). Most notable are the large, straight cephalopods in an assemblage that includes many brachiopods, gastropods, corals, and trilobites (Goldring, 1933) (Fig. Schoharie, fossils). The upper reach of Minelot Creek carves a deep, steep-sided glen through the top of the Tri-States Group (Schoharie and Esopus Formations) section (Goldring, 1935) (Fig. Schoharie, glen). Here the creek drops through the soft shaly material so rapidly that no alluvium (river sediment) collects in the channel. Thrust faulting, prominently revealed in the walls of the glen, may have exacerbated incision through the top of the Tri-States section.

The 85 to 100-foot-thick Onondaga Limestone (Middle Devonian Onondaga Formation) (Fig. Thacher, stratigraphy) caps the softer Tri-States Group below to form a second cliff, broken in the Helderberg area (Fisher et al., 1970). It is on the top of this unit (e.g. north of Beaver Dam Road) that some of the best examples of the clint and grike limestone pavement develop in the park, the grikes up to two feet in width and many tens of feet in length (Figs. Karst, pavement; Thacher, NNL boundary). Toward the southern edge of the park, south of Beaver Dam Road, the top of the unit is buried by overburden (unconsolidated sediments) shed from lower black shales of the Union Springs Formation above at the base of a slope (Goldring, 1935; Engel, 2017) (Fig. Thacher, NNL boundary). Sinkholes form in this unit where the cap of overburden lengthens the distance between voids (Fig. Karst, sinkhole). These sinkholes are regularly spaced every 100 feet or so (Engel, 2017), and surrounded by steep-sided (some 30°) cones or troughs through the overburden, up to 30 feet in thickness (Fig. Karst, sinkhole). Some of these conspicuous features, such as “Hillbilly Hole”, have been deservedly named (Engel, 2015). Water emerges from these sinks through springs at the base of the Onondaga at Uhll Be Cold Cave (200 m) (Siemion, 2006; Engel, 2017). Throughout the park 17 springs emerge at the base of the Onondaga (Engel, 2017). Although the Onondaga outcrops along portions of the eastern and southern shore of Thompson’s Lake, the lake is largely perched on the sandstones and shales of the Esopus and Schoharie Formations (discussed above) (Engel, 2017) (Fig. Thacher, bedrock). Some of the water in Thompson’s Lake sinks into the Onondaga along the southern shore to emerge some 2 km west southwest at Pitcher Farm Spring, and surface water drainages flow northeast from Thompson Lake to Outlet Brook (Engel, 2017).

The ancient reef platform environment in which the Onondaga was deposited supports a variety of fossils, though the unit is not particularly fossiliferous (Goldring, 1933) (Fig. Onondaga, fossils). Here corals predominate the assemblage, but brachiopods are abundant, and gastropods, cephalopods and trilobites are present (Goldring, 1933) (Fig. Onondaga, fossils). Fish remains are described from the unit, but not at Thacher (Goldring, 1933). The unit is laterally continuous over a broad geographic area, extending westward into Ohio and south into Pennsylvania, and thus its ash layers (Fig. Thacher, stratigraphy) provide widespread absolute age dates (Whiteley et al., 2002). Chert nodules occur at irregular intervals within the unit, especially toward the top of the basal Edgecliff Member (Fig. Onondaga, chert), likely derived from particulate biomineralized silica, such as sponge spicules (Whiteley et al., 2002).

At the top of the section at Thacher, the Union Springs Formation and Mount Marion Formation of the Marcellus subgroup (Hamilton Group) continue upslope to the southern boundary of the park (Goldring, 1935) (Figs. Thacher, bedrock, cross section, stratigraphy). Brachiopod, pteropod, and cephalopod fossils are rare in this generally dark gray to black shaly material, exposed only along a stream valley (Goldring, 1933) (Figs. Mount Marion Formation, fossils 1, fossils 2, Union Springs Formation, fossils).

4.1.2 *Explanation*

The sedimentary and paleontological history of John Boyd Thacher State Park can be interpreted as a series of five different seas, interrupted twice by withdrawal of marine waters to become land. This history comprises approximately 62 million years of geologic time (ca. 450-388 million years ago) through the Late Ordovician, Silurian, and Early to Middle Devonian Periods.

The seas that flooded Thacher Park during this time were shallow epicontinental (“on the continent”) seas. During parts of the Paleozoic and Mesozoic Eras (541-252 and 252-66 million years ago), shallow seas flooded small to large portions of the continents. Today this is relatively rare; modern examples include the Baltic Sea of Europe, Hudson and James Bays of arctic North America, and the Gulf of Carpentaria at the northern tip of Australia. Depths of epicontinental seas are generally measured in tens to hundreds of feet, analogous to the shallow continental shelves around the margins of Earth’s much deeper ocean basins.

The five seas of Thacher Park represent alternating times of siliciclastic mud and sand versus carbonate/limestone sedimentation across the region. Today shale and sandstone comprise over 80% of the thickness of the park’s approximately 1730 feet- (527 meters-) thick sedimentary rocks. They occur in three separate packages, which can be described as three different “Mud and Sand Seas”. Each formed as the result of erosion of the Appalachian Mountains during two major mountain building episodes; the Ordovician-age Taconic Orogeny, and the largely Devonian-age Acadian Orogeny. Ordovician mountain building was the result of the collision of eastern North America with a chain of volcanic islands (Taconic Orogeny), followed later by collision with a series of smaller continents (Acadian Orogeny). These episodes are analogous to the more recent continent-continent collision of the Indian subcontinent with southern Asia over the last ca. 30 million years, which has formed the Himalaya Mountains.

Erosion of the Taconic and Acadian mountains during both periods produced massive volumes of mud, sand and gravel, that was transported westward onto the North American (at that time "Laurentian") continent. In both cases tremendous thicknesses of sediments were deposited over Thacher State Park as the Queenston Delta and Catskill Delta, respectively, and far to the west; some mud from both orogenies was transported and deposited as far west as Iowa, seen as shales there today.

Sandwiched between the three "Mud and Sand Seas" are two intervals of limestone strata. These limestones, known as the Helderberg Group and the Onondaga Formation, formed during times of little to no mountain building in the Appalachians, and lower relief. This led to little or no mud or sand deposition in the Lower and Middle Devonian epicontinental sea. The sediments that were deposited chiefly consisted of whole, fragmented, or ground-to-flour size particles of invertebrate animal skeletons (e.g., shells, corals), composed of the minerals calcite or aragonite. Later cementation converted the loose calcareous sediments to limestone. Water depths in the Thacher "Limestone Seas" varied from shoreline and tidal zone of zero to a couple to few hundred feet deep. In some deepwater settings, some siliciclastic mud was also deposited, interbedded with fine-grained limestones.

Twice during the geologic history of Thacher Park's five seas, marine waters retreated from the region, and the area became land. Erosional processes dominated the land surface during those times. The longest interval of these lands occurred during the Silurian Period. Except for at the very end of the interval, no Silurian age rocks are found in Thacher Park. Even the very latest Ordovician strata, known to have been deposited on top of the remaining Ordovician strata in the park, were eroded out during the Silurian. The cause of this retreat of the seas is chiefly related to deep erosion of the Ordovician-age Appalachians. As they eroded down, their weight on the crust decreased, and the crust below the mountains rebounded upward, uplifting the broader region around them. This largely explains why there is no rock record through about 30 million years during this time (ca. 450 to 420 million years ago) in eastern New York. However, throughout this time Silurian-age sedimentary rocks were being deposited in central to western New York. This is indicative of regional erosion chiefly associated with tectonic processes, not with a global fall in sea level.

In contrast, the second withdrawal of the sea from the Helderbergs was of shorter duration. How long the area was land is unclear. However, between the withdrawal and erosion of underlying rocks, there is a disconformity with perhaps 5 million of rocks (and hence time) missing at this erosion surface, the Wallbridge Unconformity. In contrast with the longer Silurian-age sea level fall, this unconformity is recognized on various continents around the world, indicating that this time of land at Thacher largely resulted from a major global fall in sea level, not regional tectonic flexure of Earth's crust.

As encountered today, John Boyd Thacher State Park is located on the steep border of the Allegheny Cuesta, known as the Helderberg Escarpment (Albright, 2011). This cuesta was formed when sediments, deposited during a time when New York state was flooded by a shallow sea, were uplifted and the cliff face was subsequently eroded away (New York State, 2016). The cuesta at Thacher State Park is very distinctive, displaying a thick stratigraphic section on its cliff face. Accessibility of Thacher Park's cuesta within a contained area makes this location a worthy destination for both scientific and scenic purposes. For the stratigraphic and tectonic insights it provides, the section here is arguably the most important in eastern North America.

4.2 Ecological Features

Thacher Park's ecology consists primarily of Eastern Deciduous Forest, but also includes cave, swamp, meadow, and lake environments (Edinger et al., 2002, 2014) (Fig. Thacher, ecology). The great diversity of conditions and environments afforded by the geology give rise to a particularly rich forest ecosystem that hosts rare species (Cuomo and Harvey, 2013b). Variations in soil type, topography, pH, nutrients, and permeability create particular habitats for plants (Cuomo and Harvey, 2013b). Shaly bedrock corresponds to acidic soils that support plants such as Pink ladyslipper (*Cypripedium acaule*) and Hobblebush (*Viburnum alnifolium*). Sandy, acidic, and nutrient-poor soils (over sandy bedrock), e.g. the sandy Schenectady Formation that forms the steep slope at the base of the 100-foot cliff, favor stands of chestnut oak (*Quercus prinus*) (New York Natural Heritage program, 2013; Engel, 2016) (Fig. Thacher, ecology). Above, in the Oriskany and Esopus Formations, these sandy soils support cedar, juniper, hemlock and yew (Goldring, 1933). In contrast, rich carbonate soils allow a great variety of perennial herbs and ferns (Cuomo and Harvey, 2013b). Rare plants, smooth cliff brake fern (*Pellaea glabellas sp glabella*) and small mousetail moss (*Myurella julacea*) grow in the park (Engel, 2015b), and calcareous cliffs, limestone woodlands, and maple-basswood rich mesic forests comprise notable special ecological communities (Evans et al., 2000) (Fig, Thacher, ecology). High elevations and northeast shade of the 100-foot cliff provide a cool climate more similar to a mountain region than the relatively warm Hudson Valley below (National Oceanographic and Atmospheric Administration, 2004). The cliff and the great diversity of habitat support over 100 bird species to earn Thacher Park the designation "Important Bird Area" by the Audubon Society (Evans et al., 2000; Cuomo and Harvey, 2013b).

Twenty-one distinct ecological community types are found in the park (New York Natural Heritage Program, 2013; Cuomo and Harvey 2013b; Edinger et al., 2002, 2014) (Fig. Thacher, ecology). Distinct geology and topography in the northern and southern portions of the park give rise to characteristic environments in each area (Cuomo and Harvey, 2013b). To generalize, in the northern portion, dominated by the 100-foot cliff and the lower cuesta, young mixed forest, successional old fields, and grasslands are found (New York Natural Heritage Program). In the woodland at the campground a Northern White Cedar Swamp is fed by a spring (New York Natural Heritage Program). In contrast, the southern portion of Thacher Park consists generally of forested uplands corresponding to the upper units of the cuesta above the main cliff (New York Natural Heritage Program). Hemlock-Northern Hardwood forest dominates Maple-Basswood mesic forest, with limited successional Northern Hardwood Forest. Small wetlands include Shallow Emergent Swamp and Shrub Swamps (New York Natural Heritage Program).

Like the flora, the park fauna correspond to distinct habitats. The high cliffs attract various birds and bats, karst environments provide habitat for bats, bears, and other mammals, vernal ponds support nine salamander (Fig. Ecology, salamander) and six frog species, and fields along Ketcham Road are maintained as grassland habitat for birds and other animals that prefer open space (Evans et al., 2000; Cuomo and Harvey, 2013b). The park hosts all of the region's common mammals (Engel, 2015b), numerous small rodents, muskrat, beaver, mink, fisher, otter, porcupine, striped skunk, coyote, red and gray fox, raccoon, white-tailed deer, eastern cottontail, bobcat, black bear, and until recently (Engel, 2015a), eight species of bats, carefully protected at Hailes Cave (Evans et al., 2000; Cuomo and Harvey, 2013b; DeBolt, 2015), (Figs. Hailes, bats, gate, Helmus Crack). One hundred-seventy-one species of birds have been documented by the Audubon Society, and 102 of these species are likely breeding here (Evans et al., 2000; Cuomo and Harvey, 2013b). Particularly abundant are hermit thrush, winter wren magnolia, black-throated blue, black-throated green, blackburnian, Canada and worm-eating warblers, and northern waterthrushes, and common raven (Evans et al., 2000; Cuomo and Harvey, 2013b). Of special concern are the Jefferson salamander (*Ambystoma jeffersonianum*), a sharp-shinned hawk (*Accipiter striatus*), cooper's hawk (*A. cooperi*), northern goshawk (*A. gentilis*), golden-winged warbler (*Vermivora chrysoptera*) (Evans et al., 2000; Cuomo and Harvey, 2013b).

4.3 Natural History Theme Representation

Thacher Park might address a number of the National Parks Service's ecological and geological themes. Consistent with the biophysiographic province's inventory study (Baer et al., 1983), Thacher Park primarily addresses Natural Parks System Theme 15: "Late Silurian-Devonian Periods," a theme which is poorly covered in the "Appalachian Plateaus" biophysiographic province (National Parks

Service, 1990) despite a number of potential representative sites. “Cuestas and Hogbacks” (Theme 2), however, should not be overlooked a second appropriate first-order theme for Thacher, because the site’s general physiography compellingly illustrates the cuesta as a landform (Goldring, 1933). Unfortunately, this theme is poorly represented among designated National Natural Landmarks within the “Appalachian Plateaus” province, and “Plains, Plateaus and Mesas” (Theme 1) is not represented (National Parks Service, 1990). For its pervasive erosive features: karst, sinks, and glens, “Sculpture of the Land” (Theme 6) would seem an appropriate secondary theme, to the extent that karstic features address “Sculpture of the Land” as opposed to “Caves and Springs” (Theme 12), which, although present, are not as well developed here for caving (Engel, 2015a). Finally, although “Eastern Deciduous Forests” (Theme 24) are abundant in the Appalachian Plateaus province (National Parks Service, 1990), Thacher’s outstanding ecological richness nevertheless deserves mention.

Other themes are less relevant to Thacher Park. “Works of Glaciers” (Theme 9), is a less appropriate characterization. Glaciation plays a critical but indirect role in facilitating the surficial erosive features by exposing fresh Paleozoic stratigraphy. Within the park boundaries, features directly attributable to glacial processes are largely unremarkable or speculative. Glaciation enhances exposure of the cuesta surfaces, but the landform itself cannot be ascribed to glaciations (Cleland, 1930). Rather, the cuesta was ultimately carved by the Hudson and Mohawk Rivers as fluvial processes exploited structural features in eastern New York’s bedrock geology (Goldring, 1933; Fisher, 1970). In other words, incision of these rivers showcases a previous geologic feature. Thus, Thacher’s “River Systems and Lakes” (Theme 8) categorization (Baer et al., 1982) is not quite right either. The dramatic relief of the Helderberg Escarpment arises from juxtaposition of a minimally disturbed carbonate-rich Paleozoic marine section–revealed in unparalleled completeness as at Thacher Park—against older (Cambro-Ordovician) soft siliciclastics (shales and thin sandstones of the Queenston Delta sequence), upturned and faulted during subsequent orogenic activity to form the floor of the Great (Hudson) Valley (Goldring, 1933; Fisher et al., 1970; Isachsen et al., 2000). Sapping of the minimally disturbed Queenston Delta sequence then caused the Helderberg Escarpment to propagate away from the Hudson River, and the larger biophysiographic province boundary corresponds to that escarpment. Moreover, Thompson’s Lake is a now understood to represent a (relatively common) glacial feature, not a sinkhole or karstic feature as previously interpreted (Engel, 2015a).

5 <u>Physical Setting and Climate</u>

The park is located along the Helderberg Escarpment, 450’-1700’ above sea level in eastern New York, the northeastern corner of the Appalachian Plateau above the Hudson and Mohawk River Valleys (Figs. Lake Albany; Thacher, topography). Pronounced topographic contrast along the escarpment west of Albany between Altamont and New Salem earns this area the designation “Helderberg Mountains” (Goldring, 1933). Climate is humid and continental, with four distinct seasons. Winter can be very cold with temperatures often below 0°F at night and an annual average of 62.7 inches of snowfall (National Oceanographic and Atmospheric Administration, 2004). The park receives snowfall from Alberta clippers and Nor’easters. Summer is often characterized by long stretches of heat (high temperatures often above 90°F) and humidity (annual average of 38.6 inches) (National Oceanographic and Atmospheric Administration, 2004). The park’s elevation above Hudson Valley (median ~200’ above sea level at Albany) provides a predictably cooler climate with respect to Albany (sea level-378’ above;), where the region’s highest-resolution climate data are collected.

6 <u>Location and Access</u>

John Boyd Thacher State Park is accessible directly via NY-157, located some four miles northwest of the road’s intersection with NY-85 (New Scotland Road) (Fig. Thacher, NNL boundary). Park area lies in four towns: Berne, Guilderland, New Scotland and Knox. Main park offices, Indian

Ladder trail and ravine, and popular overlooks are sited along NY-157 and smaller intersecting park roads in New Scotland. To the north Hailes Cave and a northern-facing overlook are in Guilderland. Southern high elevations are in Berne and New Scotland and accessible via Beaver Dam Road. The northern portion of the park is in Knox, accessible via Carrick Road, Ryan Road, and Old Stage Road. Thompson's Lake Campground is also located in Knox, on NY-157, 1.2 miles (3.5 miles via road) west of Thacher Park's headquarters. A second entrance to Thompson's Lake Campground, serving the Emma Treadwell Thacher Nature Center (Fig. Facilities, Nature center), is on Nature Center Way (formerly Stan Levine Drive) off of Ketcham Road.

All parts of the park are accessible by motor vehicle from NY-157. Pedestrians and bicyclists can also enter the park from the main state roads (Fig. Thacher, NNL boundary). Access on foot is also available from the Long Path, a hiking trail that extends 375 miles from Fort Lee Historical Park in New Jersey to NY-146 just outside of Thacher State Park (Cuomo and Harvey, 2013a) (Fig. Thacher, topography). No bus routes provide access to the park. Nearby cities include Albany (20 mi east), Schenectady (20 mi north), Troy (25 mi northeast), and Amsterdam (30 mi northwest).

7 Ownership

Thacher Park was initially acquired by New York State in 1914 as a donation of 350 acres from Emma Treadwell Thacher following the 1909 death of her husband, New York politician, businessman, and historian, John Boyd Thacher (Torrey, 1935; Albright and Ten Eyck, 2011; New York State Office of Parks, Recreation, and Historic Preservation). In 1920 she donated 50 acres on the western shore of Thompson's Lake (Torrey, 1935). Since acquisition the (now southeastern) parcel at the Helderberg Escarpment was operated as Thacher State Park; the parcel on Thompson's Lake's western shore was established as a separate park in 1972 (New York State Office of Parks, Recreation, and Historic Preservation, date unknown). Through donations by the American Scenic and Historic Preservation Society, appropriations by the state Legislature, and with State Park Bond Issue funds, Thacher Park expanded to 820 acres by 1935 (Torrey, 1935; New York State Office of Parks, Recreation, and Historic Preservation). In the early 1950s new facilities, including a bathhouse and Olympic-sized pool were constructed (Albright and Ten Eyck, 2011). Installation of the pool almost doubled visitorship from some 280,000 in 1954 to almost 449,000 one year later (Albright and Ten Eyck, 2011). Many amenities in addition to the pool (now removed), were built over the twentieth century at Thatcher Park (New York State Office of Parks, Recreation, and Historic Preservation). In its heyday in the middle twentieth century, the park earned a reputation as the playground of the capital region, and was a popular summer destination (Albright and Ten Eyck, 2011).

