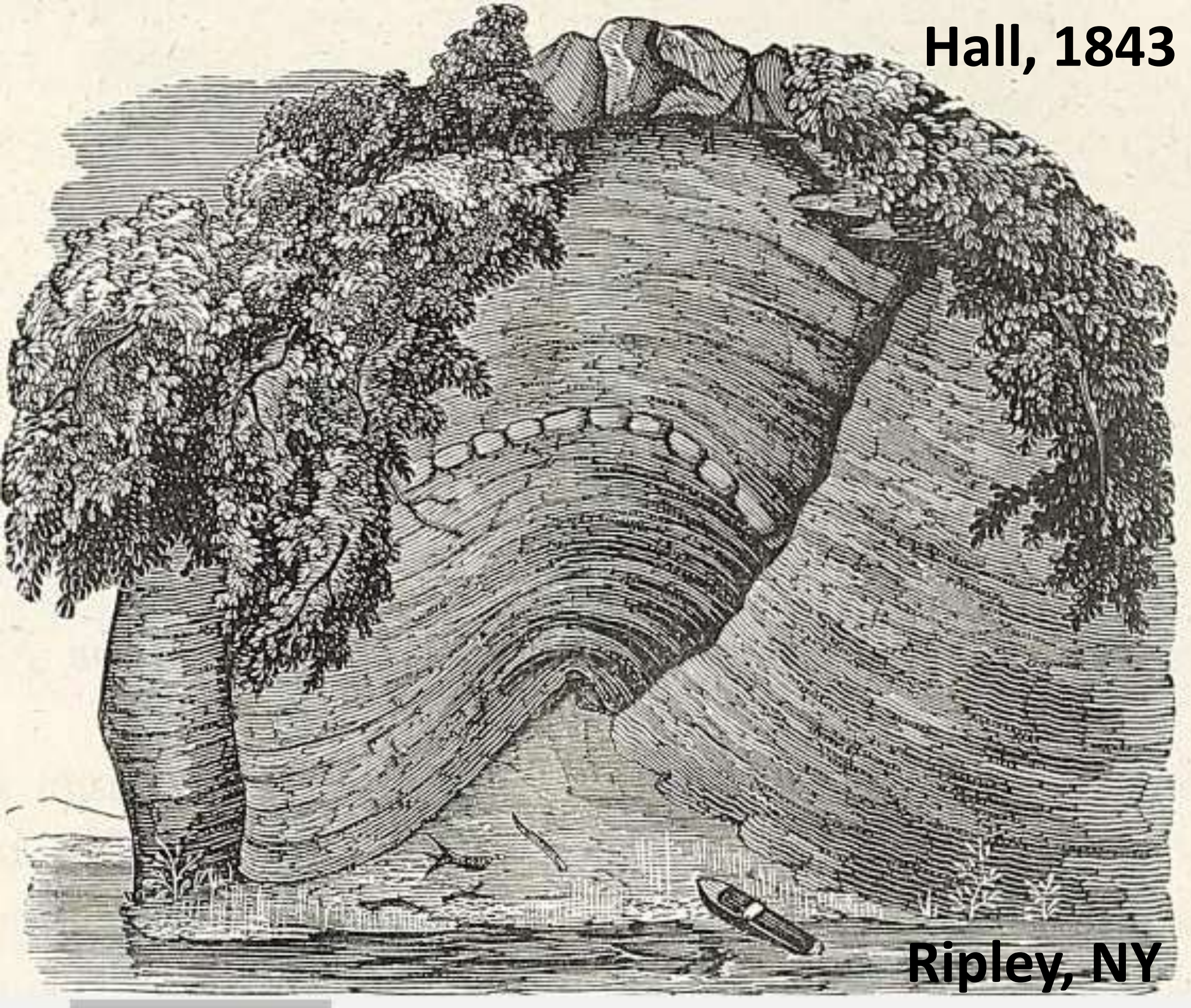
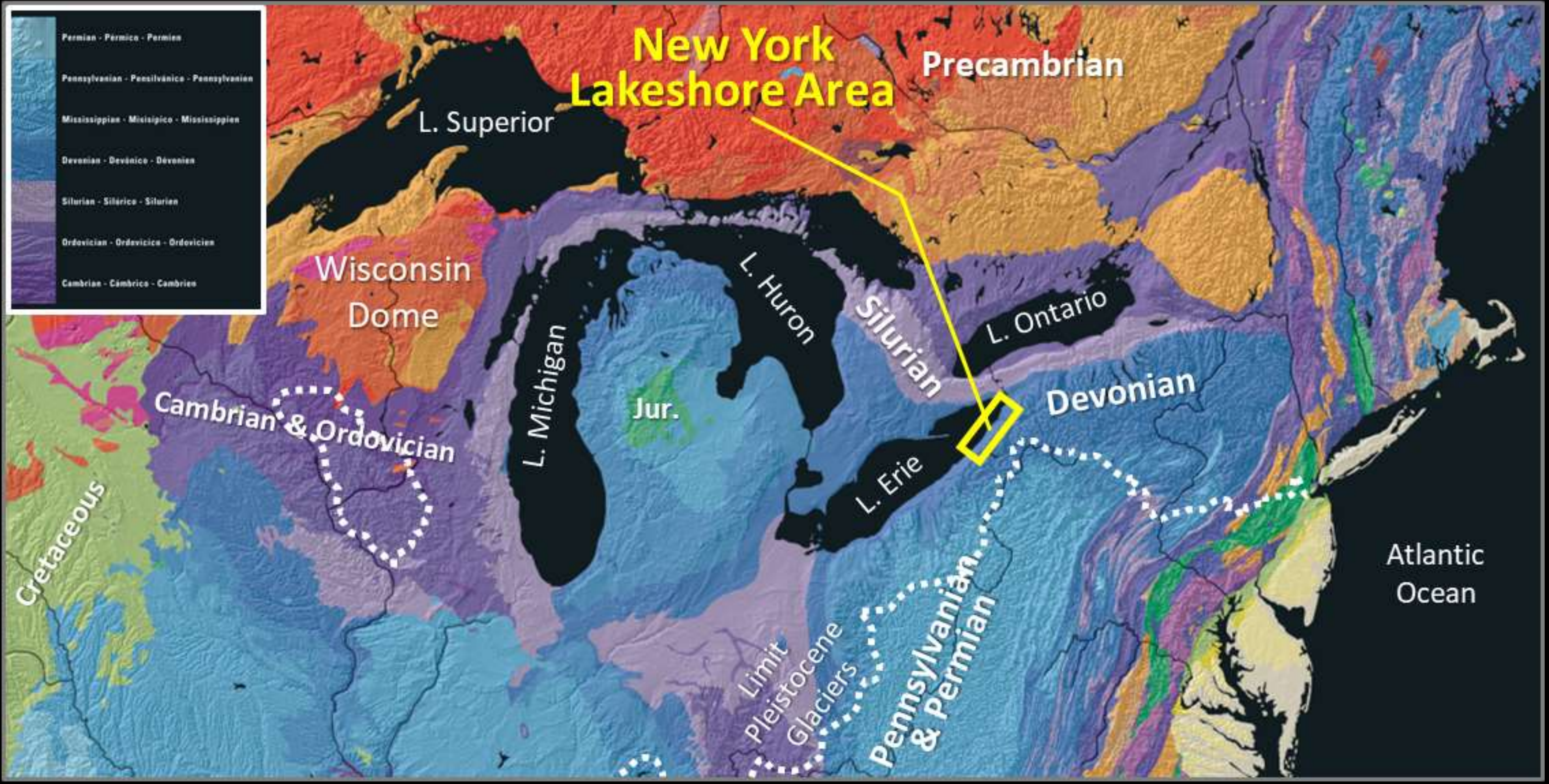
Thrust faults and folds interpreted as post-glacial pop-ups in Devonian strata of lakeshore bluffs along Lake Erie, western New York State, USA

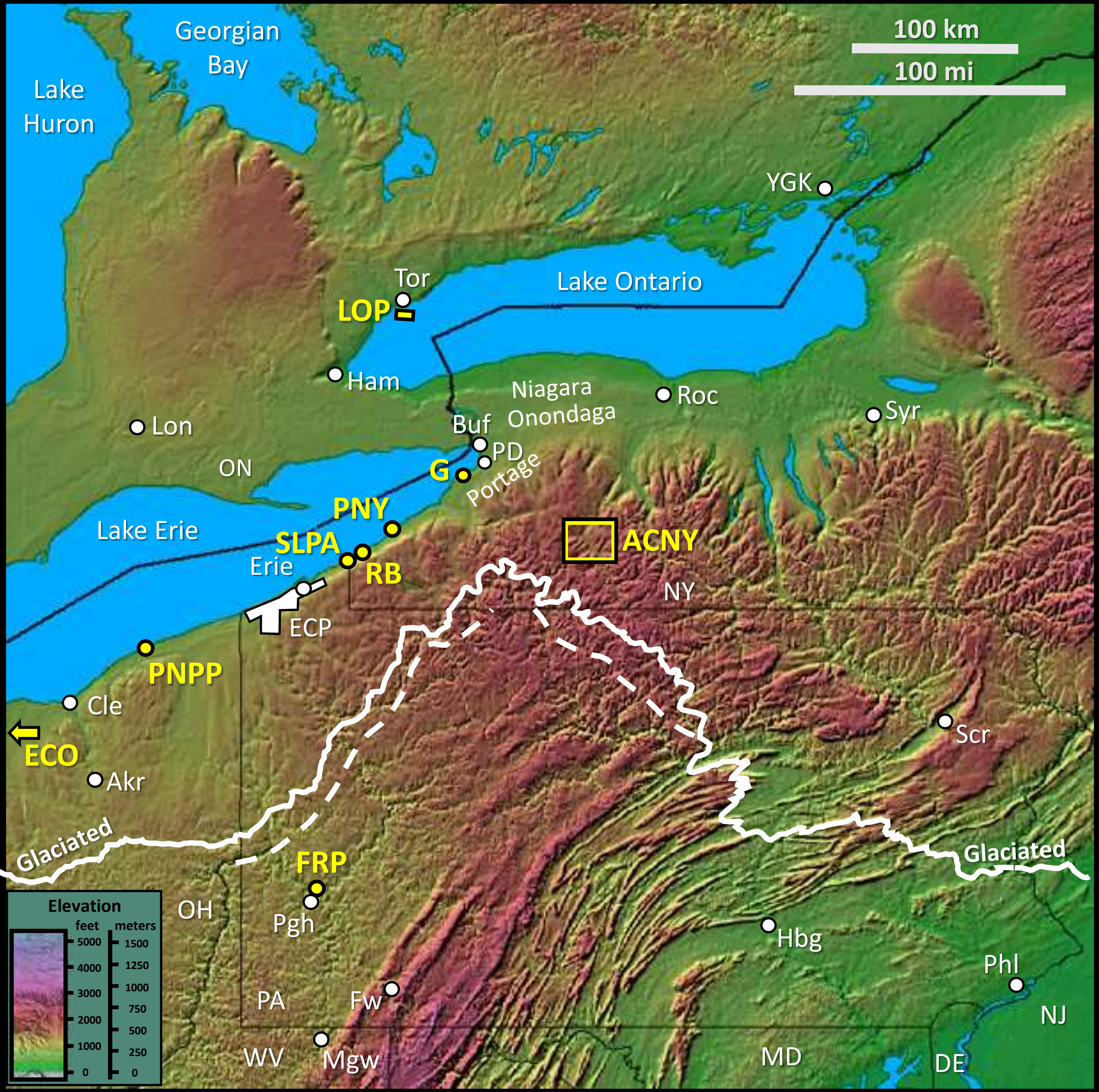
Fred Zelt, Earth Science Excursions, LLC
Robert Jacobi, Department of Geology, University at Buffalo



Regional context of study area

Geologic Map: USGS Geologic Investigations Series I-2781
Glacier Limit: Carson et al., 2023 (Driftless); Brittanica.com (other)

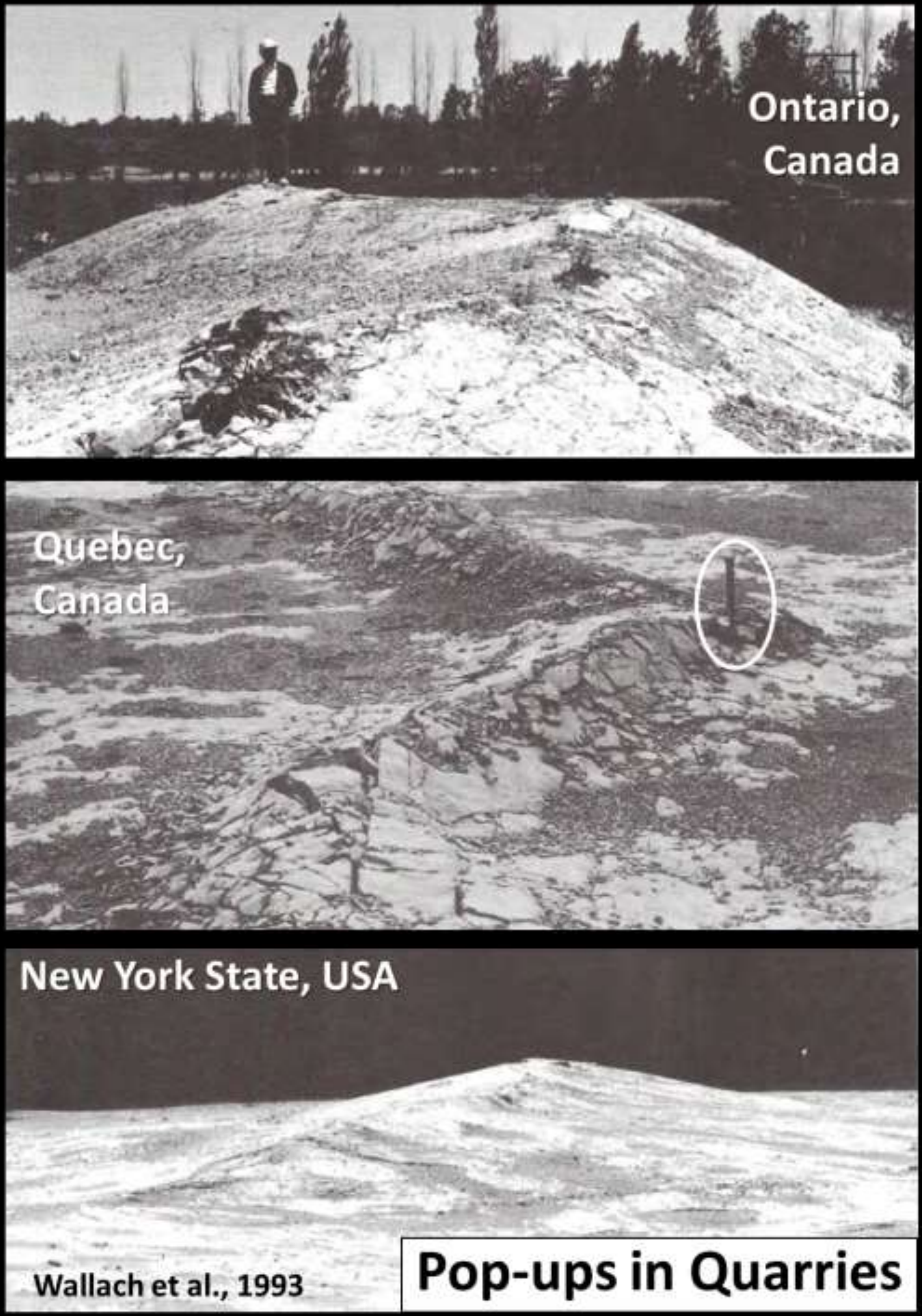


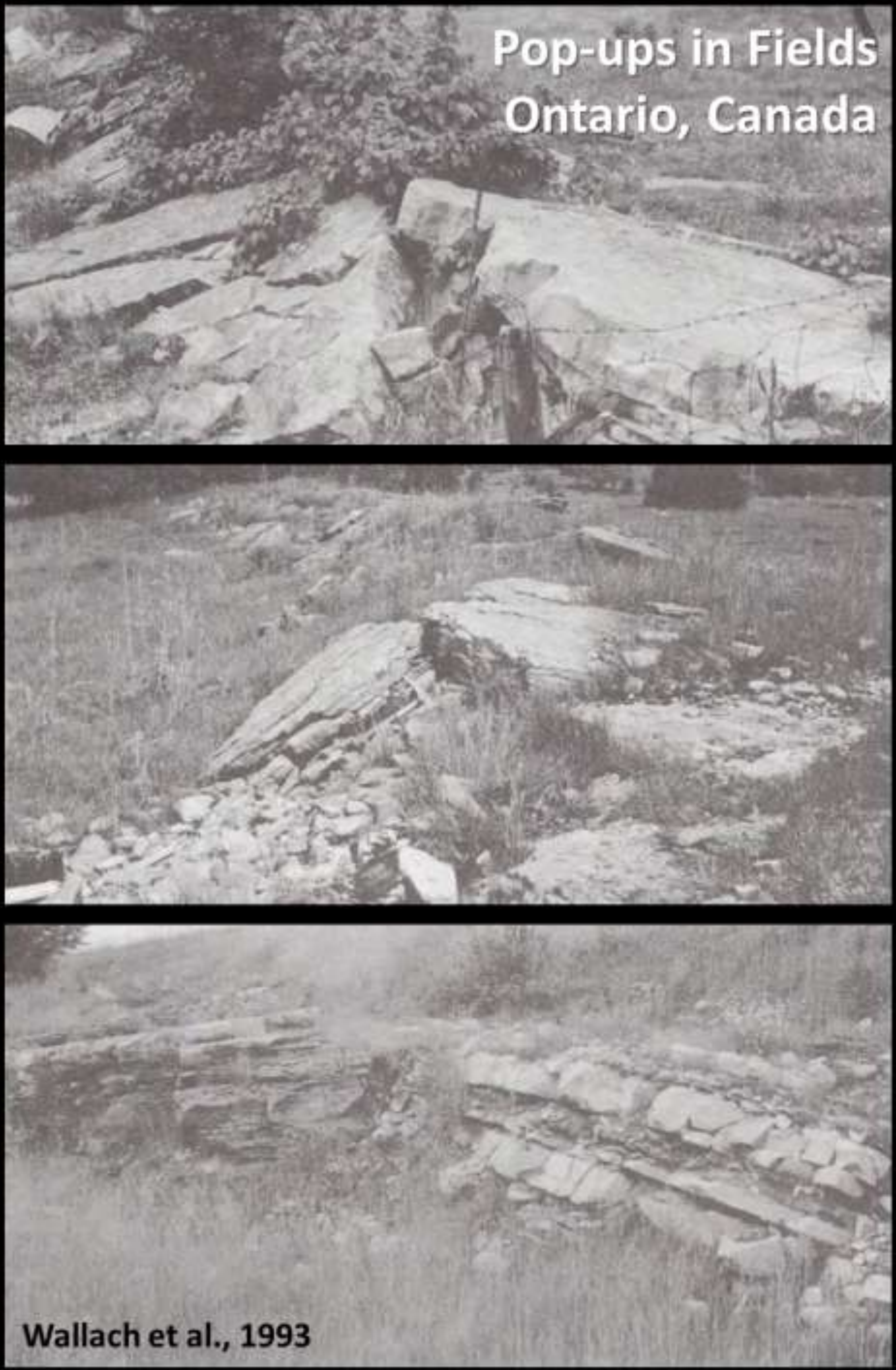


Map from Andrew Birrell with permission of Brenda Birrell

Regional context of examples

- Interpreted pop-up structures in glaciated and unglaciated Plateau (Ripley Beach, Lake Ontario, Graycliff area, Allegany County NY, Fall Run Park (**RB**, **LOP**, **G**, **ACNY**, **FRP**)
- Compressional structures with evidence of glacial shear from Portland NY, State Line PA, and Perry in northern Ohio (**PNY**, **SLPA**, **PNPP**)
- Example of Alleghanian tectonic compression in Erie County, northern Ohio (**ECO**)





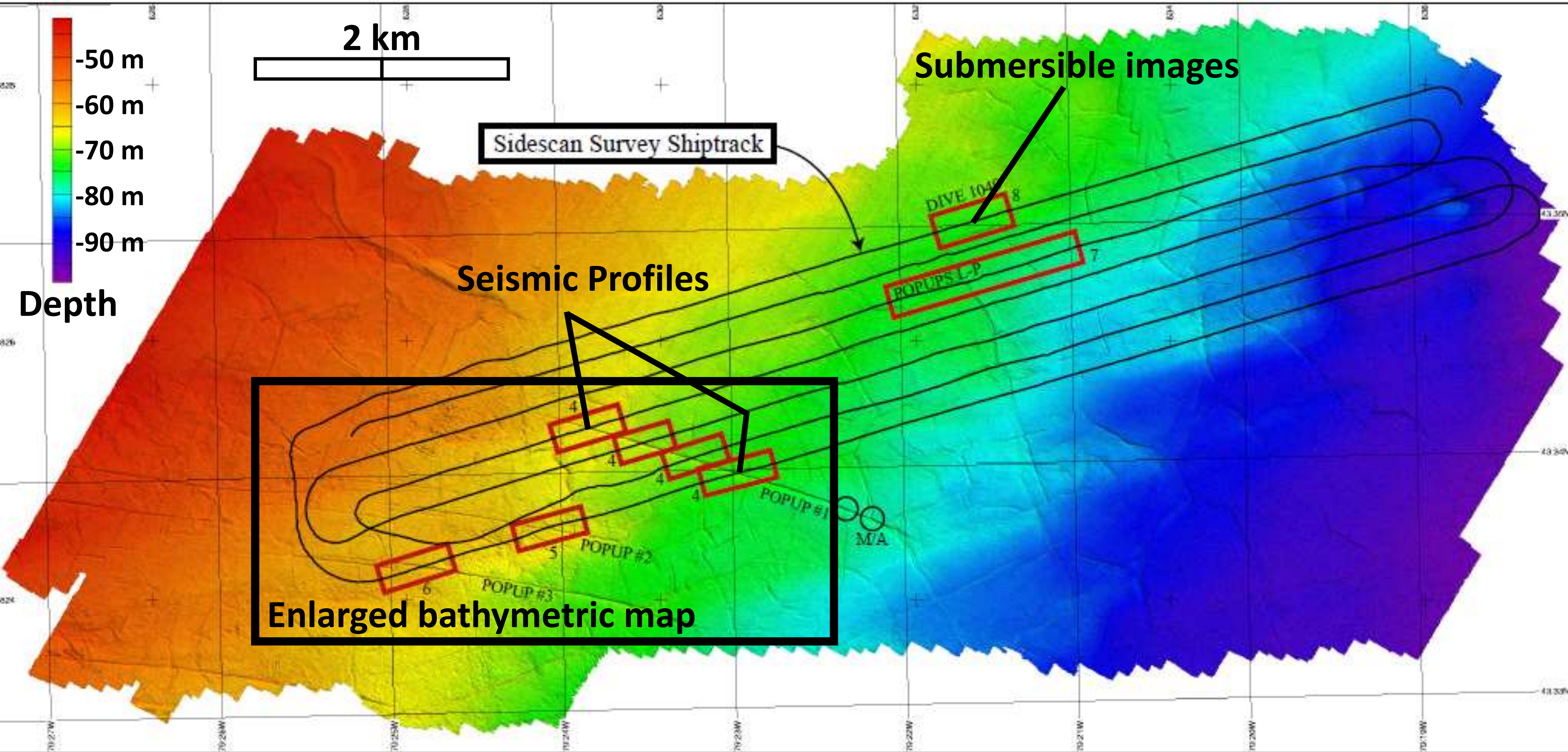
Pop-up structures in quarries and fields

