Curriculum Units by Fellows of the Yale-New Haven Teachers Institute
2024 Volume II: Dynamic Earth, Foundation and Fate of Industrial Society

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Introduction

by David Evans, Professor of Earth and Planetary Sciences

Throughout history, human development has been constrained by the limitations of our environment. Indeed, as some have quipped, “our civilization exists by geological consent, subject to change without notice.” Many past empires’ expansion phases were enabled through extensive natural resource extraction, followed by collapse in the context of resource limitation or natural disasters. Scientific and technological ingenuity of the industrial revolution gave our species -- for the first time in our planet’s history -- the ability to utilize hundreds of millions of years’ worth of stored solar energy in the form of fossil fuels, as well as billions of years’ worth of material natural resources in the form of mineral deposits, to power our explosive population growth and prosperity. As human population has ballooned to nearly 10 billion, however, we have become more vulnerable than ever to the threat of natural catastrophes beyond our control, and furthermore we have collectively become a significant geological force through environmental alteration and climate change. For these reasons, understanding the dynamic Earth is key to the decision-making ability of a citizenry that not only has inherited the resource-based foundation of today’s world of comfort, but also will steer our society’s ultimate environmental fate.

Geology – the study of Earth from its atmosphere to its deep interior – benefits from our continuous progress in fundamental mathematics, physics, chemistry, and biology, along with related technological innovations. Accordingly, our scientific ability to “read” the planet’s past and present, and to predict its future, has undergone constant refinement with measurable advances each year. To keep abreast of new insights into our planet’s workings and evolution, a well-informed teacher might benefit from reviewing an introductory geology course at mid-career, noting how the material might have changed from when they first learned it, or how their life’s experience has allowed them to relate more closely to the natural phenomena described in their curriculum. Among numerous excellent introductory geology textbooks, Stephen Marshak has reliably updated the content of *Earth: Portrait of a Planet* with current geological research and timely events in the public awareness such as recent natural disasters. This Y-NHTI seminar drew upon Marshak’s textbook as a comprehensive basic resource for geological concepts.

The Fellows’ curriculum units from this seminar covered a diverse range of specialty topics within geology. For any given subject matter in a K-12 pedagogical environment, a central challenge is how to convey a broad range of interconnected topics, often requiring numerous pillars of general scientific knowledge, to help students make meaningful connections despite variable quantitative backgrounds and perhaps quite limited experience with the natural world. Geographic awareness among students can also be quite restricted, especially if families lack the means to travel far from home. Present-day GPS-based navigation systems can provide excellent guidance to a destination, but depending on the user settings, it’s possible to follow a series of relative directions (e.g., “after 100 ft, turn right; after 300 feet, turn left, …”) without any consultation of a map. The methods developed in the present Y-NHTI seminar utilize geospatial layering, that is, superposition of diverse datasets on a consistent absolute geographic framework: the world map in the context of latitude and longitude gridlines, visualized on zoomable digital displays. This approach enhances geospatial skills, which are useful not only in geology and environmental studies, but also across a broad range of other fields including public health, geopolitics, global-scale commerce, and cultural diaspora. Geospatial layering can also assist in the deduction of cause and effect. For example, strong regional correlations exist between earthquake zones, landslide hazards, and agricultural practices that are best suited for steep hillslopes; conversely, seismically stable land areas tend to be flat, with meandering rivers and well developed soils suitable for large-scale farming. All of these observations are interconnected, with plate tectonics as the ultimate driver.

The seminar utilized the free software Google Earth (hereafter abbreviated GE), which is more user-friendly than more advanced geographic information systems (GIS) geospatial software packages. Through the past decade, I have taught introductory geology classes at Yale using GE datasets that I either downloaded as stand-alone packages from government or private agencies, or produced from point data or raster images that I overlaid into GE. The dataset layers include: (1) extraterrestrial impact craters, (2) tectonic plates, earthquakes, and volcanoes, (3) mineral deposits, (4) geologic maps, (5) soils, (6) heat flow, topography, and landslide potential, (7) rivers and groundwater, (8) weather and climate, including climate from the last glacial maximum, (9) long-term geologic history, and (10) projections of future climate. The sequence is designed to follow cause-and-effect relationships around the global tectonic cycle, through the rock cycle, and into environmental factors facing the modern world.

