GEOHERITAGE

Stark's Knob: A New Plate Tectonics Model—First Volcano Described from a Subducting Plate Margin

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Author Ken Burns saw the founding of the National Park System in the late nineteenth and early twentieth century as "America's best idea" (Duncan and Burns, 2011). This preservation ethic was mirrored in New York State during World War I by donations of five unique sites to the State Regents via the charismatic New York State Museum (NYSM) Director John M. Clarke. These eastern and central New York sites became "Scientific Reservations." All were subsumed by the New York State Parks system in 1929 (Flick, 1929), but, inexplicably, the easternmost, smallest, and geologically most significant sites, the Stark's Knob pillow basalt (Fig. 1) and Lester Park's classic stromatolites, remained under the NYSM. Not maintained for decades, they were restored by Ed Landing with volunteers by removal of junk cars, garbage, overgrowth, and trees, and installation of interpretive signs (Landing, 2004). These "teach yourself geology" sites were designated State Geoparks in 2019 by the state legislature. Both Geoparks can be visited year-round. They must be seen as irreplaceable—do not damage or collect anything.

Figure 1. East face of Stark's Knob quarry. Pillow basalt–shaley mélange contact in depressed area at upper right of photograph; rolling of hot pillows incorporated abundant, small, white-weathering clasts of inter-pillow limestone into the glassy pillow margins. Photo credit: Ed Landing.

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LOCATION AND U.S. HISTORY

Stark's Knob is a low hill (crest at 66 m, 43°07' 08.05" N, 73° 73' 18.27" W) east of the combined upper Hudson River and Champlain Canal (~27 m elevation). It is named for General John Stark, whose troops occupied the Knob at the end of the Battles of Saratoga (19 September–17 October 1777). This action blocked the British army from retreating to Canada and ended the Revolutionary War in the northern U.S. (e.g., Ketchum, 1997). In 1916, Stark's Knob and a small surrounding area were deeded to the Regents for US$1 by five Saratoga County residents (see Lord, 1997).

The steep east face of Stark's Knob resulted from quarrying for ballast for a widened Champlain Canal from 1905 to 1918 (Fig. 1). The quarry base is at the end of a path that branches north from the curve on Stark's Knob Road ~125 m west of combined routes U.S. 4 and N.Y. 32. The crest is best reached by a steep trail on the west side of the Knob. It offers views of the Adirondack Mountains massif (ca. 1.0 Ga) to the NW and N and S across lowlands underlain by the Cambrian–Ordovician shelf and synorogenic Late Ordovician mudstone. To the east are the rolling hills of the Taconic slate belt (late Ediacaran[?]–Late Ordovician) with the Green Mountains on the horizon (1.0 Ga core and cover of metamorphosed terminal Ediacaran[?]–Ordovician rift–passive margin; e.g., Landing et al., 2023, with references).

The quarry face must not be climbed—it is unstable fragmented rock.

GEOLOGIC SETTING

Stark's Knob is at the westernmost edge of the thrust and faulted Appalachian Mountains. What you see in the quarry is essentially all there is—an ~125-m-long, 39-m-thick lens of strongly dipping (vertical at N end of quarry, ~50° W at the crest) basalt pillows (10 × 20 cm to 1.0 × 2.5 m diameter). The basalt has faulted (not intrusive) contacts in a Late Ordovician shaley mélange produced during the Taconic orogeny (e.g., Kidd et al., 1995; Hayman and Kidd, 2002).

Stark's Knob and the mélange underlie the master thrust plane of the Taconian orogen. The edge of the Taconian thrust slices is ~5 km east. The roughly N–S strike of many structural elements east to the Green Mountains parallels the ancestral margin of this part of Laurentia ("ancestral North America"). This was a giant Y-shaped triple junction produced by rifting of the Rodinia supercontinent. The two active limbs of the triple junction parallel the modern Lake Champlain–Hudson River and St. Lawrence River valleys and faced the Iapetus Ocean. The NW-trending passive arm is the Ottawa-Bonnechere graben. The shape and geologic setting of the terminal Ediacaran–early Paleozoic Laurentian margin from modern southern New York to SW Newfoundland was comparable to the "Horn of Africa" formed by the rifting of Arabia.