From Wallach et al., 1993

Lake Ontario pop-up structures

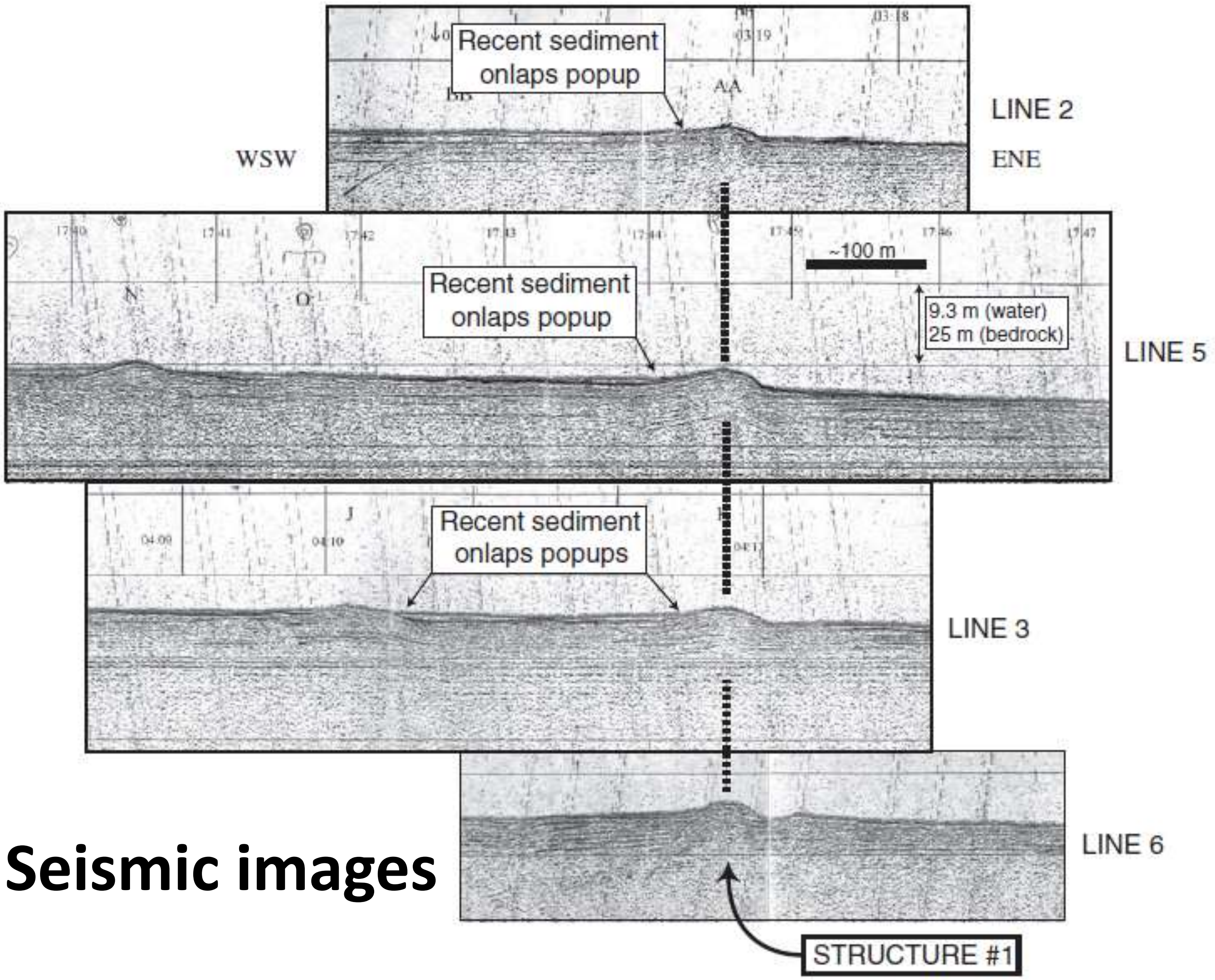
Multibeam bathymetric map

From Jacobi et al., 2007



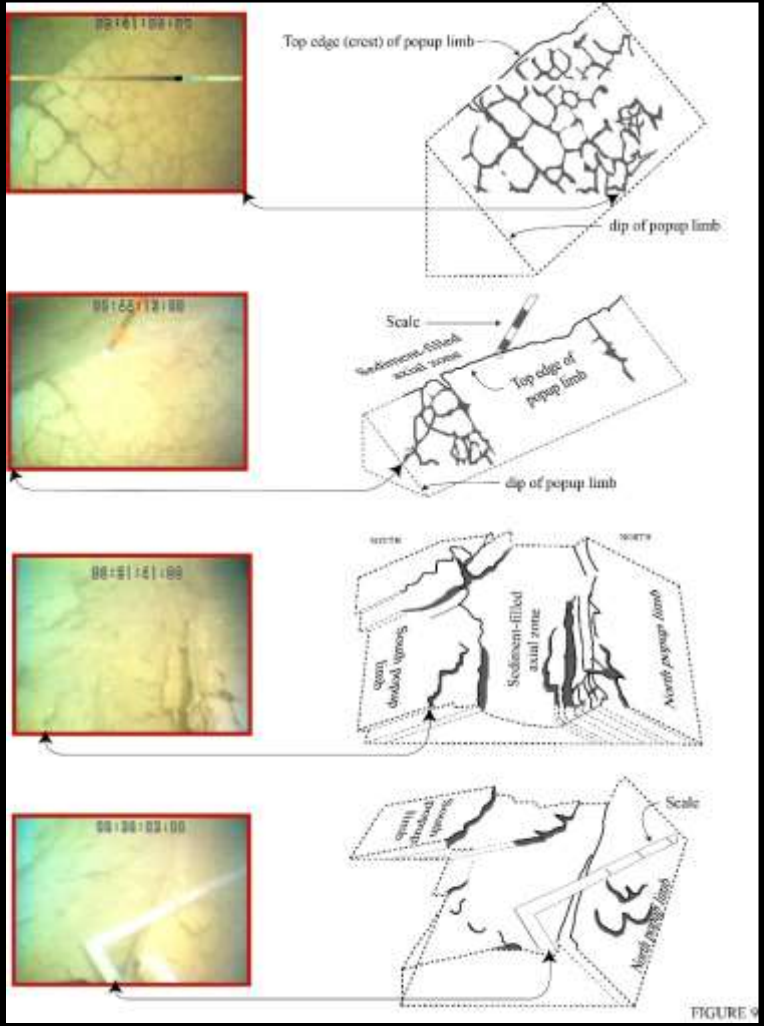
Lake Ontario pop-up structures

From Jacobi et al., 2007



Seismic images

Submersible images

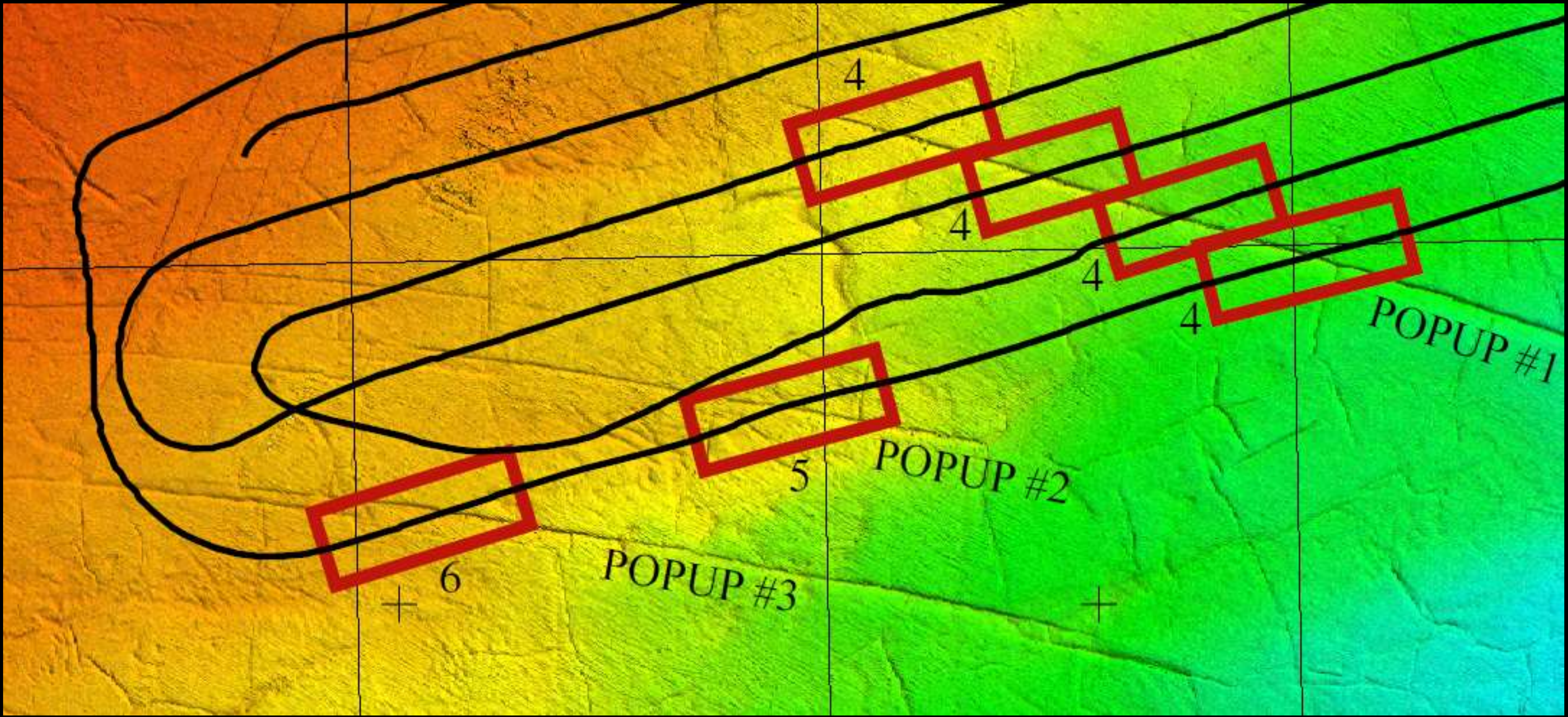


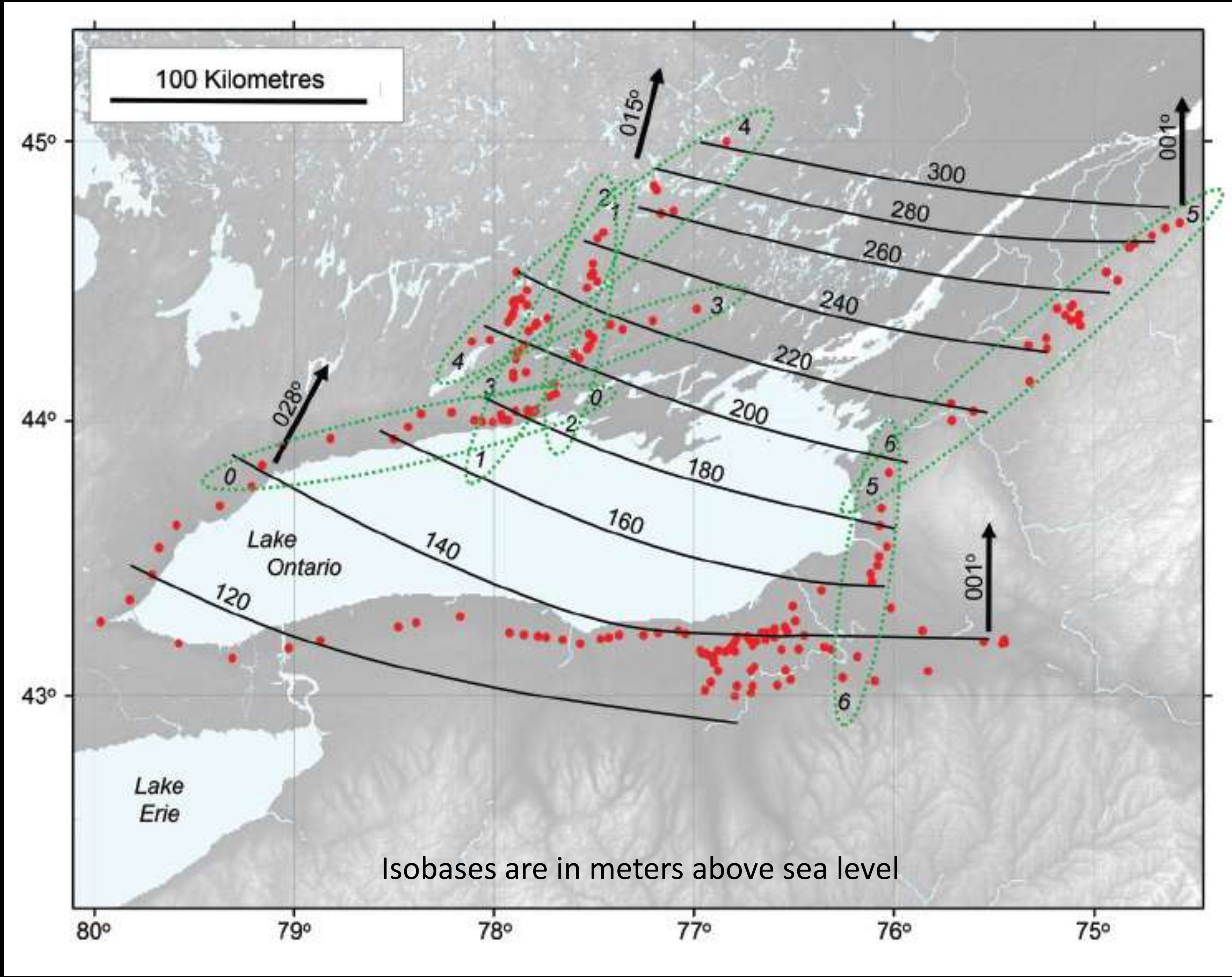
Lake Ontario pop-up structures

1 km

Multibeam bathymetric map

From Jacobi et al., 2007

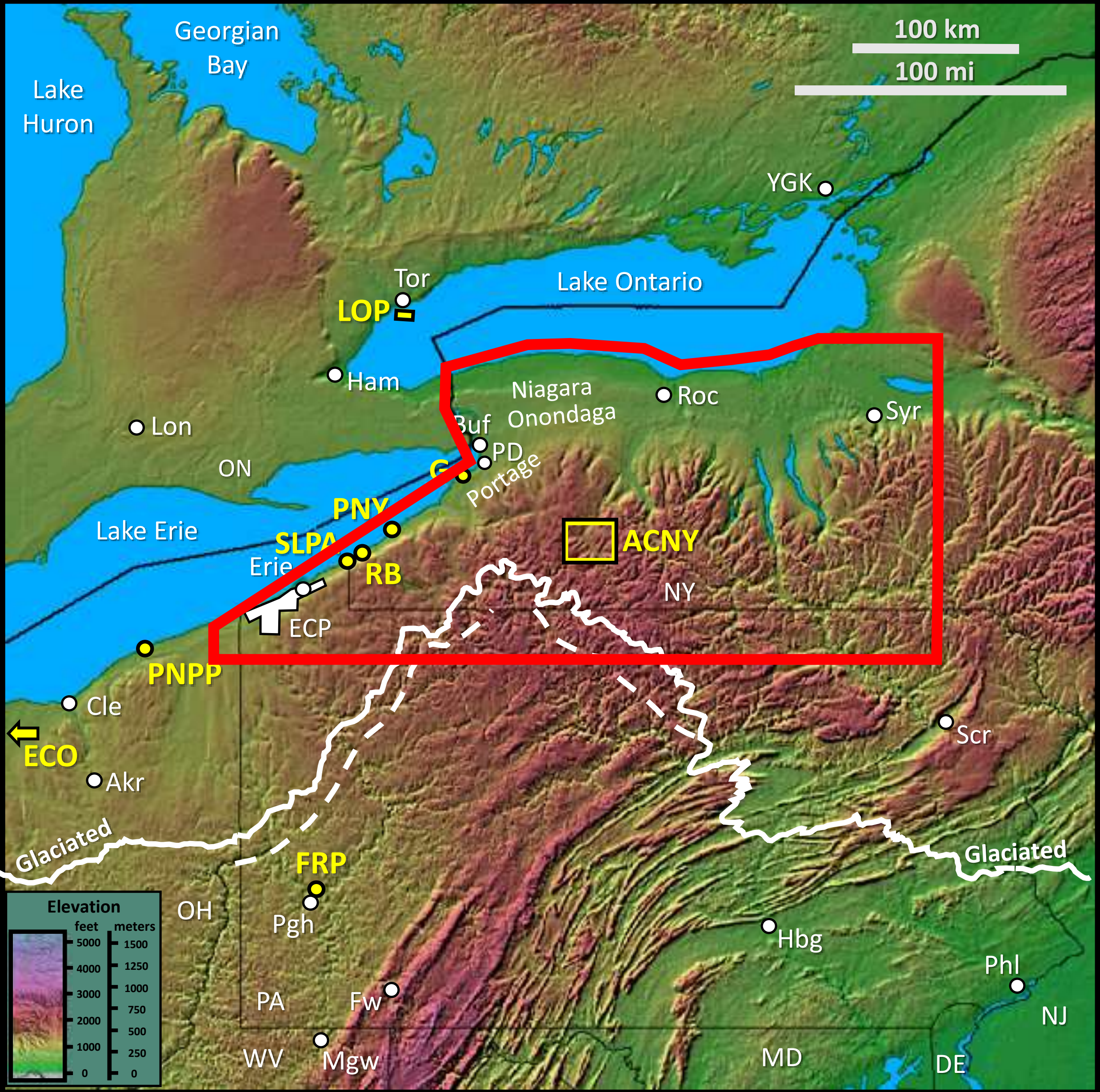




Glacial Lake Iroquois isobases

From Lewis et al., 2021

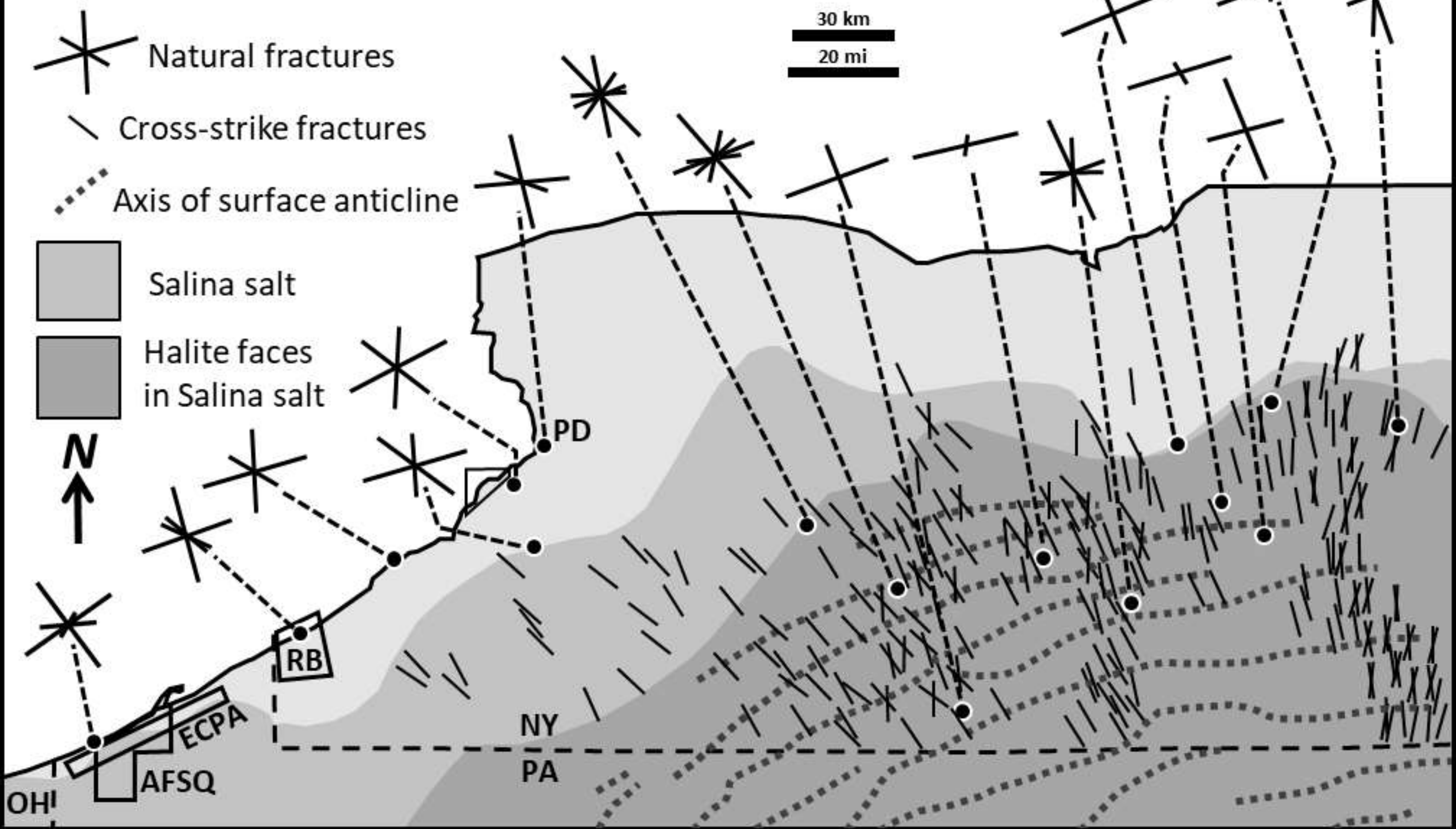
Regional context



Map from Andrew Birrell with permission of Brenda Birrell

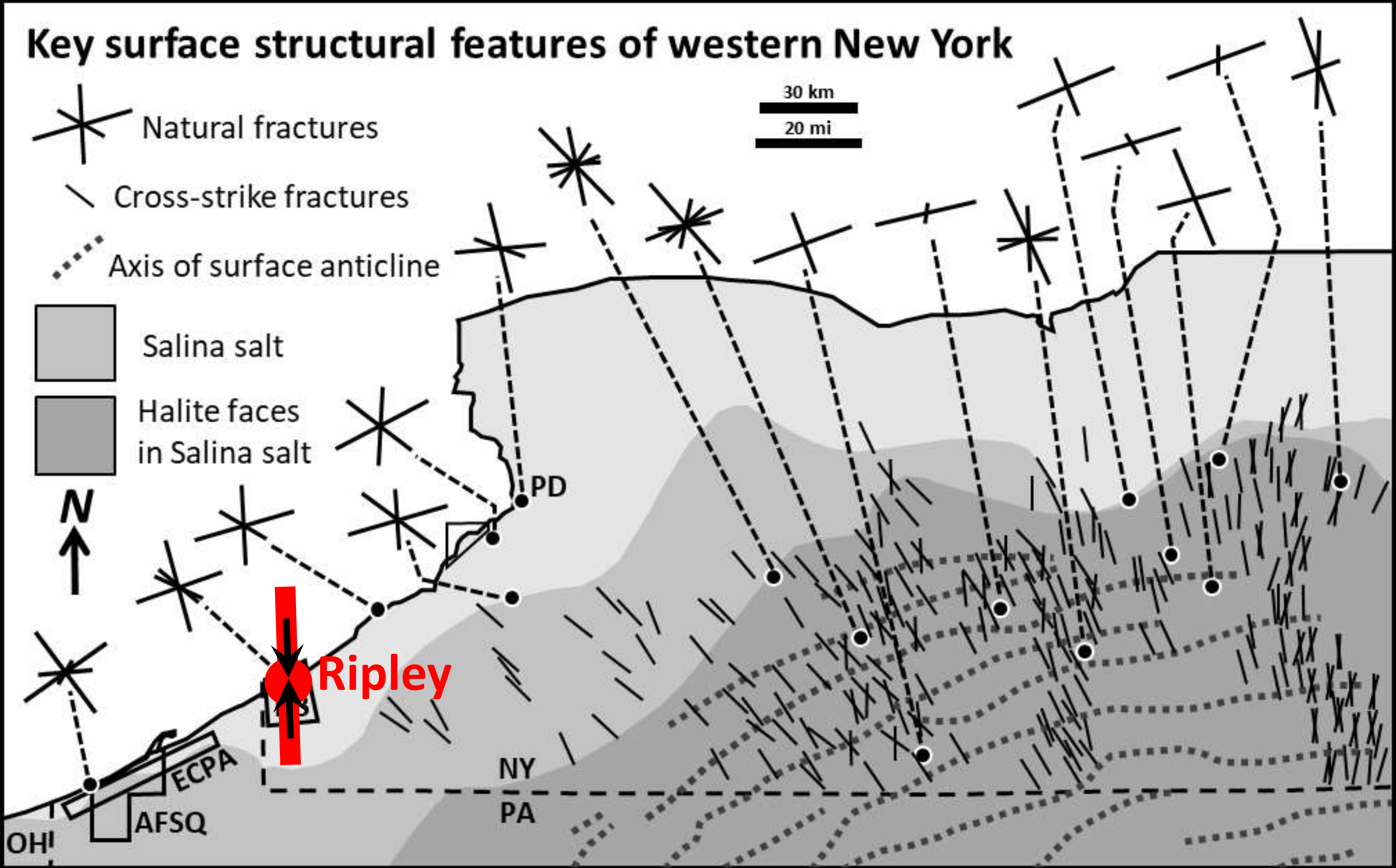
Red outline indicates area of next map

Key surface structural features of western New York



Sources: Lash et al. (2004), Lash and Engelder (2007), Engelder et al. (2009), Lang et al. (2023), Gryta et al. (2023), Zelt (2025), Engelder and Geiser (1980), Wedel (1932), Berg et al. (1980), Mount (2014), Clifford (1973), Rickard (1969).

From Zelt (2025), with permission of the Geological Society of America



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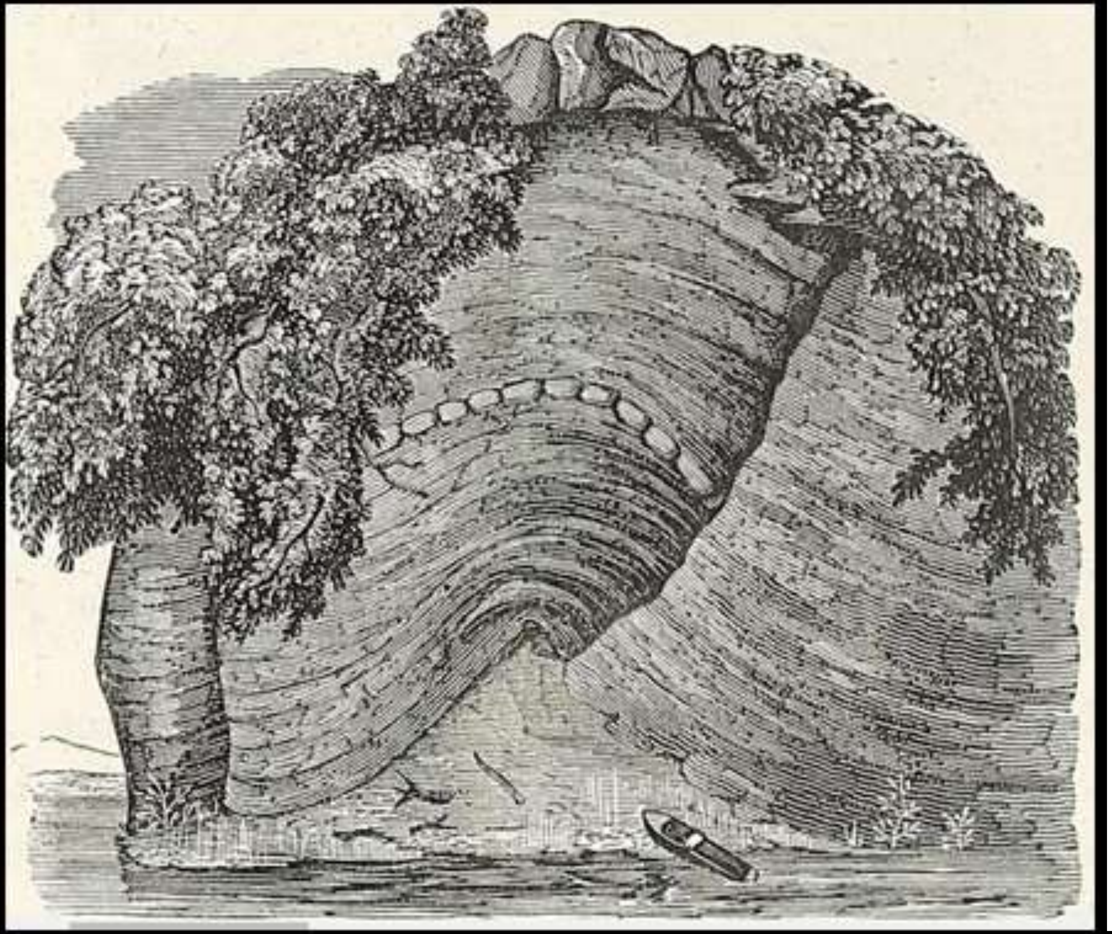
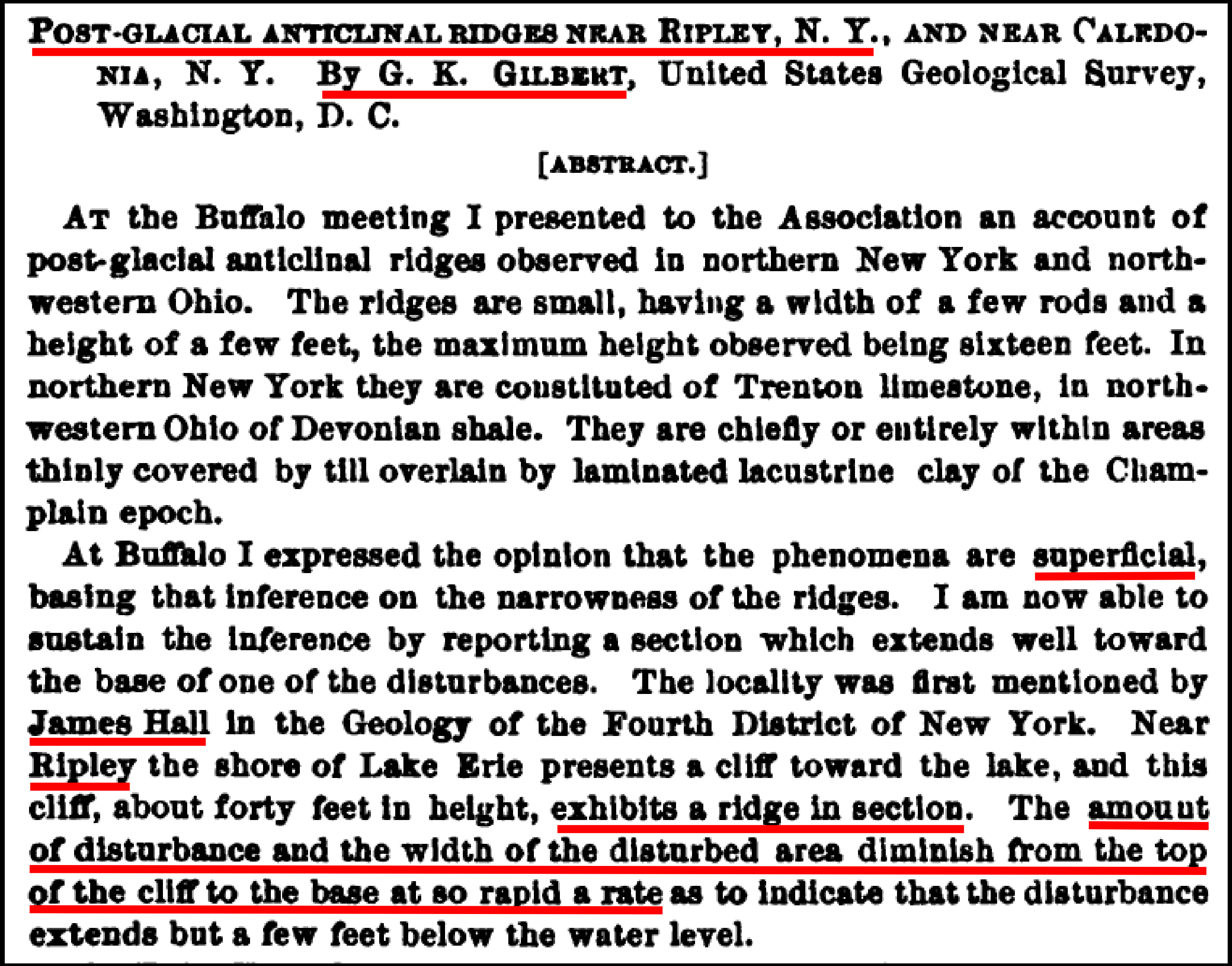
Compressional Structures on Erie lakeshore, western New York State

Ripley, NY

Drawing from Hall, 1843



Gilbert, 1892



POST-GLACIAL ANTICLINAL RIDGES NEAR RIPLEY, N. Y., AND NEAR CALEDONIA, N. Y. By G. K. GILBERT, United States Geological Survey, Washington, D. C.