John Boyd Thacher Park has grown to 2155 acres (8.72 km^2) and now includes Thompson's Lake Campground (Fig. Thacher, NNL boundary). The park expanded to 1347 acres by 1972 (Cuomo and Harvey, 2013a), and more recent additions include some 600 acres in 2004 and another 188 in 2006 (Wikipedia, 2016). Modern park facilities are described under Section 7, "Land Use…" below, and discussed in detail in *A Final Master Plan for John Boyd Thacher State Park*, published November 13, 2013 (Cuomo and Harvey, 2013a). Parcels of the park are presently somewhat discontiguous. Northern and southern sections intersect at a point at the Guilderland-Knox border and Thompson's Lake Campground is separated from the northern section by 0.5 km. A fourth parcel rises some 800 feet (from the 450' contour to the 1240' contour) through the steep slope where the Schenectady Formation outcrops along the foot of the escarpment east of the northern section (Fig. Thacher, bedrock, NNL boundary).

8 Land Use and Condition

Because of Thacher's protected status as a New York State Park, Baer et al. (1982) correctly describe the site's natural integrity as "in no apparent danger." Collection of fossils is prohibited within the park (Cuomo and Harvey, 2013b). Natural Heritage Areas are planned within Thacher Park, most prominently along the 100-foot escarpment that hosts a calcareous cliff community (Cuomo and Harvey, 2013a). An expanded Bird Conservation Area will include the entire park (Cuomo and Harvey, 2013a). Most of the land within Thacher State Park is zoned as “wild, forested, conservation lands and public parks,” consistent with its operation as a state park (Cuomo and Harvey, 2013a) (Fig. Thacher, land use). However, nearly half of the southern section (north of NY-157 and south of Beaver Dam Road in New Scotland) and large portions of the northern section are zoned simply as “vacant land.” Smaller parcels zoned “recreation and entertainment” are found in the northern section and at Thompson’s Lake Campground near historic Knox schoolhouse #5 south of Ketcham Road, where a recently restored historic one-room schoolhouse at Thompson’s Lake Campground was last used for its original purpose in the 1930s (New York State Office of Parks, Recreation, and Historical Preservation, 2012). Park grounds, facilities, and infrastructure are found to be well-maintained and in good condition.

Thacher Park maintains infrastructure that offers a number of activities for visitors. Twenty-eight miles of trails support hiking, bicycling, cross-country skiing, snowshoeing and snowmobiling in designated areas, and a rock climbing program is being implemented (Cuomo and Harvey, 2013a) (Fig. Thacher, NNL boundary). Picnic tables, grills, eleven pavilions, volleyball courts, ball fields, and three playgrounds are available in the southern portion of the park. Thompson’s Lake Campground maintains 140 tent/trailer sites, a sandy beach, a public swimming area, a boat launch, volleyball court, horseshoe pits, a playing field, playground, and offers boat rentals, fishing, and ice fishing (Cuomo and Harvey, 2013a). Programming is available through Emma Treadwell Thacher Nature Center, overlooking Thompson’s Lake (Fig. Facilities, Nature Center). The nature center also offers a geologic model of the Helderberg Escarpment, educational exhibits and displays, and restrooms. A new visitor just opened at the top of Indian Ladder includes an information center, meeting room, outdoor classroom, geology/paleontology and history exhibits, gift shop, fireplace, rental space, restrooms, and park office (Cuomo and Harvey, 2013b; www.thacherparkcenter.org).

Prior to establishment as state parks in the twentieth century, the cliffs and Thompson’s Lake and Thacher Park, the Helderbergs—Bright/Clear Mountain in Dutch—have a long history of human use. Archeological evidence suggests that Thompson’s Lake was used as a camp as early as about 6000 BCE (Cuomo and Harvey, 2013a). Native Americans travelling between Schoharie Valley and Hudson Valley fixed footpaths over the Helderberg Mountains using cut logs, referred to as “Indian Ladders” by early settlers (Albright and Ten Eyck, 2011; Cuomo and Harvey, 2013a) (Fig. Indian Ladder, sign). The “Indian Ladder” is alternatively described as a large living tree, with branches that served as the rungs of the ladder until 1820 (Torrey, 1935).

In the early seventeenth century, Kiliaen Van Rensselaer, through the West India Company, expanded the colony of New Netherland through purchase of land from the Mohican for an ambitious European settlement in the Albany area (Krol, 1630; Albright and Ten Eyck, 2011). During the American Revolutionary War (1777), Tory Cave, a shelter cave 25 feet wide, is reputed to have harbored British loyalist John Salisbury (Torrey, 1935; Cuomo and Harvey, 2013a). After the war, settlers built houses and other structures at Thacher, then rented from the Van Rensselaer patroonship in a feudal arrangement, for example at Glen Doone, Greenhouse, and south of Beaver Dam Road (Cuomo and Harvey, 2013a) (Fig. Thacher, NNL boundary). Civil unrest incited by increased pressure to pay tribute to the estates following the death of Stephen Van Rensselaer in 1839 was resolved in the courts years later with confirmation of the farmers’ land titles, which ended the feudal system (Torrey, 1935). By the 1830s, pioneering geologists began studying the Helderberg sections exposed at Thacher, establishing early understanding of North American natural history (Mather, 1843; Hall, 1849, 1852, 1859-1861; Darton, 1894; Hall and Kunz, 1914; New York State Office of Parks, Recreation, and Historical Preservation; see also Section 10, “Comparative Analysis,” below) (Fig. History, geologists). During the mid-19th century, painters such as William Hart, Thomas Cole, Homer Dodge Martin, Asher Durand, Frederic Edwin Church, John Frederick Kensett, Sanford Robinson Gifford, and Albert Bierstadt of the Hudson River School art movement depicted romantic pastoral and wilderness scenes featuring and inspired by this area's dramatic landscapes (Albright and Ten Eyck, 2011).

The Helderbergs attracted tourists and the wealthy since at least the mid-nineteenth century. On High Point, above Altamont, the Thachers built a stately white mansion in the late nineteenth century (Albright and Ten Eyck, 2011). Its contemporary, The Kushaqua, or Helderberg Inn was built on the property adjacent by Col. Walter Church (Albright and Ten Eyck, 2011). In Knox, also overlooking Altamont, Edward Cassidy built a mansion in the late nineteenth century that was later used as a women's Bible school (Albright and Ten Eyck, 2011). In the early twentieth century, Charles Bouck White, who had developed an innovative method for making brightly glazed unfired pottery, constructed an eccentric house of native stone with crooked windows in nearby Federalsberg (Albright and Ten Eyck, 2011). On Thompson's Lake, the Lakeview House was built in the late nineteenth century and replaced by the Lakeside Hotel in the early twentieth century (Albright and Ten Eyck, 2011). Grove Hotel was built adjacent to Lakeside Hotel in the late nineteenth century (Albright and Ten Eyck, 2011). The Osterhout brothers operated a restaurant and danceroom on the road to Thacher from New Salem in the early and mid-twentienth century (Albright and Ten Eyck, 2011).

Today the land surrounding Thacher Park is generally rural with low population density and classified as variously zoned parcels that complement the natural landscapes of the park and/or would enrich the park in acquisition (Cuomo and Harvey, 2013a) (Fig. Thacher, land use). Primarily classification is "residential," with the highest population densities east and south of Thompson's Lake and along NY-157 west of Thacher Park's main offices. Lesser surrounding areas are "vacant" or "unclassified." Large areas to the north (Guilderland) and south (New Scotland) of the park are zoned "community services." Adjacent to these are areas classified "recreation and entertainment," along with small "public services" parcels in New Scotland. Large tracts between Thompson's Lake Campground and northern and southern sections of Thacher Park are agricultural, and additional agricultural land is found southwest of the southern section in Berne.

9 Proposed National Natural Landmark Boundary

In the potential National Natural Landmarks site inventory Baer et al. (1982) describe a 350-acre site corresponding presumably to the original parcel at Thacher Park. This section is currently found within the southeastern section of the park. Modern park boundaries now expand to the north (below the cliff) and south, and include sizeable discontinuous parcels to the north (below the cliff) and the northeast (above the cliff; NYSOPRHP GIS Unit, 2011). The parcel at Thompson's Lake is now managed jointly with the parcels at Thacher as a single park unit (Cuomo and Harvey, 2013b). The parcels historically associated with Thacher Park (as opposed to Thompson's Lake) and its principal escarpment best illustrate the remarkable stratigraphic and landform features for which the site is primarily considered. Thus, we propose that these three parcels along the main escarpment correspond to the National Natural Landmark boundary at this site (Fig. Thacher, NNL boundary). Should the park expand through acquisition of parcels along the escarpment or adjacent, these might also be included with these present three parcels as parts of the National Natural Landmark.

10 Comparative Analysis

The Helderberg Escarpment provided the master stratigraphic section for the Silurian and Devonian of North America since the earliest days of geology, and ranks among the world's highest in fossil yield and preservation from these Periods (Torrey, 1935). Here the Mohawk and Hudson Rivers enhance exposure of a tectonic boundary in a cuesta to organically reveal over 1700 feet of the stratigraphic section at a single location, unparalleled throughout the Appalachian Plateaus (bio)physiographic province in thickness, completeness, fossil richness, and scientific importance. In the middle of this section at Thacher Park, at the Indian Ladder, the Daughters of the American Revolution and the state of New York erected a 1933 plaque embossed with representative fossils to commemorate the location's geologic significance (Fig. History, geologists). It reads, "In memory of those pioneer geologists whose researches in the Helderbergs from 1819 to 1850 made this region classic ground, among them, Amos Eaton, The John Gebhards, Sr. and Jr., James Hall, William W. Mather, Lardner Vanuxem, James Eights, Sir Charles Lyell, Benjamin Silliman, James D. Dana, Henry D. Rogers, William B. Rogers, Ferdinand Romer, Edouard de Verneuil, Louis Agassiz, Edouard Desor, Sir William Logan." Additional early notable scholars include Jean Rodolphe Aggasiz, Timothy Abbot Conrad, Ebenezer Emmons, and Josiah Dwight Whitney (Torrey, 1935).

In addition to its regionally dramatic cliffs and ravines, John Boyd Thacher State Park's great significance in 19th century geological and paleontological studies in New York and North America has long provided motivation for preservation of the Helderberg Escarpment. In one of the earliest notices of the rocks and fossils of Thacher Park, Spafford (1813, p. 134) described "*A lofty ledge of rocks, of great extent, being the main spine of the Helderbergs, on the eastern border of Bern* [Berne]*, is well worthy the attention of the curious. Its eastern front has the perpendicularity of an artificial wall or a basaltic column, presenting a lofty rampart of 200 to 500 feet elevation, with an upright or shelving precipice, in many places 200 feet high, and perfectly inaccessible but by climbing on ropes or ladders. The rocks abound much with those impressions resembling muscle-shells* [mussel-shells], *attributed to petrefaction* [petrifaction; = fossilization]. *There are many natural caverns, 2 of which are of great extent. One of these has been traced 12 rods under a fine soil on a plain, where the exploring party ascended through a natural shaft or tunnel. Another very extraordinary one opens by a narrow entrance in one of the above noticed precipices, and has been explored about 400 feet, through some spacious openings or rooms*."

By the 1820, pioneering geologist Amos Eaton (1776-1842) published a geological survey of Albany County (Eaton and Beck, 1820). His early forays were followed through the century by regionally to internationally significant geologists and paleontologists (Engel, 2016), recognized in the 1933 plaque placed in Thacher State Park by the Daughters of the American Revolution. The plaque is still prominently displayed at the west end of the Indian Ladder Trail. Geological and paleontological research continued at Thacher and the Helderbergs through the 20th century, and studies are still active today.

The Rensselaer School (later Rensselaer Polytechnic Institute) was founded in 1824 by Eaton. The New York State Geological Survey (NYSGS) was established in 1836, in Albany. As a result, the Troy-Albany area become one of the key early centers of geological and paleontological studies in the U.S. in these still young and developing fields (Friedman, 1998; Aldrich, 2000; Spanagel, 2014). James Hall of the NYSGS/State Museum, a student of Eaton's at the Rensselaer School, became one of the leading American paleontologists and geologists of the 19th century (Clarke, 1921; Fakundiny and Yochelson, 1987). Hall's emphasis on the middle Paleozoic stratigraphy as revealed at the Helderbergs and elsewhere across New York State offered critical insight into early understanding of the Appalachian Mountains (Hall, 1883; Rast, 1989). The combination of being a significant research center, and the proximity of the classic New York rock strata attracted geologists to Albany from across the continent and around the world. In 1856 Louis Agassiz, the 19th century father of glacial geology, famously said "*When European men of science come to this country their first question is: 'Which way is Albany*?'" (Clarke, 1921).

The Helderbergs were of such esteem geologically by the mid-19th century that they were said to be "the key to the geology of North America." The proximity of the Helderbergs to Albany and Troy, the excellent exposures of Late Ordovician to Middle Devonian strata, and their abundant fossils, brought many geologists and paleontologists to the Helderbergs during their visits to Hall and other NYSGS scientists, and Eaton. Following two visits to the Helderbergs in the early 1840s, Great Britain's Sir Charles Lyell, the father of modern geological thought, wrote "the Helderberg outcrops must be known to every geologist if he were to understand his science."

Around the turn of the nineteenth to twentieth centuries, John Boyd Thacher travelled to Europe multiple times, doing historical research. John C. Clarke has written "*On one of his returns he told me that he had heard so much of the Helderbergs, their rocks and their fossils, among circles of savants with whom he was thrown that he determined to do his part to preserved this famous cliff* [today's high cliffs at Thacher Park] *from any danger of invasion, because of its natural beauty and extraordinary scientific interest*." (Clarke, 1914, p. 418). Following this, Mr. Thacher began quietly buying up property, which in 1914 became the first 350 acres of the Helderbergs to be preserved, as John Boyd Thacher State Park.

To again quote John Clarke, "*Next, perhaps, to the Schoharie Valley, the Helderbergs and the Indian Ladder have the most intimate and ancient association with the history of geology in this state and are really a classic ground in American geological science*." (Clarke, 1914). Thacher Park, now at 2155 acres, preserves a significant slice of earth and life history between 450 to 388 million years ago. It also is a reserve that was of great significance in the early development of the sciences of geology and paleontology in America. While of less significance today than in the early to mid-19th century, the Helderbergs at John Boyd Thacher Park continue to be a center of geological research and earth science education for professionals, students and the public.

10.1 Late Silurian-Devonian Periods: Rise of Vertebrates, First Forests

10.1.1 *Recognized Contemporaries*

Fall Brook Gorge (42°46'32" N, 77°49'43" W) in Livingston County, NY is the only designated National Natural Landmark that addresses the Silurian-Devonian period theme in the same biophysiographic province (Appalachian Plateau) (National Parks Service, 1990). It also plots within the same region (Glaciated Allegheny Plateau) of the province. However, the Middle to Upper Devonian stratigraphic section at Fall Brook Gorge lies slightly higher in the sequence, thus representing a younger interval of time with respect to the natural record at Thacher. Fall Brook Gorge exposes the Moscow Formation at the top of the Hamilton Group, and the Geneseo Shale of the eponymous Group above (Grossman, 1938; Wells, undated; Fisher et al., 1970). In this region these units are siliciclastic and terrigenous with relatively high sedimentation rates, sandstones and shales with few fossils (De Witt and Colton, 1978; Whiteley et al., 2002), despite the Hamilton's general fossil richness (Whiteley et al., 2002). In a bed at the top of the Geneseo Shale, the inarticulate brachiopod *Orbiculoidea lodiensis* dominates an assemblage of small invertebrates (Cole et al., 1959). The falls and the gorge seem to be the primary geologic resources here rather than the Middle Paleozoic stratigraphy or fossils. Moreover, although Fall Brook Gorge is accessible via hiking trails, the parcel is privately owned and less accessible than Thacher, its natural resources less well protected.

10.1.2 *Proposed Sites*

Aside from Thacher, six potential National Natural Landmark sites in the Appalachian Plateau would address the Silurian-Devonian rise of vertebrates and the first forests (Baer et al., 1982). In Thacher's section (Glaciated Allegheny Plateau) these are: Chenango Valley State Park (NY), Chittenango Falls (NY), Letchworth Gorge (NY), Syracuse Meltwater Channels (NY), and Watkins Glen State Park (NY). Unlike Thacher, these are in central and western regions of New York State. In the Finger Lakes and Niagara Regions of New York State, stratigraphic groups express themselves somewhat differently than in the Mohawk Valley-Catskill Mountains Region, where Thacher is located, and facies, lithology, and formation names change accordingly toward the west. Nonetheless, two of these, Syracuse Meltwater Channels and Chittenango Falls, are immediate Upper Silurian-Lower Devonian stratigraphic contemporaries of Thacher Park. Moving up through the thick Middle and Upper Devonian siliciclastic Catskill Delta sequence encounters Chenango Valley, Watkins Glen, and Letchworth Gorge. Within the unglaciated Allegheny Plateau of the Appalachian Plateaus province, World's End State Park (PA) also addresses the Silurian-Devonian rise of vertebrates and the first forests theme. The section at Worlds End includes the uppermost Devonian, but is mostly in fact Carboniferous in age.

