

To rush into the secret house of death: The fate of a Tournaisian plant

Robert A. Gastaldo^{1,2,*}, Patricia G. Gensel³, Ian J. Glasspool^{1,4}, Steven J. Hinds⁵, Olivia A. King^{6,7}, Adrian F. Park⁵, and Matthew R. Stimson^{6,7}

¹Department of Geology, Colby College, Waterville, Maine 04901, USA

²Department of Paleobiology, Smithsonian National Museum of Natural History, Washington, D.C. 20560, USA

³Department of Biology, University of North Carolina–Chapel Hill, Chapel Hill, North Carolina 27599, USA

⁴Field Museum of Natural History, Chicago, Illinois 60605, USA

⁵Geological Surveys Branch–New Brunswick Department of Natural Resources, Fredericton, New Brunswick E3B 5H1, Canada

⁶New Brunswick Museum, Saint John, New Brunswick E2K 1E5, Canada

⁷Department of Geology, Saint Mary's University, Halifax, Nova Scotia B3H 3C3, Canada

ABSTRACT

Tournaisian-age failure of marginal lacustrine sediments, and their bulk collapse into an inland rift-basin lake in the Moncton Subbasin, Canada, led to the entrainment of rare, almost complete, three-dimensionally preserved non-woody trees. Preservation of these unique fossils from the Albert Formation was a consequence of contemporaneous seismicity. Synsedimentary structures include an array of soft-sediment deformational features and a field of cross-cutting sand boils indicating multiple seismic shocks >4.6 Mw. This tectonically controlled event, entombing trees whose novel growth form is both evolutionarily and ecologically transitional and unlike other Paleozoic plants, is a one-off in the paleobotanical record.

INTRODUCTION

Mississippian-age continental rocks are rare in North America when contrasted with Pennsylvanian strata. A Macrostrat analysis (Peters et al., 2018) of Tournaisian and Viséan deposits reveals that surface-and-subsurface rocks of this age comprise only 0.06% to 0.03% of the record. The majority of terrestrial deposits represent alluvial, fluvial, and coastal settings. Here, plant fossils are typically small and fragmentary (e.g., Gensel and Skog, 1977; Skog and Gensel, 1980; Gensel, 1988; Gensel and Pigg, 2010) and are preserved as either adpressions (Knaus, 1995) or permineralizations (Gastaldo et al., 1993). Evidence of trees is limited to in situ stumps, rooting structures (Rygel et al., 2006; Leslie and Pfefferkorn, 2010; Gastaldo et al., 2024), or transported wood (Matten, 1972). Interior continental depositional sites are even rarer and reportedly without megafossils.

We describe the unique taphonomy of extraordinary, rare Tournaisian-age non-woody trees with intact 3-D canopies—*Sanfordiacaulis*

densifolia (Gastaldo et al., 2024)—and detail evidence of mass transport coincident with pervasive seismicity in a rift-basin lake. These trees were quickly transferred from life position along the lake margin and buried at depth in it. As a result of this temporally unique event, a previously undescribed and unanticipated tree morphology, indicative of biological experimentation, was preserved in the Moncton Subbasin, far inland of the coastal settings that typify the majority of Carboniferous-age floras.

REGIONAL GEOLOGICAL SETTING

Tectonically influenced accretion of multiple terranes with extensive lateral and temporal variability resulted in a complex regional depositional history in the Maritimes basins (Fig. 1A; Gibling et al., 2019). Late Paleozoic extensional and transtensional block-faulting in New Brunswick produced NE-trending half grabens and grabens (Waldron et al., 2017), where fully continental sediment accumulated. Here, six lithostratigraphic groups are separated by regional unconformities (St. Peter and Johnston, 2009), with the Horton Group assigned a mid-Tournaisian age based on palynostratigraphy (355–350.5 Ma; Gastaldo et al., 2024).

The tropical to subtropical (Dietrich et al., 2011) Horton Group consists of the basal Memramcook Formation overlain by the Albert Formation (Fig. 1B) and capped by the Bloomfield Formation (St. Peter and Johnston, 2009). Plant fossils (Figs. 2 and 3) occur in the Hiram Brook Member of the Albert Formation. These rocks exhibit lateral variability of coeval depositional environments and are interpreted as fluvial, floodplain, marginal lacustrine shoreface, delta-top, and deep-lacustrine facies of a meromictic lake (Greiner, 1974; Falcon-Lang, 2004; Keighley, 2008).