[ABSTRACT.]

AT the Buffalo meeting I presented to the Association an account of post-glacial anticlinal ridges observed in northern New York and northwestern Ohio. The ridges are small, having a width of a few rods and a height of a few feet, the maximum height observed being sixteen feet. In northern New York they are constituted of Trenton limestone, in northwestern Ohio of Devonian shale. They are chiefly or entirely within areas thinly covered by till overlain by laminated lacustrine clay of the Champlain epoch.

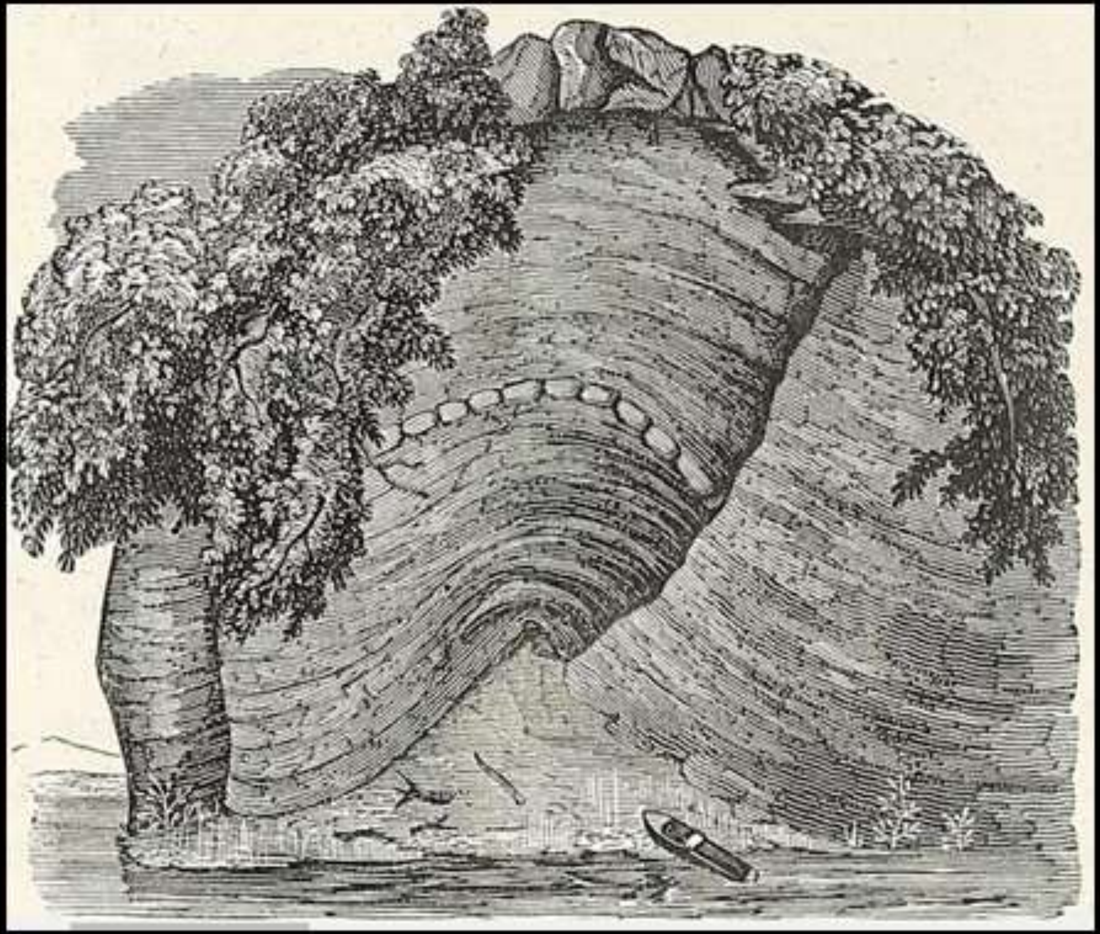
At Buffalo I expressed the opinion that the phenomena are superficial, basing that inference on the narrowness of the ridges. I am now able to sustain the inference by reporting a section which extends well toward the base of one of the disturbances. The locality was first mentioned by James Hall in the Geology of the Fourth District of New York. Near Ripley the shore of Lake Erie presents a cliff toward the lake, and this cliff, about forty feet in height, exhibits a ridge in section. The amount of disturbance and the width of the disturbed area diminish from the top of the cliff to the base at so rapid a rate as to indicate that the disturbance extends but a few feet below the water level.

Compressional Structures on Erie lakeshore, western New York State

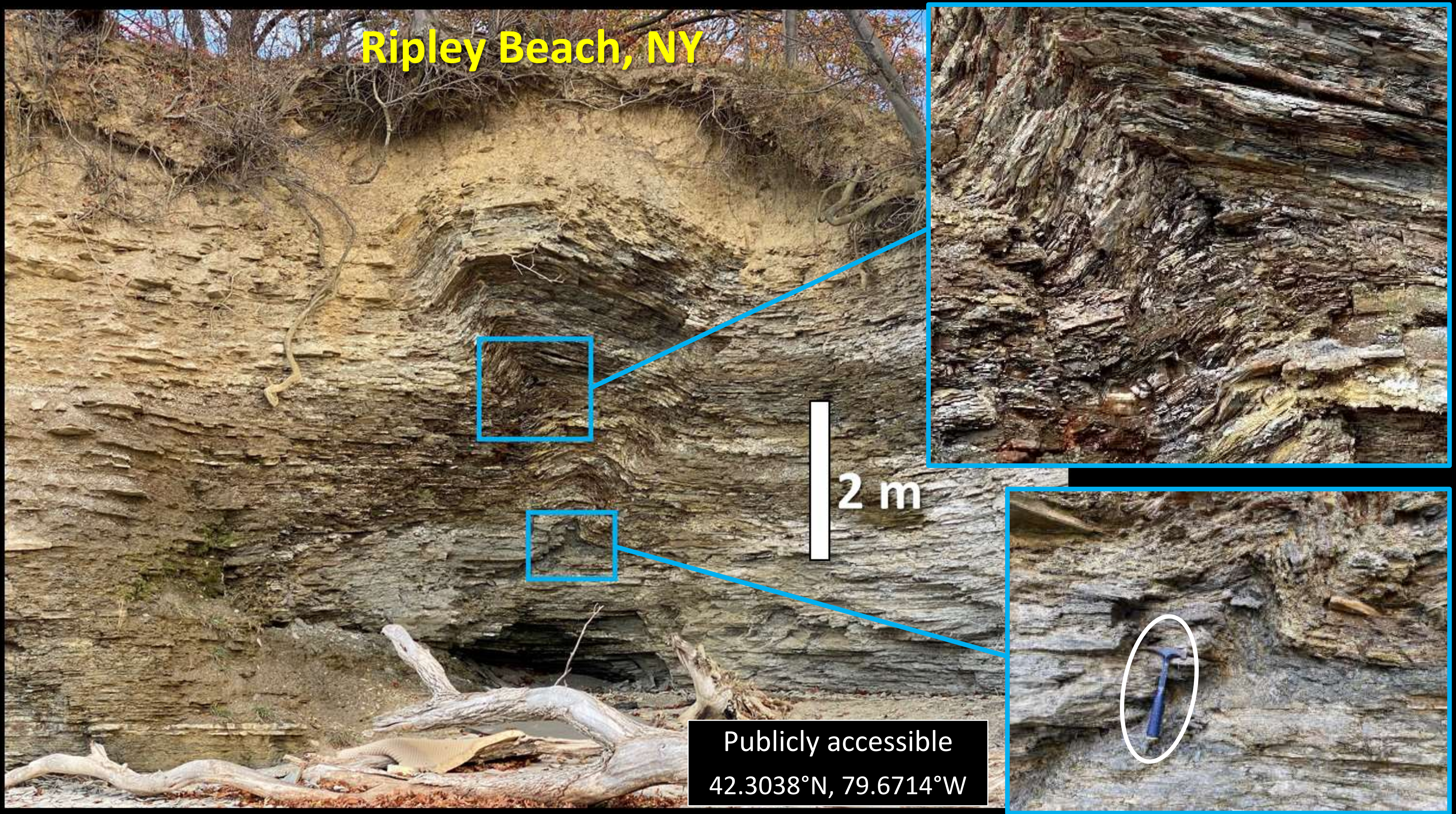
Ripley, NY

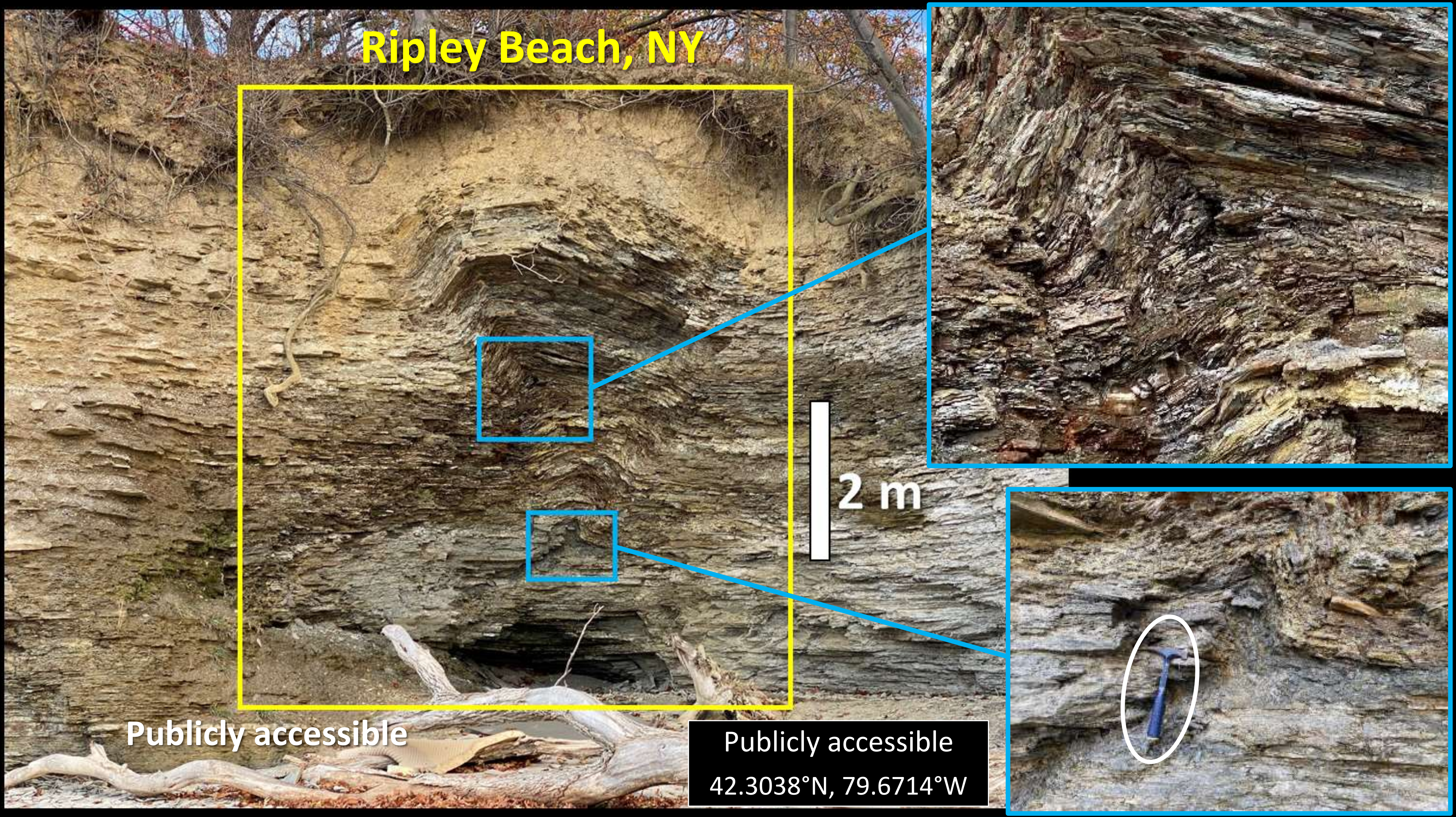
Publicly accessible
42.3038°N, 79.6714°W

Drawing from Hall, 1843



Ripley Beach outcrop of Zelt, 2025

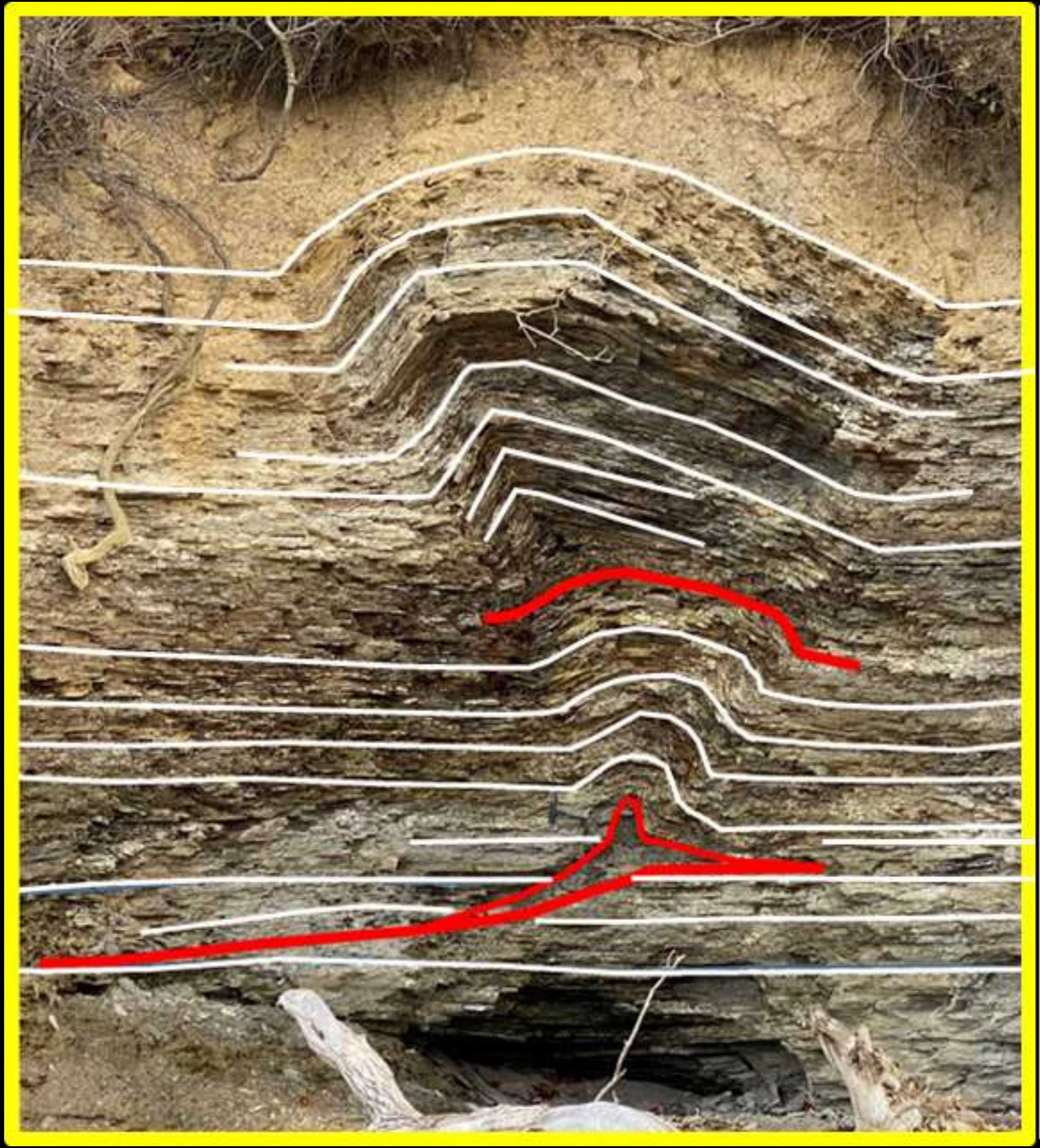

Ripley Beach, NY
2 m
Publicly accessible
42.3038°N, 79.6714°W

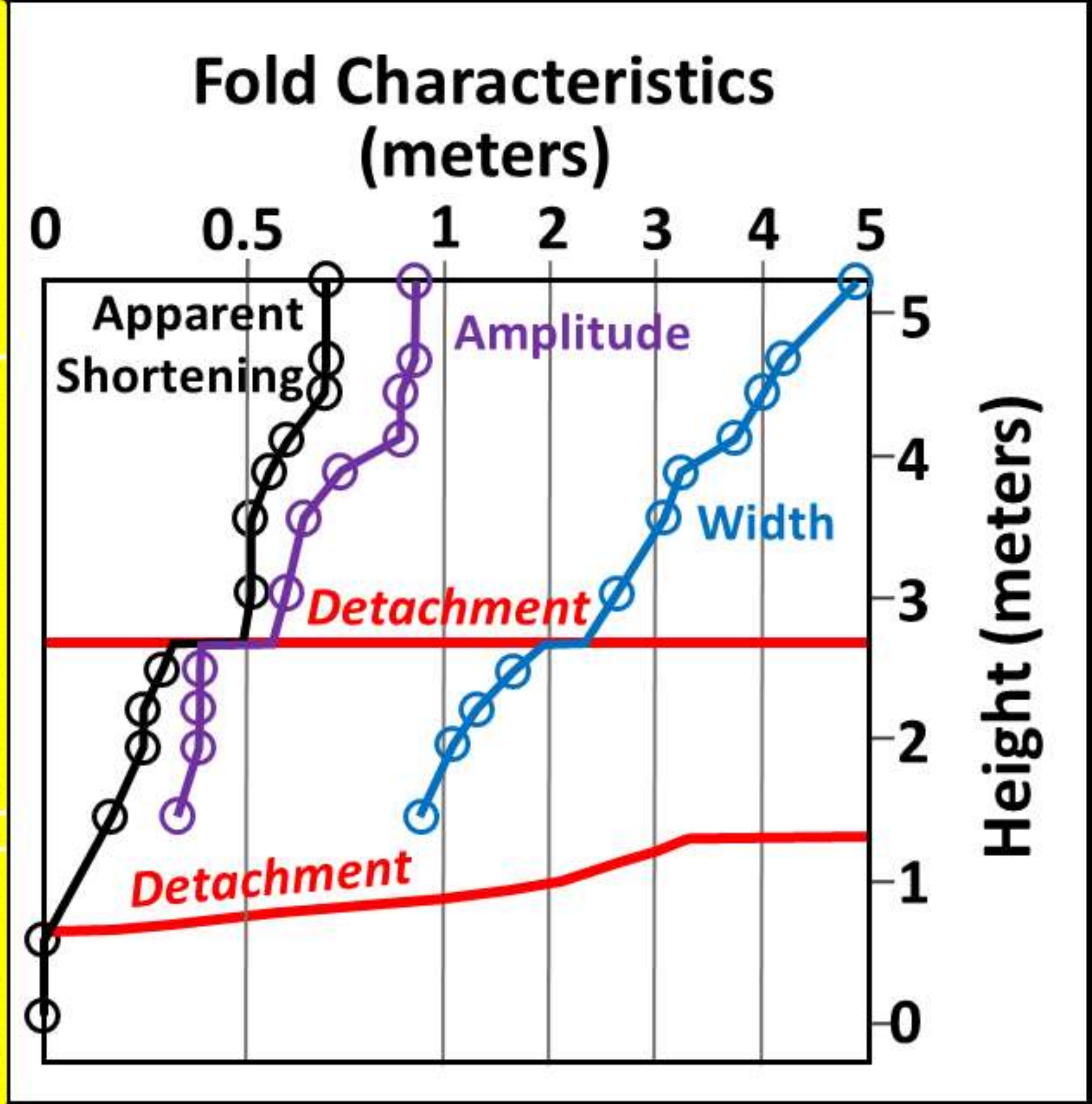

Ripley Beach, NY
2 m
Publicly accessible
Publicly accessible
42.3038°N, 79.6714°W

