Figure 1. Mount Monadnock rises 600 m above the rolling plains at its base. Photo credit: Jonwmcinenrey via Wikimedia Commons. https://creativecommons.org/licenses/by-sa/3.0/deed.en.

Mount Monadnock: A Geologic Type Locality

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Among the entries for the letter "M" in the American Geological Institute's Dictionary of Geological Terms (Bates and Jackson, 1984), you will find:

> **monadnock** (mo-nad'-nock): A hill or mountain rising conspicuously above the general level of a peneplain in a temperate climate, representing an isolated remnant in a region that has been largely beveled to its base level.

Mount Monadnock, the type locality for this landform, stands a mere 965 m above sea level, but rises in splendid isolation 600 m above the rolling plains of southern New Hampshire (Fig. 1). The mountain is located 75 km west of Manchester and boasts an extensive trail system, making it a good day-trip destination that can be done in conjunction with GSA's 2024 Northeastern Section Meeting.

The influential Harvard geographer William Morris Davis introduced the term monadnock to the geologic literature in an 1896 *National Geographic* article describing the landscape of northeastern France (Davis, 1896). He used the name of the prominent mountain near his Massachusetts home as the appellation for all similarly prominent peaks that rise from comparatively flat plains. Davis was hardly the first person to take special note of Mount Monadnock's prominence amidst flat surroundings; its name comes from the Indigenous Abenaki language and is thought to translate as "the mountain that stands alone" (Anderson, 2022).

Davis was one of several American geologists, including John Wesley Powell, Clarence Dutton, and Grove Karl (G.K.) Gilbert, who pioneered the new discipline of geomorphology during the second half of the nineteenth century. The idea of a monadnock was part of Davis's conceptualization of a geomorphic cycle in which a landscape is uplifted and subsequently eroded to its base level, going through stages of youth, maturity, and old age. In old age the landscape is reduced to a peneplain, a gently rolling plain near base level (typically sea level). But Davis noted that places composed of especially resistant rock would erode more slowly than average, causing them to stand above the peneplain as a monadnock. He made no attempt to quantify the relative resistance between the rocks of the monadnock and those of the surrounding peneplain to gauge how long one of his hypothesized cycles lasts, commenting in one essay that he "has given no particular attention to the composition of the monadnock rocks" because one can simply "infer their greater resistance on account of their form" (Davis and Johnson, 1909). Davis's ideas formed the foundation of the discipline of geomorphology until the middle of the twentieth century, but his influence has since waned as the discipline gravitated back to the more quantitative and process-oriented approach of his contemporaries Gilbert and Dutton.

MONADNOCK'S RESISTANT ROCKS

New Hampshire's Mount Monadnock consists entirely of the Littleton Formation, a 5200-m-thick pile of Early Devonian marine sandstone/mudstone that was later metamorphosed into an alternating sequence of quartzites and mica schists (Fowler-Billings, 1949). When it was deposited, the coastline of Laurentia, the nucleus of today's North America, was located near the Vermont–New Hampshire border, and the great sediment pile that would later become the Littleton Formation was accumulating far to the east (in modern coordinates), offshore of a microcontinent called Avalonia.

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As the oceanic lithosphere that was attached to Laurentia subducted beneath Avalonia, it brought the microcontinent ever closer to Laurentia. This subduction progressively narrowed the western Iapetus Sea, which separated the continent and the microcontinent until, by the Middle Devonian, it was entirely consumed. During the ensuing collision, this pile of sand and mud was buried to a depth of 12 km, where the sandstone was metamorphosed to quartzite and the mudstone to a garnet-sillimanite schist (a mineral assemblage that records high pressure metamorphism; N. Davis, 2019). Abundant, lath-like pseudomorphs of sillimanite up to 7.6 cm long cover some rock exposures. Because the sillimanite resists erosion better than the surrounding rock, these laths stand out in stark relief, leading to their "turkey tracks" nickname (Fowler-Billings, 1949).

The Littleton Formation was intensely folded during the Laurentia-Avalonia collision, which is known as the Acadian Orogeny. Mount Monadnock lies near the axis of a major syncline, and the mountain's rocks host numerous smaller-scale folds. One especially photogenic isoclinal fold (Fig. 2), 5.5 m tall and 9 m long, lies just west of the summit and can be accessed from the Smith Summit or White Arrow trails. It is known as the "Billings Fold" because it gained geologic notoriety as the cover image of the 1942 edition of Marland Billings' well-known *Structural Geology* textbook (Thompson, 2013).

Figure 2. The Billings fold lies just below the summit. Photo credit: EdwardEMeyer via Wikimedia Commons. https://creativecommons.org/licenses/by-sa/4.0/deed.en.

During the orogeny's late stages, in the Late Devonian, voluminous granites and a few mafic dikes intruded across New Hampshire. The granites erode more rapidly than the Littleton Formation, so they are the dominant rock type in the lowlands surrounding the mountain. Only a few small dikes and sills cut through the Littleton Formation on Mount Monadnock (Thompson, 1988). These granites were extensively quarried throughout the state, with quarrying reaching a zenith between 1850 and 1900, when New Hampshire supplied millions of dollars' worth of granite building stone across New England (Fowler-Billings, 1949), earning it the nickname of the Granite State. The first quarry near Mount Monadnock was opened in 1812, and many more followed; several are now filled with water, forming scenic ponds. You can walk or bike past several abandoned quarries on the Cheshire rail trail, one of many trails that has been created from old railroad right of ways. It passes 4 km west of Mount Monadnock on its way between the towns of Fitzwilliam and Keene.