SANFORD QUARRY

The Hiram Brook Member in the Sanford Quarry, Norton, New Brunswick, Canada (Figs. 1B and 2A; N 45.627786°, W 65.691610°) consists of 10+ m of siltstone and sandstone, and is composed of four lithologic units (Fig. 3A). Unit 1 is an upward-coarsening mudstone and siltstone to very fine sandstone. The basal siltstone is massive with an abrupt upper contact to a sandstone, which is planar-bedded (laminar) or internally cross-bedded. Symmetrical wave-ripple bedforms and mudcracks are common. Bedding planes preserve microbial-induced sedimentary structures (MISS), wrinkles, and “elephant-skin textures” (Bottjer and Hagadorn, 2007). Plant fossils are absent, but ichnofossils in the sandy upper 30 cm include *Skolithos* (≤1 cm), small-scale *Cruziana*, and *Rusophycus* (≤5 mm). Unit 1 represents marginal lacustrine facies (Fig. 3A) without evidence of soft-sediment deformation (SSD). An undulatory contact separates Unit 1 from Unit 2.

Conformable Unit 2 varies from 60 to 140 cm in thickness, is a succession of light-to-medium

Robert A. Gastaldo  <https://orcid.org/0000-0002-7452-8081>
*ragastal@colby.edu

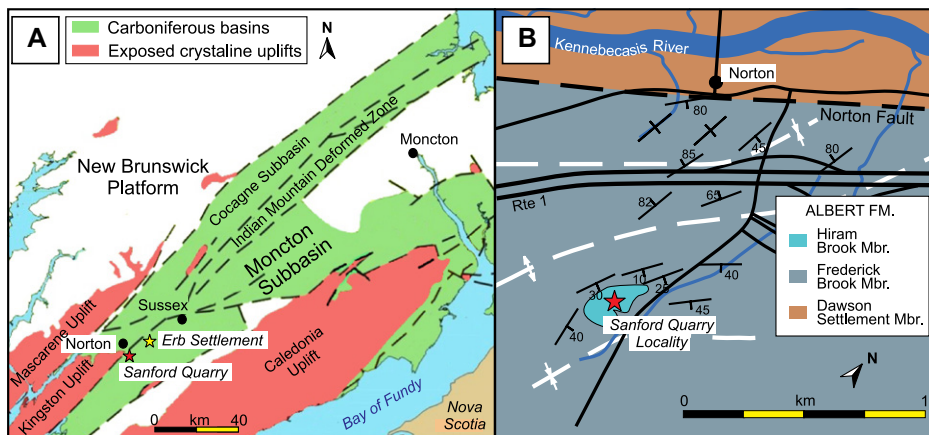


Figure 1. Geological context of the Sanford Quarry locality. (A) A map of the Moncton Subbasin in relation to peripheral Carboniferous basins and uplifted regions. (B) Geologic map of strata around Norton, New Brunswick, Canada, and the location of the Sanford Quarry, in which the Hiram Brook Member is exposed.

gray siltstone to sandstone preserving abundant plant fossils. The sandstone displays ball-and-flame structures (Fig. 3C; balls ≤ 1 m wide) and polyaxial folding of beds (Fig. 3E). Although cross-bedding is pervasive, the unit exhibits extensive SSD features at centimeter to meter scale. Bedding surfaces are swaly (Fig. 3B), cross-bedding is contorted, and crossbed sets are often reoriented to impossible depositional angles (Figs. 4C and 4D). A small exposure of conical, centimeter-scale sand boils occurs at

the upper contact (a hand sample is illustrated in Fig. S1 in the Supplemental Material¹). In

¹Supplemental Material. Evidence of Sanford Quarry sand volcanoes (boils) and megaflora preserved in association with *Sanfordiacaulis densifolia*. Mohr circle analysis between normal and shear stress, cohesive strength, and angle of repose for the Albert Formation used as the basis for the interpretation of sediment slumping. Please visit <https://doi.org/10.1130/GEOL.S.26275852> to access the supplemental material; contact editing@geosociety.org with any questions.

addition to *S. densifolia*, fragmentary plant fossils include: *Sphenopteridium*, *Aneimites*, and eremopteroid-type pinnules (Cleal et al., 2009; Figs. S2A–S2D); lycopods (i.e., cf. *Lepidodendropsis*; Figs. S2E–S2F); and comminuted axes and articulated branches exhibiting a preferential orientation. To date, five tree trunks of *S. densifolia* (Fig. 2B; Gastaldo et al., 2024), with attached crown leaves distributed on multiple bedding surfaces, are preserved in an ~ 125 m² area of the quarry. The plant holotype and associated debris are surrounded by deformed climbing current ripples. Laterally equivalent deposits contain abundant, macerated, coalified plant fragments and axes mixed with the contorted and disturbed marginal lake sediments.