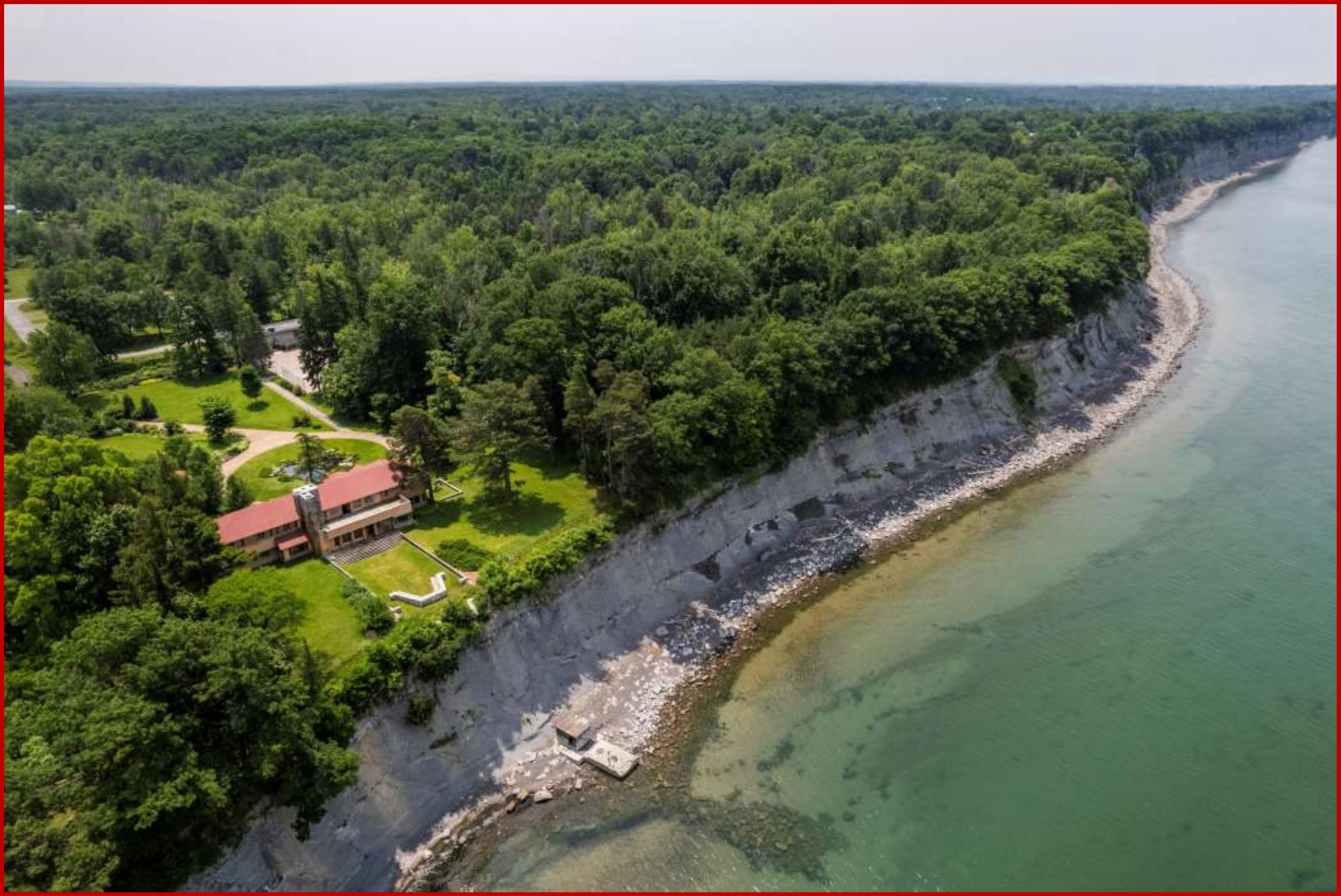
Ripley Beach, NY

Publicly accessible

42.3038°N, 79.6714°W

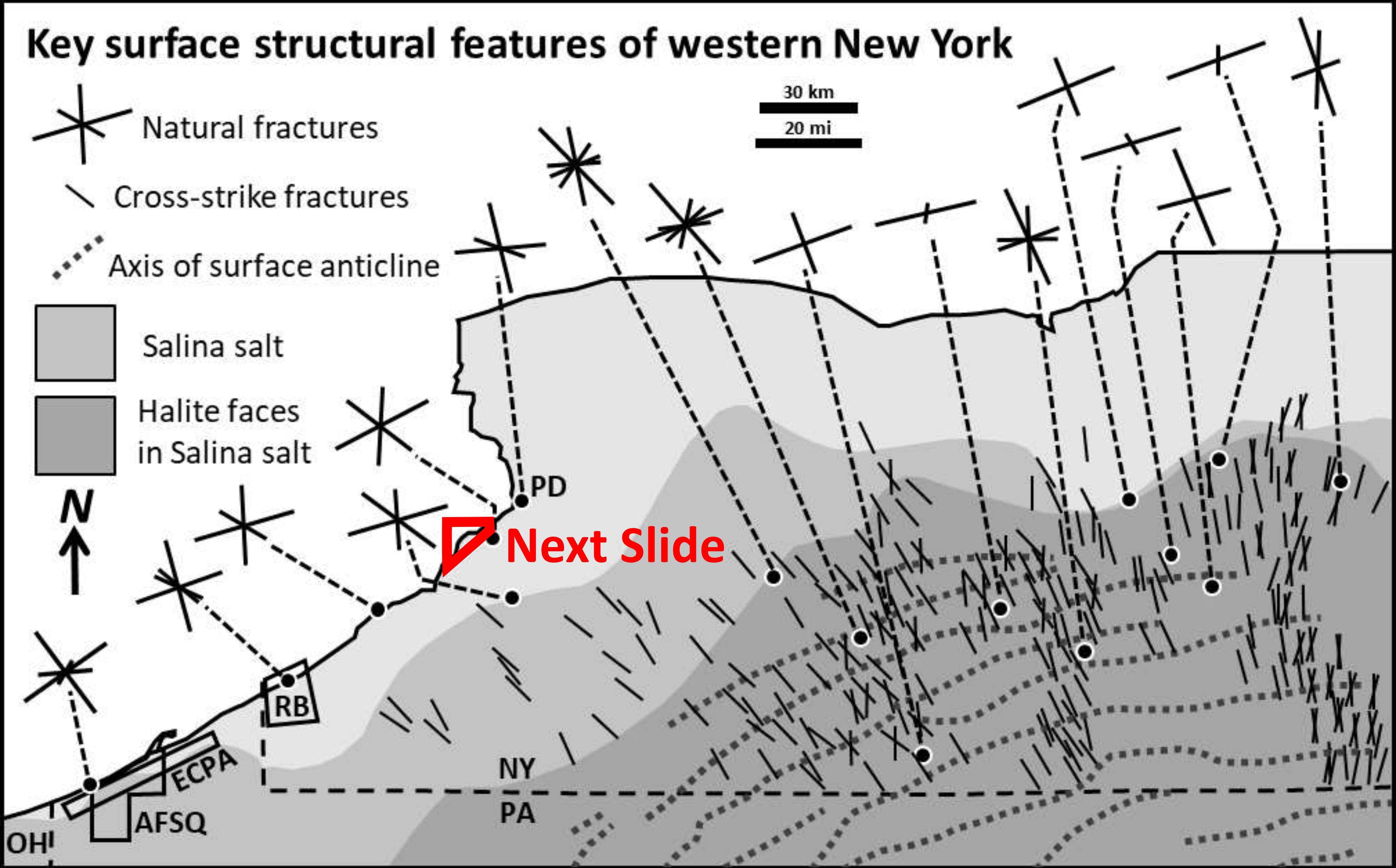






Graycliff perspective view

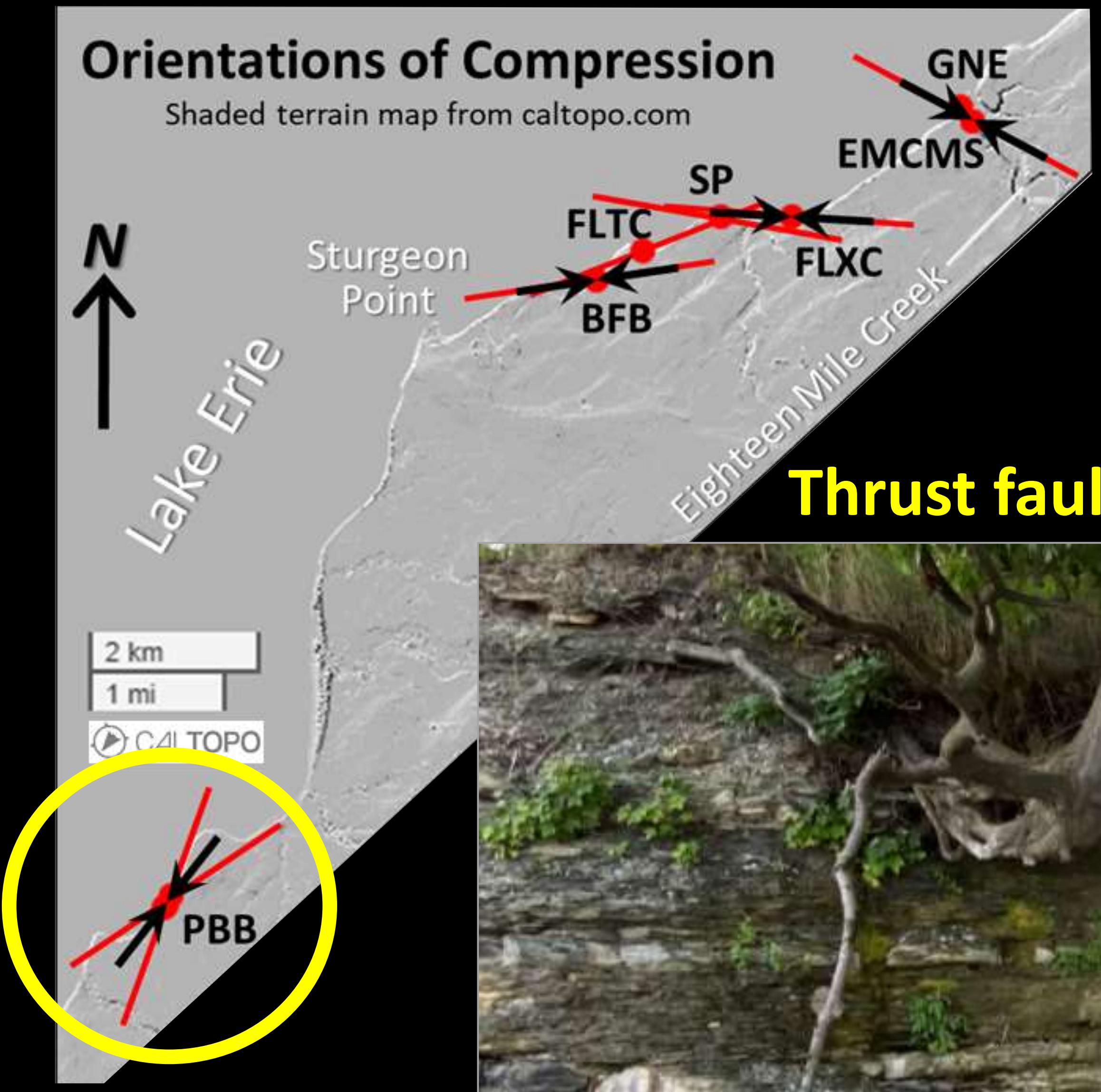
Photo by Matthew Digati, courtesy of the Graycliff Conservancy



Sources: Lash et al. (2004), Lash and Engelder (2007), Engelder et al. (2009), Lang et al. (2023), Gryta et al. (2023), Zelt (2025), Engelder and Geiser (1980), Wedel (1932), Berg et al. (1980), Mount (2014), Clifford (1973), Rickard (1969).

From Zelt (2025), with permission of the Geological Society of America

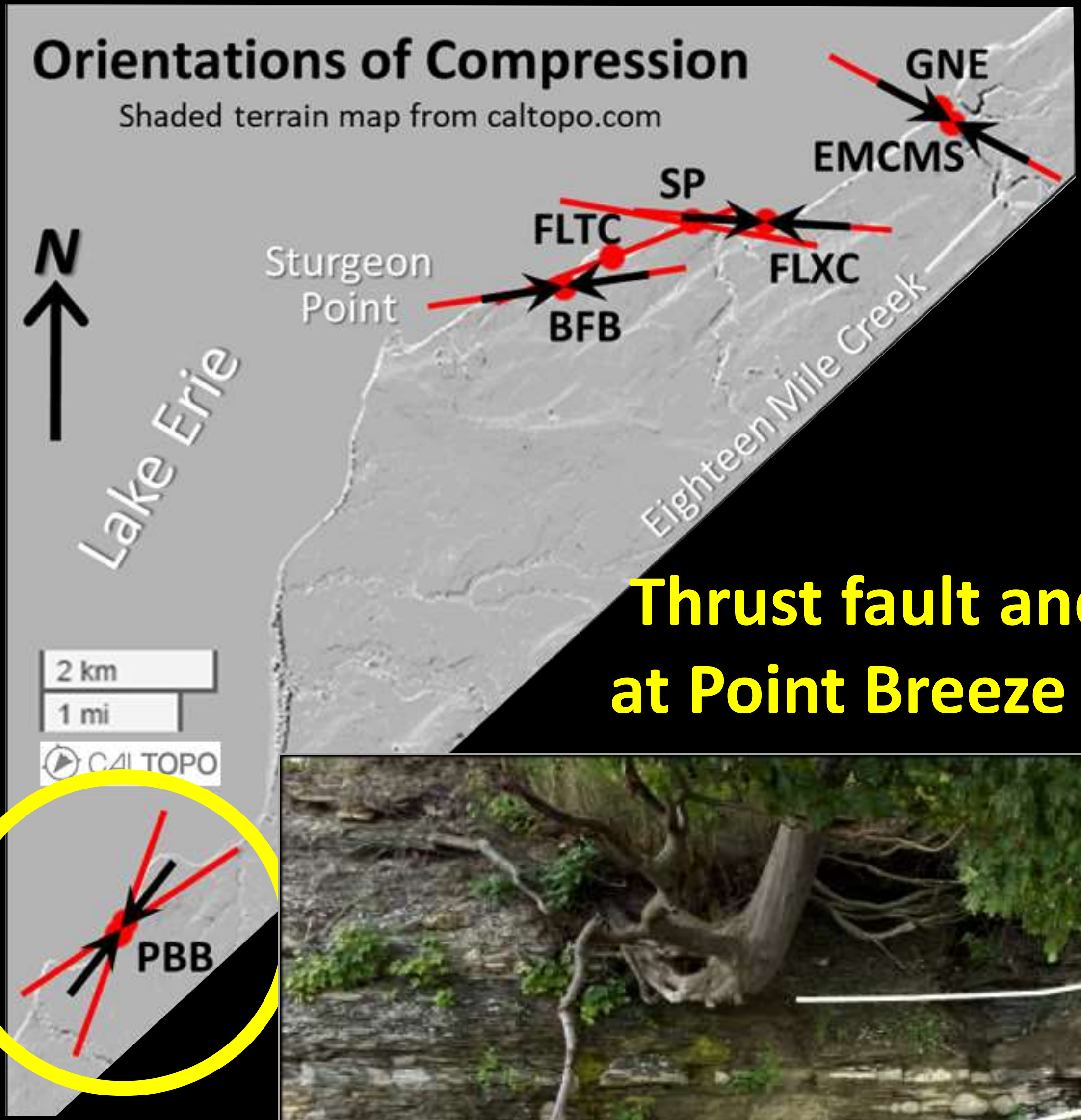
Shaded relief map generated from CalTopo.com, reproduced with permission; W3D30 data courtesy of Japan Aerospace Exploration Agency.



Public beach

42.6336°N, 79.0827°W

Thrust fault and fold at Point Breeze Beach

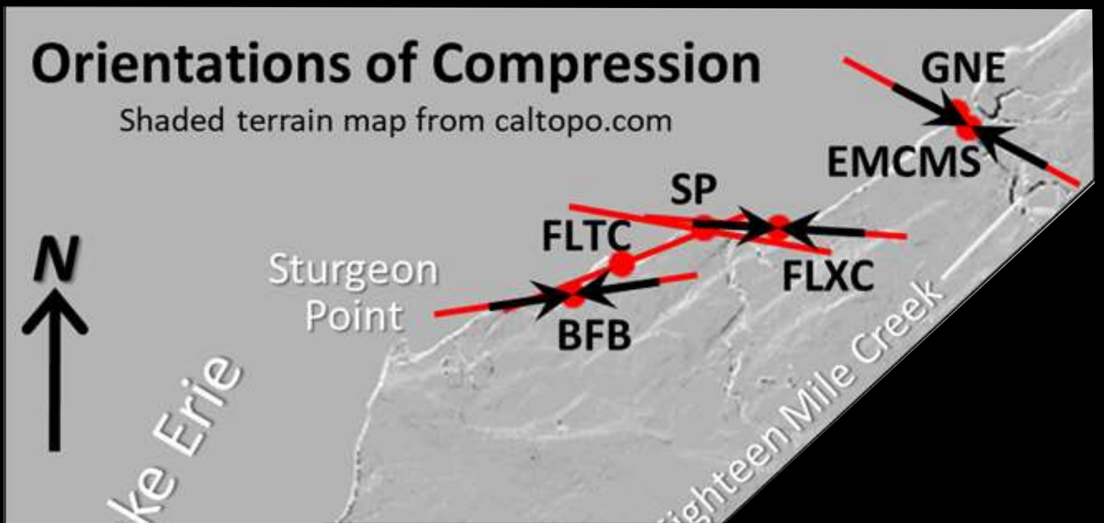
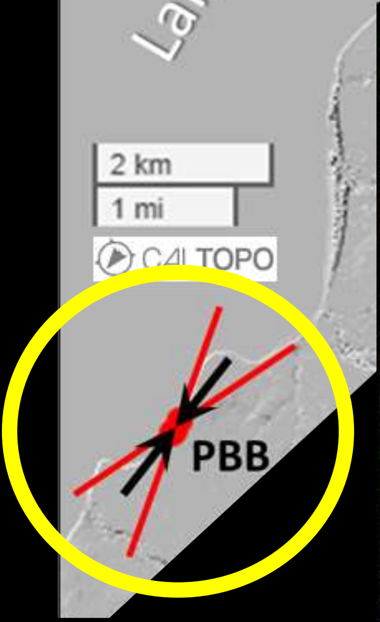


Thrust fault and fold at Point Breeze Beach

Shaded relief map generated from CalTopo.com, reproduced with permission; W3D30 data courtesy of Japan Aerospace Exploration Agency.

Public beach

42.6336°N, 79.0827°W

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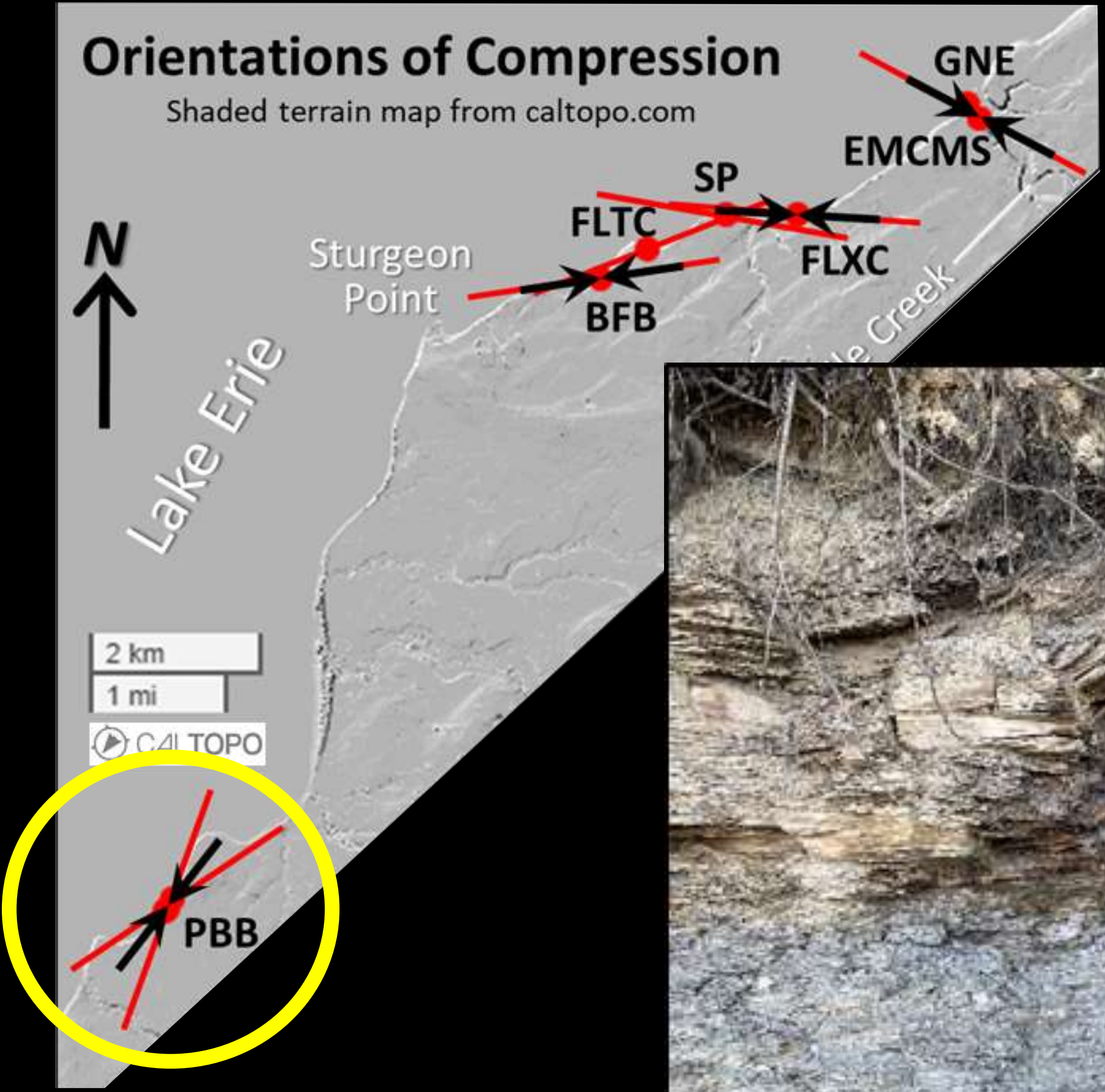
Public beach
42.6325°N, 79.0836°W

Buckle fold with irregular, open axial fracture at Point Breeze Beach

Second buckle fold with irregular, open axial fracture at Point Breeze Beach



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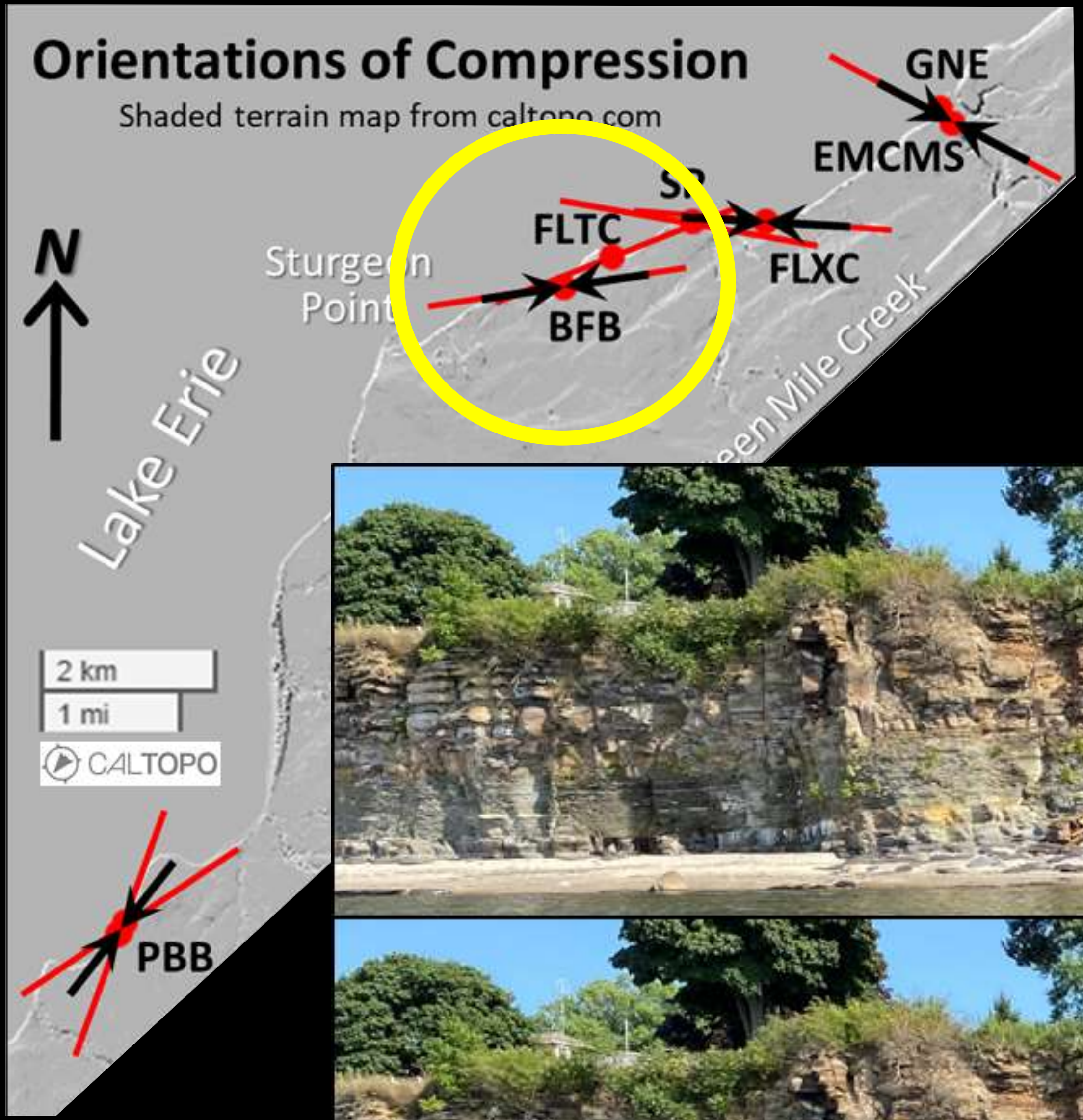
Public beach
42.6328°N, 79.0834°W



Shaded relief map generated from CalTopo.com, reproduced with permission; W3D30 data courtesy of Japan Aerospace Exploration Agency.

42.6972°N, 79.0231°W

Broad fold at Broad Fold Beach

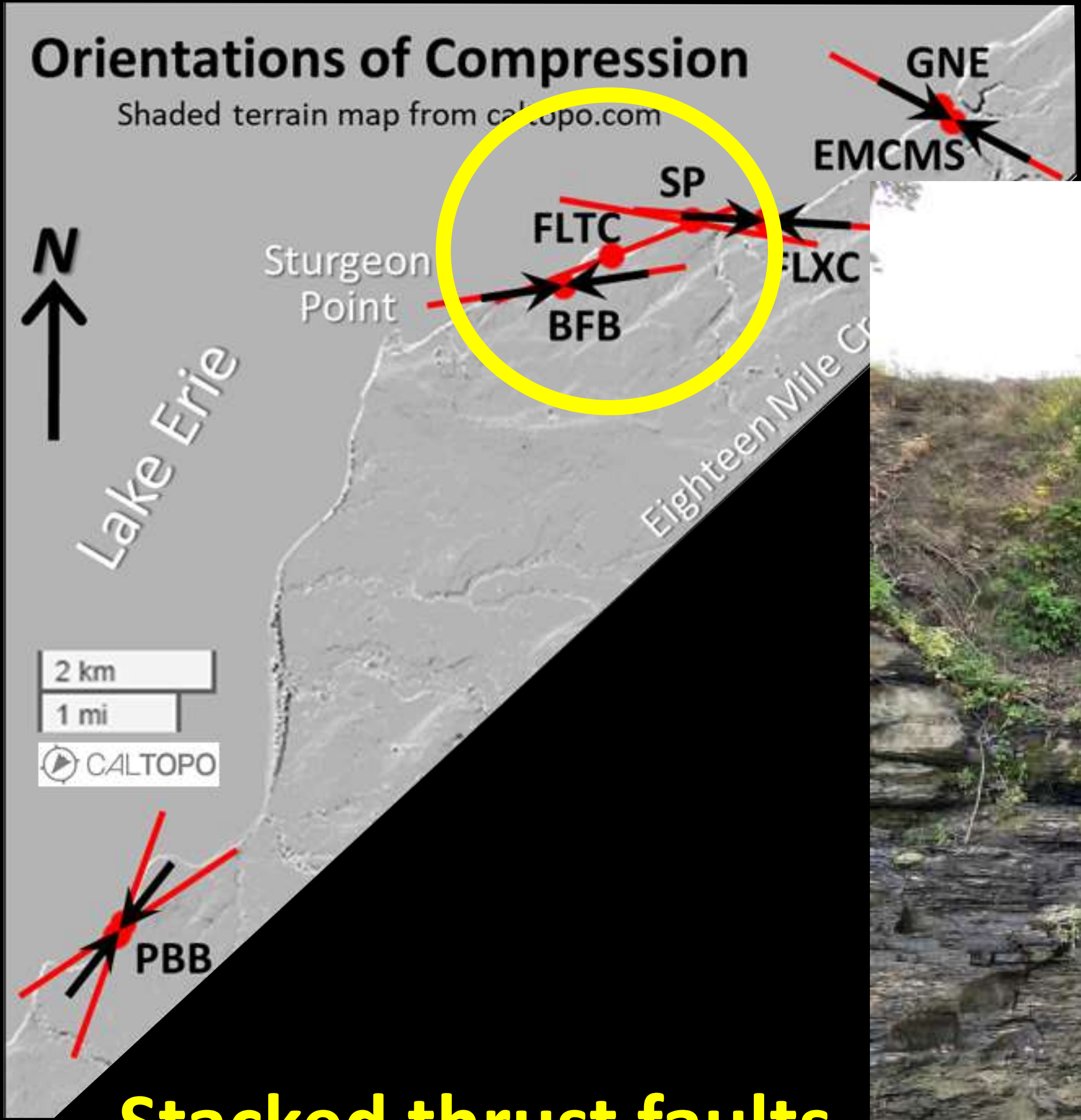
42.6961°N, 79.0256°W

Faulted fold 240 m SW of Broad Fold

This strike of this small faulted fold is 342°, similar to the Broad Fold strike of 352°

Gray fault gouge at Broad Fold Beach

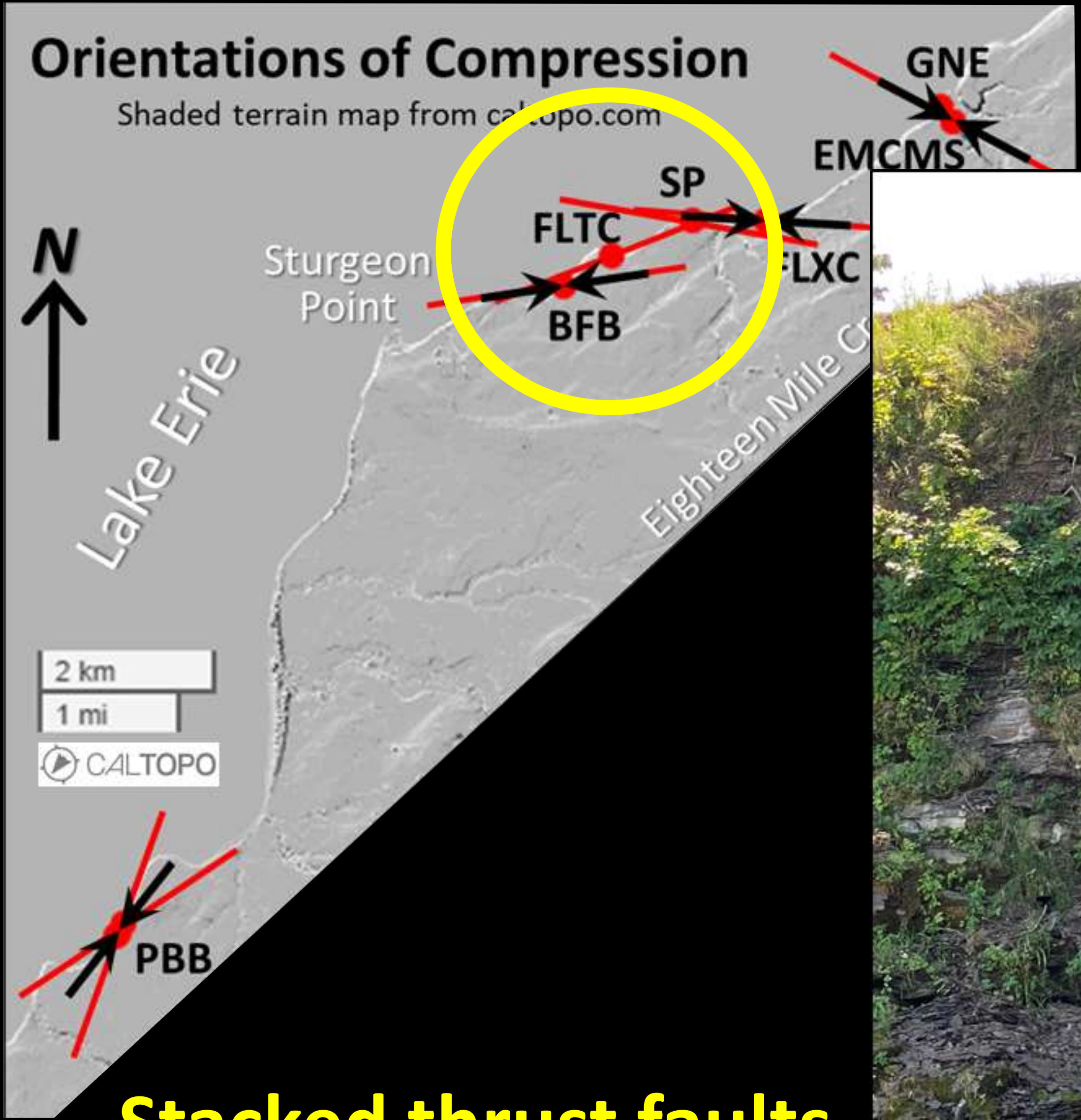
- Bedding-parallel with upward splays
- Gouge post-dates at least some joints in black shale



Shaded relief map generated from CalTopo.com, reproduced with permission; W3D30 data courtesy of Japan Aerospace Exploration Agency.