MAKING A MONADNOCK

The Acadian Orogeny marked the closing of the western Iapetus Ocean between Laurentia and Avalonia. This was followed by the Alleghenian Orogeny, which occurred when the eastern Iapetus Sea closed during the Carboniferous, triggering continent–continent collision between Laurentia and Gondwana. This collision completed the assembly of Pangaea. The Pangaean supercontinent then began to break apart during the Triassic, with North Africa separating from New England. Part of the old Avalonia microcontinent was left attached to New Hampshire and today forms much of Massachusetts (Davis, 2019). Several fault zones in the Monadnock area that were formed during these tectonic episodes provided conduits for silica-charged fluids, which precipitated as 100-m-wide silicified zones near Sip Pond, located just south of the mountain (Fowler-Billings, 1949).

Pangaea's breakup was the last major tectonic episode to affect the Mount Monadnock region; erosion has been the dominant geologic process for the last 200 million years. That prolonged period of erosion reduced the former mountains to today's gently undulating peneplain, leaving several resistant monadnocks, including Mount Monadnock, rising from it.

The mountain has a steep, craggy south flank, and a smoother, gentler north flank whose rocks display parallel striations. This shape is a legacy of one last, important geologic episode—Pleistocene glaciation. When the last Laurentide ice sheet moved south out of Canada during the Wisconsin glacial episode, about 75–15 ka, it completely covered Mount Monadnock. That burial by ice sculpted the mountain into an especially large roche moutonnée. The flow of ice over the summit smoothed and polished the mountain's northern (up-ice) flank and left glacial striations trending S20°E, the direction of ice flow (Fowler-Billings, 1949). The pressure shadow that formed on the south (lee) side of the mountain triggered freeze-thaw cycles that quarried large blocks, resulting in the craggy nature of the south face. When the glacier melted it dropped many such plucked blocks all around the mountain. Some of these exotic blocks were transported hundreds of kilometers from where they were plucked from the bedrock, so they are called glacial erratics. The most famous erratic in the area is a large, rectangular boulder called the Sarcophagus that stands at about 850 m elevation on the scenic Pumpelly Ridge trail, which ascends the mountain's east flank (Fowler-Billings, 1949).

A VIEW FOR THE AGES

Thanks to Mount Monadnock's eye-catching prominence and proximity to major population centers, it is climbed by more than 125,000 people each year, making it one of the most-climbed mountains in the world (Anderson, 2022). More than a dozen different trails ascend the mountain from every direction, with the Pumpelly Ridge trail considered the easiest thanks to its gentler gradient. The southern trails are short and steep, thanks to the glacial plucking on the mountain's lee side, with the White Dot trail climbing 600 m in less than 2.5 km.

On a clear day, the view from the top is stunning, encompassing several states and the Atlantic Ocean. Few New England mountains of comparable stature offer such expansive views because most are covered in forest. Monadnock's distant views are a prod-

uct of massive nineteenth-century fires that burned the forest and sterilized the ground. Henry David Thoreau, who visited the mountain four times between 1844 and 1860, recorded in his journal the story that settlers lit a fire in 1800 to drive away wolves but it raged out of control and burned to the summit. Although one might imagine that Thoreau, who usually delighted in making careful biological observations, would decry this forest destruction, he instead extolled the geologic value of Monadnock's bald top, remarking enthusiastically in his journal, "but what a study for rocks does this mountaintop afford!" (Thompson, 2013).

The extensive rock outcrops exposed by the fires make Mount Monadnock an especially good place to examine the area's abundant evidence of glacial sculpting. Thoreau repeatedly described features like striations and erratics, but his journal entries don't identify their glacial origin. That is somewhat surprising given that he was familiar with Louis Agassiz's glacial hypothesis for such landscape features. The likely explanation for this omission is that the glacial hypothesis was controversial at that time, with many geologists still favoring the flooding (diluvial) hypothesis for the presence of such features in New England. Another nineteenth-century luminary, Ralph Waldo Emerson, who visited Mount Monadnock in 1866, was clearly already convinced of the role glaciers had played in sculpting the New England landscape, noting the "uniform presence on the upper surface of the glacial lines or scratches, all in one self-same direction" (Thompson, 2013).

Ascents of Mount Monadnock were already popular in Thoreau's time, and he lamented the "newspaper and eggshell" debris left by the visitors. Climbers in the 1800s also enjoyed chiseling their names into the rock at the summit. Although Thoreau disapproved of the practice, he seemed not to be overly worried about it, predicting that the "bog and lichen" would soon claim the graffiti (Thompson, 2013). Fortunately, the mountain is now the protected centerpiece of Monadnock State Park, where such vandalism is forbidden.

If you are in New Hampshire to attend GSA's 2024 Northeastern Section Meeting, consider joining the longstanding tradition of summiting this iconic peak. There you can sign the summit register, revel in the expansive view, and peruse isoclinal folds and glacial striations from atop this landform type locality.

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