Late Ordovician collision with a volcanic island arc now in central New England closed Iapetus. This Taconic orogeny was the earliest Phanerozoic orogeny in this part of Laurentia. The Avalonia microcontinent later collided with NE Laurentia in the second Appalachian mountain-building event, the Acadian orogeny (e.g., Landing et al., 2023, and sources therein).

> THE AGE AND GEOLOGIC SIGNIFICANCE OF STARK'S KNOB HAVE LONG BEEN PROBLEMATICAL, AS COMPARABLE ROCKS ARE RARE IN THE REGION.

GEOLOGIC ENIGMA OF STARK'S KNOB

The age and geologic significance of Stark's Knob have long been problematical, as comparable rocks are rare in the region. Early comparisons were with the Triassic–Jurassic mafic rocks of the Palisades bordering the lower Hudson River valley–Newark, New Jersey, lowlands, with limestone lenses on the pillows (Fig. 2) thought to come from the underlying Cambrian–Ordovician shelf (e.g., Cushing, 1914). By contrast, the Triassic–Jurassic rocks are sills and flows, not extrusive basalt pillows and lava tubes through which molten rock poured. Basalt pillows dominate Stark's Knob (Fig. 1), with the lava tubes flattened by overlying pillows. A collapsed lava tube low in the quarry shows multiple lava shelves with limestone caps (Fig. 3). These formed as lava retreated down the tube, paused, and developed a frozen basalt skim on which limestone was deposited before the next fall in lava level.

Two theories of Stark's Knob formation dominated twentieth-century thought. One was that the basalts were transported (allochthonous) and were extruded onto deep-water Late Ordovician sediments that became part of the Taconian allochthon. The allochthonous pillow-bearing rock itself was then overrun by the rest of the allochthon during thrusting (e.g., Fisher, 1977). This meant Stark's Knob was extruded east of the Green Mountains and was transported >75 km to its present position. A second allochthonous interpretation was that the Knob was isolated in synorogenic sediment as young as or even younger than anything in the allochthon (Landing, 1988). As Taconian mélange blocks of many ages and lithologies (Late Ordovician mudstone to Mesoproterozoic ["Grenville"] granulite) and sizes (to 10 km long) were known (Zen,

Figure 2. Limestone lens from pillow top showing basalt clasts on base, internal lamination, and top baked reddish by overlying pillow. Mm scale to right. Photo credit: Ed Landing.

1967), the age and relation of the Knob to the evolution of northeast Laurentia remained unknown.

RESOLVING THE ENIGMA I: LIMESTONES AND A FOSSIL SNAIL

The problems were as follows: what is the Knob's age (1.0 Ga to ca. 455 Ma?) and, thus, what is its tectonic significance? Allochthonous or autochthonous—a part of the Taconic allochthon or essentially in situ? The age and unexpected geologic significance of the Knob were revealed by detailed study (Landing et al., 2003, summarized below).

Zircons that could provide geochronologic control were not recovered from the basalt. However, the fine-grained, thin (≤12 cm) limestones in inter-pillow depressions (Fig. 2), on lava shelves (Fig. 3), and sheared into pillow margins (Fig. 1) suggested a biostratigraphic resolution of the extrusion age. Fifty-six limestone samples (several 3.5 kg) did not yield acid-resistant fossils (i.e., conodont elements, acritarchs, other phosphatic or silicified sclerites). Macrofossils were very limited—single trilobite and echinoderm sclerites were noted on sawed limestone slabs. Fortunately, one gastropod conch (*Leiospira*?) was found.

This snail indicates a correlation with the Trenton Group (middle Upper Ordovician, Katian Stage) on the Laurentian shelf. This is younger than the highest unit in the slope–rise succession of the Taconic allochthon (lower Upper Ordovician, Sandbian Stage, Austin Glen Formation). This means Stark's Knob is not allochthonous, and the basalt volcanism took place on synorogenic sediment (now mélange) in front of the advancing Taconic allochthon.

The limestones have minimal siliciclastic sediment (≤0.05%) derived by erosion of the Taconic orogen; lack the diverse, abundant fauna of the Trenton Group; and were deposited during extrusion of pillows, which also rolled across the limestone lenses (Figs. 1 and 2). The pillows have fine calcite-filled amygdules (≤0.5 mm) from glassy margin to core, suggesting relatively deep water. The limestones have horizontal laminae indicating very low-flow rates or a simple settling of lime mud.