42.7004°N, 79.0164°W

Stacked thrust faults at Faults Cove



Shaded relief map generated from CalTopo.com, reproduced with permission; W3D30 data courtesy of Japan Aerospace Exploration Agency.

42.7004°N, 79.0164°W

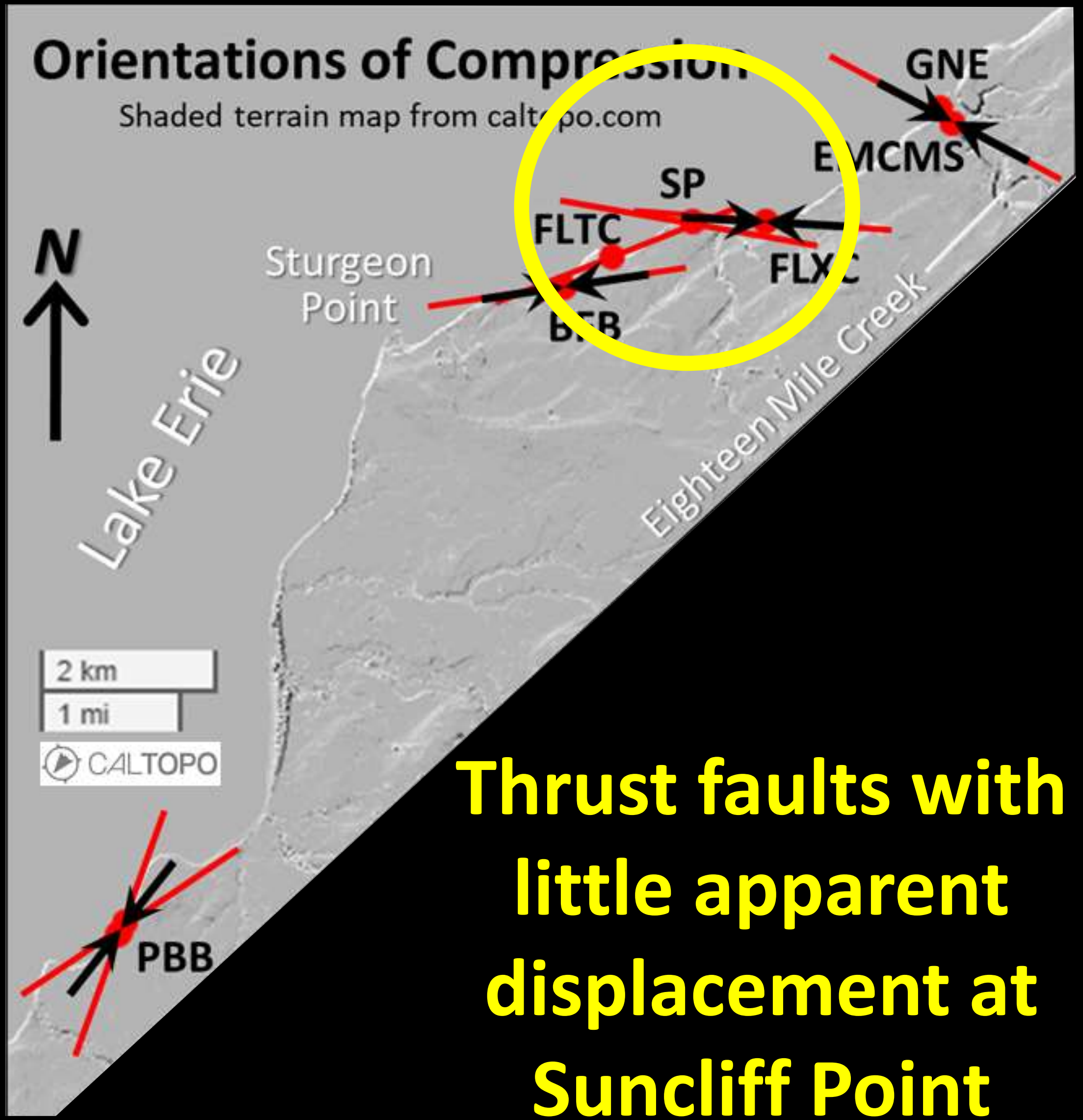
Stacked thrust faults at Faults Cove

Lower fault zone at Faults Cove

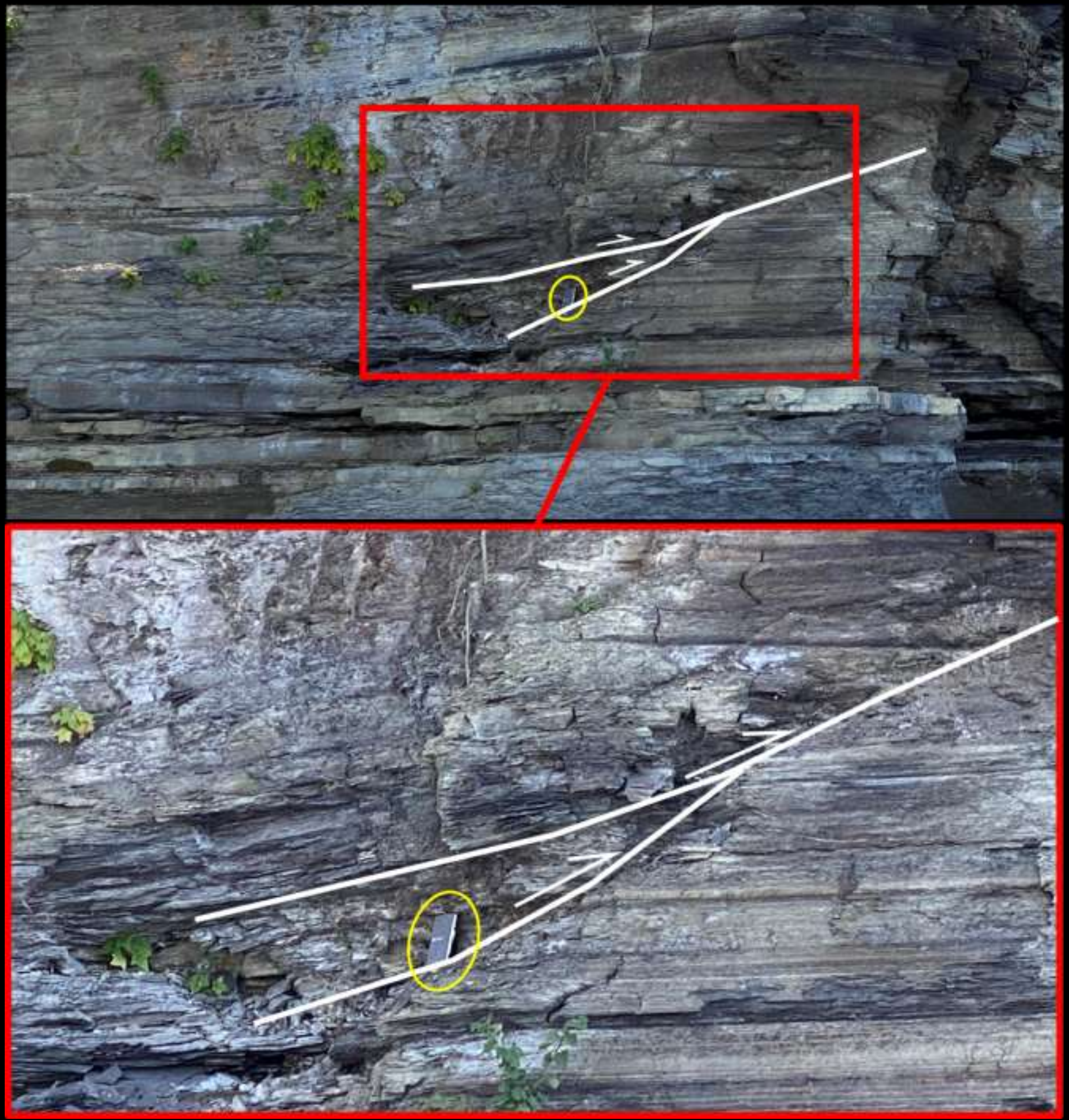
42.7004°N, 79.0164°W

Upper fault with fold at Faults Cove

42.7004°N, 79.0164°W



Thrust faults with little apparent displacement at Suncliff Point



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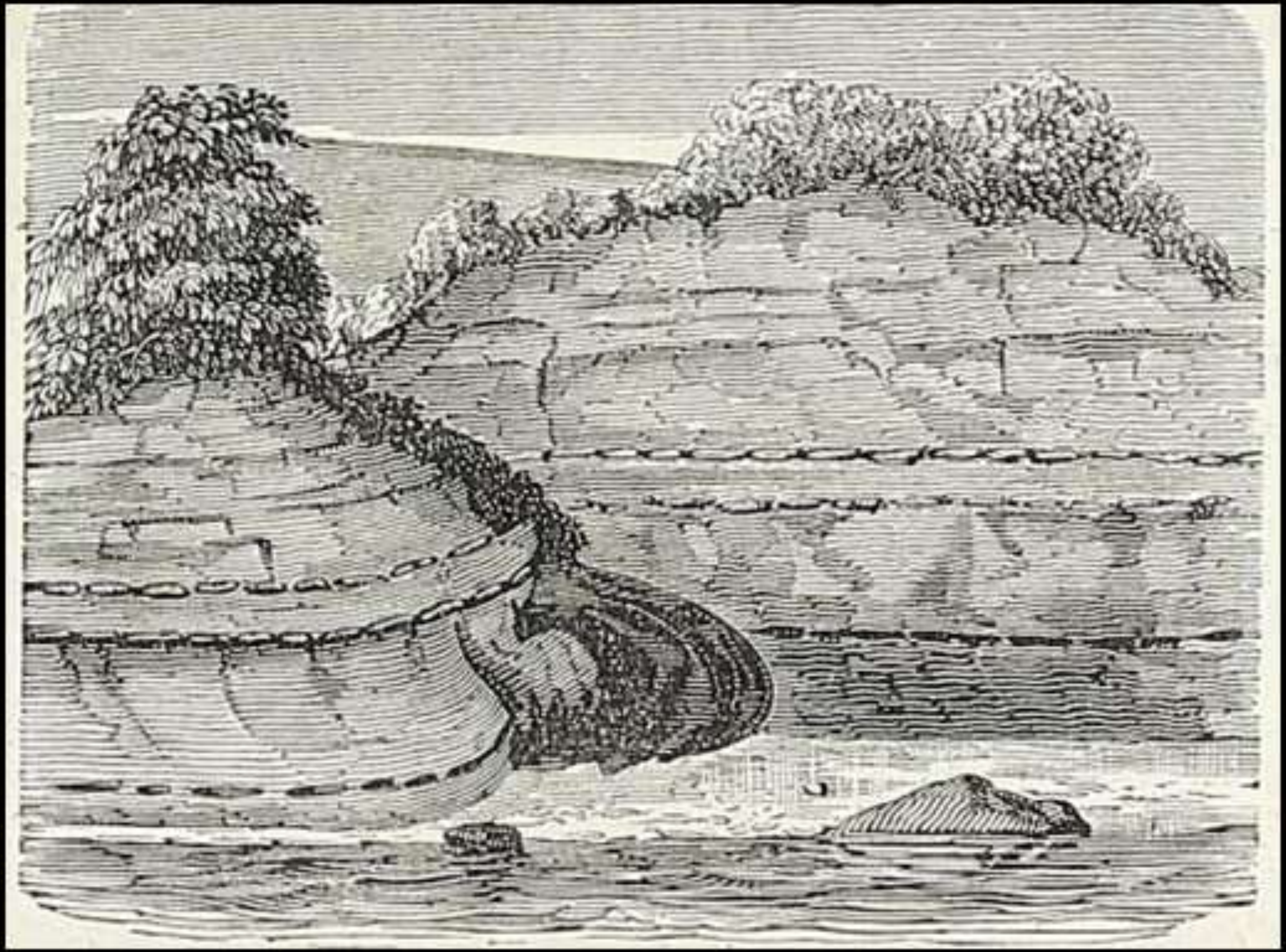
42.7039°N, 79.0053°W

Compressional structures on Erie lakeshore, western New York State

1.5 mi SW of Eighteen Mile Creek

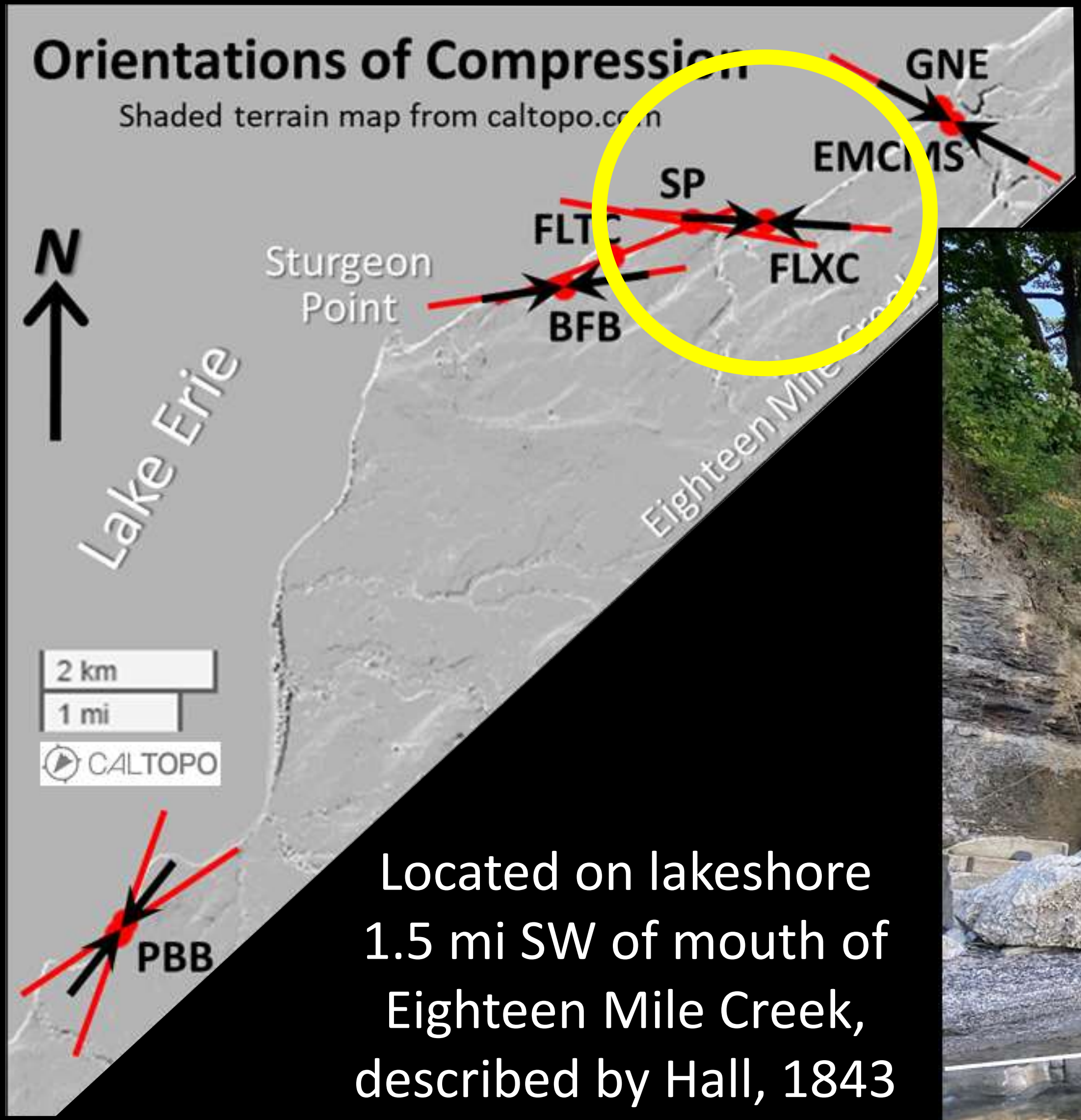
Drawing from Hall, 1843



Flexure Cove outcrop of Zelt, 2025

42.7040°N, 78.9955°W

Stacked thrust faults at Flexure Cove



Shaded relief map generated from CalTopo.com, reproduced with permission; W3D30 data courtesy of Japan Aerospace Exploration Agency.

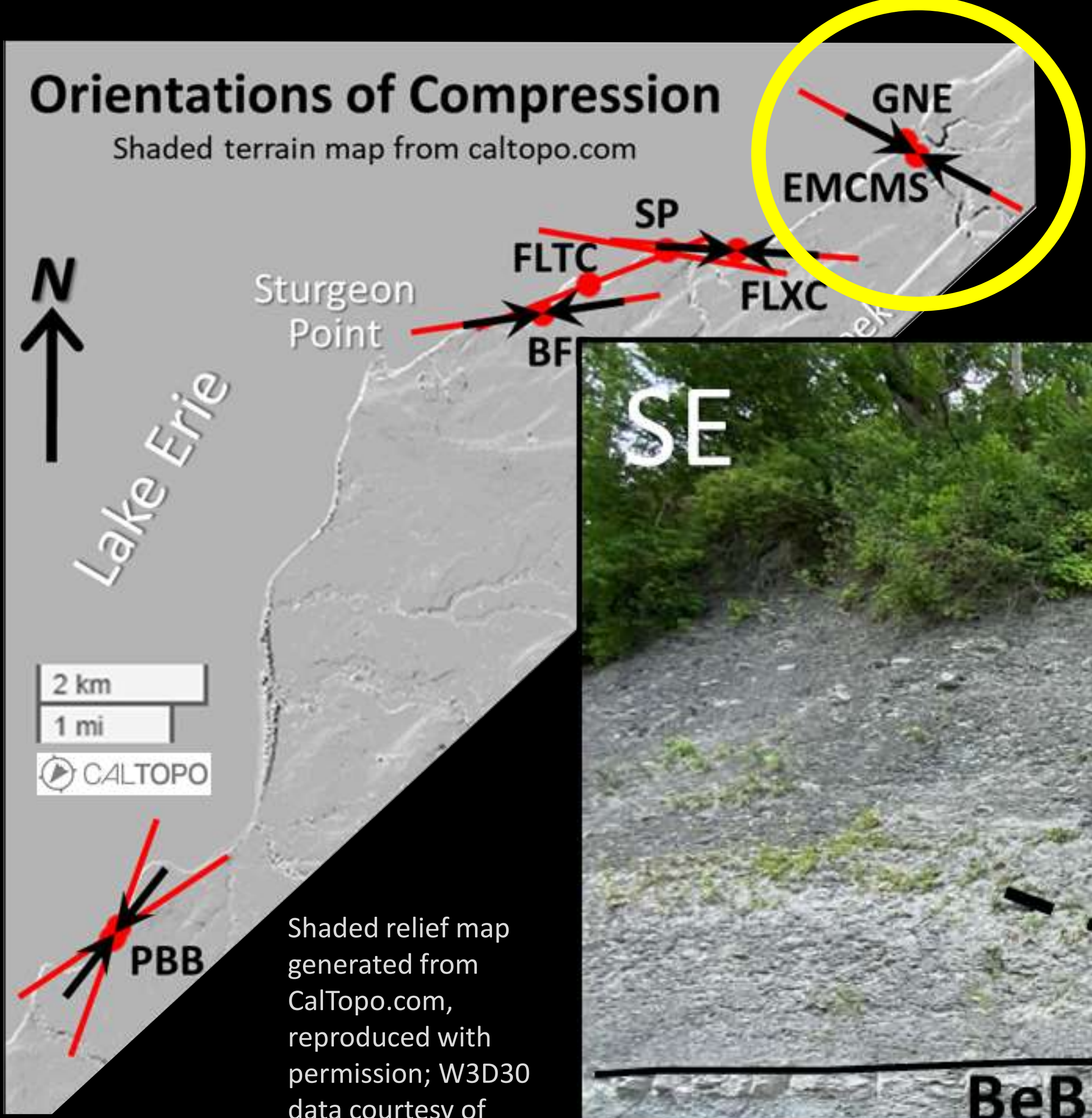
Located on lakeshore 1.5 mi SW of mouth of Eighteen Mile Creek, described by Hall, 1843 and Grabau, 1898

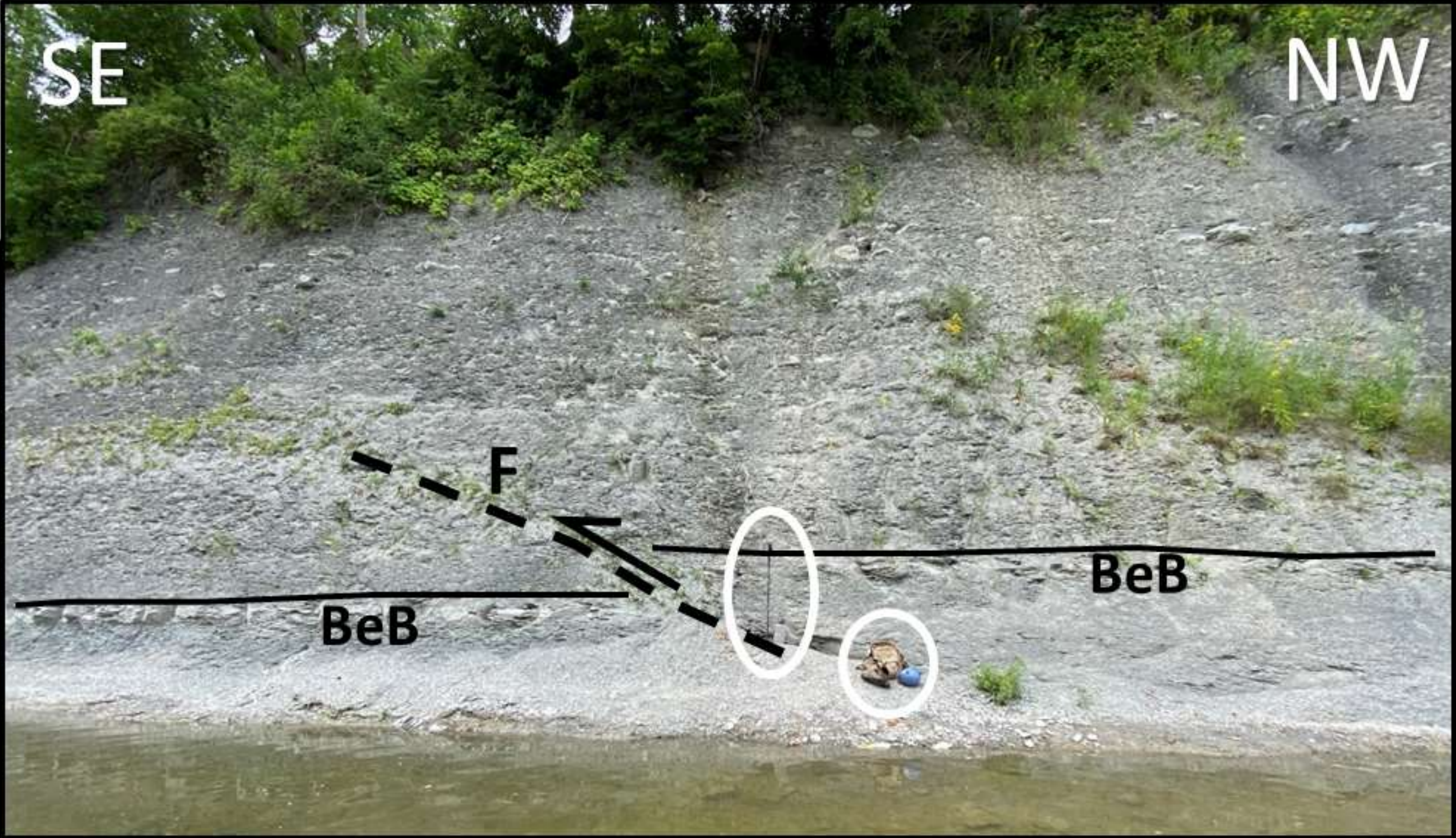
42.7040°N, 78.9955°W

Stacked thrust faults at Flexure Cove

42.7040°N, 78.9955°W

Thrust fault with fold on Eighteen Mile Creek

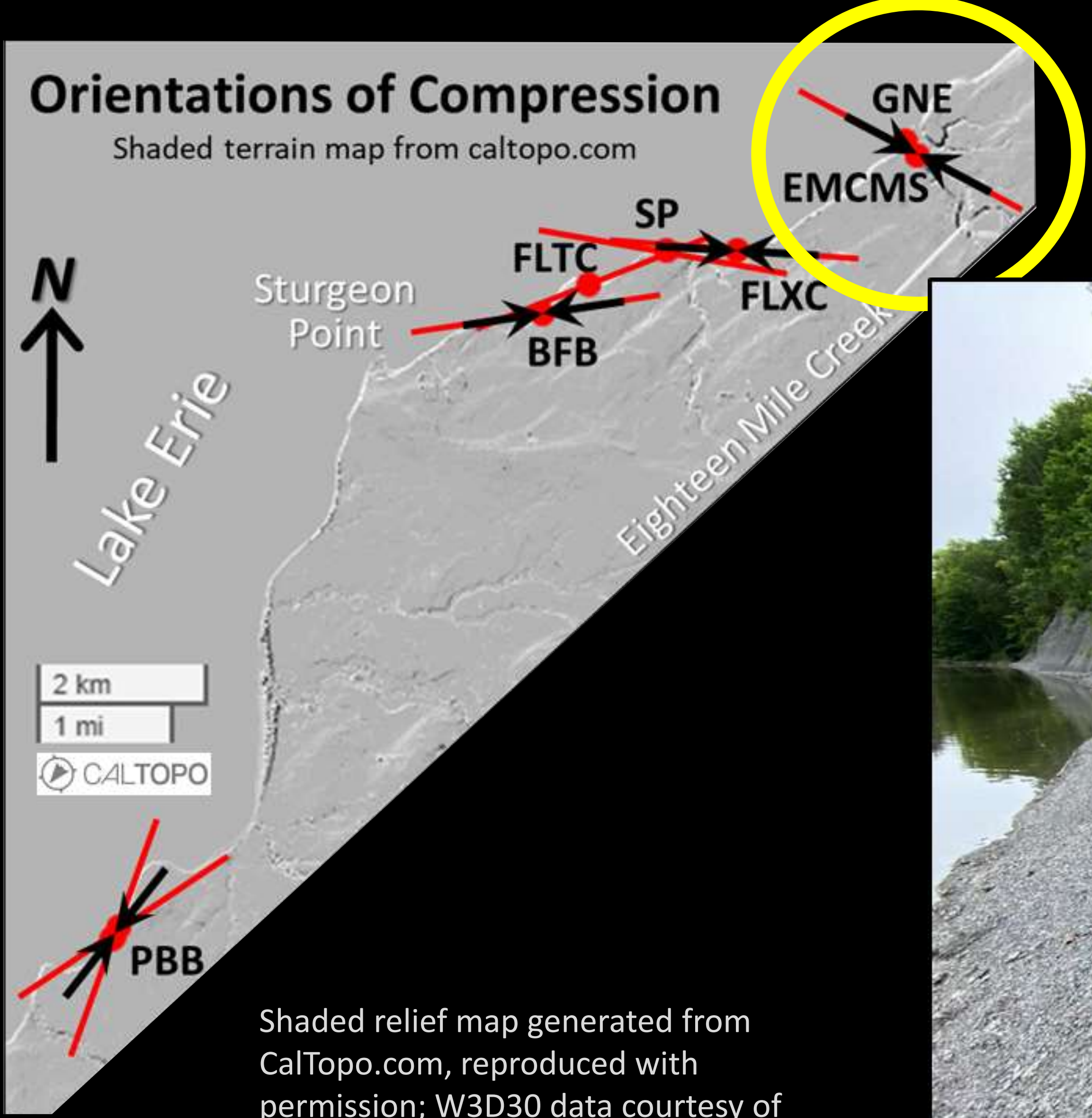




Shaded relief map generated from CalTopo.com, reproduced with permission; W3D30 data courtesy of Japan Aerospace Exploration Agency.