In the context of such geospatial layering, I advised each Fellow to focus their Y-NHTI experience on several geographic locations to study, depending on their curricular goals and prior lived experience. One Fellow wanted primary school art students to visualize flowing water in all its forms, so two local areas with contrasting bedrock geology (and hence soils and groundwater flow) were selected: one in the fractured crystalline bedrock of the eastern Connecticut “highlands” (Branford) and the other in the low-lying coastal plain of the sediment-filled central Connecticut rift valley (New Haven). Another Fellow wanted to teach kindergartners about the world beneath their feet, so two contrasting locations were chosen from areas she knew well: one urban (New York City) and the other rural (Chesapeake Bay lowlands in Maryland). A third Fellow selected Venezuela as a country where some of her students had ethnic heritage, so three contrasting locations were studied: a small montane city in the high Andes (Mérida), a moderate-sized city along the vast Orinoco River plains (Ciudad Bolivar), and the sprawling capital city squeezed into a narrow valley within the northern coastal ranges (Caracas). The fourth Fellow wanted to investigate how the Roman Empire developed within the geologic contexts of diverse landscapes spanning a continent, so three contrasting locations highlighted these differences: the volcanic heart of the empire (Rome and Pompeii, Italy), its distal frontier (London, UK), and an important landlocked mining district (Rio Tinto, Spain). Summary geologic contexts are provided for all of these regions in the paragraphs to follow.

Steph Smelser: Branford, CT

The geologic history of Branford begins with volcanic island chains in the Iapetus Ocean, which existed 500-300 million years ago (Ma), situated to the present east of ancestral North America. In Greek mythology, the titan Iapetus was father of Atlas; consequently, Iapetus was the name given to the now-vanished ocean that was directly ancestral to the modern Atlantic. The Iapetan island chains have geological remnants correlated between New England and Newfoundland, and even into the British Isles and northern Europe, that are distinguishable by diagnostic stratigraphic features. They are given the geologic-historical names Ganderia and Avalonia. Throughout late Paleozoic time, Iapetus Ocean narrowed via subduction, and Ganderia and Avalonia successively accreted to the eastern margin of Laurentia; according to some correlations, the collisional suture between Ganderia and Avalonia is between North Branford and Branford, respectively. The ultimate collision with Africa formed the supercontinent Pangea at about 300 Ma. Rocks formed at about this time include the famous Stony Creek Granite, well known as the base of the Statue of Liberty. Between 300 and 200 Ma, the Appalachians were directly connected to similar terrains in Europe, northwestern Africa, and northern South America, as part of an enormous mountain range that likely resembled today's Himalayas. Rocks of the middle crust have been exhumed across New England, which results in swirly patterns on the geological map, as the continental collision mangled and stirred together the Ganderian and Avalonian rocks. Many of the ancient fault lines and tectonic folds are visible as ridges and valleys in the present-day landscape, due to the differing erodibility of foliated gneisses, schists, quartzites, and marbles. Surface water (rivers and lakes) and groundwater flows haphazardly through such broken and contorted bedrock *en route* to Long Island Sound.