The Syracuse Meltwater channels (NY) (43° 00’ N 76° 02’ W) are located parallel to East Seneca Turnpike (NY-173) west of Jamesville, New York, and are made use of by various private owners. Seven channels were carved by erosive stream power of receding glaciers within a relatively small area, at times by very severe flooding of meltwater flowing west to east (Baer et al., 1982). In the southwest section of the channels is a large quarry, the Kinsella Quarries’ Barrett Pit. Here Devonian limestone is mined in the form of various types of stone and gravel including gabion stone, mason and concrete sand (T.H. Kinsella, 2015) (Baer, 1982). In addition to quarrying, the meltwater channels are home to a golf course, woodlots, a railroad, tailings pond, and residences (Baer, 1982). In the east, the Butternut Trough leads to a glacial lake filled with deltaic till from one of these flooding events (Baer, 1982). The meltwater channels are situated in a region where a compressed latest Silurian to Middle Devonian section is exposed (Fisher et al., 1970), and so provides an immediate stratigraphic contemporary to Thacher. The section at the Meltwater Channels begins in the Cobleskill Limestone (gray limestone with argillaceous dolostone), composed of the Camillus Shale and Bertie Dolostone, and ranges upward through the Rondout (locally Chrysler) Dolostone, the Manlius Formation of the Helderberg Group, and into the Oriskany, Schoharie, and Onondaga Formation above the Wallbridge Unconformity (Isachsen et al., 1991). The Bertie, deposited in a very shallow-water setting is known to contain eurypterids and some of the oldest land plants, although the plants are focused in the Niagara Peninsula (Edwards et al., 2004). The Cobleskill contains abundant crinoids, coral, stromatoporoids, and other skeletal remains (Whiteley et al., 2002). The Rondout/Chrysler Formation (dolomite) is much thicker in this part of New York State versus in the east and the Manlius manifests as thinly layered micritic (carbonate mud) facies, and stromatoporoid biostromal reef buildups (Isachsen et al., 1991). In the Syracuse area the Manlius Limestone is only 10 meters or less thick, and is the only unit of the Helderberg Group present (DeMicco and Smith, 2007); in contrast, the Helderberg Group at Thacher Park comprises 5 different formations, and is 66 meters thick (Rickard, 1962). Overlying sandstones are assigned to the Lower Devonian Oriskany and Schoharie (Carlisle Center Member) Formations (Ver Straeten). Through the northern Finger Lakes Region to the Niagara Peninsula, as at Chittenango Falls (discussed below) the lower Onondaga Formation is dominated by crinoidal packstones to wackestones (limestone with varyingly dispersed fossils) (Cassa and Kissling, 1982). The section here offers varying natural features of interest in its fossils and shallow-water sedimentary structures. Middle Paleozoic stratigraphy is widely exposed especially in the large Jamesville Quarry – however access is limited, especially in the quarry, and it is even difficult now for geologists to visit. Moreover, as the site’s name implies, the principal geologic features of interest here are the glacial meltwater channel forms rather than any Middle Paleozoic stratigraphy thereby exposed. As far as the availability of so many different Paleozoic rock units across a longer interval of time, and the nearly full access to rock strata and features, Thacher Park is a much more significant site than the Syracuse Meltwater channels.

Chittenango Falls (NY) (42° 58’ N 75° 50’ 30” W), is a state park in Madison County, NY, located between Cazenovia Lake and NY-13/Chittenango Creek. This park’s most impressive feature is its narrow 167-foot-high gorge (Baer, 1982). Like many of the other scenic fluvial (riverine) landforms in New York, it was formed by erosive meltwater and glacial drift during glacial intervals (Holmes, 1935). Chittenango State Park is known for its Early and Middle Devonian limestones exposed within the gorge and visible from certain specific viewpoints. The waterfalls of Chittenango Gorge are composed of unconformably deposited limestones from the Onondaga and Helderberg Formations (Van Diver, 1985). Onondaga Limestone, named after Onondaga County, PA, is a gray-blue crinoidal limestone shoal in the northern Finger Lakes region (Fisher, 1970; Cassa and Kissling, 1982) while the Helderberg Group contains limestone and dolostone formations thinner here in the west than in eastern New York (Fisher, 1970). Overall, Chittenango Falls State Park is roughly another stratigraphic contemporary of Thacher Park. However, older Ordovician shales and sandstones associated with uplift and erosion of the Taconic Orogeny are absent at this site. And as at the Syracuse Channels, most of the Lower Devonian Helderberg

Group is absent. Again, Uppermost Silurian micritic limestones of the Manlius Formation, formed in shallow-water peritidal or subtidal environments, are well developed. Only a few meters of the Lower Devonian Coeymans Formation overlies the Manlius Limestone at Chittenango Falls (DeMicco and Smith, 2007). It is a coarser-grained crinoid- and brachiopod-rich grainstone or packstone representing a high-energy shoal environment, (Isachsen et al., 1991; Rickard, 1975, 1981). The remainder of the Helderberg Group and younger pre-Onondaga Lower Devonian strata present at Thacher Park (six formations) are absent at Chittenango Falls State Park. Above the Wallbridge Unconformity, the Onondaga Limestone is widespread and contains bentonite beds, forming an important stratigraphic marker of the Middle Devonian in eastern North America (Whiteley et al., 2002). This unit's basal Edgecliff Member forms the hard lip of the falls (NYS Geological Association, 2007; Chittenango Falls State Park, 2017). This region of New York would have been a shelf environment where crinoidal grainstone rich in crinoid columns, a diversity of corals, and trilobites was deposited (Cassa and Kissling, 1982; Brett and Ver Straeten, 1994; Whiteley et al., 2002). Despite this relatively rich Middle Paleozoic stratigraphy at Chittenango Falls, the section is much smaller and less complete than at Thacher.

Chenango Valley State Park (NY) (42° 12' 30" N 75° 50' W) is located north of Binghamton in Broome County, south of Chenango Forks. It has an impressive landscape influenced by the area's deglaciation with features such as kettle lakes where motionless blocks of ice were covered with sediment and thawed, resulting in deep depressions as well as hills where sediment deposits were carved away into distinctive shapes (Brigham, 1897). This state park's bedrock geology consists of Upper Devonian rock groups, including formations of the Genesee Group and Sonyea above. Chenango Valley State Park is bordered by the Chenango River, incised to reveal underlying bedrock formations, including the regional border between Sonyea and Genesee groups (Van Diver, 1985). The Genesee Group that underlies the Sonyea is composed of primarily shale and limestone (Fisher, 1970). These predominantly clastic sediments were deposited in a dysoxic to anoxic environment that would have inhibited marine life (Whiteley et al., 2002). However, such an environment would have favored preservation of organisms sinking to the seafloor from above after death, and driftwood fragments and fossils of swimming organisms (goniatites, nautiloids, conodonts) are locally common in these rocks (Whiteley et al., 2002). The Sonyea Group is made up of shale and siltstones, too: Cashaqua Shale, Rock Stream Siltstone, and Pulteney Formation are the primary constituents in this region (Colton and de Witt, 1958). These are thick delta facies deposits, generally poor in fossils except for brachiopod and bivalve coquinas (shell hash) in some beds (Whiteley et al., 2002). The Middlesex Formation, though an important part of this group, pinches out before Chenango Valley State Park. In sum, it seems that the glacial and fluvial features of Chenango Valley are more remarkable than its Middle Paleozoic stratigraphy and fossil assemblages. None of the strata found at Thacher State Park are present at Chenango Valley; nor is the diversity of their rock strata and fossils. And the park's strata comprise a relatively short interval of geologic time and history relative to Thacher Park.

Watkins Glen State Park (NY) (42° 22' 37" N 76° 52' 18" W) is a 668-acre park whose most impressive feature is a 300-foot gorge carved by glaciers and postglacial erosion (Baer, 1982), found in Schuyler County at the southernmost edge of Seneca Lake. The state park boasts nineteen waterfalls within a two mile expanse that display variously exposed Devonian formations. Venturing downstream in Glen Creek leads to the Geneseo Shale of the Upper Devonian Genesee Group (Van Diver, 1980). Above is the Sonyea Group, which accounts for the bulk of the section at Watkins Glen (Van Diver, 1985). Specifically these are the Enfield siltstone and shales cut by Glen Creek (Van Diver, 1985). Characterized by rapidly deposited siliciclastic sediments of the Catskill Delta, the Upper Devonian section is generally poorly fossiliferous as discussed above (Whiteley et al., 2002). Nonetheless, beds within the gorge contain invertebrates including brachiopods, gastropods, trilobites, crinoids, molluscs, and corals (Baer, 1982). The fluvial features and associated landforms (i.e. slot canyon, waterfalls) represent the primary geologic features of interest, the stratigraphy and sedimentary rock characters deserving lesser attention here. Again, none of the strata found at Thacher State Park are present at Watkins Glen, whose homogenous and poorly fossiliferous character also preserve only a relatively short interval of geologic time and history.

In western New York Letchworth State Park (42° 38’ 5” N 77° 59’ 30” W) forms a 2-3-km-wide buffer stretching over 20 kilometers along the Wyoming/Livingston County line. Here the Genesee River famously eroded a canyon known as Letchworth Gorge or the “Grand Canyon of the East” to expose Middle Paleozoic bedrock. The young gorge results from the rerouting of the Genesee River to the west following deglaciation (Roseberry, 1982). There are three major waterfalls here as well as an abundance of stunning scenic overlooks (Baer et al., 1982). Up to six hundred feet of relief in parts of the gorge (Baer et al., 1982) expose a thick Upper Devonian section consisting of sandstones and black to gray shales of the West Falls Group and the shales interbedded with the Sonyea Group (Van Diver, 1980). Letchworth Gorge’s upper falls are capped by thick sandstone beds interbedded with shale of the Nunda Formation (Van Diver, 1985). The capstone for the middle falls is the Gardeau Formation, shale with some siltstone and another part of the West Falls Group (Fisher, 1970). The lower section of the gorge containing Mt. Morris Dam exposes the West Falls Group (Rhinestreet Formation) as well as formations from the Sonyea Group (Middlesex and Cashaqua) and a small section of the Genesee Group’s West River Shale and Genundewa Limestone (Van Diver, 1985). As discussed in Section 3, “Distribution…,” and above for Chenango Valley State Park, these siliciclastic units are generally poor in fossils. Despite the impressive thickness of this section, elevated sedimentation rates mean that this extensive package represents a relatively short interval of geologic time (some 3-5 million years) during the Frasnian Stage of the Late Devonian (NYSM Letchworth Gorge, 2017), much less time than at Thacher. The spectacular landform of the fluvially-carved gorge or canyon and its impressive size seems to account for most of the richness in natural resources or beauty here. And indeed these are remarkable: in 2015 Letchworth was voted best state park in the nation by the readers of USA Today (USA Today 10 best, 2017). However, once again, the diversity of strata and fossils, and the length of time represented by the strata here are much less than in the Upper Ordovician to Middle Devonian strata at Thacher Park.

Directly south of Ithaca, NY, over the Pennsylvania border lies World’s End State Park (41° 28’ 17” N 76° 34’ 07” W) - west of PA-220 in Forksville (PA). As a part of the Unglaciated Allegheny Plateau, glacial influence here has been reduced. Previous glaciations, however, have deposited till and boulders, and wetlands formed after glacial scouring (Royer, 1980). Landscape topography of the area has been molded primarily by continental uplift and the subsequent erosion of areas with increased elevation, forming flat-topped hills incised by rivers (Royer, 1980). Its largest river, Loyalsock Creek, has carved an 800-foot-deep gorge through the middle of the park (Royer, 1980). The plateau-like character of the mountains in this area is due to erosion of the horizontally bedded sedimentary formations that make up their underlying structure. The highest elevations in the park are composed of the Pottsville Formation, a Pennsylvanian formation consisting of light-gray quartzose sandstone and coarse-grained, weathering-resistant conglomerate (Royer, 1980; Szabo, 1988). Underlying the Pottsville Formation is the Mississippian Mauch Chunk Formation, a unit of red sandstone and shale that forms the walls and rim of the Loyalsock Creek Gorge (Royer, 1980; Berg, 1980). Mississippian Burgoon sandstone, a gray sandstone with secondary constituents of conglomerate and shale, lies below, and the Mississippian/Upper Devonian Huntley Mountain Formation forms the gorge’s base layer of rock (Royer, 1980; Berg, 1980). The Huntley Mountain Formation is primarily a non-resistant olive-gray sandstone with gray-red shale (Royer, 1980). Trace fossils, lungfish burrows, are found at World’s End state park near the Devonian-Carboniferous boundary (Royer, 1980). Despite these fossils, the substantial thickness of the section at World’s End, and the large interval of geologic time thereby represented, this material is chiefly younger than the middle Paleozoic interval of focus. Moreover, the stratigraphy does not provide the chief geologic feature of interest. As implied by the park’s dramatic name, the landscape and gorge are the main focus here.

10.1.3 *Comparison Summary*

We conclude that Thacher State Park's Middle Paleozoic stratigraphy is unparalleled among it contemporaries and recommend the site for desgination as a National Natural Landmark on this basis. Its extensive cuesta naturally showcases the Silurian-Devonian strata, and hiking trails, road cuts, and natural cliffs invite visitors to its exposures. In contrast, among Thacher's contemporaries, exposure of Silurian and Devonian rocks owe instead to incision by rivers and thus manifest as gorges and falls, with limited emphasis on—and in many cases, exposure of and access to—the stratigraphy. The Syracuse meltwater channels are lacking in accessibility due to land development and privatization. The dramatic topography of the gorges, while exposing thick sections, often limits accessibility. Thacher sets itself apart from the rest of these potential natural landmarks again with its 1700-foot-thick fossil-rich stratigraphic section, rivaled only by Letchworth Gorge and World's End in thickness. The interval of Middle Paleozoic time recorded at Thacher is even more impressive. Thacher's stratigraphy spans from the Late Ordovician (Schenectady Formation), captures the Late Silurian, extends through the Early Devonian and into the Middle Devonian. It's a critical interval of time, as the completeness of the record here links the Queenston Delta and the Catskill Delta to provide stratigraphic keys that unlocked early understanding of the Appalachian region of eastern North America (Hall, 1883; Rast, 1989; Isachsen et al., 2000). We now understand the corresponding orogenic activity to be more continuous than discrete Taconic and Acadian episodes (Hibbard et al., 2006; Domeier, 2016). Nonetheless the longstanding view of sedimentary packages corresponding to mountain building provided useful first-order understanding of eastern geology in Eastern North America through the twentieth century. Thacher's immediate Lower Devonian contemporaries, Syracuse Meltwater Channels and Chittenango Falls, suffer from a smaller interval of time represented not only due to the thickness of the section, but by a longer Wallbridge Unconformity, which widens the gap in coverage of the Early Devonian interval. Higher up in the section, rapid sedimentation of siliciclastic material in the Catskill Delta sequence reduces fossil richness and prevents even Letchworth Gorge's thick section from capturing more than a few million years of time. Sadly, no proposed sites capture the Middle Devonian Hamilton Group's fossiliferous limestones, which might rival Thacher's stratigraphic resources through evolution of life in the fossil record. Moreover, Thacher's contemporaries are recognized primarily for other impressive geologic features while their stratigraphy is of secondary importance. The glacial and fluvial features of these sites are no doubt notable and deserve recognition as potential landmarks: their gorges, waterfalls, kettle lakes, channels, etc. are geologically and scenically valuable. But at Thacher, remarkable Middle Paleozoic stratigraphy has long been and remains the site's central focus.

10.2 Cuestas and Hogbacks

10.2.1 *Recognized Contemporaries*

Only one established National Natural Landmark, Buzzardroost Rock-Lynx Prairie-The Wilderness (OH), (38.77°N, 83.45°W) addresses the Cuestas and Hogbacks theme within the Appalachian Plateaus biophysiographic province. Like Thacher, this site straddles the boundary of the Appalachian Plateaus province with an adjacent lowland province, this one to the southwest (Interior Low Plateau). Nearly flat-lying early Middle Paleozoic rocks of various lithologies are cut by Brush Creek and its tributaries in proximity to the maximum extent of Illinoian (penultimate) glaciation (National Park Service, 2007). These conditions, combined with the few hundred feet of vertical relief, make for a natural showcase of prairie, wetland, and various forest environments, which enjoyed a long history of study over the twentieth century, and numerous rare species are supported in these habitats here (National Park Service, 2007). Thus, the cuesta supports an ecologically significant area that provided critical understanding in the conceptual development of the Eastern Deciduous Forest Biome (National Park Service, 2007).

10.2.2 *Proposed Sites*

Among proposed National Natural Landmark sites within the Appalachian Plateaus province, only Tug Hill (NY, in the Mohawk Section) (43°30’-44°00’N, 75°15’-76°00’W) would address the Cuestas and Hogbacks theme. Tug Hill, or Tug Hill Plateau—the landform is a 3000-4000-square-mile area—is characterized by high elevations (up to 2100 feet) and its own severe weather (Baer et al., 1982). The plateau margin receives an average of over 150 inches of snowfall annually, and over 200 inches annually in the interior (Muccilli, 2015). In the eastern United States, Only Mount Washington receives more snow, but Tug Hill spans a much larger area (Muccilli, 2015; Coin, 2015). Too deep to freeze in the winter, Lake Ontario, to the west, provides lake effect snows all winter long (Coin, 2015). Accordingly, two Level IV Environmental Protection Agency ecoregions are recognized corresponding to the increasingly severe weather toward the higher elevations in the center of the plateau (Bryce et al., 2010). Some 885 species of plants, 52 rare or endangered, are described at Tug Hill Plateau and the center of the plateau is covered by unbroken forests (Baer et al., 1982). A cuesta is cut into the Ordovician sediments of the Queenston Delta at the intersection of the Black River Valley and the eastern margin of Tug Hill Plateau, as exemplified at Whetstone State Park and Gomer Hill (2100 feet) (Baer et al., 1982). Higher elevations along the cuesta afford scenic vistas of the Black and Mohawk Valleys, and the cuesta illustrates a transitional ecoregion between the deciduous forests further south in the Appalachian Plateaus province and the more alpine coniferous forests of the Adirondacks to the east (Baer et al., 1982; Bryce et al., 2010).

10.2.3 *Comparison Summary*

Although the Helderberg Escarpment is not as extensive as the cuesta at Tug Hill, and perhaps does not provide the level of ecological richness at Tug Hill or Buzzardroost Rock-Lynx Prairie-The Wilderness, Thacher’s cuesta nonetheless provides attractive and impressive scenic vistas and greatly increases ecological diversity, thereby enriching and complementing the primary focus on its stratigraphy.