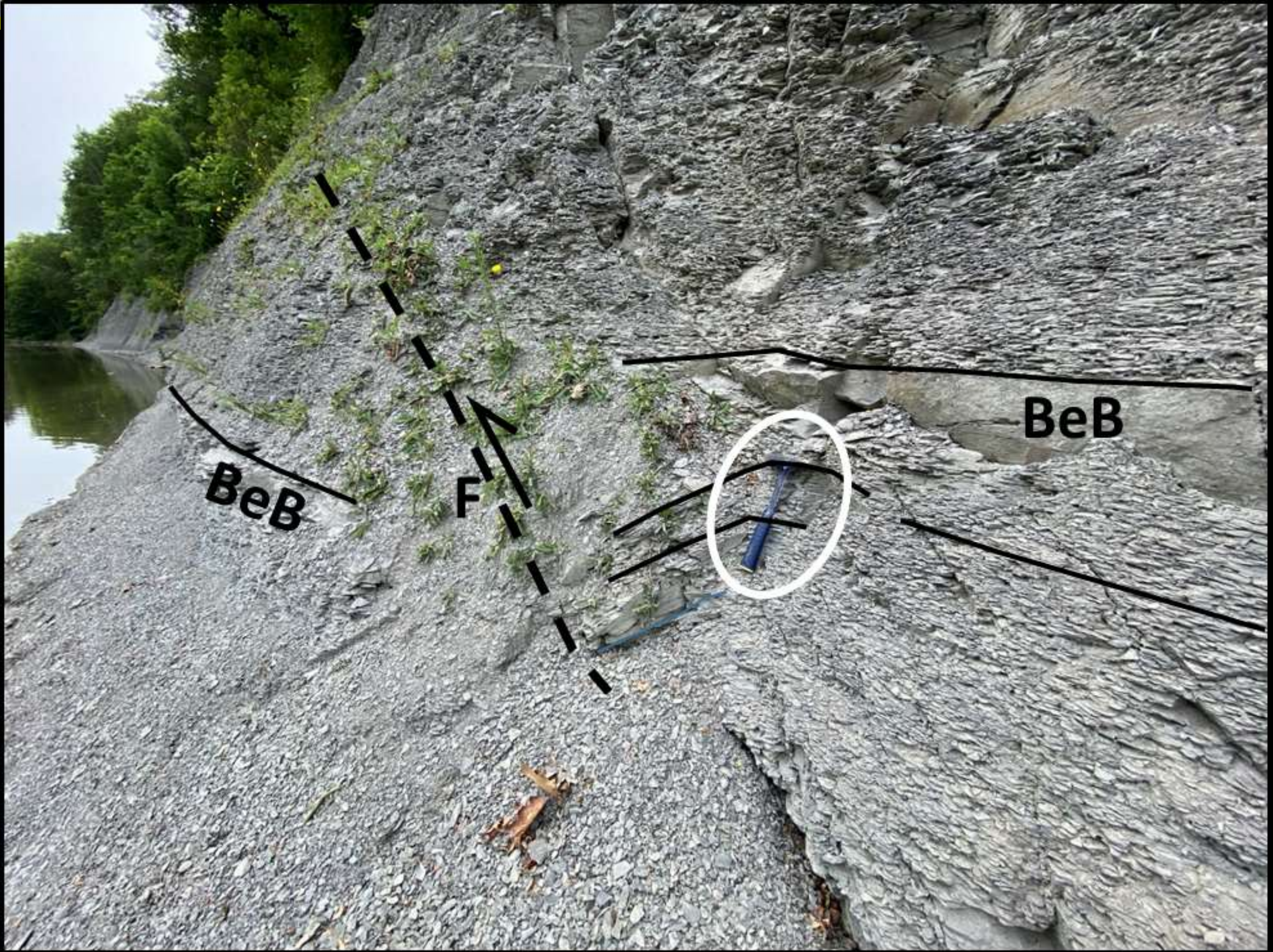
42.7138°N, 78.9701°W

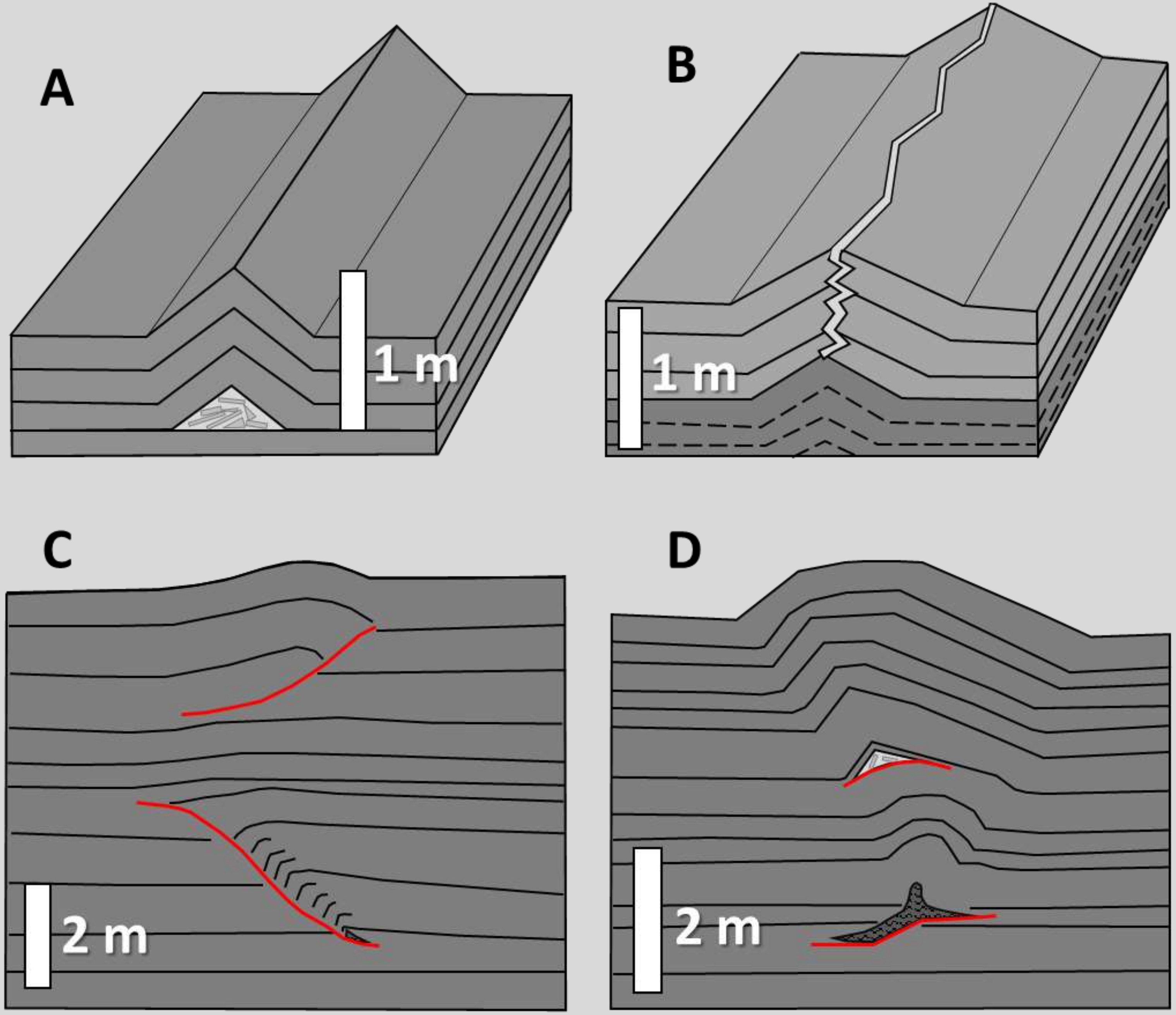
Thrust fault with fold on Eighteen Mile Creek



Shaded relief map generated from CalTopo.com, reproduced with permission; W3D30 data courtesy of Japan Aerospace Exploration Agency.

42.7138°N, 78.9701°W





Characteristics of interpreted pop-up structures on Erie lakeshore, western NY

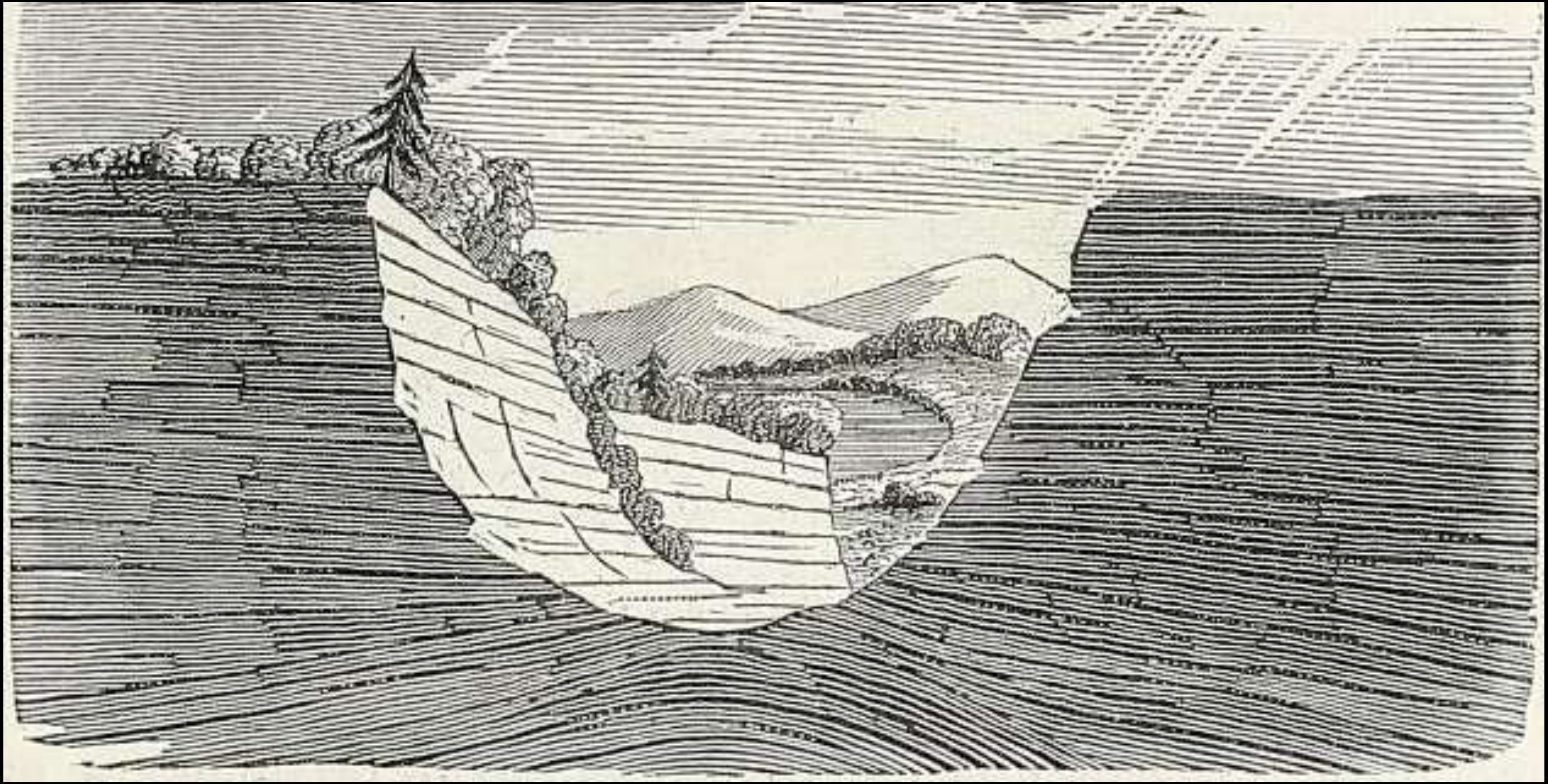
Buckle folds with axial voids or open, irregular axial fractures

Stacked thrust faults or folds with opposing vergences

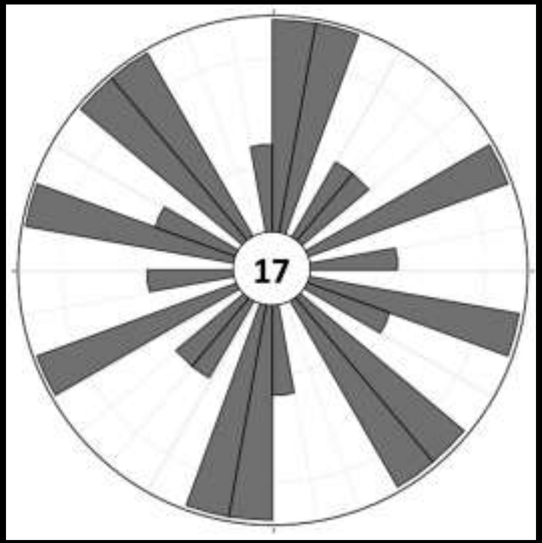
May include fault gouge, or void in fold hinge

Valley anticline, South Branch of Cattaraugus Creek, NY

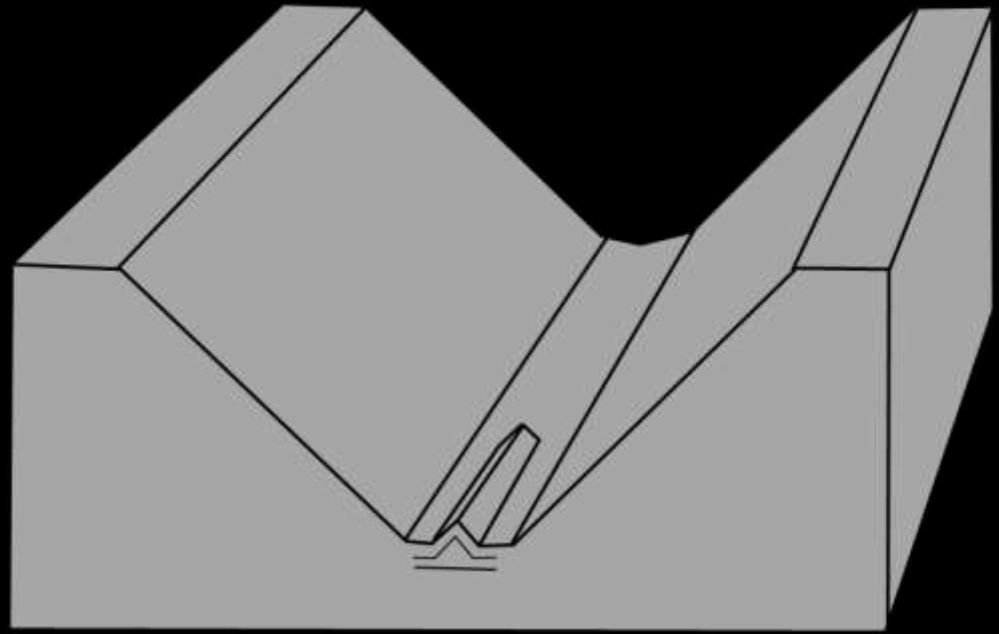
From Hall, 1843



Bedrock buckle folds in Allegany County, NY stream valleys

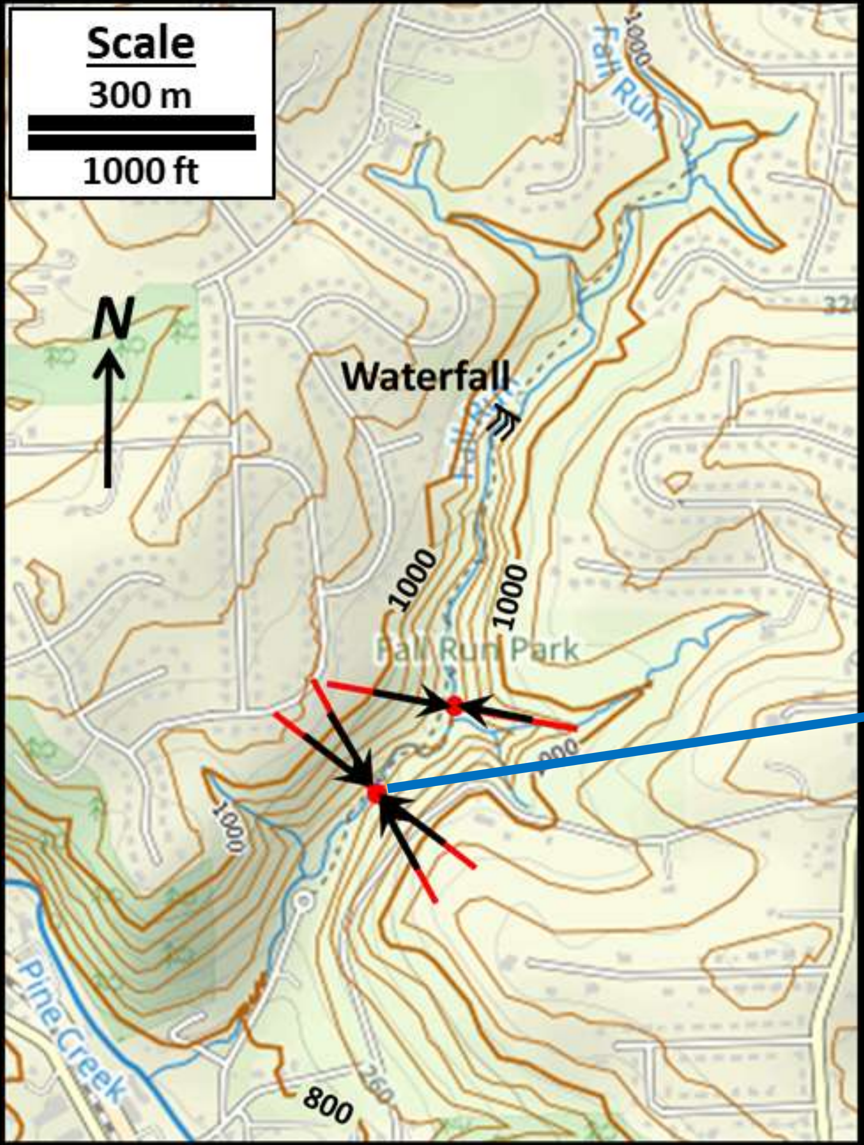


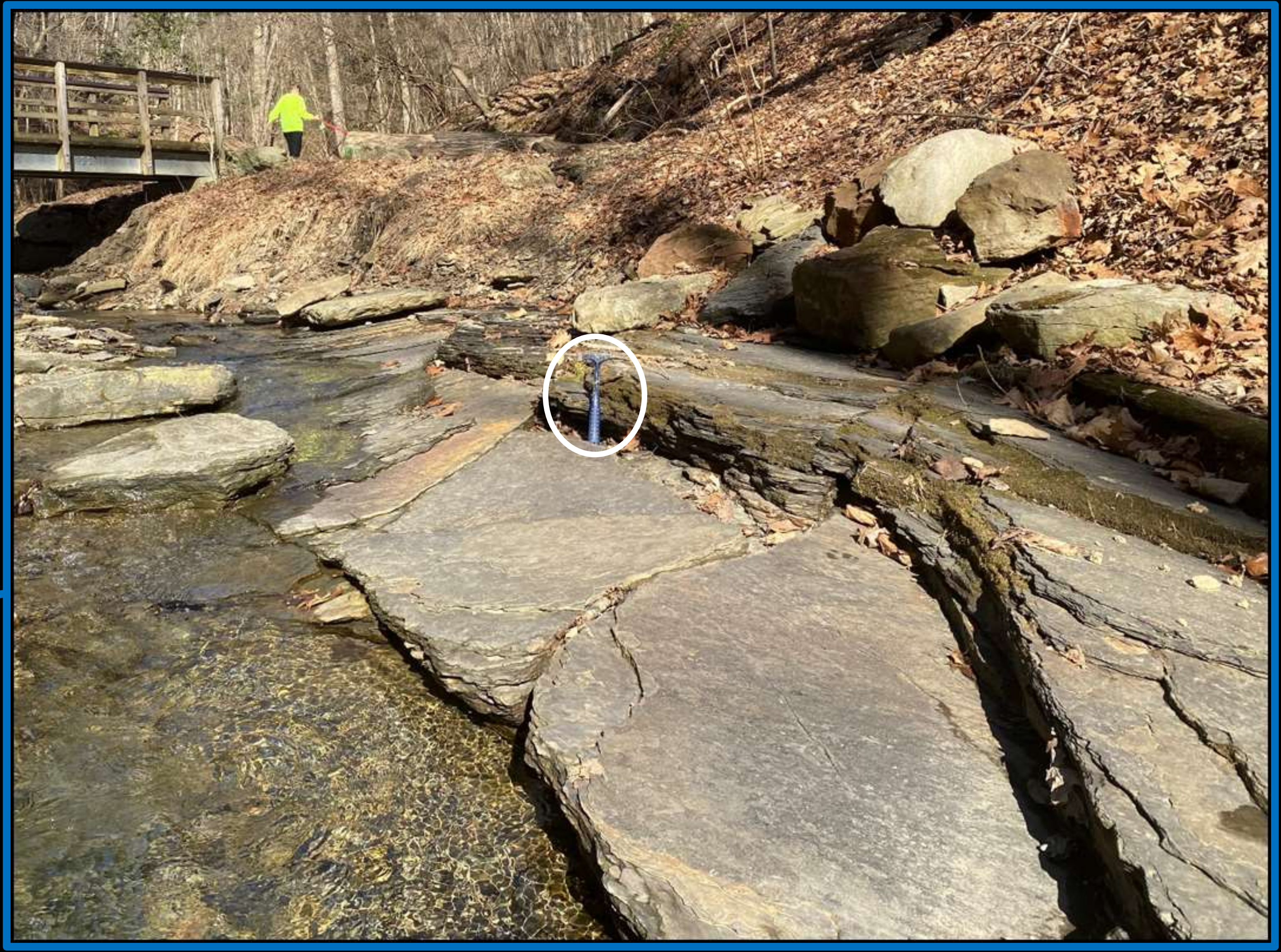
Orientations of fold axes



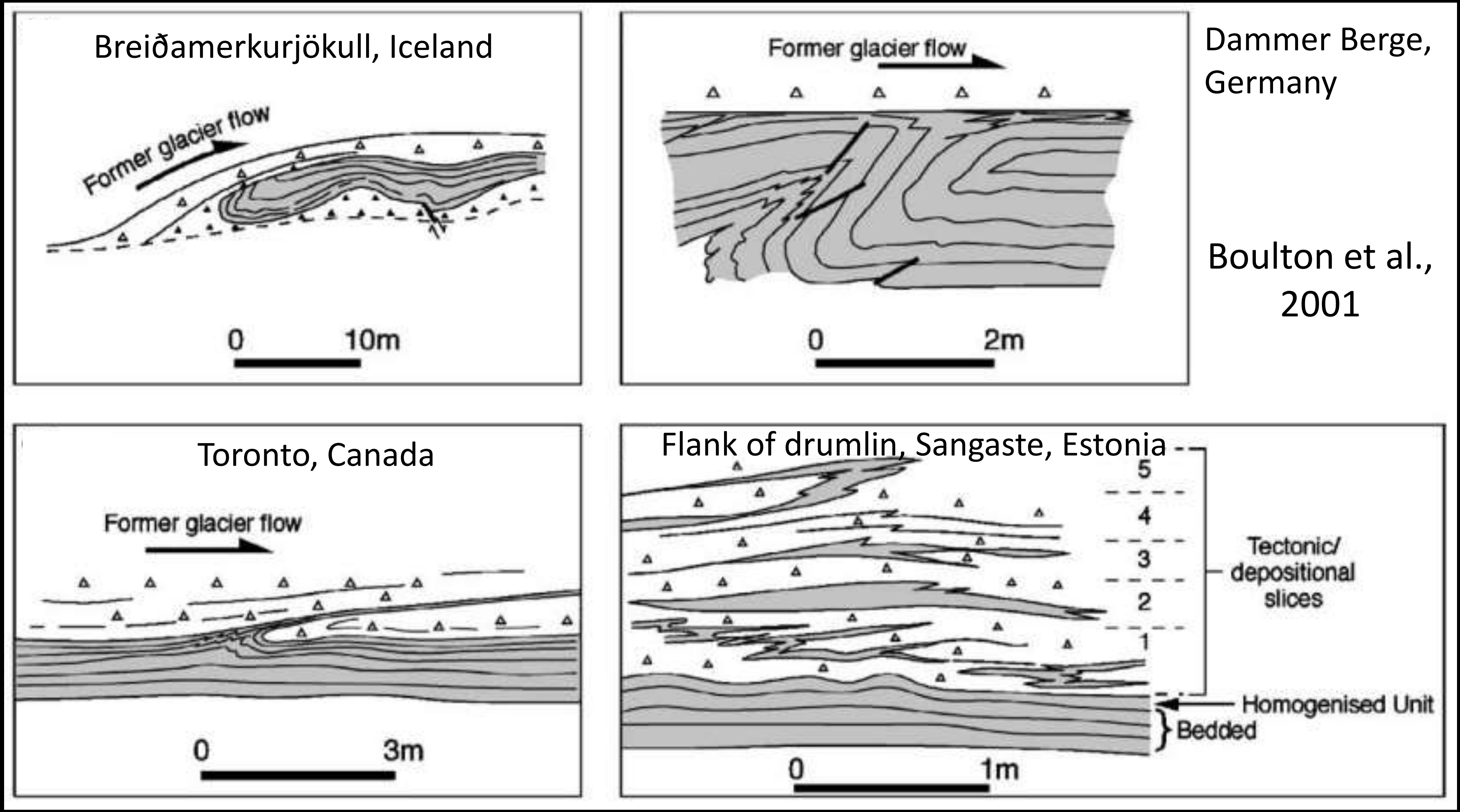
- Pop-up buckle folds in Upper Devonian shales and sandstones documented by Jacobi and Fountain, 1996
- Fold axis orientations are highly variable
- Sixteen of the 17 folds have axes sub-parallel or parallel to stream valley floor
- Stream reaches follow bedrock faults and fractures
- **Pop-ups are stream or valley anticlines, in incised stream valleys**