Steph Smelser: New Haven, CT

Due to a planetary-scale tectonic reorganization at about 200 Ma, the sites of former subduction and collision across New England became a rift zone that would eventually open the modern Atlantic Ocean. The rift valley of Hartford Basin, extending from New Haven northward through Massachusetts, is one of several "failed" arms of that ocean spreading: a crack that only widened moderately before stabilizing – for unknown reasons – while the "successful" rift zone jumped to the present-day continental shelf. As an aside, if the Hartford rift had in fact developed fully into ocean opening, all of eastern New England would have ended up as part of Africa. Nonetheless, as the Hartford Basin stretched apart through lower Jurassic time (about 200-180 Ma), sedimentary rocks (e.g. New Haven Arkose) and volcanic rocks (e.g. traprock diabases of West Rock, East Rock, Totoket Mountain, Sleeping Giant) filled the subsiding hole between the western and eastern highlands of the state. The contrasting permeability of sedimentary versus igneous rocks within the Hartford Basin has profound effects on topography and erosion, soil, groundwater, and subsequent land usage by humans. Like the crystalline highlands of the state, volcanic traprock ridges are resistant to erosion, topographically steep, and thus more forested than farmed. Groundwater and surface streams and rivers will flow readily through the arkosic sedimentary rocks and along ancient fault lines, but must flow around the impermeable traprock except where it has been locally fractured. All of New England was covered by a vast ice sheet during the last glacial maximum at about 20 thousand years ago (ka), advancing as far as Long Island NY, which is "long" because of a continuous ridge of unsorted glacial debris (called a terminal moraine) derived and transported southward from upland sources throughout New England. When the ice front receded due to natural warming from small variations in Earth's orbit around the Sun, the lithosphere rebounded upward from the removal of the weight of that ice; present-day glacially eroded landforms dominate the southern New England landscape, even if partially covered by till, soil, and vegetation. Eventually, global sea level rose, creating Long Island Sound as we know it today. Anthropogenic global warming threatens to melt Earth's remaining ice caps in Greenland and Antarctica, and if no countermeasures are taken, coastal communities will bear the brunt of inundation, coastal erosion, and salty groundwater intrusion due to further sea level rise over the coming centuries.

Carol Boynton: New York, NY

New York City is built astride geological features that span a billion years of Earth history. The oldest rocks, named the Fordham and Yonkers Gneisses, are high-grade metamorphic rocks formed during collision about 1100 million years ago (Ma) between ancestral North America ("Laurentia") and other proto-continents to form a supercontinent that has been named Rodinia. Ore deposits of the Franklin district in northern New Jersey, and rocks throughout the Adirondack and Berkshire Mountains, were also created at that time. After several hundred million years, supercontinent Rodinia began to fragment, and Laurentia once again became isolated when the Iapetus Ocean opened to create a new eastern shoreline. The Inwood Marble was once a vast ~500 (Ma) shallow carbonate sedimentary bank (like today's Florida) covering the ancient passive margin, which lay across the equator in that era. Clastic sedimentary deposits from farther offshore on the continental shelf and slope were protoliths that eventually metamorphosed to become the Manhattan Schist and Hartland Formation. All of the aforementioned rocks, exposed throughout the Bronx and Manhattan, were compressed and tightly folded together about 450 Ma when intra-Iapetus volcanic arcs began colliding with the Laurentian margin. The landscape at that time would have looked similar to modern New Guinea, where the northern edge of Australia is beginning to subduct under Indonesia; because of the Australian plate's buoyancy relative to the Earth's mantle and adjacent oceanic crustal rocks, it resists subduction back into the planet's interior and instead forces up the New Guinea highlands to nearly 5 km above sea level (where alpine glaciers tower above equatorial rainforests). During one of the ancient Iapetan arc-continent collisions, a sliver of oceanic lithosphere detached from the subducting seafloor and was scraped into the mountain belt; this eventually became exposed to the surface as the Staten Island Serpentinite. The faulting and folding of all these rocks continued until final collision of Laurentia with Africa to form Pangea, about 300 Ma.