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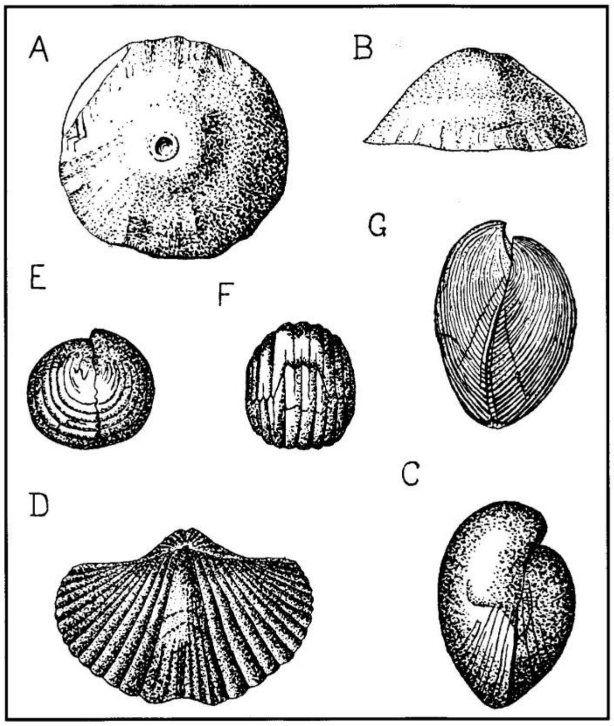
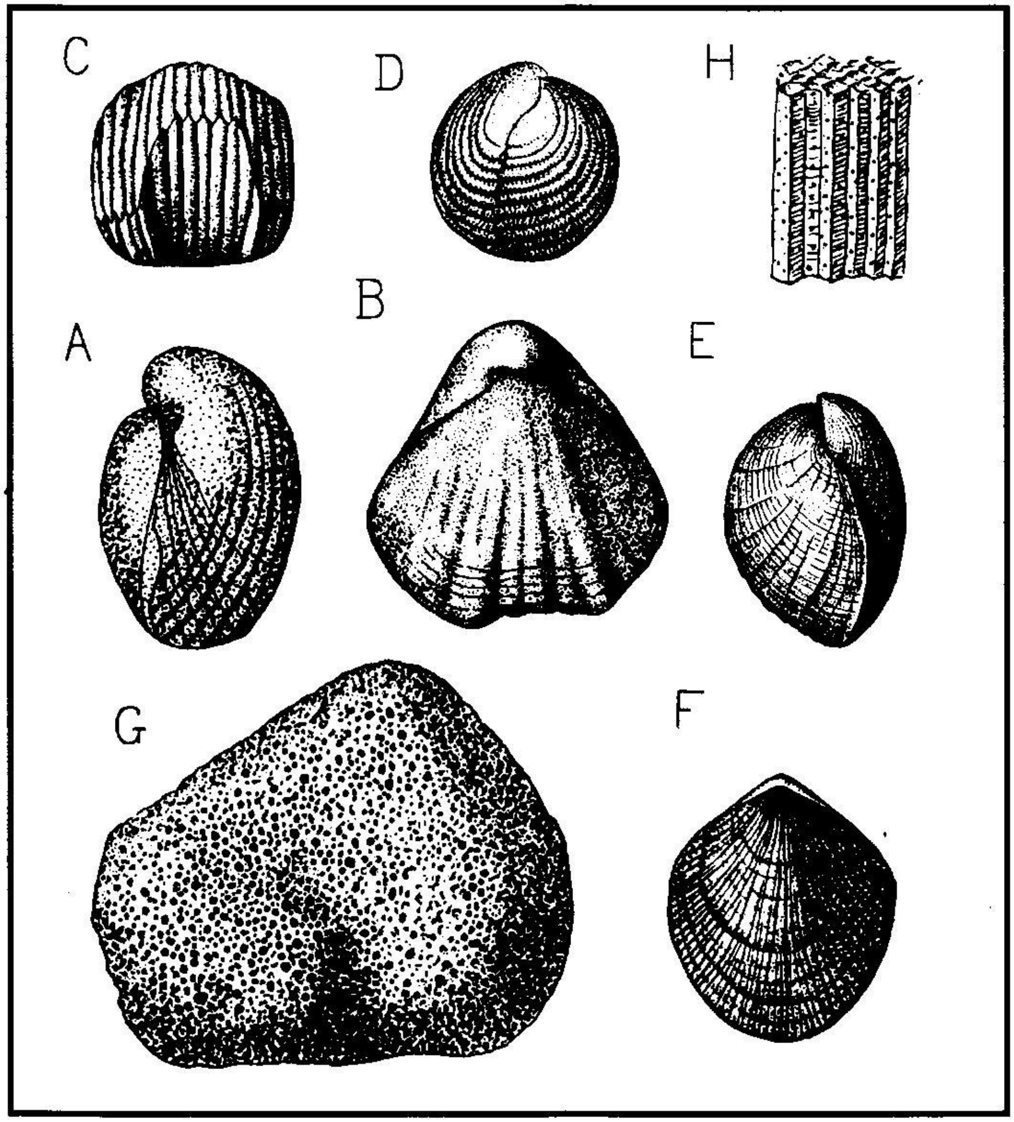


Becraft, fossils. A, B: crinoid bases; C-G: brachiopods. A, B: *Aspidocrinus scutelliformis*. C: *Gypidula pseudogaleata*; D: *Concinnispirifer concinnus*; E, F: *Uncinulus ventricosa*; G: *Schizophoria multistriata*. All illustrated at actual size. From Goldring (1933).

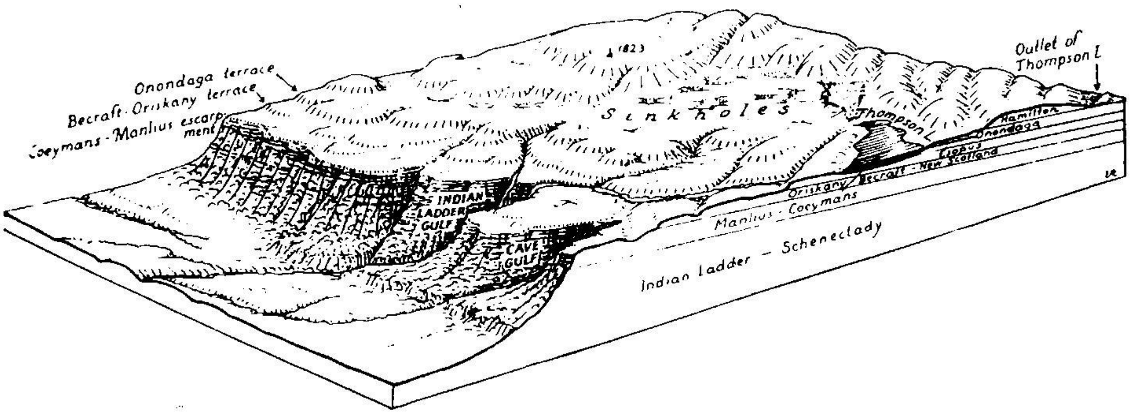
Coeymans, brachiopods. Fossilized brachiopods weather out of the Coeymans skeletal limestone. Finger for scale. Photo by D. DiQuinzio (NPS), September 2014.

Coeymans, coral. *Favosites helderbergiae*, a solitary coral, in Coeymans limestone at the entrance to Indian Ladder trail. The coral is on the order of 30 centimeters in width. Photo by C. Ver Straeten, July 2015.

Coeymans, crinoids. Crinoid columns weather out of the Coeymans skeletal limestone. Columns approach 10 cm in diameter. Photo by D. DiQuinzio (NPS), September 2014.



Coeymans, fossils. A-F: brachiopods; G, H: coral. A, B: *Gypidula coeymanensis* (AKA *Gypidula galeata*), actual size; C, D: *Uncinulus mutabilis*, actual size; E, F: *Atrypa reticularis*, actual size; G, H: *Favosites helderbergiae*, 2/3x, with enlargement of coralites. From Goldring (1933).



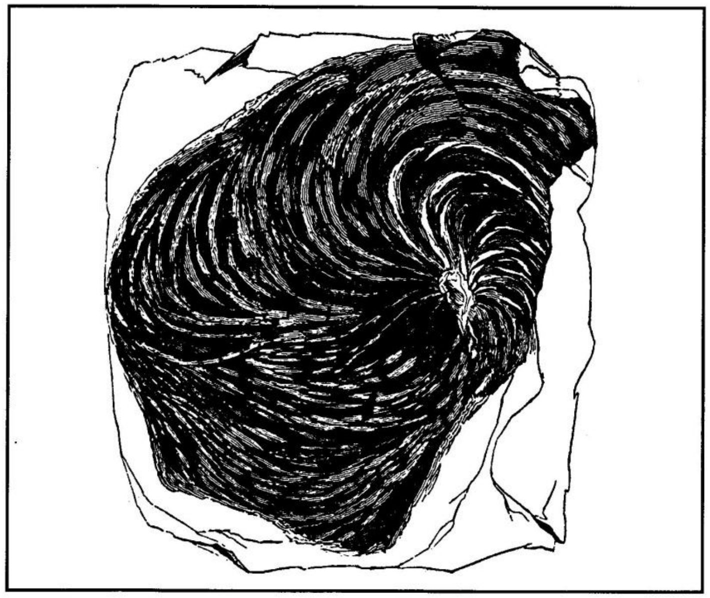
Cuesta, block diagram. Illustration of the Helderberg Escarpment at Thacher State Park from the northeast showcases the cuesta landform. From Goldring, 1933. After Cleland (1930).

Cuesta, southeast vista. View facing southeast from the Coeymans-Kalkberg contact at the Horseshoe, a promontory at Thacher Park. Photo by D. DiQuinzio (NPS), September 2014.

Ecology, salamander. A red eft along a layer in the limestones on Indian Ladder trail. Photo by D. DiQuinzio (NPS) September 2014.

Escarpment, 100-foot. The most dramatic cliff in the Helderberg Escarpment cuesta is found in the lower Helderberg Group and introduces vertical relief of some 100 feet. Photo by D. DiQuinzio (NPS), September 2014.

Escarpment, facilities. Much of the infrastructure and improvements to Thacher's grounds are built above the 100-foot cliff on the lower Kalkberg. Photo by D. DiQuinzio (NPS), September 2014.



Esopus Formation, fossils. Trace fossil of a worm burrow, or cockstail, *Zoophycos caudagalli*. From Goldring (1933).

Esopus, glen. The upper reaches of Minleot Brook cut a small steep-sided glen through the Tri-States Group in the southwest of Thacher Park. Photo by N. Venti, December 2015.

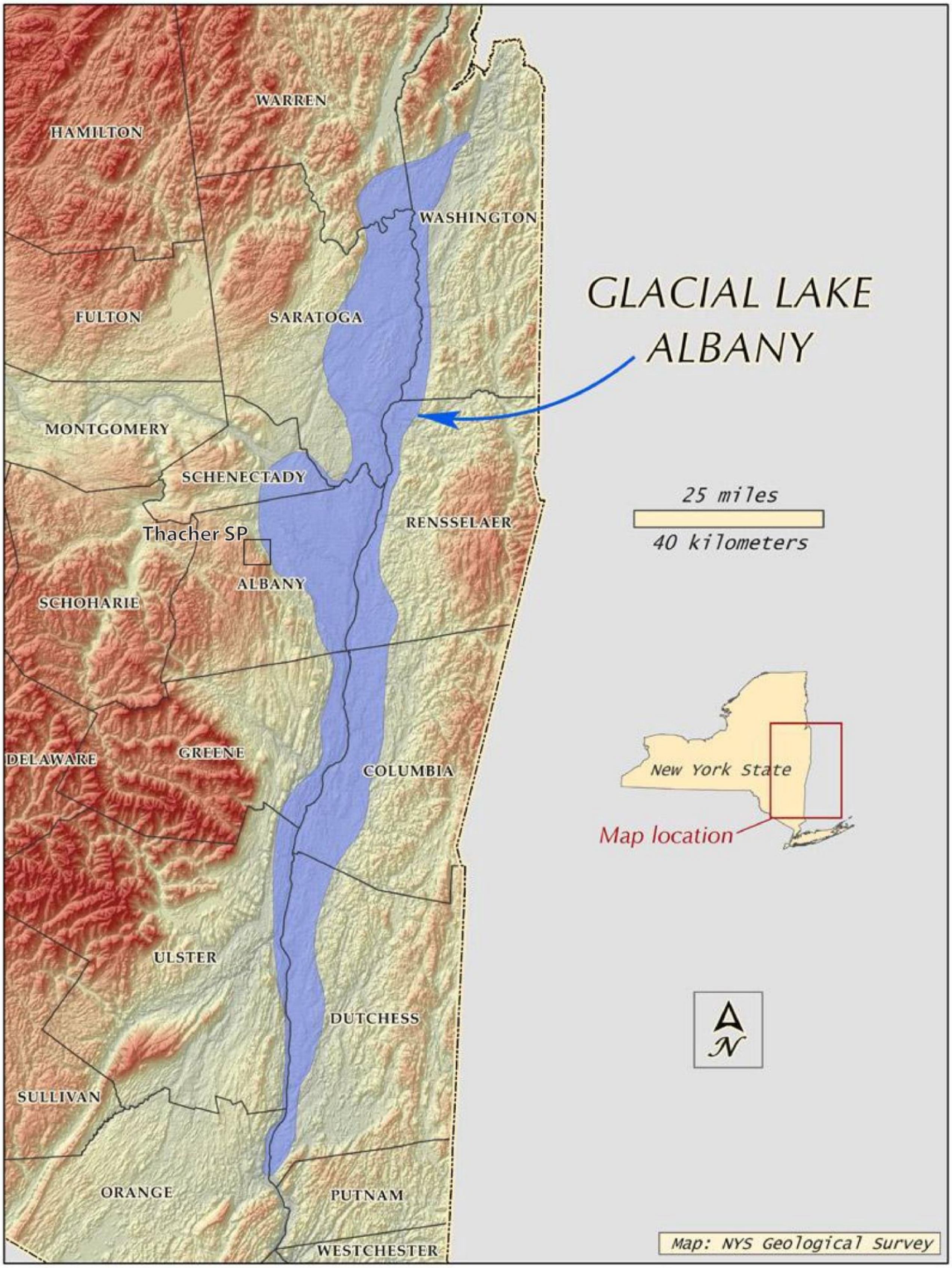
Facilities, Nature center. Information and programming about the natural resources of Thacher Park: ecology, wildlife, geology, and fossils (and this model of the park, which illustrates the cuesta landform) is provided at the Nature center at Thompson's Lake. Photo by D. DiQuinzio (NPS), September 2014.

Facilities, overlook. The top of the 100-foot cliff at the lower Kalkberg Limestone affords a number of scenic vistas across the valleys to the north and east. Photo by D. DiQuinzio (NPS), September 2014.

Falls, Minelot Creek. Minelot Creek scours a pavement on the Kalkberg and Coeymans Limestones and provides a thrilling view from the top of the 100-foor cliff. Photo by D. DiQuinzio (NPS), September 2014.

Falls, Minelot dry. Indian Ladder trail provides an impressive view of the cliff at Minelot Falls, even without any water. Photo by C. Ver Straeten, June 2003.

Falls, Minelot flowing. Minelot Creek flows over the 100-foot cliff above Indian Ladder trail, cutting into the Coeymans limestone at the top of the frame. Photo by C. Ver Straeten, October 2003.

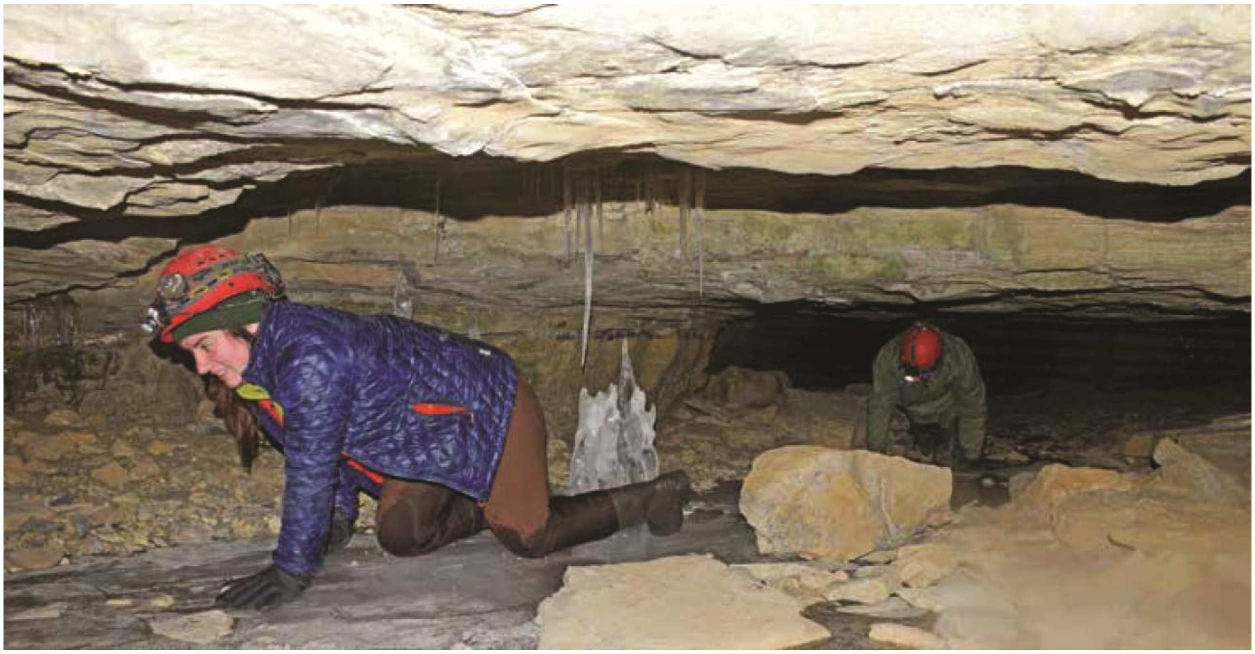

GLACIAL LAKE ALBANY
WARREN
HAMILTON
WASHINGTON
FULTON
SARATOGA
MONTGOMERY
SCHENECTADY
Thacher SP
ALBANY
RENSSELAER
SCHOHARIE
25 miles
40 kilometers
DELAWARE
GREENE
COLUMBIA
New York State
Map location
ULSTER
DUTCHESS
N
SULLIVAN
ORANGE
PUTNAM
WESTCHESTER
Map: NYS Geological Survey

Glacial Lake Albany (New York State Museum and Geological Survey, Hudson River Lake Clay Exposures, 2017)

Hailes, bats. Haile's Cave provides a critical hibernaculum for bats. Photo from DeBolt (2015).

Hailes, gate. A gate at the entrance to Haile's Cave prevents cavers from disturbing bats. Photo from DeBolt (2015).

Hailes, Helmus Crack. An expanded joint through the Coeymans Limestone, known as Helmus Crack, or Fat Man's Misery, now closed to the public, would allow access to Haile's Cave. Here bat ecologists carry steel to weld a gate at the cave entrance. Photo from DeBolt (2015).



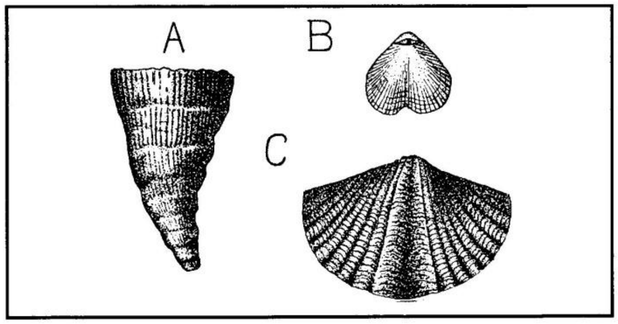
Hailes, interior. A bat survey team crawls through Hailes Cave. Photo from DeBolt (2015).


IN MEMORY OF
THOSE PIONEER GEOLOGISTS
WHOSE RESEARCHES IN THE
HELDERBERGS FROM 1819 TO 1850
MADE THIS REGION CLASSIC
GROUND · AMONG THEM ·
AMOS EATON
THE JOHN GEBHARDS, SR. & JR.
JAMES HALL
WILLIAM W. MATHER
LARDNER VANUXEM
JAMES EIGHTS
SIR CHARLES LYELL
BENJAMIN SILLIMAN
JAMES D. DANA
HENRY D. ROGERS
WILLIAM B. ROGERS
FERDINAND ROEMER
EDOUARD DE VERNEUIL
LOUIS AGASSIZ
EDOUARD DESOR
SIR WILLIAM E. LOGAN
PLACED BY
TAWASENTHA CHAPTER, N.S. D.A.R.
AND THE STATE OF NEW YORK
IN THE YEAR 1933

History, geologists. The plaque at the Indian Ladder lists notable early geologists of the Helderberg region. Photo by C. Ver Straeten, October 2003.

Indian Ladder, sign. The Indian Ladder trail leads visitors down the 100-foot cliff, along the base of the Helderberg Group, and back up to the cliff top. It begins at Indian Ladder, once a notched tree, then a long ladder, and now a set of stairs with handrails. Photo by D. DiQuinzio (NPS), September 2014.

Indian Ladder, trail. Indian Ladder trail leads Thacher's visitors on a scenic hike through the stratigraphy of the lower Helderberg Group. Photo by D. DiQuinzio (NPS), September 2014.