Bedrock buckle folds in Fall Run Park, unglaciated Plateau





Asymmetrical structures in sediment sheared by flow of overlying glaciers



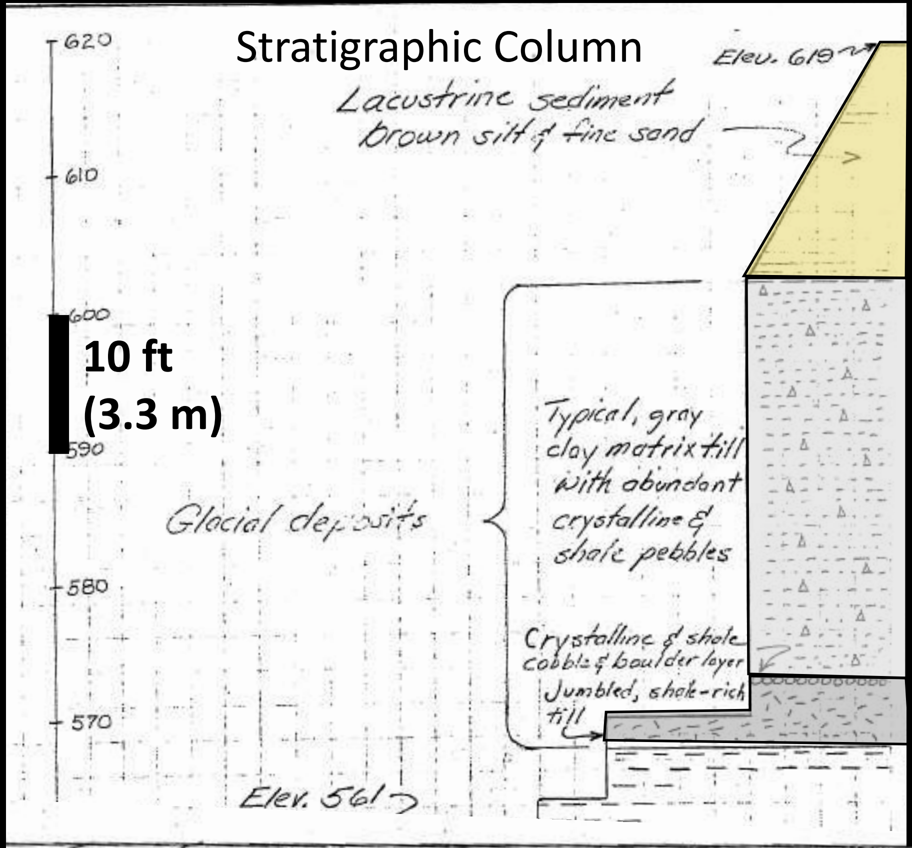
Hall, 1843

k = clay and rock fragments “insinuated between the strata”

from the library of Bob Jacobi

g = rock fragments “intermingled with glacial drift in the greatest possible confusion”

From Herdendorf, 1975

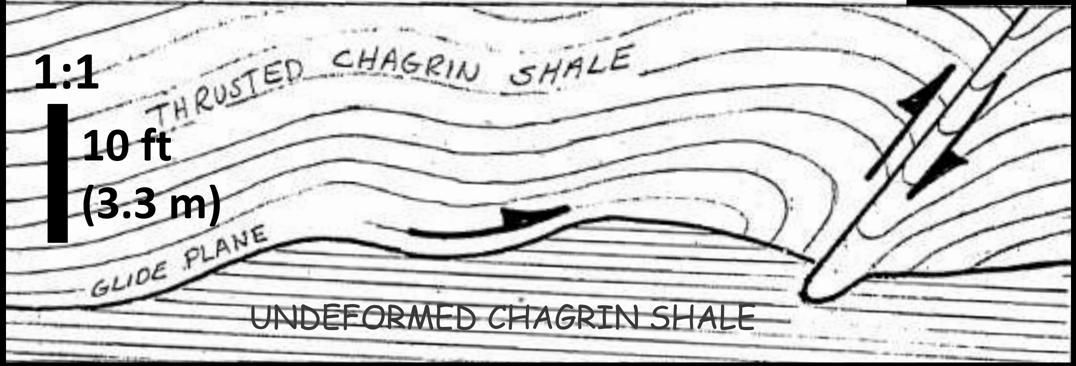


Brown silt and sand (lacustrine)

Typical till with crystalline and shale clasts

Clay with clasts of shale bedrock

Shale bedrock



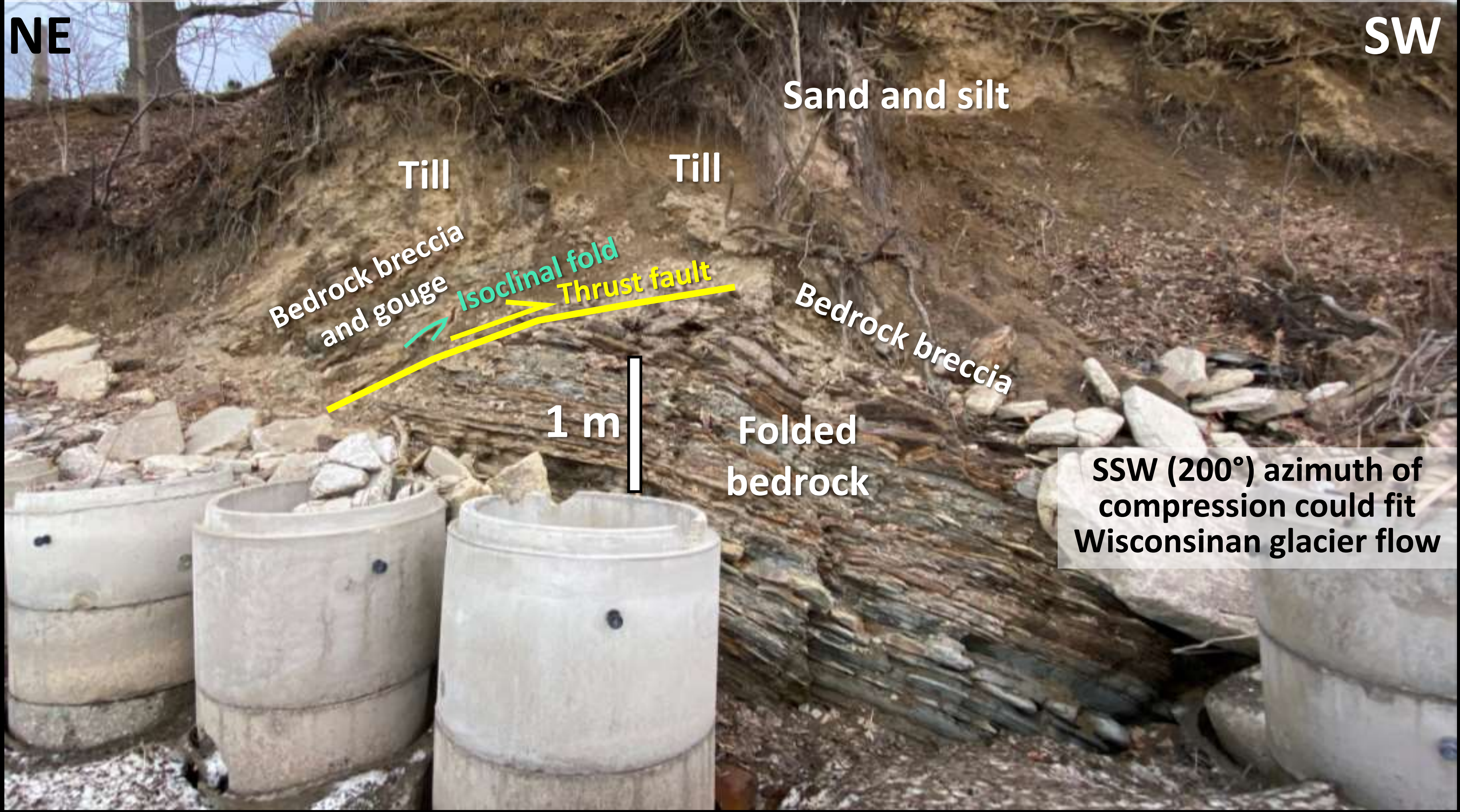
Generalized Cross Section

Perry Nuclear Power Plant, NE Ohio
Evidence of glacial shear of shale bedrock

- **Overlying till and lacustrine silt/sand not deformed**
- **Deformed shale bedrock overlain by layer with gray clay and abundant shale clasts**
- **Asymmetrical compressional structures in Devonian shale bedrock including imbricate thrust faults and recumbent folds**
- **Orientation of compression fits direction of glacial flow (to SE)**
- **Intensity of deformation decreases downward**

41.8010°N, 81.1432°W

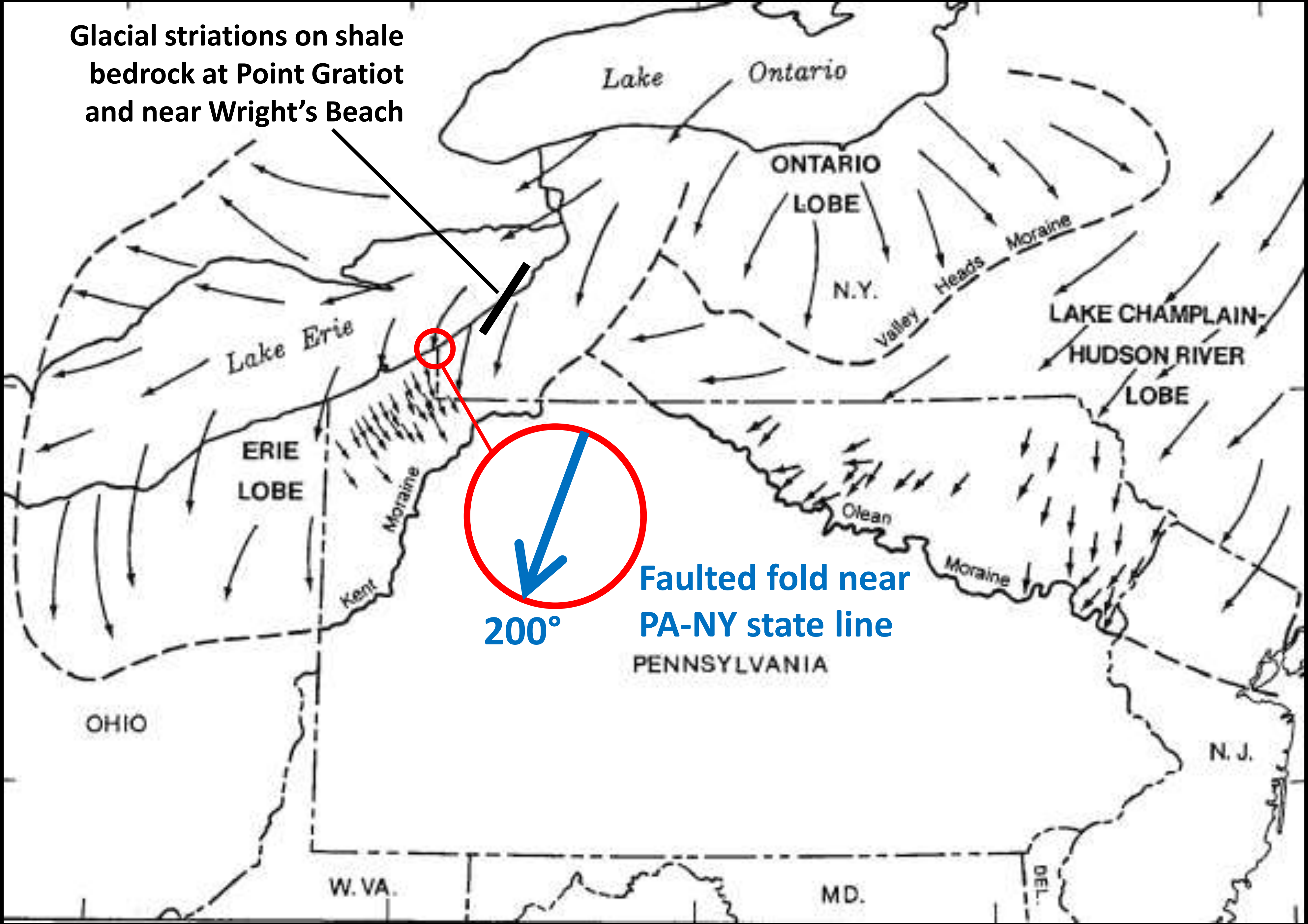
Faulted fold in Upper Devonian bedrock on Lake Erie shoreline near PA-NY boundary with characteristics of sub-glacial shear



- Asymmetrical structure overlain and in fault contact with bedrock breccia
- Breccia grades upward to till
- Youngest beds of sand/silt were not deformed
- Elevation of top of bedrock fold equivalent to till nearby

Near State Line, PA

42.2668°N, 79.7767°W



Late Pleistocene directions of glacier flow

Map from Crowl and Sevon, 1999

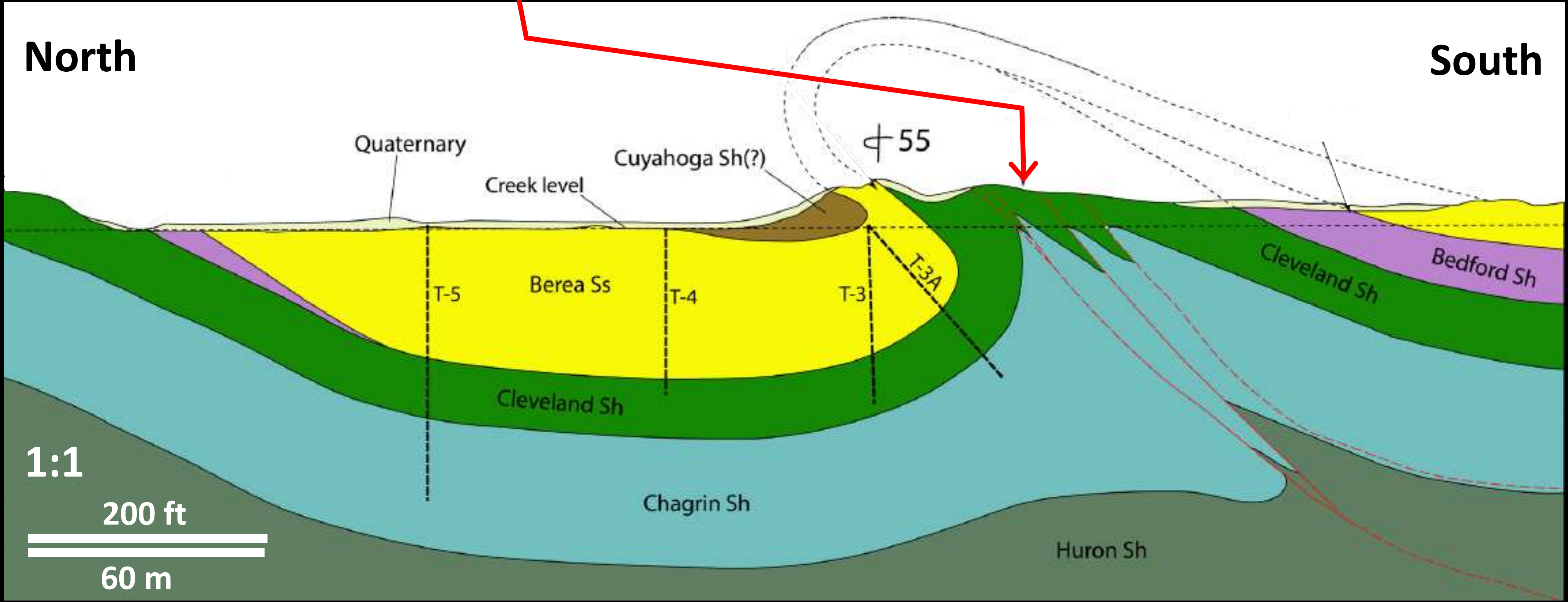
Direction of compression indicated by faulted fold near PA-NY state line

Locations of glacial striations in Hegna et al., 2025

Interpreted deep, Alleghanian deformation of Devonian shales, Erie County, northern Ohio

Asymmetrical structures including overturned fold and imbricate thrust faults verge NW

Fakhari et al, 2021



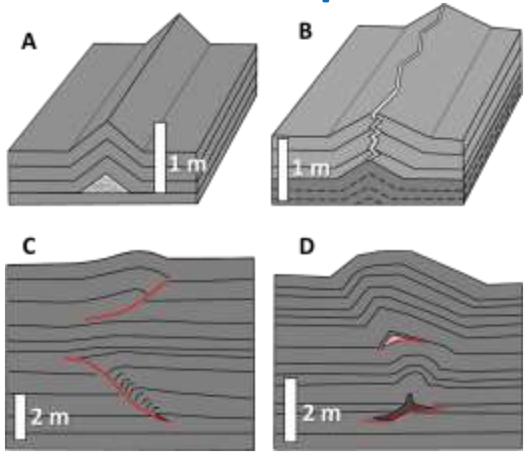
Many of the faults and folds indicate NW-SE compression consistent with Alleghanian tectonics, and are not aligned with incised stream valleys

Field Recognition of Shallow vs. Deep-formed Compressional Structures in Plateau Shales

Shallow-formed Pop-ups

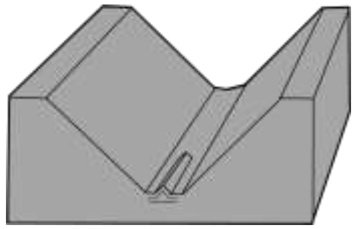
All can include fault gouge and bedding-parallel faults

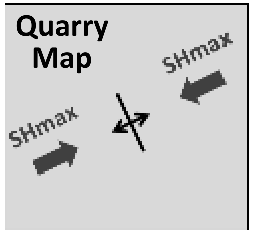
Glaciated Open Terrain

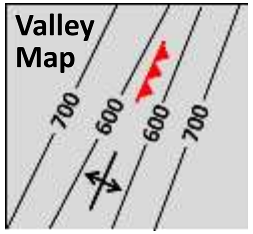


- Formed shallow, w/little overburden
- Orientation can vary
- Symmetrical, vertical structures, can be stacked
- Can include voids
- Little apparent displacement
- Faults die out at depth
- Can deform Quaternary sediment
- Preferential orientation: Parallel to valley edge or perpendicular to regional SHmax in quarry
- May be best developed with compression parallel to present-day SHmax
- Can form as deep as 300 ft (91 m)

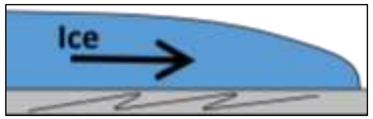
Valley and Quarry





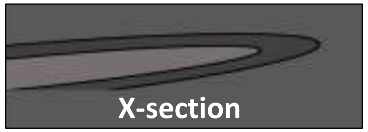


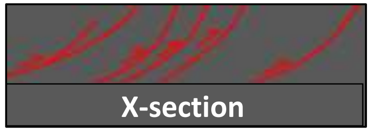
Sub-Glacial

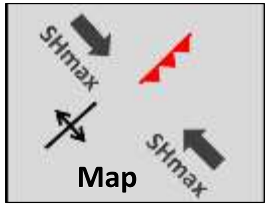


- Asymmetrical, with recumbent folds
- At top of bedrock, dies out with depth
- Associated with bedrock breccia
- Deformed bedrock and breccia overlain by undeformed sediment
- Direction of compression fits glacial flow

Deep-formed, Orogenic







- Asymmetrical, can include recumbent folds and >2 imbricate thrust faults
- Faults continue at depth
- Apparent displacement can be large
- Direction of compression fits orogenic stress

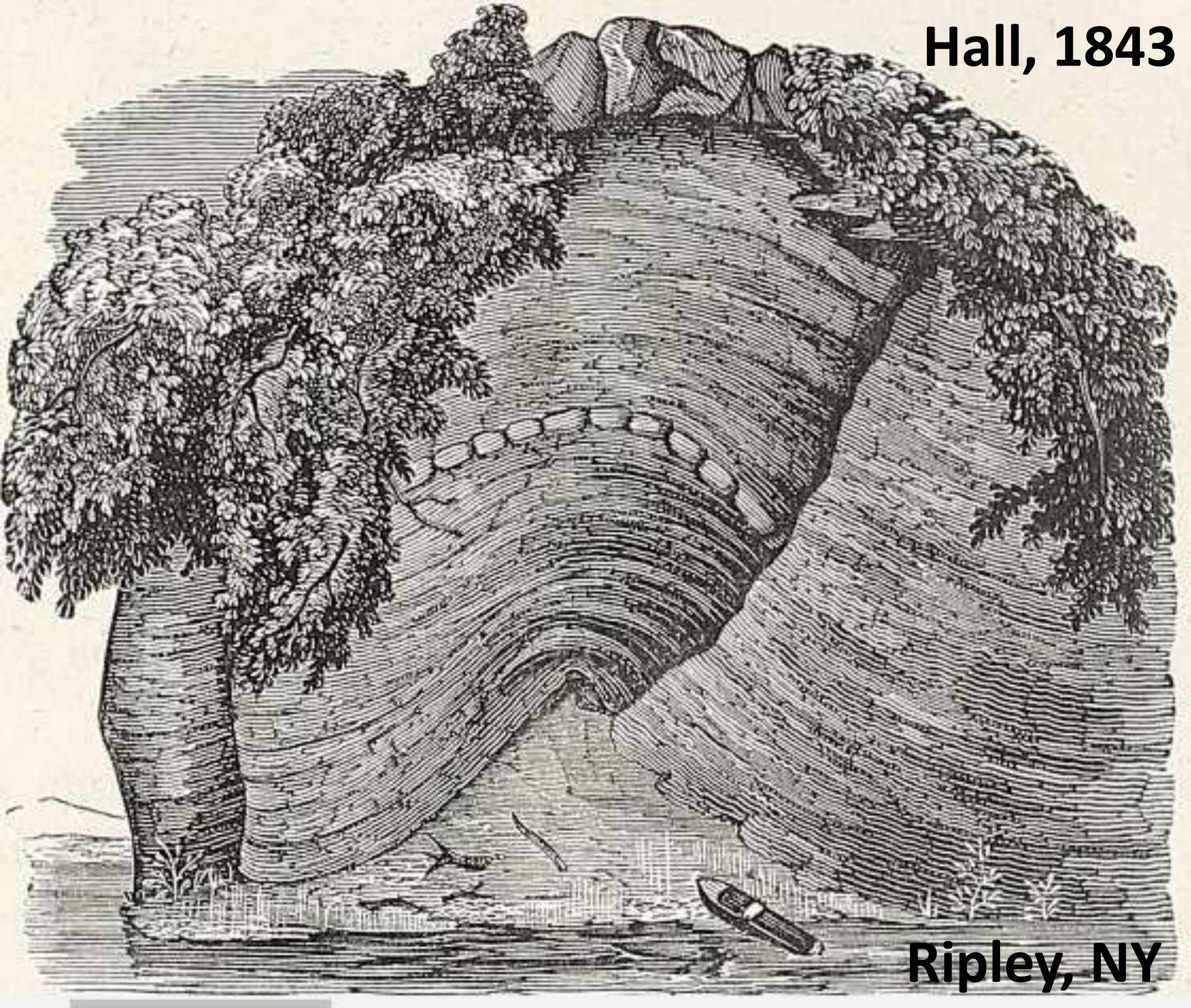
Being mindful of products of shallow, soft-sediment deformation such as:

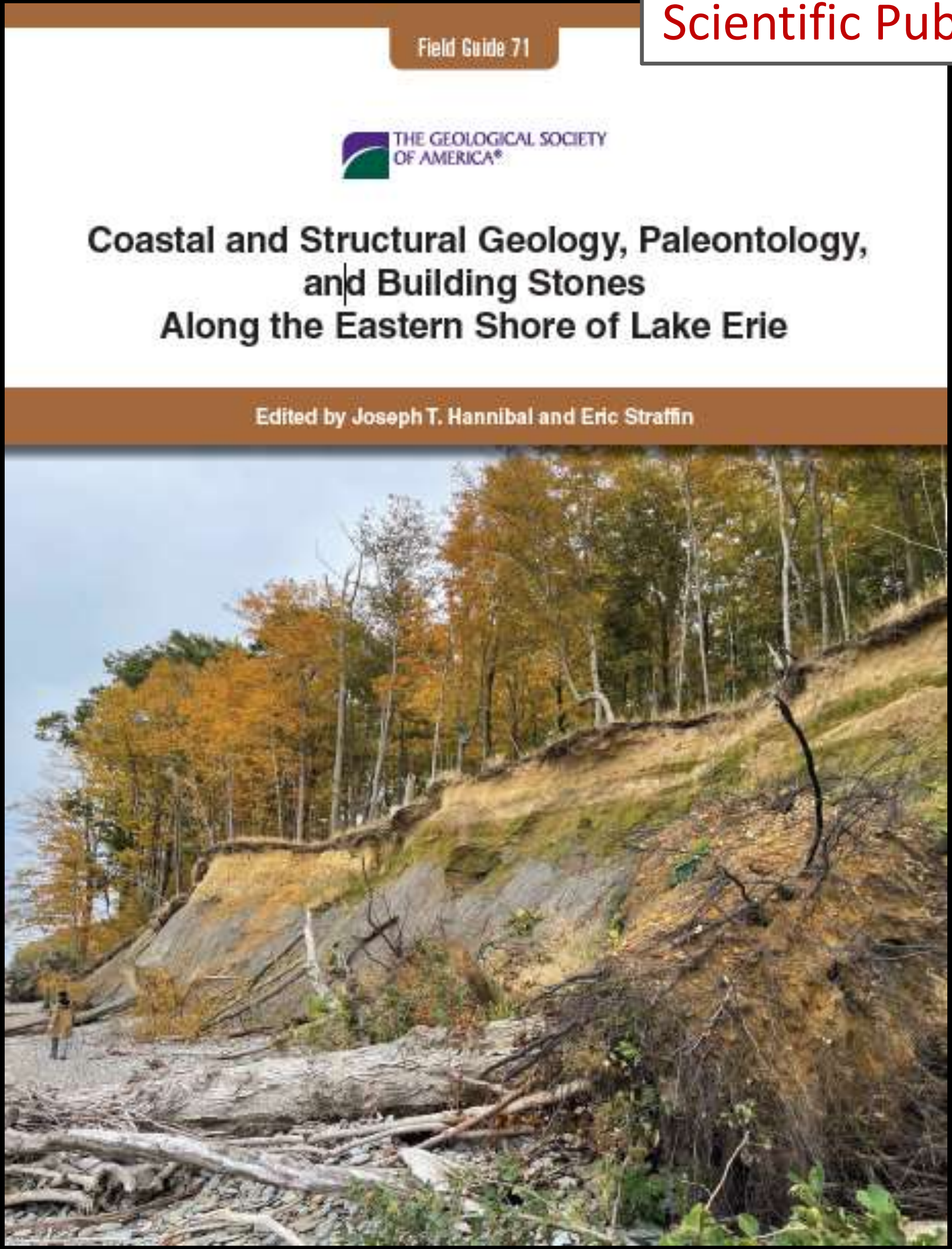
- Clastic sills and dikes
- Asymmetrical soft-sediment folds and faults
- Dewatering structures
- Slumps
- Mass transport complexes

Thrust faults and folds interpreted as post-glacial pop-ups in Devonian strata of lakeshore bluffs along Lake Erie, western New York State, USA

Fred Zelt, Earth Science Excursions, LLC

Robert Jacobi, Department of Geology, University at Buffalo





Scientific Publication

Opportunity for further exploration

Geological Society of America Field Guide 71

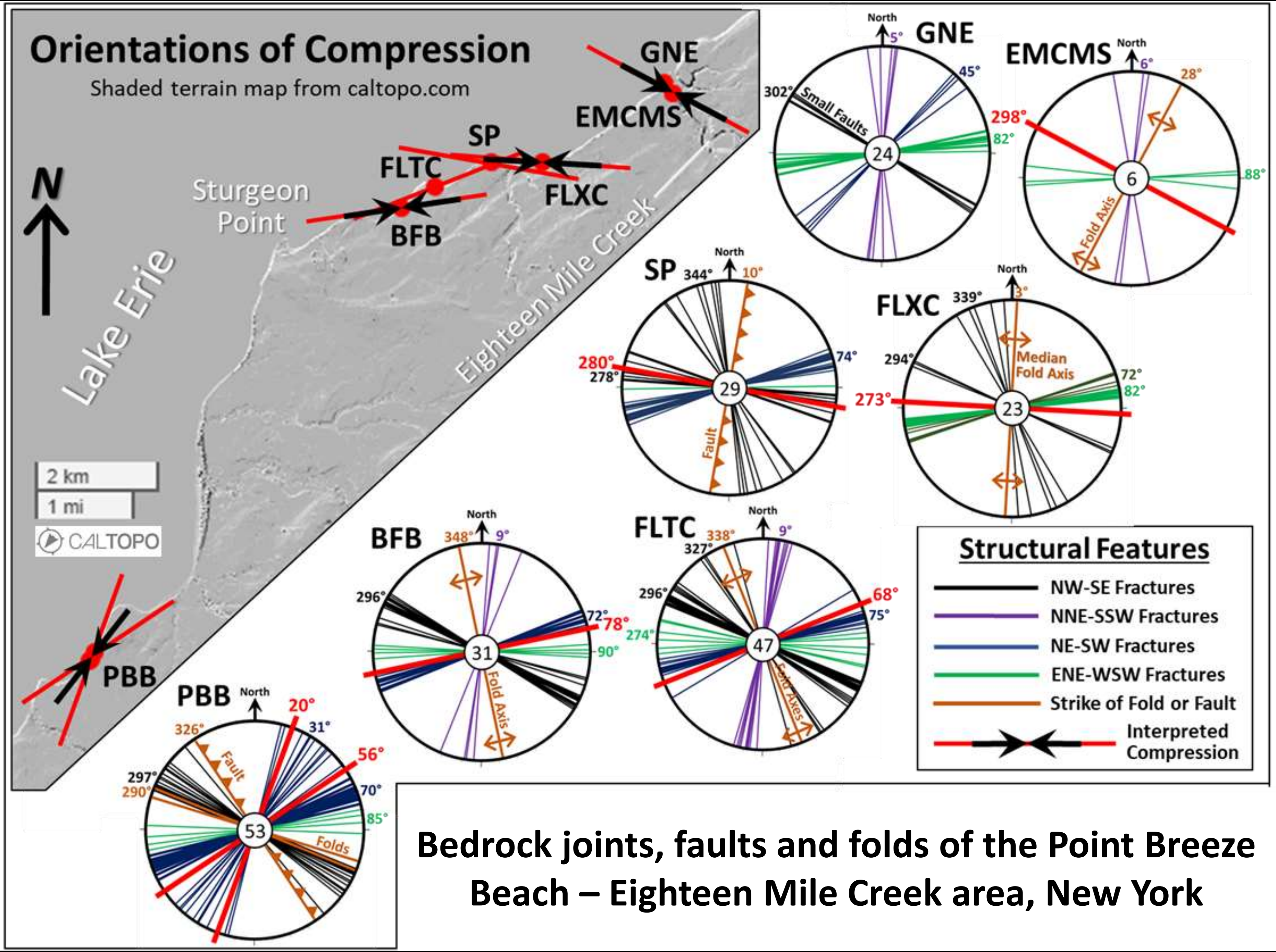
<u>Contents Include</u>

Frank Lloyd Wright's Graycliff on Lake Erie in western New York State, USA: Geology, organic design, and associated structures

by Fred Zelt, 2025

Also – Slide set for this talk on GSA meeting website, and possible Pennsylvania Geology article, "Post-glacial Pop-up Structures Rediscovered"

Extra Slides



Bedrock joints, faults and folds of the Point Breeze Beach – Eighteen Mile Creek area, New York

Shaded relief map generated from CalTopo.com, reproduced with permission; W3D30 data courtesy of Japan Aerospace Exploration Agency.

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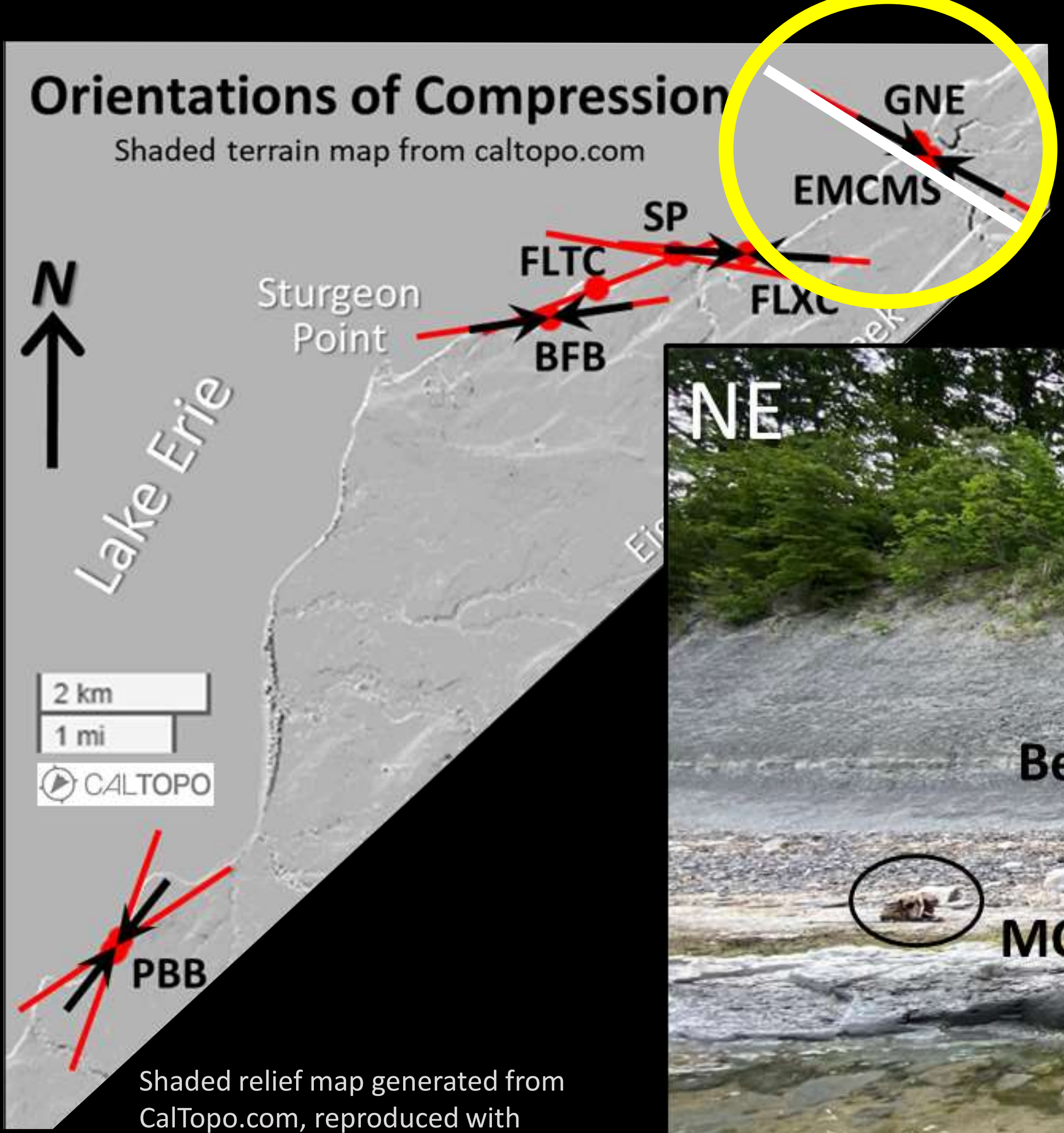
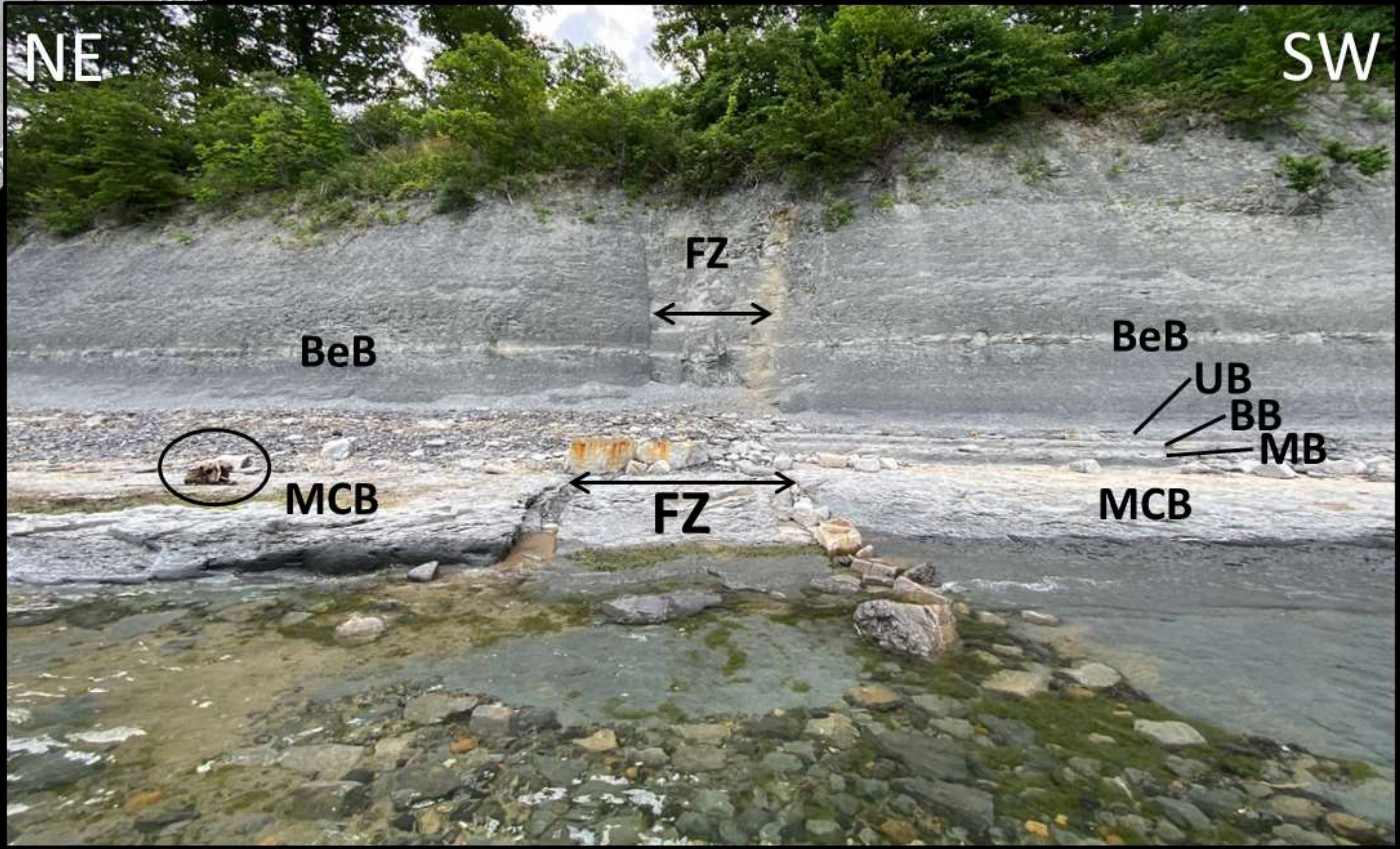
Gray fault gouge at Broad Fold Beach

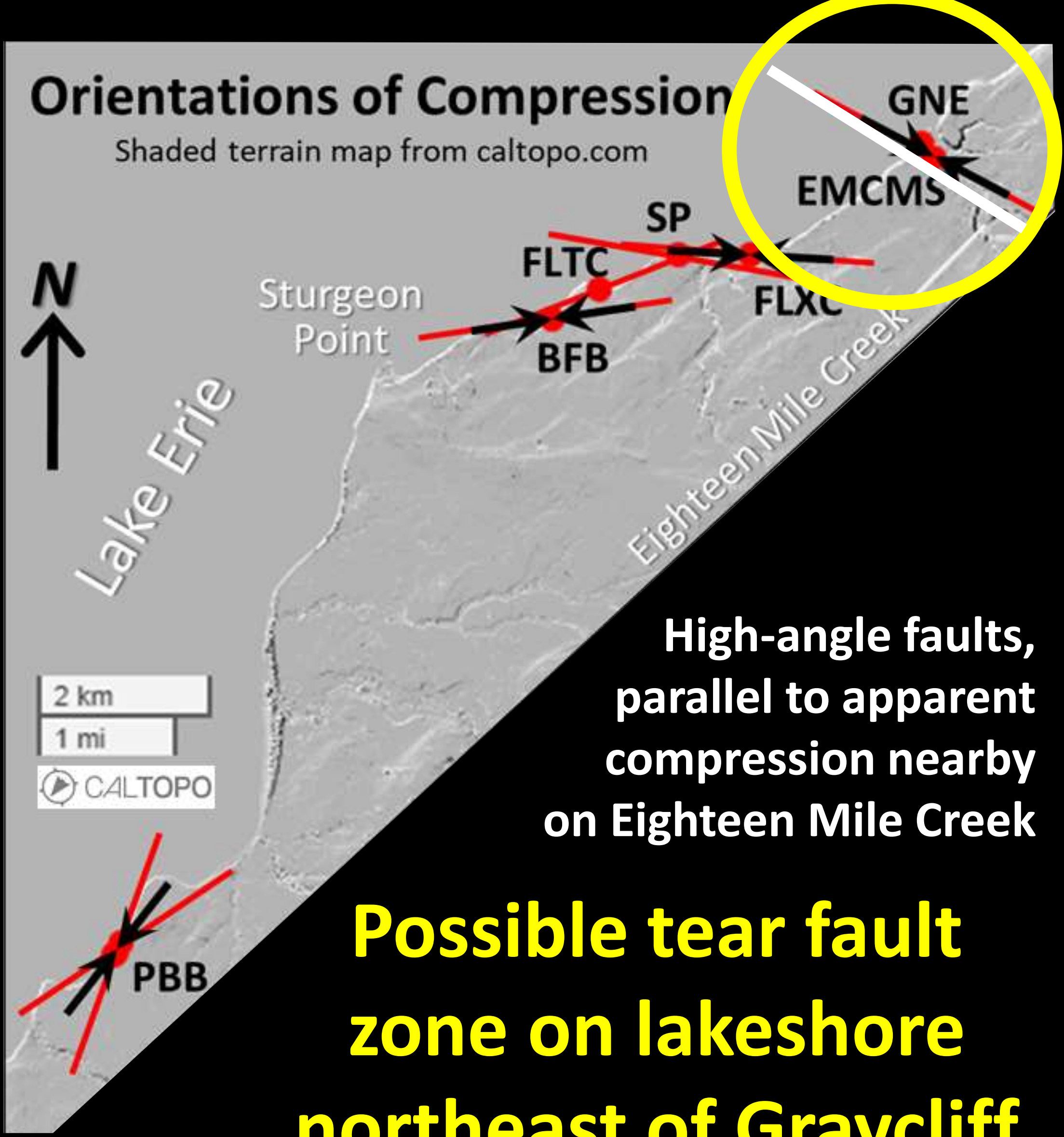
Fault zone on lakeshore northeast of Graycliff



Shaded relief map generated from CalTopo.com, reproduced with permission; W3D30 data courtesy of Japan Aerospace Exploration Agency.

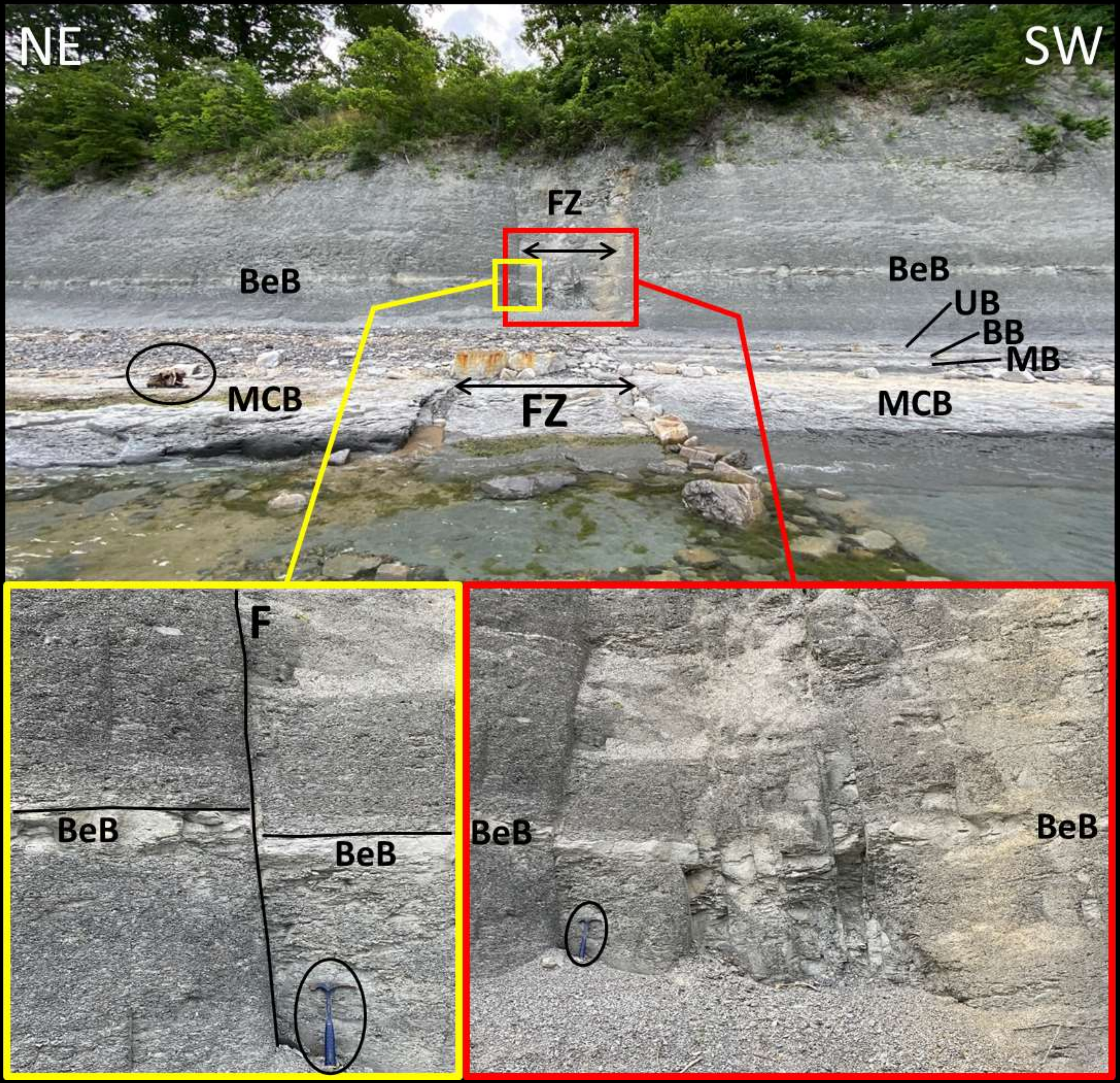
42.7152°N, 78.9718°W





High-angle faults, parallel to apparent compression nearby on Eighteen Mile Creek

Possible tear fault zone on lakeshore northeast of Graycliff



42.7152°N, 78.9718°W

Shaded relief map generated from CalTopo.com, reproduced with permission; W3D30 data courtesy of Japan Aerospace Exploration Agency.

Picture windows in dining room

Photo courtesy of Graycliff Conservancy

Organic basis of Diamond Window

Photos courtesy of the Graycliff Conservancy

Natural fractures in Tichenor Limestone create Diamond Theme

Graycliff

Graycliff Area

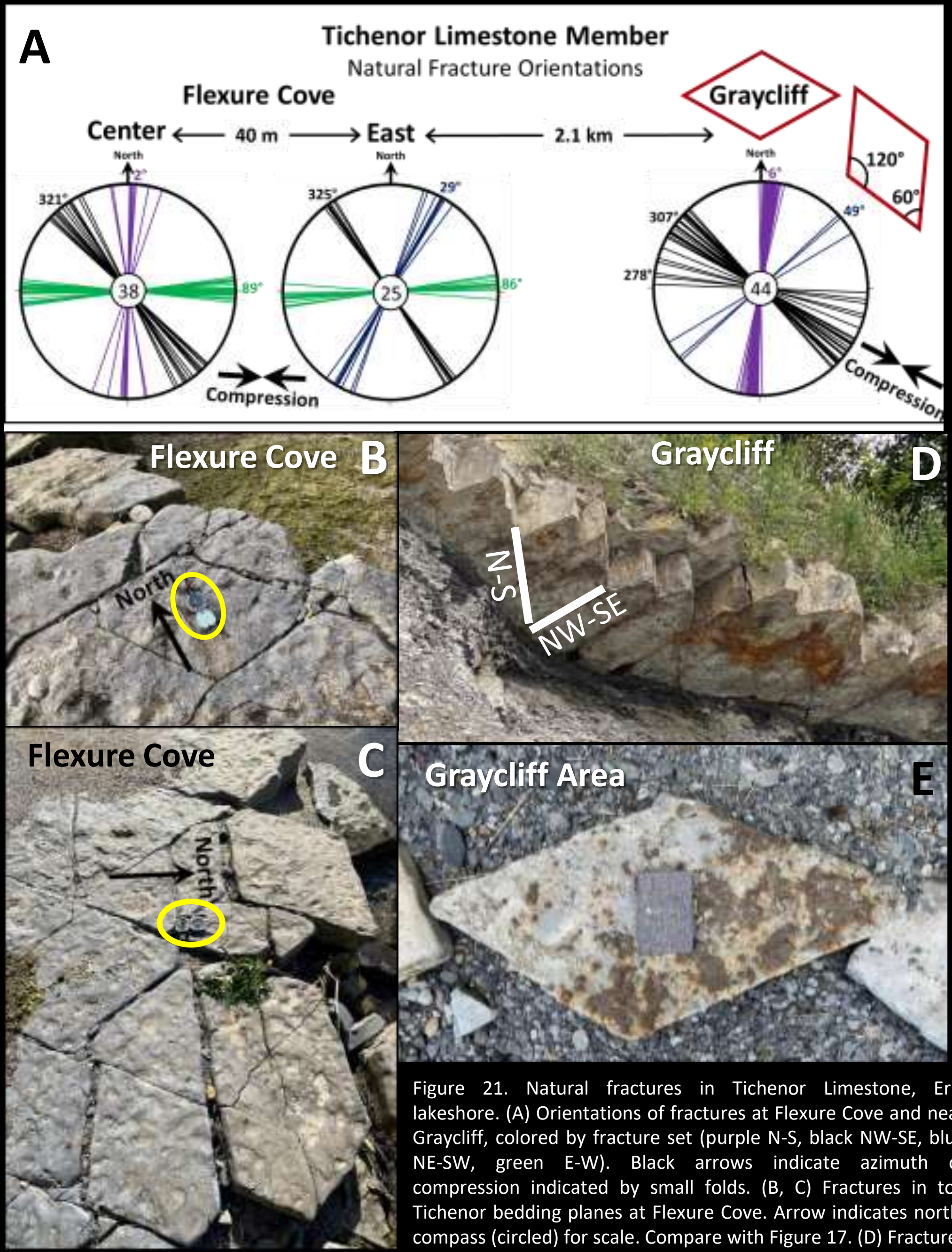


Figure 21. Natural fractures in Tichenor Limestone, Erie lakeshore. (A) Orientations of fractures at Flexure Cove and near Graycliff, colored by fracture set (purple N-S, black NW-SE, blue NE-SW, green E-W). Black arrows indicate azimuth of compression indicated by small folds. (B, C) Fractures in top Tichenor bedding planes at Flexure Cove. Arrow indicates north, compass (circled) for scale. Compare with Figure 17. (D) Fractures on bottom of Tichenor Limestone near top of lakeshore bluff at Graycliff. E. Diamond-shaped boulder of Tichenor Limestone on lakeshore beach near Graycliff. Notebook is 5.5 x 8.3 in (14 x 21

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