After a hiatus of about 100 million years, near the end of the Triassic Period and into the Jurassic Period, Pangea began to break apart, forming an ever-widening sliver of the Atlantic Ocean. Newark Basin, exposed throughout north-central New Jersey and the western side of Staten Island, is a mirror image of Hartford Basin as described above. It contains low-lying brownstone sedimentary rocks (e.g. Stockton Formation) and cliff-forming traprocks such as the Palisades Sill that dominates the west bank of Hudson River. The Hudson River itself, following an impressively straight course like the Connecticut River, likely follows an extinct Triassic-Jurassic fault zone whose broken rocks were easier for the river to erode than their surroundings. As the mid-Atlantic spreading ridge receded ever-farther offshore in the widening ocean, the eastern passive margin of North America cooled and subsided, allowing sedimentary rocks of the Cretaceous (~100 Ma) Monmouth Group and Raritan Formation to blanket the basement rocks of the former collisions. These formations underlie eastern Staten Island, Brooklyn, Queens, and areas farther eastward across the length of Long Island (and onward to Martha's Vineyard and Nantucket). Subsequent sedimentary deposits on the Atlantic passive margin are only preserved offshore, or farther south across the coastal plains of the eastern seaboard.

Within the last few tens of thousands of years (~0.02 Ma), continental ice sheets advanced as far south as New York City. Their enormous erosive power sculpted the ancient bedrock (with beautiful striations on outcrops of Manhattan Schist in Central Park) and dumped their debris in terminal moraines across Long Island. "Brooklyn" which by some accounts means "broken land" in Dutch, is an apt description of the hummocky hills constituting those unsorted glacial debris piles. Modern New York City avails itself of its diverse geological history by exploiting all of the aforementioned features: the natural harbor and easy access to the deep continental interior via Hudson River, construction from the brownstones and traprock in the Newark rift zone, and sturdy metamorphic bedrock under downtown and midtown providing robust foundations for Manhattan skyscrapers.

Carol Boynton: Lexington Park, MD

Chesapeake Bay is a giant coastal plain estuary with tectonic stability and consequent lack of topographic relief. The “Fall Zone” (or Fall Line, named for abundant waterfalls or rapids along rivers draining the Appalachians) is a topographic escarpment separating the coastal plain from the Appalachian piedmont; to the northwest of this boundary, rolling hills expose Mesozoic and older bedrock; to the southeast only Cenozoic sediments are exposed as they cover the older rocks. The Fall Zone is well developed between Richmond VA and New York NY, roughly following the I-95 highway because the latter connects eastern US cities that were initially founded strategically along rivers at the upstream limit of their commercial navigability by seafaring ships. Lexington Park lies well within the coastal plain, sitting atop about 800m of Cenozoic sedimentary rocks. Below these broad flat layers lie relatively narrow Mesozoic rift basins, from the time of initial Atlantic Ocean opening as described above, which cover even deeper layers of Paleozoic metamorphic rocks that likely mark the original collisional suture zone between Laurentia and Africa during the 300-Ma assembly of Pangea. Thus, as one imaginatively drills deeper into the crust, evermore ancient history is encountered. One peculiar addition to this typical story of the US Atlantic margin is the giant Chesapeake Bay bolide (asteroid or meteor) impact, which occurred about 35 Ma and left a crater 40 km in diameter. The circular fractures of bedrock are buried below hundreds of meters of overlying sediment, but the land/sea surface remained subtly influenced by the crater, steering ancient river courses across that ancient depression on their way to the sea. Modern-day Chesapeake Bay owes its fractal coastline to the dendritic drainage network of those ancestral river valleys, and was only geologically recently flooded after the last-glacial maximum (LGM, about twenty thousand years ago, or 0.02 Ma) polar ice caps melted and raised global sea levels more than 100 meters.