The lime mud (now fine microspar) could have been produced from cold seeps (natural gas, brine, petroleum) known on passive and convergent margins, including accretionary prisms, or hydrothermal vents and volcanics in a rift setting—these are all limestones with highly negative $\delta^{13}C$ values. By comparison, Stark's Knob limestones have the slightly positive $\delta^{13}C$ values of seawater. Thus, they were produced as a sort of submarine limey snow by simple heating of sea water by hot pillows that raised pH with CO_2 loss.

RESOLVING THE ENIGMA II: BASALT GEOCHEMISTRY

Basalt geochemistry helped resolve where and how the Stark's Knob basalt was produced, with consequences for other submarine volcanics related to subduction zones. The Late Ordovician (Katian) setting of the autochthonous Stark's Knob basalt featured western advance (in modern coordinates, actually northerly at that time) of the Taconian thrust belt. Thus, the basalts seemingly reflect a convergent, subduction setting—an interpretation substantiated by basalt geochemistry. The pillows show a nearly complete loss of primary minerals from the polygonally fractured chilled margins to the coarser-grained cores. After removal of veinlets with alteration minerals, study of immobile elements that reflect eruptive setting shows that they fall in the mid-oceanic ridge basalt (MORB) field. The depletion of light rare earth elements (REEs) is comparable to N-type (normal) MORBs, which is emphasized by abundant Zr, Ti, and Y; the REE distribution; and low Cr/Al ratio of chromian spinel (the only unaltered mineral). The high Nb is unlike island arc tholeiites or volcanic arc basalts.

The geochemistry and geologic setting of Stark's Knob are comparable to the Late Ordovician, MORB-type Jonestown volcanics in the Taconic orogen (Harrisburg klippe) of eastern Pennsylvania. In both areas, it seems that craton margin–arc collision led to (1) a change from subduction to strike-slip and formation of fault-bounded, short, *en echelon* spreading centers or (2) development of extensional faults parallel to the subduction zone as the Laurentian plate was (a) forced into the trench, possibly over a fore-arc bulge, or (b) pulled, due to high density of the cold Laurentian margin, into the hot lithosphere of the lower subduction zone. By all models, the faulting would have allowed vertical movement of deep magma and extrusion as lava on the sea floor.

Figure 3. Lava ledges with limestone caps in crushed lava tube; white pen at base of figure is 10 cm long. Photo credit: Amy Frappier, Skidmore College.

Watch a fascinating video about this geoheritage site. **https://bit.ly/3KSuIrG**

STARK'S KNOB AND THE "WEAK SIDE" OF THE PACIFIC RING OF FIRE

After recognition of Stark's Knob as a then (2003) unexpected development (i.e., a volcano on the subducting plate), volcanoes were announced to be present on the subducting Pacific plate on the Japan outer trench slope (Hirano et al., 2006). Subsequent work termed these "petit-spot volcanoes" (Hirano, 2011), and showed that these small volcanoes were widespread on Pacific outer trench slopes over the last 8 Ma (i.e., late Miocene to Recent; see Hirano and Shiki, 2022; Azami et al., 2023, and references therein). These east Pacific studies do not note the older Stark's Knob and Jonestown volcanics, but the evidence is that outer subduction zone volcanism extends into the late Proterozoic (1.88 Ga; i.e., review by Schoonmaker et al., 2016).

Outer trench slope/fore-arc volcanism likely accompanied the onset of plate tectonics on Earth. It produces small volcanoes that differ from the large arc, hot spot, and large igneous province (LIP) volcanoes. Indeed, the explosive, felsic, giant arc volcanoes typically shown in reconstructions of the "Pacific ring of fire" should be shown facing parallel lines of small fore-arc, trench-parallel basaltic edifices.

REFERENCES CITED

Azami, K., Machida, S., Hirano, N., Nakamura, K., Yasukawa, K., Kogiso, T., Nakanishi, M., and Kato, Y., 2023, Hydrothermal ferromanganese oxides around a petit-spot volcano on old and cold oceanic crust: Communications Earth & Environment, v. 4, no. 191, https://doi.org/10.1038/s43247-023-00832-3.