Kalkberg, fossils. A: coral, *Streptelasma (Enterolasma) strictum*, actual size; B: brachiopod, *Dicoelosia varica*, 1 1/3x; C: brachiopod, *Howellella cyclopterus*, actual size. From Goldring (1933).

Kalkberg, terrace. The Kalkberg Limestone forms a low terrace, broken in the area of Thacher Park, outcropping on the southwest side of the cuesta dip slope opposite the 100-foot cliff. Photo from D. DiQuinzio (NPS), September 2014.

Karst, Bridal Chamber. The Bridal Chamber, or Giant's Castle, in the Manlius Limestone, is one of many shelter caves in the lower Helderberg Group. Photo by D. DiQuinzio (NPS), September 2014.

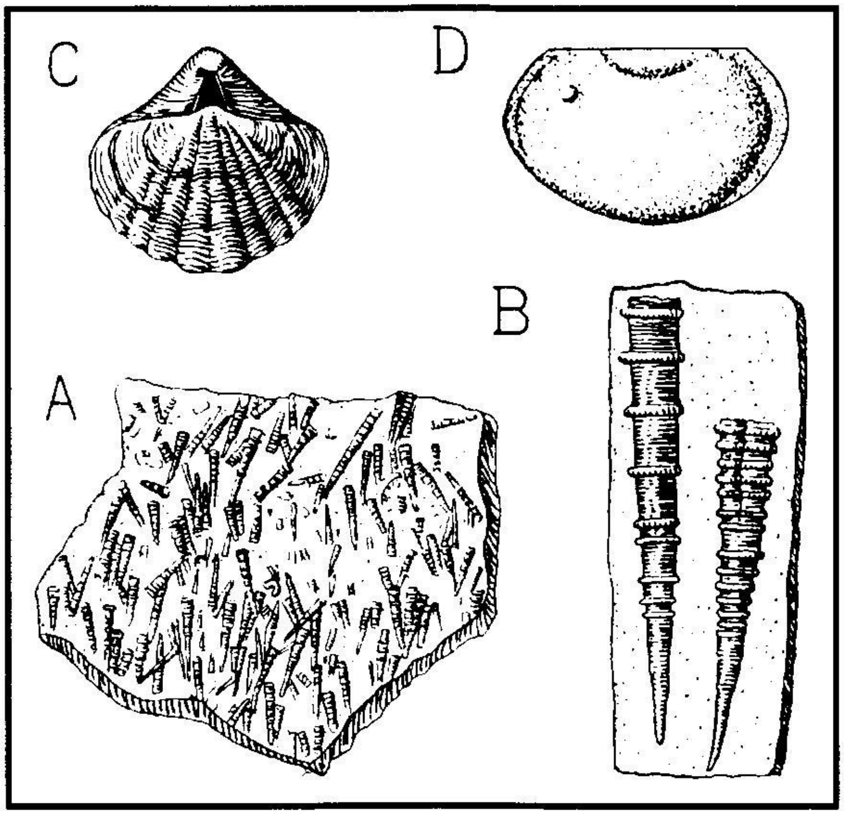
Karst, Fools Cave. Fools's Cave, Thacher's second longest, extends far into the lower Helderberg Group and emerges as a spring at the contact of the Manlius Limestone with the underlying, more resistant Rondout Dolostone along Indian Ladder trail. Photo by D. DiQuinzio (NPS), September 2014.

Karst, outlet. In the Helderberg area numerous springs emerge at the base of the Helderberg Group, at the contact of the Manlius and underlying Rondout Dolostone, Here the Indian Ladder trail passes the entrance to Fools Cave and its spring. Photo by D. DiQuinzio (NPS), September 2014.

Karst, pavement. Chuck Ver Straeten cautiously examines a grike on the surface of the Onondaga Limestone north of Beaver Dam Road. Photo by N. Venti, December 2015.

Karst, shelter cave. The Manlius Limestone, less resistant to weathering than the Coeymans Limestone above, develops shelter caves, as seen here along Indian Ladder trail. Photo by D.DiQuinzio (NPS), September 2014.

Karst, sinkhole. Where covered by overburden, steep-sided cone- and trough-shaped sinkholes, like this one south of Beaver Dam Road form in the Onondaga Formation. Photo by N. Venti, December 2015.



Manlius, fossils. A: *Tentaculites gyracanthus*, actual size; B: *T. gyracanthus*, 4x; C: brachiopod, *Spirifer vanuxemi*, 3x; D: ostracode, *Leperditia alta*, 4x. From Goldring (1933).

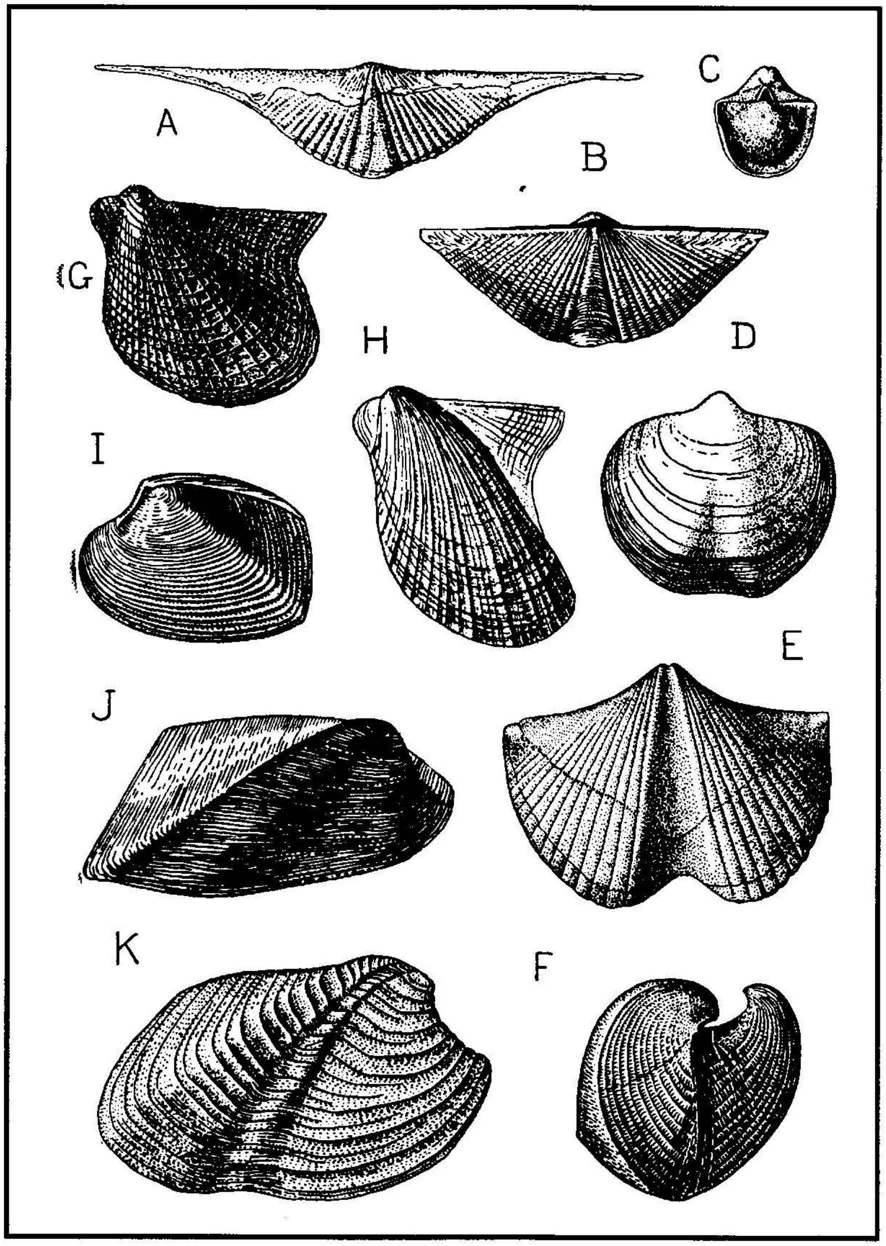
Manlius, Indian Ladder. Charles "Chuck" Ver Straeten and Nancy Engel along Indian Ladder trail below thin beds of Manlius limestone. Photo by N. Venti, December 2015.

Manlius Limestone. A thin, less resistant and buff-gray weathering dolostone layer in the upper Manlius Limestone, is bounded by limestones with stromatoporoid sponge reefs. Photo by D. DiQuinzio (NPS), September 2014.

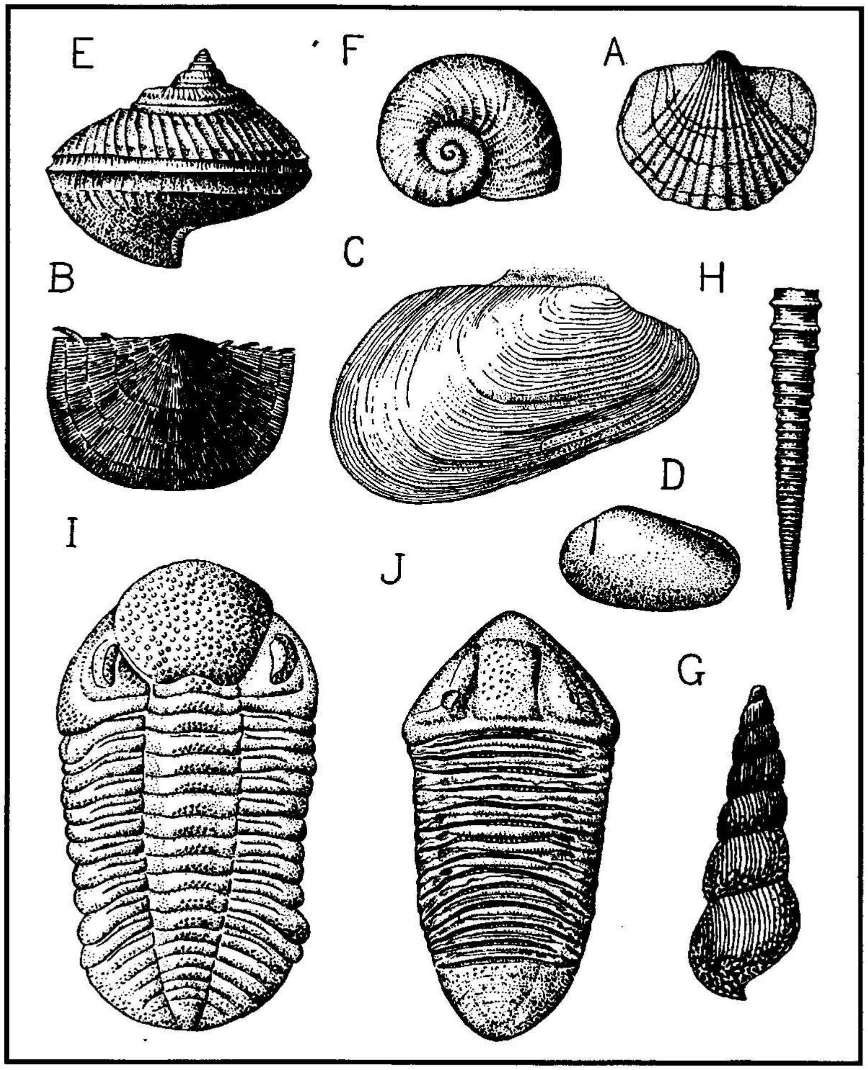
Manlius, mudcracks. Mudcracks in parts of the the Manlius Limestone are one line of evidence that the rocks were deposited in tidal environments, sometimes above, within or just below the tidal zone. The “dessication” crack here indicate the paleoenvironment was periodically exposed to the atmosphere. Photo by C. Ver Straeten, October 2003

Manlius, thin bedded limestones. The Manlius is generally composed of a thinly bedded or laminated limestone. Such very-fine-grained textures in limestones illustrate micrites. Photo by D. DiQuinzio (NPS), September, 2014.

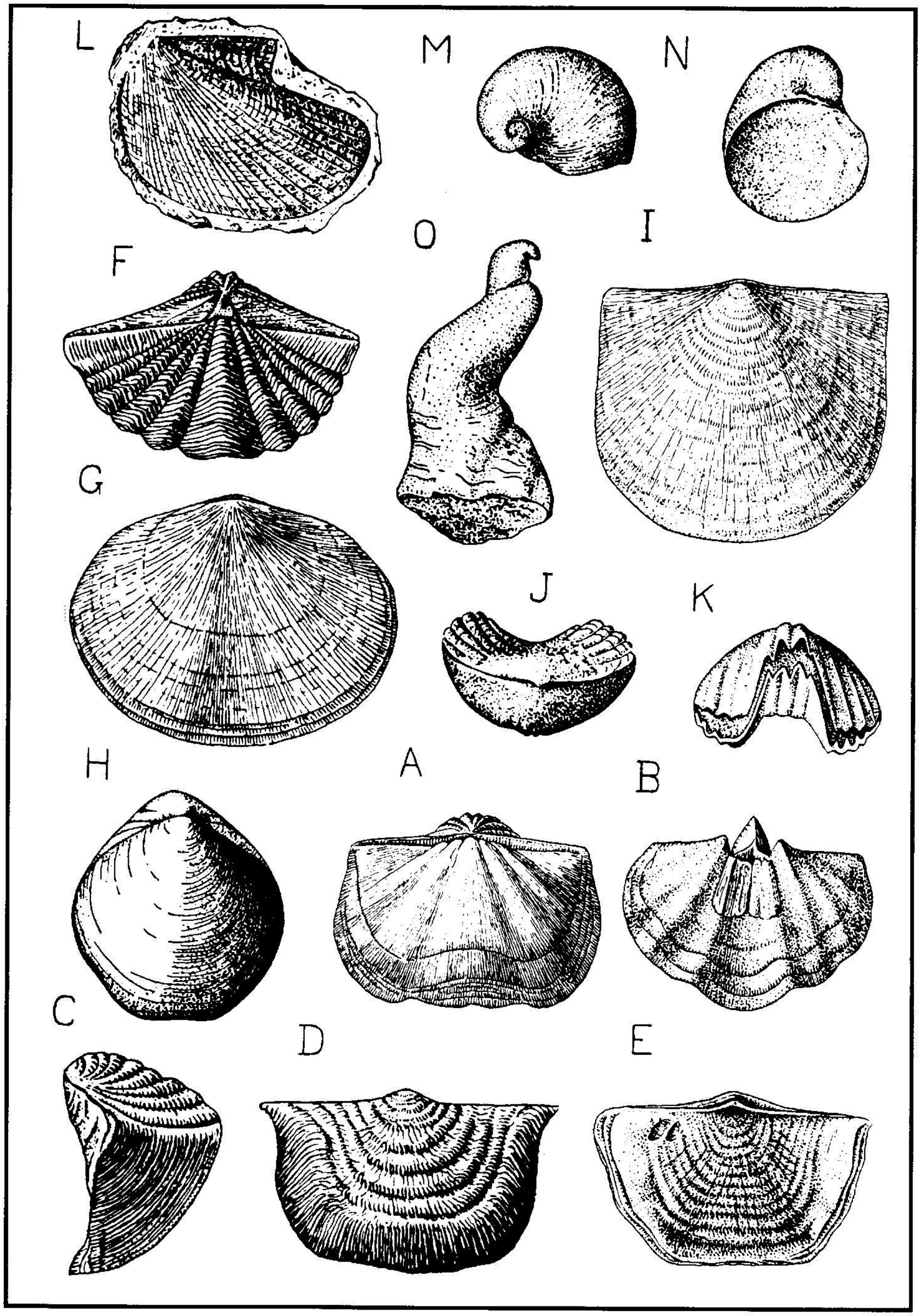
Manlius, thrombolite. Bacterial thrombolite mound in the Manlius Limestone. Quarter for scale. Photo by C. Ver Straeten, October 2003.



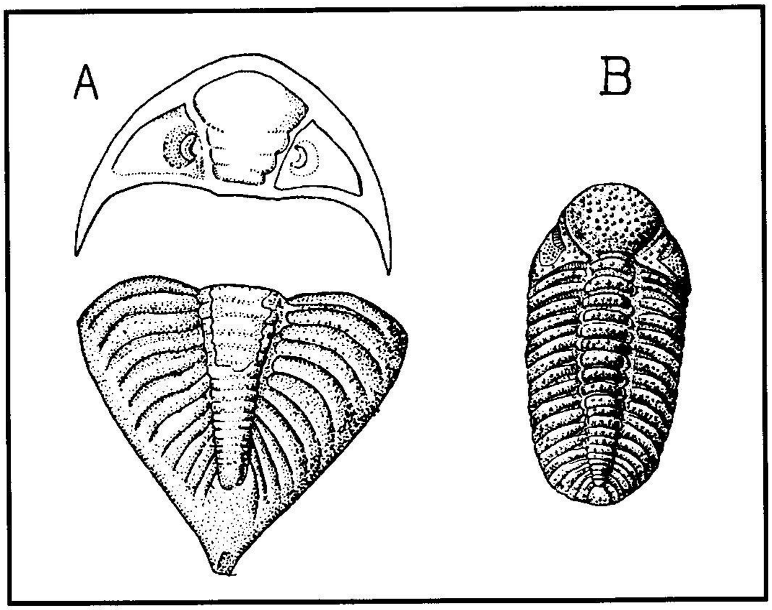
Mount Marion, fossils 1. A-F: brachiopods; G-K: pelecypods. A, B: *Mucrospirifer mucronatus*, actual size; C: *Ambocoelia umbonata*, actual size; D: *Athyris spiriferoides*, actual size; E, F: *Spinocyrtia granulosus*, actual size; G. *Actinopteria boydi*; H: *Pterinea flabellum*, 2/3x; I: *Cypricardella bellistriata*, actual size; J: *Goniophora hamiltonensis*, actual size; K: *Grammysia bisulcata*, actual size. From Goldring (1933).



Mount Marion, fossils 2. A, B: brachiopods; C, D: pelecypods; E-G: gastropods; H: tentaculitid; I, J: trilobites. A: *Tropidoleptus carinatus*, actual size; B: *Devonochonetes coronatus*, actual size; C: *Modiomorpha mytiloides*, 1 1/3x; D: *Nuculites oblongatus*, actual size; E: *Bembexia sulcomarginata*, actual size; F: *Diaphorostoma lineatum*, actual size; G: *Loxonema hamiltoniae*, 1 1/3x; H: *Tentaculites bellulus*, 2 2/3x; I: *Phacops rana*, 2/3x; J: *Homalonotus (Dipleura) dekayi*, 1/2x. From Goldring (1933).