Nancy Wattnem: Merida, Venezuela

Merida lies within the easternmost splay of the northern Andes, in a small and narrow fault-bounded valley amid rugged terrain. Eastward propagation of the Andes subduction zone within the last 30 million years has dramatically uplifted the range (Pico Bolivar rises nearly 5000m above sea level) in a tectonically active belt that has generated a multitude of moderate earthquakes, but none over M7 in recorded history. Bedrock geology of the Merida Andes is quite complex, with numerous NE-striking faults and folds that commingle Paleozoic metamorphic and igneous rocks with Mesozoic sedimentary rocks. Bailadores copper deposits, exploited by a major mine in the region, formed within an ancient tectonic analog to the modern Andes subduction zone. The Merida Andes have a wedge-like cross-sectional structure, squeezing upward and thrusting outward, over both the oil-rich Maracaibo Basin to the NW, and the Rio Apure Llanos floodplains to the SE. Exploitable hydrocarbons in both basins formed from the burial of organic-rich sediments derived from the adjacent rising mountains.

Nancy Wattnem: Ciudad Bolivar, Venezuela

Ciudad Bolivar sits on the Orinoco River, firmly within the stable continental interior of the South American tectonic plate. Basement rocks of the Guiana Shield are exposed to the south, consisting of Archean to Paleoproterozoic (3-2 billion years old) gneisses, migmatites, granites, and metavolcanic greenstones. Those latter rocks host the major gold mines of El Callao district, formed about 2100 Ma when the Amazon craton was initially forming through collisions of volcanic island arcs. Since that time, the region has been tectonically stable, occasionally subsiding and covered by sedimentary rocks (including the ca.1900 Ma Roraima Sandstone that has since been broadly uplifted and eroded into flat-topped tepuis that host the world’s highest waterfall, Angel Falls, and inspired the imaginative forays of Arthur Conan Doyle’s “Lost World” and Pixar’s “Up”). The same broad arching of the continent that exposes basement rocks to the south of the Orinoco has removed all previously overlying sedimentary cover. A slight downward tilt to the north, followed by gentle regional uplift, has preserved and exposed a thin veneer of Neogene clastic sediments (Mesa

Formation), which is a several-million-year-old precursor of the Orinoco floodplain and contains vast but largely unexploited petroleum reserves. The modern river takes its course along the boundary between Mesa Formation terraces to the north, and uplifted basement rocks to the south. Due to the intense seasonality of rainfall throughout the Orinoco catchment area, the river level rises and falls about 15m each year. The river's rainy season discharge ranks third globally, surpassed only by the Amazon and Congo (central Africa). Ciudad Bolivar occupies a strategic location where the river channel narrows; its high terraces remain emergent even in the wet season, allowing continuous settlement in proximity to the watercourse. The mighty river was only spanned by a bridge near Ciudad Bolivar as recently as 1967, taking advantage of the unusually high grounds on both banks at that location.

Nancy Wattnem: Caracas, Venezuela

Caracas occupies a narrow valley south of the Cordillera de la Costa, which separates city from sea. The region is tectonically active, as the Caribbean Plate slides eastward past the northern edge of South America – occasionally generating large earthquakes. Coastal mountains rise to about 2000m above sea level, and represent wrinkles along that right-lateral transform boundary (similar to the coastal ranges of central California). Within the Venezuelan coastal ranges, the northern edge of Amazon Craton Precambrian rocks, along with a poorly understood complex of Paleozoic igneous and metamorphic rocks, are uplifted and exposed in an E-W striking anticline. Mesozoic sedimentary rocks dip away to the north and south, on both sides of that structure, which is dissected by numerous faults of variable orientations and causing a rugged hilly landscape. The city of Caracas exploits a relatively spacious (though still narrow in absolute terms) flat valley floor within that landscape, created by a local downdropping of crust that was filled by recent sediments derived from modern erosion of the coastal mountains. Narrowness of the valley implies that Caracas's three million residents need to contend with both water and air pollution, and also increasing landslide hazards as the city expands upward into the Cordillera's flanks.