Cushing, H.P., 1914, The Northumberland volcanic plug, *in* Cushing, H.P., and Ruedemann, R., eds., Geology of Saratoga Springs and Vicinity: Albany, New York State Museum Bulletin, v. 169, p. 115–135.

Duncan, D., and Burns, K., 2011, The National Parks: America's Best Idea: New York, Alfred A. Knopf, 432 p.

Fisher, D.W., 1977, Correlation of the Hadrynian, Cambrian, and Ordovician rocks of New York State: New York State Museum, Map and Chart Series, no. 25, 75 p.

Flick, A.C., 1929, Suggestions of a state policy relating to historic and scientific reservations, *in* Adams, C.C., ed., Twenty-Third Report of the Director of the Division of Science and the State Museum: Albany, New York State Museum Bulletin, v. 284, p. 68–71.

Hayman, N.W., and Kidd, W.S.F., 2002, Reactivation of pre-thrusting, synconvergence normal faults as ramps within the Ordovician Champlain-Taconic thrust system: Geological Society of America Bulletin, v. 114, p. 476–489, https://doi.org/10.1130/0016-7606(2002)114<0476:ROPSNF>2.0.CO;2.

Hirano, N., 2011, Petit-spot volcanism: A new type of volcanic zone discovered near a trench: Geochemical Journal, v. 45, p. 157–167, https://doi.org/10.2343/geochemj.1.0111.

Hirano, N., and Shiki, M., 2022, The mantle structure below petit-spot volcanoes: Communications Earth & Environment, v. 3, no. 110, https://doi.org/10.1038/s43247-022-00438-1.

Hirano, N., et al., 2006, Volcanism in response to plate flexure: Science, v. 313, p. 1426–1428, https://doi.org/10.1126/science.1128235.

Ketchum, R.M., 1997, Saratoga: Turning Point of America's Revolutionary War: New York, Henry Holt, 545 p.

Kidd, W.S.F., Pleach, A., and Vollmer, F.W., 1995, Lithofacies and structure of the Taconic flysch, melange and allochthon, in the Capital District, *in* Garver, J.I., and Smith, J.A., eds., Field Trip Guide for the 67th Annual Meeting of the New York State Geological Association, p. 57–80.

Landing, E., 1988, Depositional tectonics and biostratigraphy of the western portion of the Taconic allochthon, eastern New York State, *in* Proceedings, The Canadian Paleontology and Biostratigraphy Seminar, Albany, September 1986: New York State Museum Bulletin, v. 462, p. 96–110.

Landing, E., 2004, America's oldest scientific parks: John M. Clarke's "Scientific Reservations": Geological Society of America Abstracts with Programs, v. 36, no. 2, p. 115.

Landing, E., Pe-Piper, G., Kidd, W.S.F., and Azmy, K., 2003, Tectonic setting of outer trench slope volcanism: Pillow basalt and limestone in the Ordovician Taconian orogen of eastern New York: Canadian Journal of Earth Sciences, v. 40, p. 1773–1787, https://doi.org/10.1139/e03-076.

Landing, E., Webster, M., and Bowser, S.S., 2023, Terminal Ediacaran–Late Ordovician evolution of the NE Laurentia palaeocontinent: Rift–drift–onset of Taconic Orogeny, sea-level change, and "Hawke Bay" onlap (not offlap), *in* Nance, R.D., Strachan, R.A., Quesada, C., and Lin, S., eds., Supercontinents, Orogenesis, and Magmatism: Geological Society of London Special Publication 542, https://doi.org/10.1144/sp542-2023-4.

Lord, P., 1997, Stark's Knob: The historical significance of a "Scientific Reservation": Report to the New York State Board of Regents, 65 p.

Schoonmaker, A., Kidd, W.S.F., and Ashcroft, T., 2016, Magmatism and extension in the foreland and near-trench region of collisional and convergent tectonic systems: Geoscience Canada, v. 43, p. 159–168, https://doi.org/10.12789/geocanj.2016.43.100.

Zen, E., 1967, Time and Space Relationships of the Taconic Allochthon and Autochthon: Geological Society of America Special Paper 97, https://doi.org/10.1130/SPE97-p1.