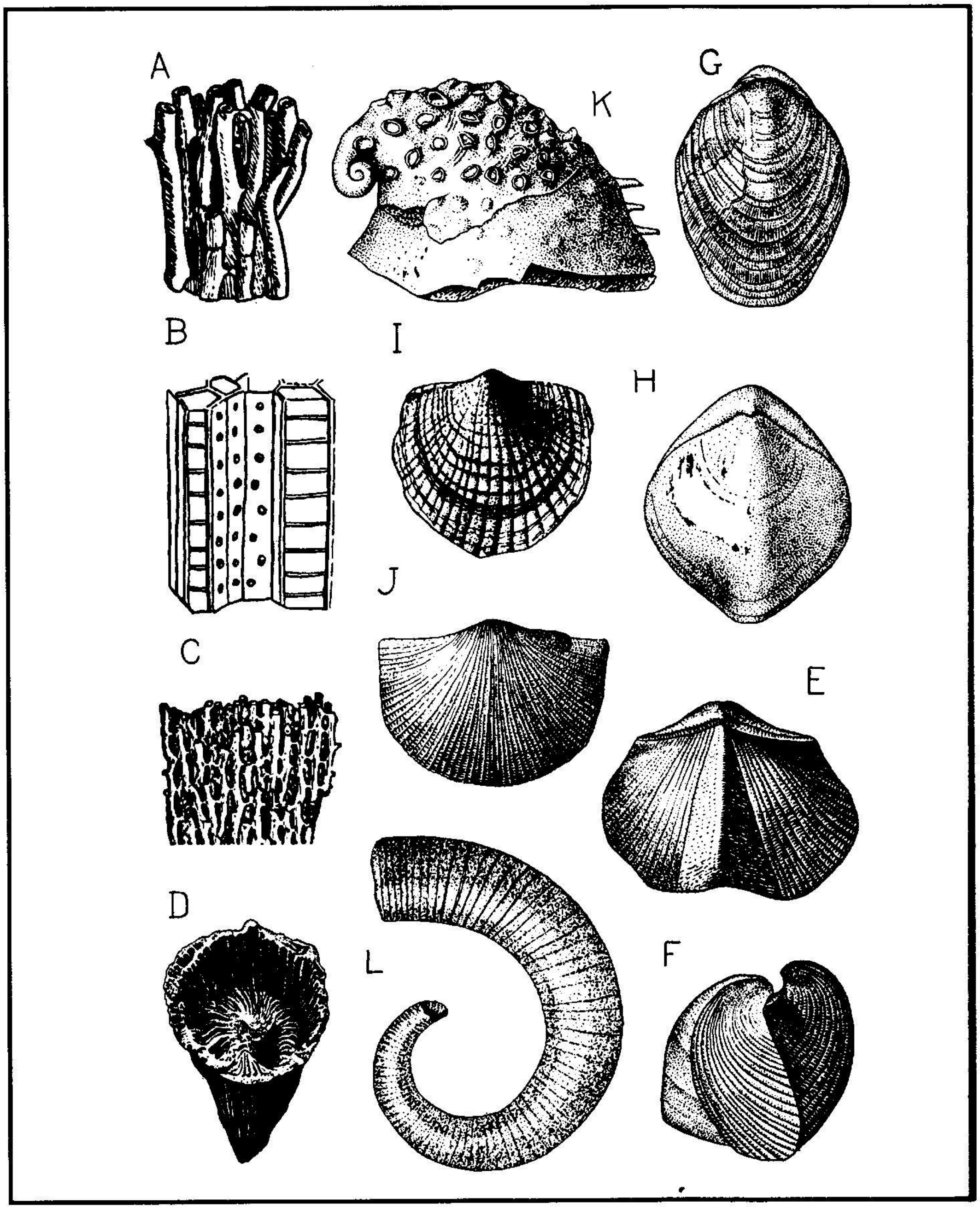


New Scotland, fossils. A-K: brachiopods; L: pelecypod; M-O: gastropods. A: *Macropleura macropleura*, 2/3x; B: *M. macropleura* mold, 2/3x; C, D, E: *Leptaena rhombodialis*, two valves and lateral view (C) 2/3x; F: *Megakozlowskiella perlamellosa*, actual size; G: *Discomyorthis oblata*; H: *Meristella laevis*, actual size; I: *Rystistrophia becki*, actual size; J, K: *Eatonia medialis*, actual size; I: *Actinopteria textilis*, actual size; M, N: *Platystrpha ventricosa*; O: *Platyceras spirale*, 2/3x. From Goldring (1933).

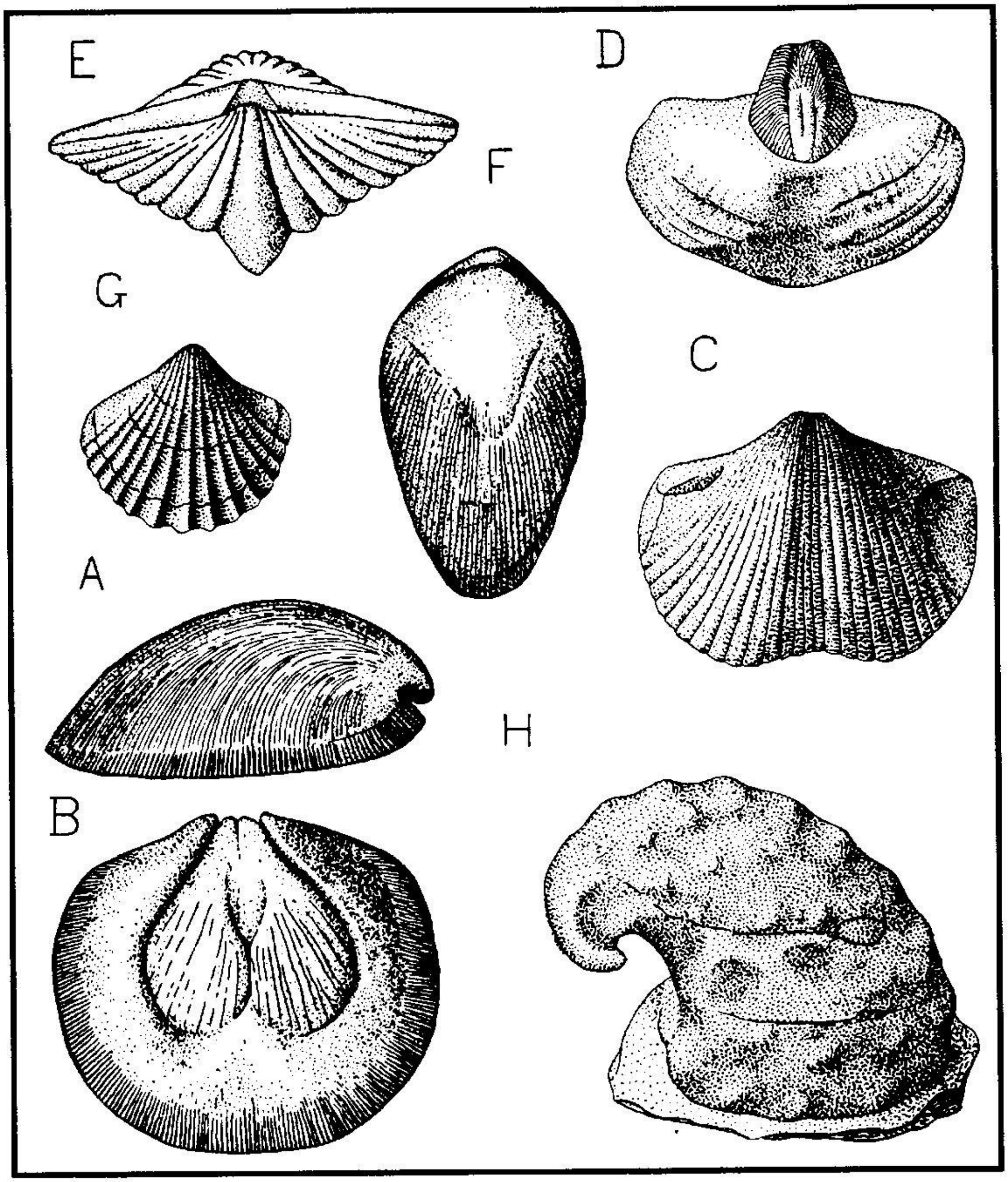


New Scotland, trilobite fossils. A: *Synphoroides pleuroptyx*, 2/3x; B: *Paciphacops logani*, actual size. From Goldring (1933).

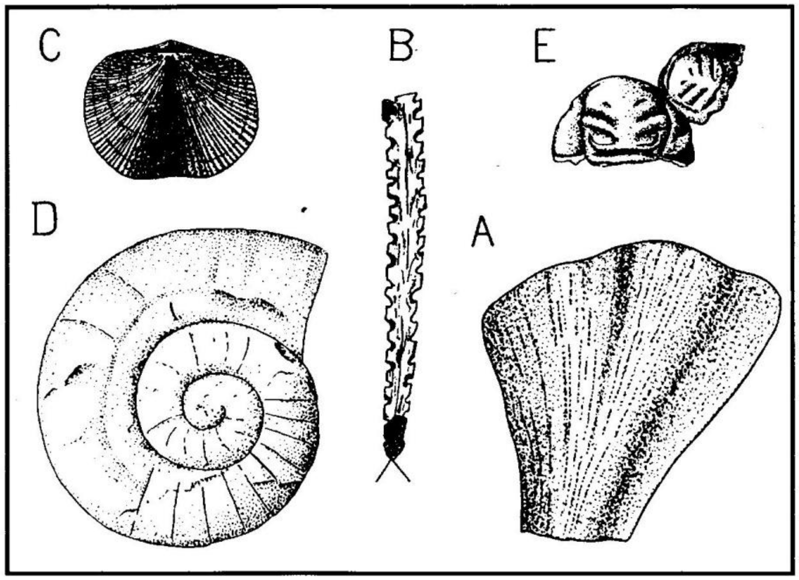
Onondaga, chert. Chert lenses occur irregularly in beds within the Onondaga Formation, otherwise a limestone, such as here in the basal Edgecliff Member. Chert often allows excellent fossil preservation. Photo from Cherry Valley, NY, by C. Ver Straeten, September 2013.



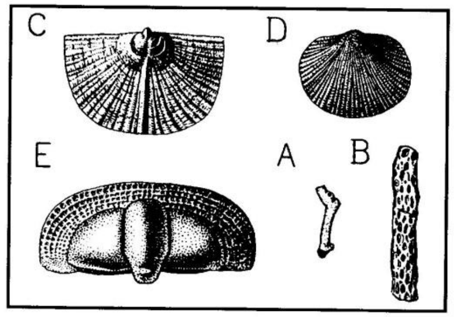
Onondaga, fossils. A-D: corals; E-J: brachiopods; K: gastropod; L: cephalopod. A: *Syringopora maclurei*; B: corallites of *Favosites basalticus*, enlarged; C: *Syringopora hisingeri*; D: *Zaphrentis prolifica*, 2/3x; E, F: *Paraspirifer acuminatus*, full size; G: *Amphigenia elongata*, 2/3x; H: *Meristella nasuta*, actual size; I: *Spinatrypa spinosa*, actual size; J: *Megastrophia inaequiradiata*, actual size; K: *Spiniplatyceras dumosum*, actual size; L: *Ryticeras (Gyroceras) trivolve*, 4/9x. From Goldring (1933).



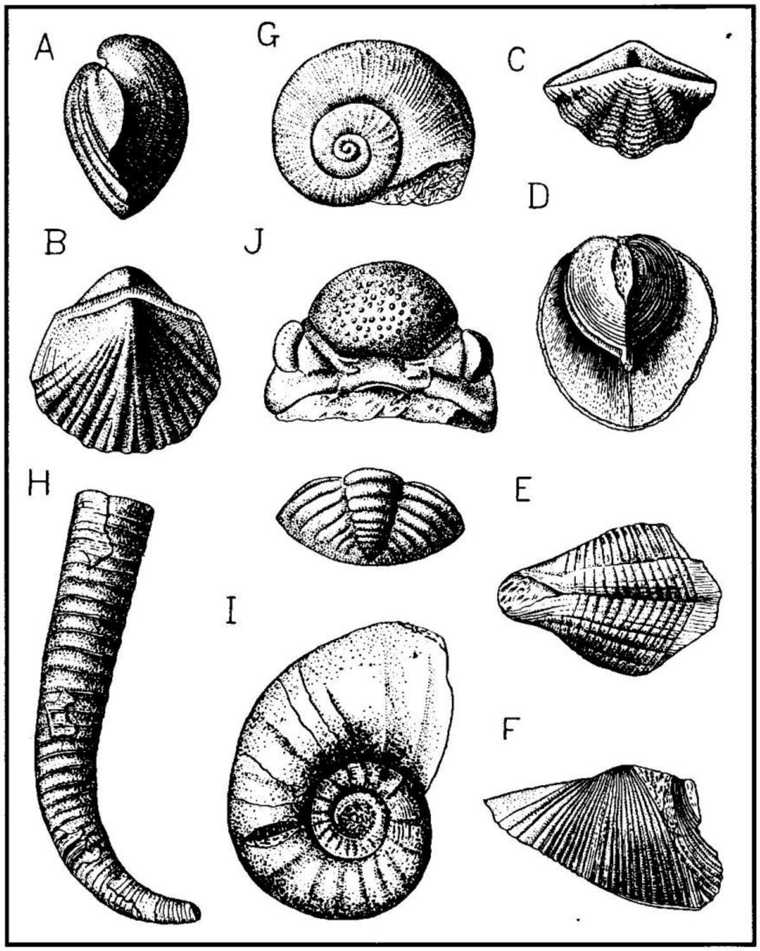
Oriskany, fossils. A-G: brachiopods; H: gastropod. A, B: *Hipparionyx proximus*; actual size; C: *Costispirifer arenosus*, actual size; D: *C. arenosus mold*, actual size; E: *Spirifer murchisoni*, 1 1/2x; F: *Rensselaeria ovoides*, actual size; G: *Leptocoelia flabellites*, 2x; H: *Platyceras nodosum*, actual size. From Goldring (1933).



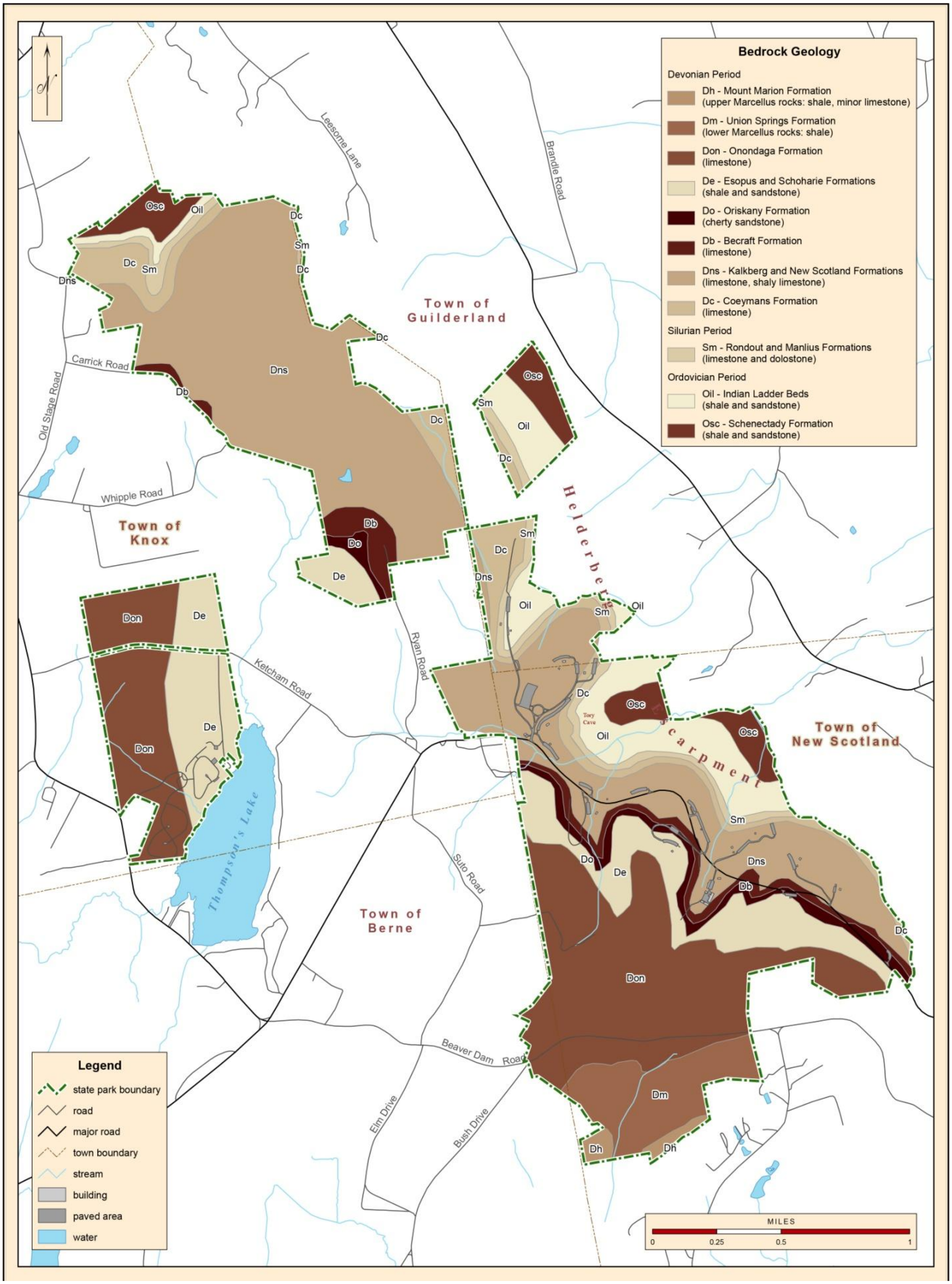
Schenectady Formation, fossils. A: seaweed, *Sphenophycus latifolius*, actual size; B: graptolite, *Climacograptus spinifer*, 3 1/3x; C: brachiopod, *Dalmanella rugata*, actual size; D: cephalopod, *Trocholites ammonius*, 2/3x, E: trilobite head, *Triarthrus becki*, 1 1/3x. From Goldring (1933).



Schectady Formation, Indian Ladder beds fossils. A: bryozoan, *Hallopora onealli*, 2x; B: *H. onealli*, 4 1/2x; C: brachiopod, *Rafenesquina ulrichi*, 5x; D: brachiopod, *Dalmanella multisecta*, actual size; E: trilobite head, *Cryptolithus bellulus*, actual size. From Goldring (1933).