Matt Schaffer: Rome, Italy

Seven hills above the Tiber River provided strategic advantage over that waterway as it connected interior agricultural regions with the Mediterranean Sea; and thus the city of Rome was founded. The river flows westward through a topographic gap between two dormant calderas of the Roman (or "Lazio") volcanic province; neither has erupted in recorded history, but their ash and flow deposits have been used extensively in Roman urban development, and they dominate the low-relief landscape of west-central Italy. Magmatism along the western Italian peninsula, in the Roman volcanic province as well as Campania with active Vesuvius, is due to lithospheric extension behind an eastward-migrating "rollback" of the Adriatic subducting slab. The counterintuitive key to understanding Italian bedrock geology is that the Adriatic Sea is actually underlain by thinned continental crust, whereas the crest of the Apennine Mountains is composed almost entirely of thrusted slices of Mesozoic deep-sea sediments. The Adriatic seafloor was once a Bahamas-like carbonate bank extending northward as a peninsular prong of the African tectonic plate. After it collided with Europe to form the Alps ca. 30 Ma, the western Mediterranean destabilized and subduction tore off pieces of southern Europe, which rode on the upper tectonic plate above the southward-retreating subduction zone. Some of those fragments became stranded as islands (Mallorca, Sardinia, Corsica) when the plate boundary interface jumped further southward around 15 Ma, and others continued to sweep all the way to the Kabylie Ranges of northern Africa. Eastward, as the Adriatic slab drops into the mantle, the Italian peninsula manifests a tectonic wave propagating across the Mediterranean: narrowing the Adriatic while simultaneously widening the Tyrrhenian Sea. Thus, eastern Italy experiences compressional faulting and folding in front of the wave, while western Italy experiences extension and volcanism in its wake.

Matt Schaffer: London, UK

London is located in the interior of the Eurasian plate, which explains its lack of tectonic activity and low topographic relief. A relatively thin cover of Jurassic-Eocene (200-50 Ma) sedimentary strata lies horizontally above a mildly folded Paleozoic (500-300 Ma) sedimentary sequence that itself probably rests on Ediacaran (ca.600 Ma) volcanic-arc basement whose nearest surface exposure is in the Welsh borderlands. Pleistocene glaciers advanced from the Scottish highlands as far south as Hertfordshire (the low hill country just north of London), but the Thames River valley only experienced periglacial conditions during recent ice ages. The Thames itself is tidal as far west as the London metropolitan area, and narrows from its broad estuary mouth to the place where Romans built their colonial fortifications at a strategic place to cross the river. Today's London must accommodate the environmental consequences (e.g., groundwater pollution) of breathtaking urban expansion across a low-relief landscape that will undoubtedly feel the effects of 21st -century sea level rise.

Matt Schaffer: Rio Tinto, Spain

The vastly rich sulfide mines of Rio Tinto, which runs red because of oxidative weathering of pyrite, have been exploited for thousands of years. The metals include zinc, copper, lead, silver, gold, tin, and others; they were concentrated during subduction magmatism ca. 350 Ma, during a complex process of collisional phases ("Variscan") of the assembling Pangea supercontinent. The orebodies are found in a volcanic-sedimentary succession that is moderately folded and intruded by late-Variscan granites as a result of the collision(s). The entire region was recently (last 5-10 million years) exhumed in a broad arch due to initial lithospheric buckling in advance of the westward-migrating Betic-Rif mountain belt (in both southeastern Spain and northeastern Morocco, with a letter-C shape dissected by the Strait of Gibraltar). The hilly country around Rio Tinto, and its characteristically dry Iberian climate, is transected by small ephemeral streams. Ores extracted from this mining region don't have the benefit of a major river allowing transport to markets, thus the Roman road-based infrastructure was well suited for their early exploitation.

In the context of these geological vignettes, the curricular units developed by Y-NHTI Fellows, described in the following sections, draw upon their exploratory studies of these regions. The geospatial skills that the Fellows developed can be used in any area of the world, and transmitted to their students whether through explicit usage of Google Earth or through complementary methods and media. As global-scale challenges face generations to come, it is hoped that these units will help future citizens and leaders recognize our special geological gifts that are the foundation of industrial society, as well as understand the actions we must collectively take to secure a desirable fate for both our own species and the entire world's environment that we now steward.