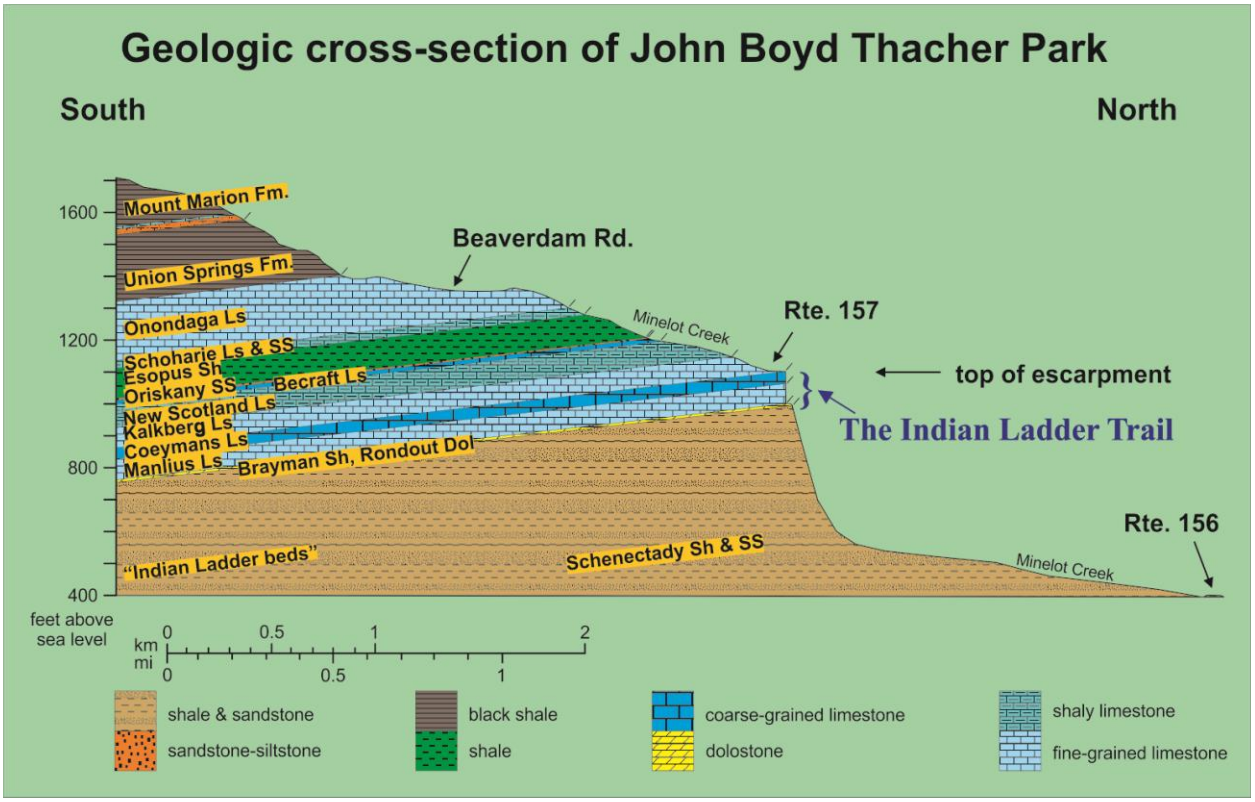


Schoharie Formation, fossils. A-C: brachiopod; D-F: rostroconch (extinct Paleozoic mollusk class); G: gastropod; H, I: cephalopods; J: trilobite. A, B: *Pentamerella arata*, 1 1/3x; C: *Sprifer raricostatus*, 1 1/3x; D-F: *Conocardium cuneus*, actual size; G: *Pleurotomaria arata*, 2/3x; H: *Cyrtoceras (Rhyticeras) eugenium*, 2/3x; I: *Trochoceras discoideum*, 1 1/3x; J: *Phacops cristata* head, actual size. From Goldring (1933).

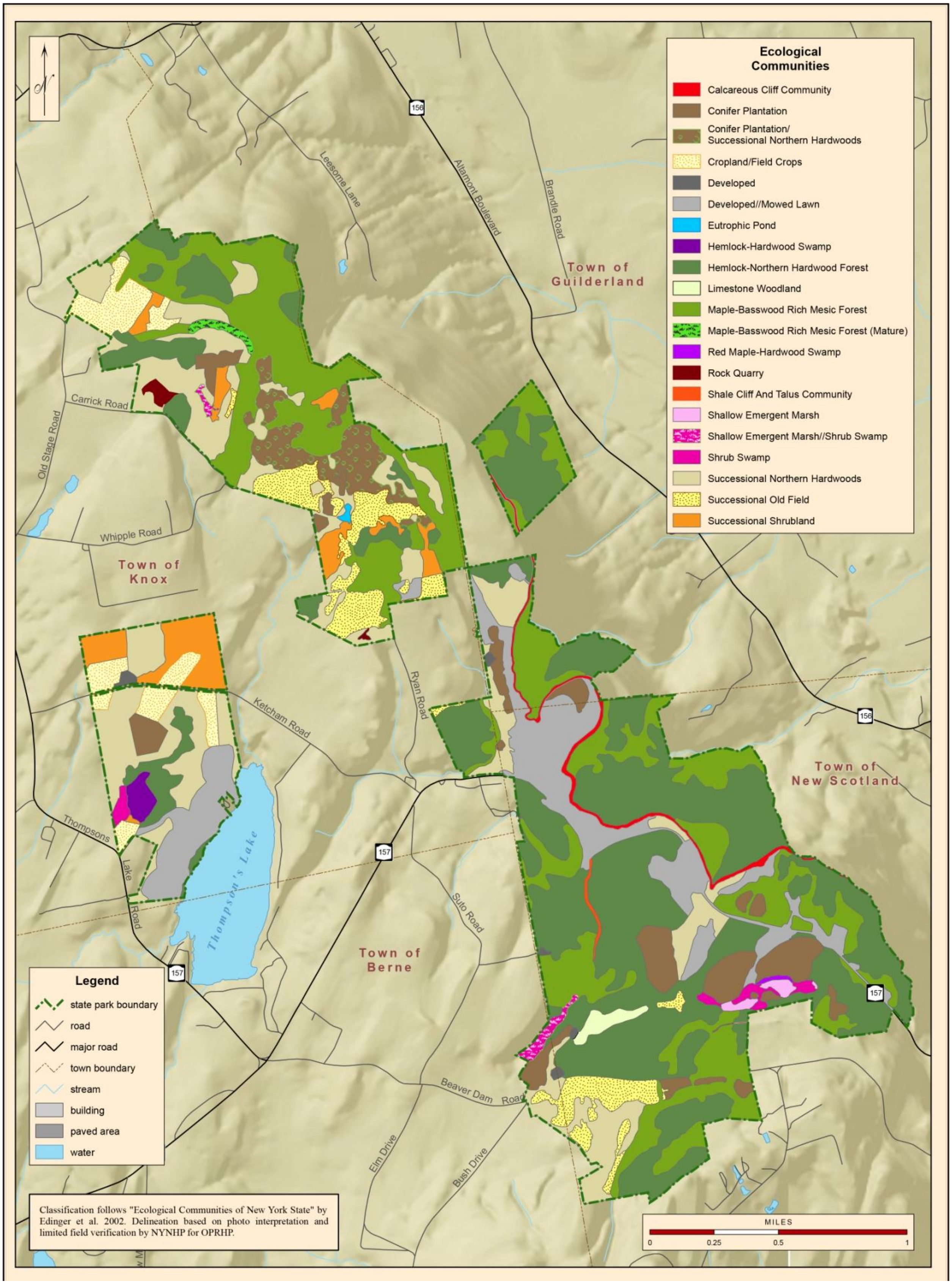


Bedrock Geology
Devonian Period
Dh - Mount Marion Formation (upper Marcellus rocks: shale, minor limestone)
Dm - Union Springs Formation (lower Marcellus rocks: shale)
Don - Onondaga Formation (limestone)
De - Esopus and Schoharie Formations (shale and sandstone)
Do - Oriskany Formation (cherty sandstone)
Db - Becraft Formation (limestone)
Dns - Kalkberg and New Scotland Formations (limestone, shaly limestone)
Dc - Coeymans Formation (limestone)
Silurian Period
Sm - Rondout and Manlius Formations (limestone and dolostone)
Ordovician Period
Oil - Indian Ladder Beds (shale and sandstone)
Osc - Schenectady Formation (shale and sandstone)
Legend
state park boundary
road
major road
town boundary
stream
building
paved area
water
MILES
0
0.25
0.5
1
Town of Guilderland
Town of Knox
Town of New Scotland
Town of Berne
Helderberg Escarpment
Thompson's Lake
Leesome Lane
Brandle Road
Carrick Road
Old Stage Road
Whipple Road
Ketcham Road
Ryan Road
Sulo Road
Beaver Dam Road
Elm Drive
Bush Drive
Tory Cave

Thacher, bedrock. Thacher Park bedrock geology reproduced from Cuomo and Harvey (2013a), created by New York State Office of Parks, Recreation, and Historic Preservation Geographic Information Systems Unit, October 23, 2013. Geologic mapping follows 15-minute quadrangle-scale (1:62,500) mapping by Ruedemann (1930) and Goldring (1935) and statewide 1:250,000-scale composite by Fisher et al. (1970).

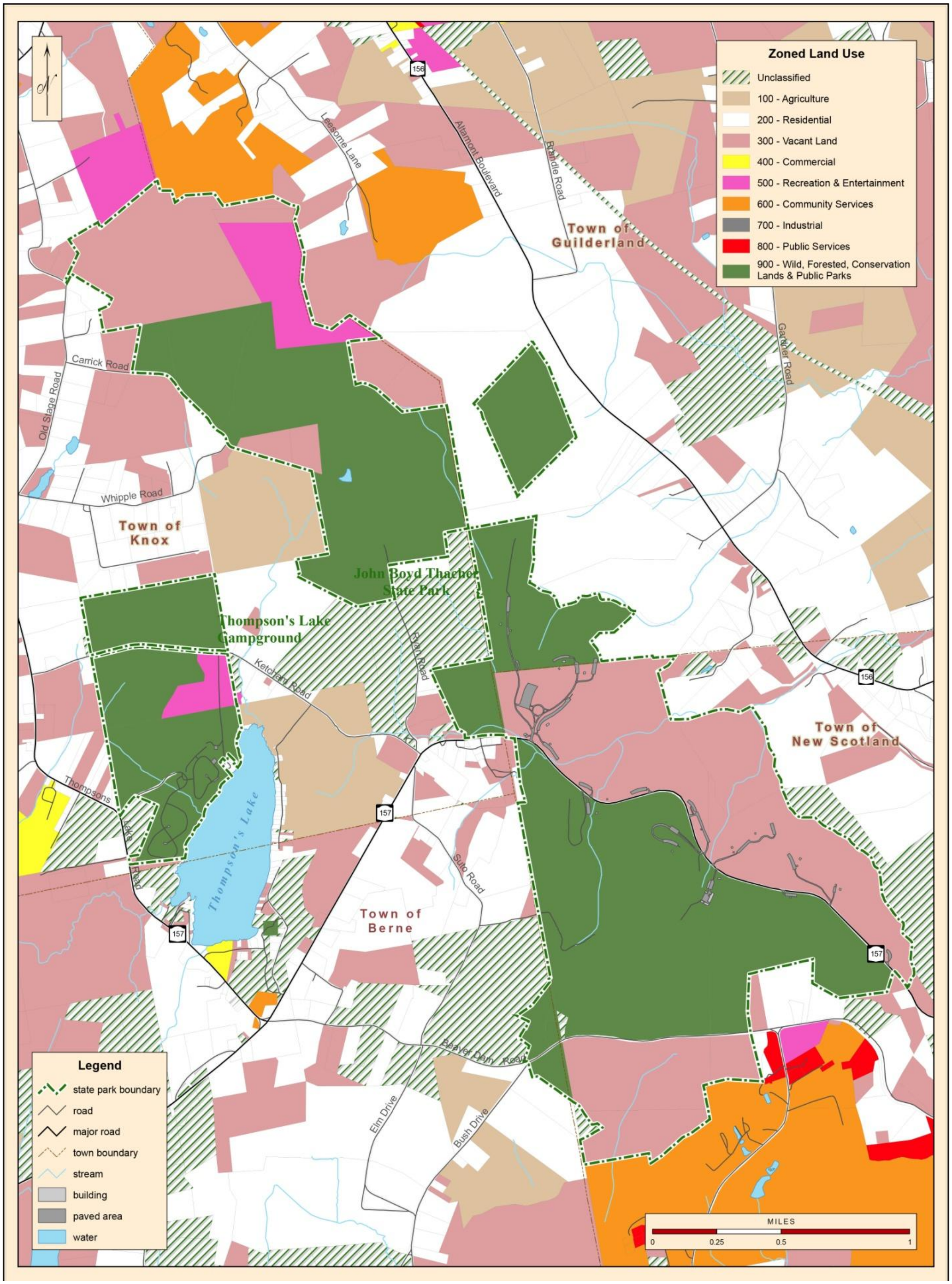


Thacher, cross section. Approximation of a westward-facing view illustrating Silurian-Devonian units exposed by the Helderberg Escarpment. Cross-section largely follows Minelot Creek. Unit thicknesses are measured at Thacher Park. Units dip uniformly 1.5° to the south and appear exaggerated here. Figure produced by C. Ver Straeten.



Ecological Communities
Calcareous Cliff Community
Conifer Plantation
Conifer Plantation/ Successional Northern Hardwoods
Cropland/Field Crops
Developed
Developed//Mowed Lawn
Eutrophic Pond
Hemlock-Hardwood Swamp
Hemlock-Northern Hardwood Forest
Limestone Woodland
Maple-Basswood Rich Mesic Forest
Maple-Basswood Rich Mesic Forest (Mature)
Red Maple-Hardwood Swamp
Rock Quarry
Shale Cliff And Talus Community
Shallow Emergent Marsh
Shallow Emergent Marsh//Shrub Swamp
Shrub Swamp
Successional Northern Hardwoods
Successional Old Field
Successional Shrubland
Town of Guilderland
Town of Knox
Town of New Scotland
Town of Berne
Leesome Lane
Altamont Boulevard
Brandle Road
Carrick Road
Old Stage Road
Whipple Road
Ketcham Road
Ryan Road
Thompsons Lake Road
Thompson's Lake
Suto Road
Beaver Dam Road
Elm Drive
Bush Drive
156
157
Legend
state park boundary
road
major road
town boundary
stream
building
paved area
water
MILES
0
0.25
0.5
1
Classification follows "Ecological Communities of New York State" by Edinger et al. 2002. Delineation based on photo interpretation and limited field verification by NYNHP for OPRHP.

Thacher, ecology. Figure reproduced from Cuomo and Harvey (2013a), created by New York State Office of Parks, Recreation, and Historic Preservation Geographic Information Systems Unit, October 23, 2013. Classification of ecological communities follows Edinger et al. (2002). Delineation based on photo interpretation and limited field verification by New York Natural Heritage Program.


Zoned Land Use
Unclassified
100 - Agriculture
200 - Residential
300 - Vacant Land
400 - Commercial
500 - Recreation & Entertainment
600 - Community Services
700 - Industrial
800 - Public Services
900 - Wild, Forested, Conservation Lands & Public Parks
Legend
state park boundary
road
major road
town boundary
stream
building
paved area
water
MILES
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0.25
0.5
1
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Ketcham Road
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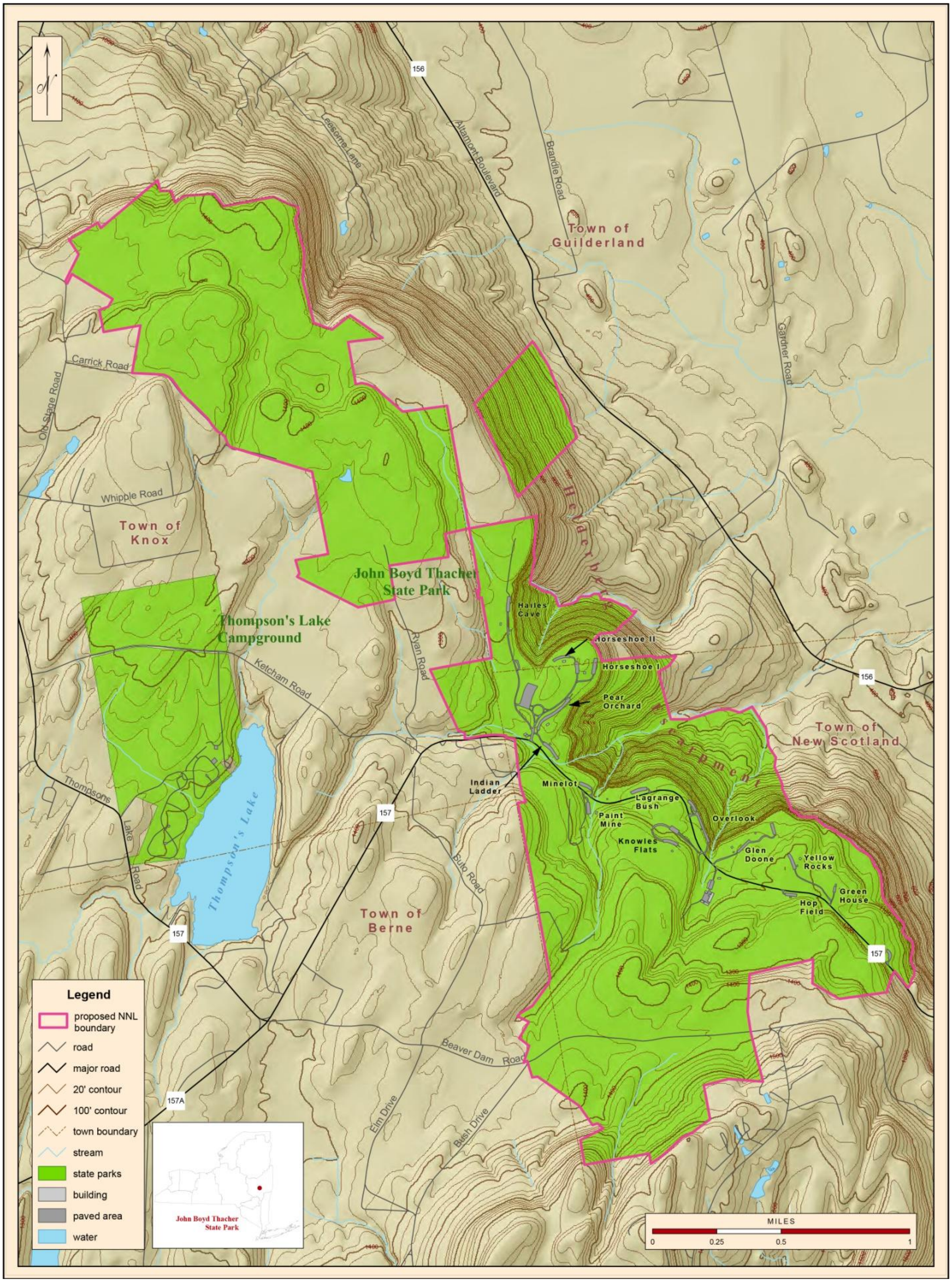
Thompsons Lake Road
Sulo Road
Beaver Dam Road
Elm Drive
Bush Drive
156
157

Thacher, land use. Land zoning at Thacher Park and surrounding area. Figure reproduced from Cuomo and Harvey (2013a), created by New York State Office of Parks, Recreation, and Historic Preservation Geographic Information Systems Unit, October 23, 2013.



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Gardner Road
Beaver Dam Road
Elm Drive
Bush Drive
Bulo Road
156
157
157A
Hailes Cave
Horseshoe II
Horseshoe I
Pear Orchard
Indian Ladder
Minelot
Lagrange Bush
Paint Mine
Overlook
Knowles Flats
Glen Doone
Yellow Rocks
Green House
Hop Field
Legend
proposed NNL boundary
road
major road
20' contour
100' contour
town boundary
stream
state parks
building
paved area
water
John Boyd Thacher State Park
MILES
0
0.25
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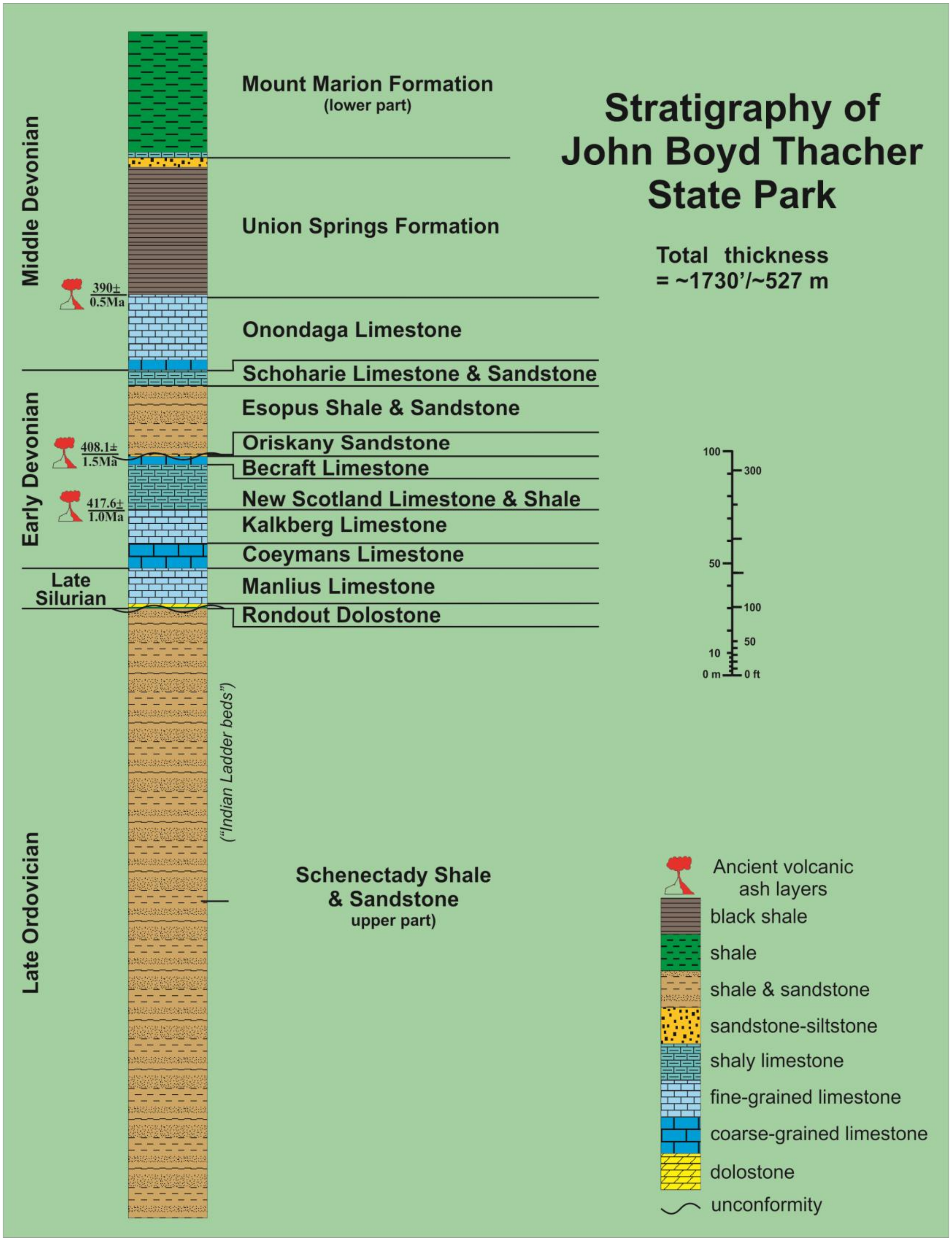
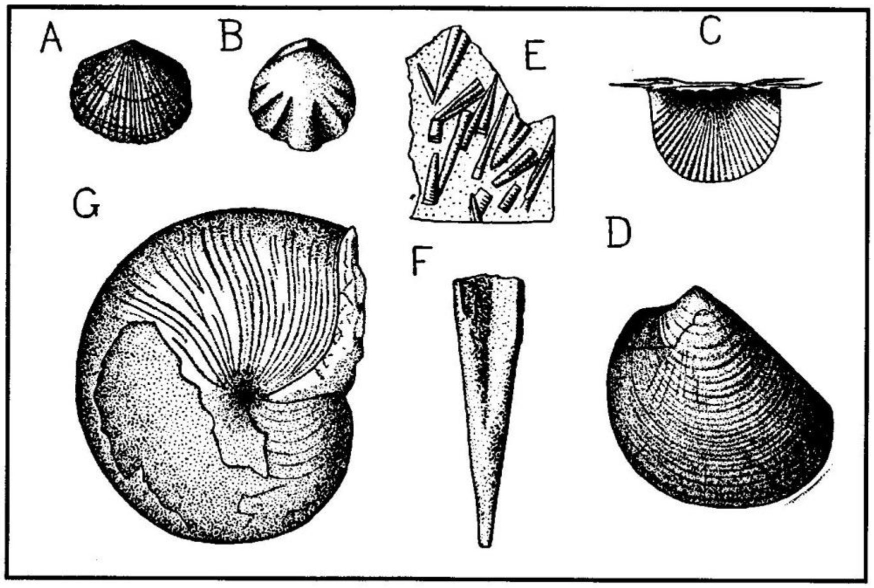
1

Thacher, NNL boundary. Basemap by New York State Office of Parks, Recreation, and Historic Preservation Geographic Information Systems Unit, October 23, 2013.



Thacher, stratigraphy. Image generated by C. Ver Straeten.



Union Springs, fossils. A-C: brachiopods; D: pelecypod; E-F: pteropod; G: cephalopod. A: *Leiorhyncus limitaris*, 1 1/3x; B: *L. mysia*, 1 1/3x; C: *Devonochonetes mucronatus*, actual size; D: *Lumulicardium marcellense*, actual size; E: *Styloilina fissurella*, 4x; F: *S. fissurella* 8x. G: Paradiceras discoideum, x 3/4. From Goldring (1933).

Glossary

agnathan A paraphyletic group of jawless fish following a primitive vertebrate form (Cope, 1889; Purnell, 2001). (Excluded from this group are vertebrates with jaws.) Members of this group are generally ectothermic (cold-blooded), have caudal (tail) and sometimes dorsal fins, but lack paired appendages and a distinct stomach (Romer and Parsons, 1985). Examples include hagfish and lamprey, both extant, as well as a number of extinct (mostly Early and Middle Paleozoic) forms (Donoghue and Aldridge, 2001).

ammonoid Marine cephalopods among the subclass *Ammonoidea*, known for their chambered, spiral shells that form in saddles and lobes. These organisms arose in the Devonian and went extinct in the Cretaceous, though their characteristic range, habitat, and easily identifiable features lend ammonoids to being good index` fossils (Jackson and Bates, 1984; Rafferty, 2011, and others).

anoxia Characterized by very low (negligible) oxygen concentration.

arthropod A group of invertebrates characterized by jointed appendages and segmented bodies, first appearing in the Cambrian and still extant (Bates and Jackson, 1984). Examples include trilobites (extinct), as well as shrimp and other extant crustaceans.

basin A low-lying area. On land, a basin contains or defines a watershed system, but the term also describes low-lying marine areas, too.

bedrock Solid, coherent rock, held together by either cementing agents or an interlocking crystal matrix, underlying loose unconsolidated surficial materials.

brachiopod A filter-feeding marine invertebrate, also known as a lamp shell, with bilateral symmetry about the plane of their two valves. These organisms are members of the Phylum Brachiopoda, they first appeared in the Cambrian and some still live today, most commonly as sessile bottom dwellers (Bates and Jackson, 1984; Stanley, 1999; Cooper, 2016, and others).

brackish Water with salinity intermediate between fresh and marine.

bryophyte The oldest terrestrial plant lineage, containing hornworts, liverworts and mosses. These non-vascular plants reproduce through spore production and can have separate stems and leaves (Bates and Jackson, 1984; Stanley, 1999; Schofield, 2016, and others).

bryozoan A group of aquatic invertebrates characterized by colonial growth and a branching, twig-like skeleton (Bates and Jackson, 1984; Stanley, 1999). Ordovician to Modern (Bates and Jackson, 1984).

capstone (or caprock) A bedrock unit or layer relatively resistant to weathering with respect to surrounding earth materials such that it protrudes above surrounding terrain, often as a promontory or cliff.

carbonate A mineral or sediment whose anionic unit is CO_3^{2-}. Such minerals would include calcite, aragonite, siderite and sedimentary rock examples are limestone and dolostone.

Carboniferous Period The Paleozoic interval of earth history beginning at the end of the Devonian Period (359 Ma) and before the Permian Period (299 Ma) (Walker et al., 2012). In North America, the Mississippian Period (355-323 Ma) and Pennsylvanian Periods (323-299 Ma) are alternatively used (Walker et al., 2012).

cephalopod A type of swimming mollusk with a head surrounded by tentacles, emerging in the Cambrian Period (Early Paleozoic, 541-485 Ma) and still extant today—think squid, octopus (Bates and Jackson, 1984).

chert Cryptocrystalline quartz precipitated from solution, often partially hydrated or amorphous, in other words, opaline (Bates and Jackson, 1984)

chronostratigraphy The discipline of dating rocks in time using stratigraphic relationships, fossils, and radiometric clocks in mineralized materials.

conglomerate Sedimentary rock containing larger-size grains (gravel, cobble, or boulders) that indicate ancient high-energy environments.

conodont Small, primitive, phosphatic, disjunct tooth-like fossils occurring from the Cambrian through the Triassic (Bates and Jackson, 1984), and recently understood to have belonged to jawless, eel-like soft-bodied swimming animals (Donoghue et al., 2000; Milsom and Rigby, 2004).

crinoid A class of marine echinoderm with a globular body, about which arms radiate, that sits atop a flexible, jointed stem and is rooted to the sea floor. Ordovician to Modern (Bates and Jackson, 1984).

delta The nearly flay-lying tract of sediments found at the mouths of rivers, often taking a triangular form to resemble the Greek letter (Bates and Jackson, 1984).

Devonian Period An interval of geologic time from 419.2 Ma to 358.9 Ma (House, 2016, and others), during the Paleozoic Era between the Silurian and the Carboniferous Periods (Jackson and Bates, 1984).

dip Angle of intersection in the vertical dimension between an inclined plane (or stratum) measured perpendicular to the azimuthal (strike) direction of this intersection.

doline The early stage of a sinkhole, a shallow depression formed by dissolution of karstic terrain.

dolostone A carbonate rock whose principal constituent is the mineral dolomite, $CaMg(CO_3)_2$. Dolomite is white to light-colored, has perfect rhombohedral cleavage, and is formed by replacement of calcium with magnesium in limestone (Bates and Jackson, 1984).

echinoderm Members of a marine invertebrate phylum, Echinodermata, characterized by five-fold symmetry. They range from Cambrian to Modern (extant) and include sea stars, sea urchins, and crinoids (extinct).

erosion The wearing away (and implied removal) of earth materials at the surface through weathering (Bates and Jackson, 1984).

escarpment A long continuous cliff or steep slope facing one general direction and separating two flatter areas and owing to erosion or faulting, for example, the steep side of a cuesta (Bates and Jackson, 1984).

eurypterid An extinct type of arthropod, also known as a "sea scorpion" that inhabited brackish and freshwater environments from the Ordovician to the Permian Period. This group is characterized by a segmented body, paddlelike appendages, and large size: some species could grow up to 2.5 meters in length (Bates and Jackson, 1984; Tikkanen, 2011, and others).

facies The character (e.g. lithology, texture, color, etc.) of a rock, usually with particular relevance to its origin or depositional environment (Bates and Jackson, 1984).

fault A fracture within the earth upon which earth materials have moved past each other.

fracture A crack or break in rock.

gastropod Snails, the largest and most diverse class of mollusk. Cambrian to Modern.

graptolite A floating marine organism, commonly colonial, known for their bilaterally symmetrical, tube-shaped exoskeletons. Members of the class *Graptolithina*, these organisms existed between the mid-Cambrian Period to the Carboniferous Period and are often found in black shale. (Jackson and Bates, 1984; Pallardy, 2008a).

greywacke (or graywacke) A hard, dark-colored fine-grained marine sedimentary rock deposited on continental shelf edges and slopes composed of sand and silt-sized mineral (quartz and feldspar) fragments and a substantial clay mineral (illite, sericite, chlorite) component (Stanley, 1999; Bates and Jackson, 1984).

igneous (rock) Formed from melt, for example, resulting from volcanic activities.

karst Land surface formed over carbonate (limestone, dolostone) or gypsum terrain by dissolution and characterized by dolines, sinkholes, caves, and underground drainage (Bates and Jackson, 1984).

limestone A sedimentary rock composed of, primarily, calcium carbonate ($CaCO_3$) as well as lesser amounts of magnesium carbonate. Deposits form from a variety of different sources such as accumulated organic debris from calcium-carbonate producing organisms, directly from calcium carbonate precipitation or the consolidation of pre-existing limestone or other calcium-carbonate-rich sediments (Stanley, 1999; Bates and Jackson, 1984; Pallardy, 2012, and others).

lithology The physical character or description of a rock, often with emphasis on color, mineralogy, grain size, texture, and other distinctive properties as relevant (Bates and Jackson, 1984).

lycopsid (also known as lycophyta, or lycopods) The *Lycopodiophyta* group represents an early evolved Division of organisms within Kingdom Plantae, with *Baragwanthia longifolia* appearing during the Silurian, near 425 Ma (Rickards, 2000; McElwain et al., 2002). These vascular plants alternate between spore and macroscopic generations that feature microphylls, or single-veined leaves (Cronquist et al., 1966; Cantino et al., 2007). Some 1300 extant species are recognized today (Christenhusz and Byng, 2016). Examples include club-mosses, spike-moss, and quillwort.

Ma (mega anon) Millions of years in the past. 500 Ma, for example is understood to mean 500 million years ago.

metamorphic (rock) Derived from pre-existing rocks, deformed and reworked under pressure and temperature, usually at depth within the earth (Bates and Jackson, 1984).

mollusk (or mollusc) These organisms arose in the Cambrian and are members of the diverse phylum *Mollusca*, dwelling in freshwater, saltwater and terrestrial environments. They typically have external calcium carbonate shells secreted by a fleshy mantle and include species such as snails, bivalves, octopuses and cuttlefish (Jackson and Bates, 1984; Stanley, 1999; Salvini-Plawen, 2016, and others).

Ordovician Period An Early Paleozoic interval of geologic time following the Cambrian Period (485 Ma) and ending with the Silurian Period (444 Ma) (Walker et al., 2012).

orogeny Large-scale tectonic folding and deformation of rocks occurring in a linear or arcuate geometry and usually resulting in mountains, i.e. mountain building (Bates and Jackson, 1984).

ostracoderm An informal term describing a group of armored jawless fish appearing in the Ordovician and extinct by the end of the Devonian (Donoghue et al., 2000; Ostracoderm, 2017)

outcrop Exposure of bedrock at Earth's surface.

Paleozoic Era (or Palaeozoic): This interval of geologic time spanned from 571 Ma to 252 Ma, encapsulating the largest diversification of animals (Cambrian explosion) to the largest extinction (end-Permian extinction) in the history of the Earth (Jackson and Bates, 1984; Robison and Crick, 2016, and others). The interval is divided into the Early Paleozoic (Cambrian and Ordovician Periods), Middle Paleozoic (Silurian and Devonian Periods) and Late Paleozoic (Carboniferous and Permian Periods) (Robison and Crick, 2016, and others).

pelecypod Members of a Class of benthic mollusks with bilaterally symmetrical bivalve shells, hatchet-shaped foot and sheetlike gills (Bates and Jackson, 1984). Think bivalve (clam, scallop, mussel, etc.). Ordovician to Modern.

rugose coral Members of solitary (horn-shaped) and reef-forming Order *Rugosa*, Ordovician to Permian (Rugosa, 2017).

sandstone A sedimentary rock composed of sand-sized grains, typically of quartz and other silicate minerals, held together by a natural cementing agent, and often including a matrix of finer silt- and clay-sized particles (Bates and Jackson, 1984).

sapping Erosion along the base of a cliff or escarpment. Erosion of weaker materials there beneath more weather-resistant materials above, capstones, undercuts the capstone to produce the cliff form.

section An exposed portion of bedrock. In the case of sedimentary rocks, section refers to a stratigraphic interval exposed. See sediment, strata, stratigraphy.

sediment Solid disjointed materials transported from atmospheric elements (wind, water, ice) or biologic agents and deposited (Bates and Jackson, 1984).

shale A fine-grained, relatively soft and easily weathered sedimentary rock composed of clay, silt, or mud and deposited in fine layers on which the rock splits easily (Bates and Jackson, 1984).

shelf The broad shallow marine area along the margins of continents, typically less than 150 meters depth in the modern ocean.

silicate A compound with a crystal structure composed of silicate (SiO_4) tetrahedra, and the most common group of rock-forming minerals on Earth's surface (Bates and Jackson, 1984).

siliciclastic Descriptive of sedimentary rocks composed mostly of quartz grains, with lesser components of common rock-forming silicate minerals (feldspars, micas, etc.) or silicate rock fragments (Bates and Jackson, 1984).

Silurian Period Beginning 443.8 Ma and ending 419.2 Ma, this period of the Paleozoic lies between the Ordovician and Devonian Periods (Jackson and Bates, 1984; Johnson, 2016, and others). It is characterized by extensive and complex coral reef communities, and appearances of primitive plants and vertebrates (fish) (Johnson, 2016, and others).

slate A low-grade metamorphic—formed at depth within the earth but not melted—rock composed of fine grains (particles) known for its characteristic sheet-like breakage along cleavage planes and usually formed from shale (Jackson and Bates, 1984; Stanley, 1999).

strata The plural of stratum. A stratum refers to a layer, or bed, of sedimentary rock, deposited in a horizontal planar geometry directly on the surface below, often another bed just older (Bates and Jackson, 1984).

stratigraphy The study of rock strata, their relationships and properties (Bates and Jackson, 1984).

stromatoporoid coral A variety of prolific reef-forming sponges during the Ordovician to Devonian Periods that have since gone extinct (Cambrian - Cretaceous). These marine organisms were sessile (attached and immobile), benthic (bottom dwelling) creatures whose calcium carbonate skeletons created reef-like structures when in a colony (Stanley, 1999; Jackson and Bates, 1984; House, 2016, and others).

tabulate coral A reef-building colonial coral that existed from the Ordovician to the Jurassic known for secreting skeletons of calcite. These organisms formed colonies alongside stromatoporoids to create tabulate-stromatoporoid reefs (Stanley, 1999; Pallardy, 2008b).

tectonic Referring to the broad architecture (often continental scale) of the outer part of the earth (Bates and Jackson, 1984).

tetrapod An informal term to describe four-footed vertebrate animals, which emerged in the Late Devonian and are still extant today. Generally these are amphibians, reptiles, and mammals as opposed to fish (finned) or animals without limbs (Bates and Jackson, 1984).

Triassic Period An interval of earth history following the Permian Period (299 Ma) and before the Jurassic Period (201 Ma) (Walker et al., 2012). This is the first Period of the Mesozoic Era, known for its dinosaurs.

trilobite An extinct arthropod characterized by its chitinous exoskeleton and three lobes: cephalon (head), thorax (body), and pygidium (tail). They were primarily vagile (mobile) bottom dwellers, though there were some floating and burrowing varieties. Trilobites existed from the Cambrian to the Permian Period and are commonly used as index fossils (Stanley 1999; Jackson and Bates, 1984; Pallardy, 2011, and others).

unconformity A temporal gap in the rock record. These surfaces are often subtle, as sedimentation can resume after millions of years of non-deposition or erosion without apparent disruption of the lower surface. Unconformities are often recognized by the absence of a distinctive unit deposited elsewhere in the sequence or of a fossil group expected to occur during the missing interval of time.

weathering The destruction of earth materials at the surface by atmospheric agents and physical processes (Bates and Jackson, 1984).