Unit 3, a pyrite-nodule-bearing, massive sandstone, is capped with wrinkled MISS. Pyrite nodules vary in size at the centimeter scale. While the upper contact is relatively planar, the basal contact has a wavy, pointed cusate surface, at the scale of meters to tens of meters laterally (Fig. 2C), that overlies Unit 2's SSD features. Bed thickness varies, and a single sandstone splits laterally into multiple beds with wave ripples that onlap the cusate "crests." Unit 3 shows no syn-sedimentary SSD. The upper contact preserves a carbonized megaflora and thick, calcareous microbial mats with plant debris. Microbial mats thicken and wrinkle, forming large concentric MISS shapes (*Rugulichnus* sp.) where millimeter to centimeter scale microstromatolites impart a pustulose texture in this marginal lake setting.

Unit 4 terminates the succession with a sharp, conformable basal contact. It is a 7.5 m massive or, less commonly, laminated, pyrite-rich, dark gray mudrock. Scarce, basal pyrite nodules are overlain by fine, thin current-rippled sandstone and SSD structures; burrows are rare. The unit marks a return to deep-water lacustrine conditions of the underlying Frederick Brook Member, with sandstone beds interpreted as tempestites or turbidity current deposits.

PLANT TAPHONOMY

Five *S. densifolia* trees occur in close spatial proximity in Unit 2. These are monopodial, non-woody trunks, ≤ 16 cm in diameter and >0.75 m in length with spirally arranged, compound, frond-like leaves. In the holotype, the leaf organization consists of sets of ~ 13 leaves distributed along ~ 14 cm of vertical trunk distance (Fig. 2B), resulting in a functional crown of >250 leaves, each >1.75 m long, with a crown volume of >20 – 30 m³ (Gastaldo et al., 2024). Trunks are decayed, partially mud-filled, and compressed. Decayed leaf bases occur below attached crown leaves, distributed on numerous bedding planes indicating that trees were transferred collectively in a natural growth position to the sediment-water interface. Trunk-and-leaf decay and 3-D entombment occurred on the lake bottom, evidenced by their compression

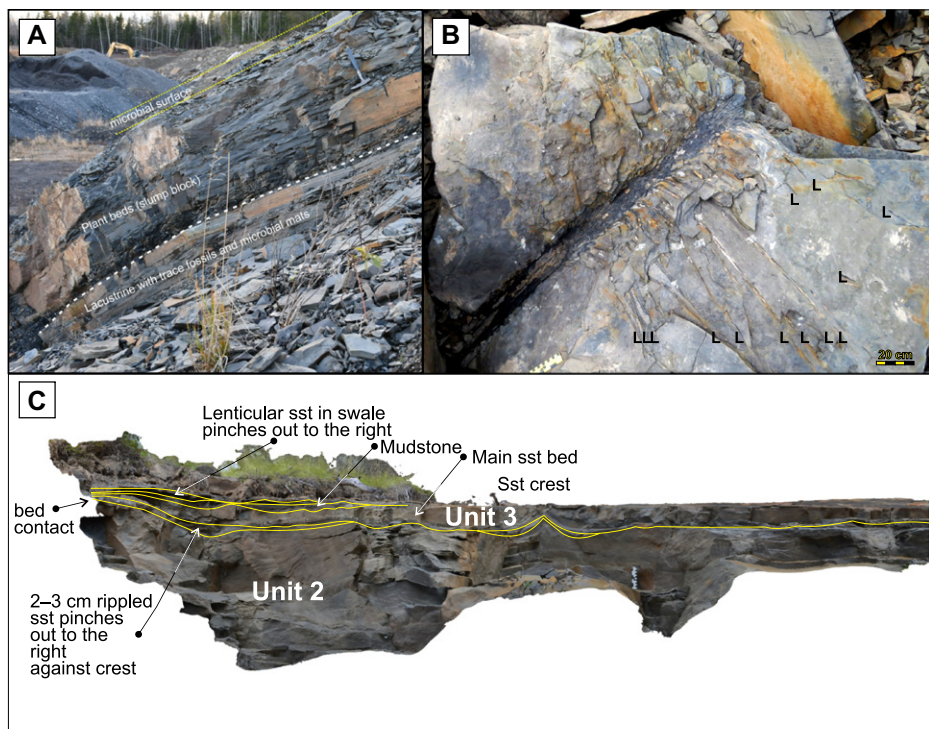


Figure 2. Field images and trunk of *Sanfordiacaulis* (Sanford Quarry, Norton, New Brunswick, Canada). (A) Quarry exposure of Units 1–3. (B) Field image of *S. densifolia* with compound leaves (L; Gastaldo et al., 2024). (C) Evidence of Unit 2 seismicity in Sanford Quarry showing Unit 3's basal contact (lower yellow line) that is a continuation of Unit 2's soft-sediment deformation features. Sst—sandstone.

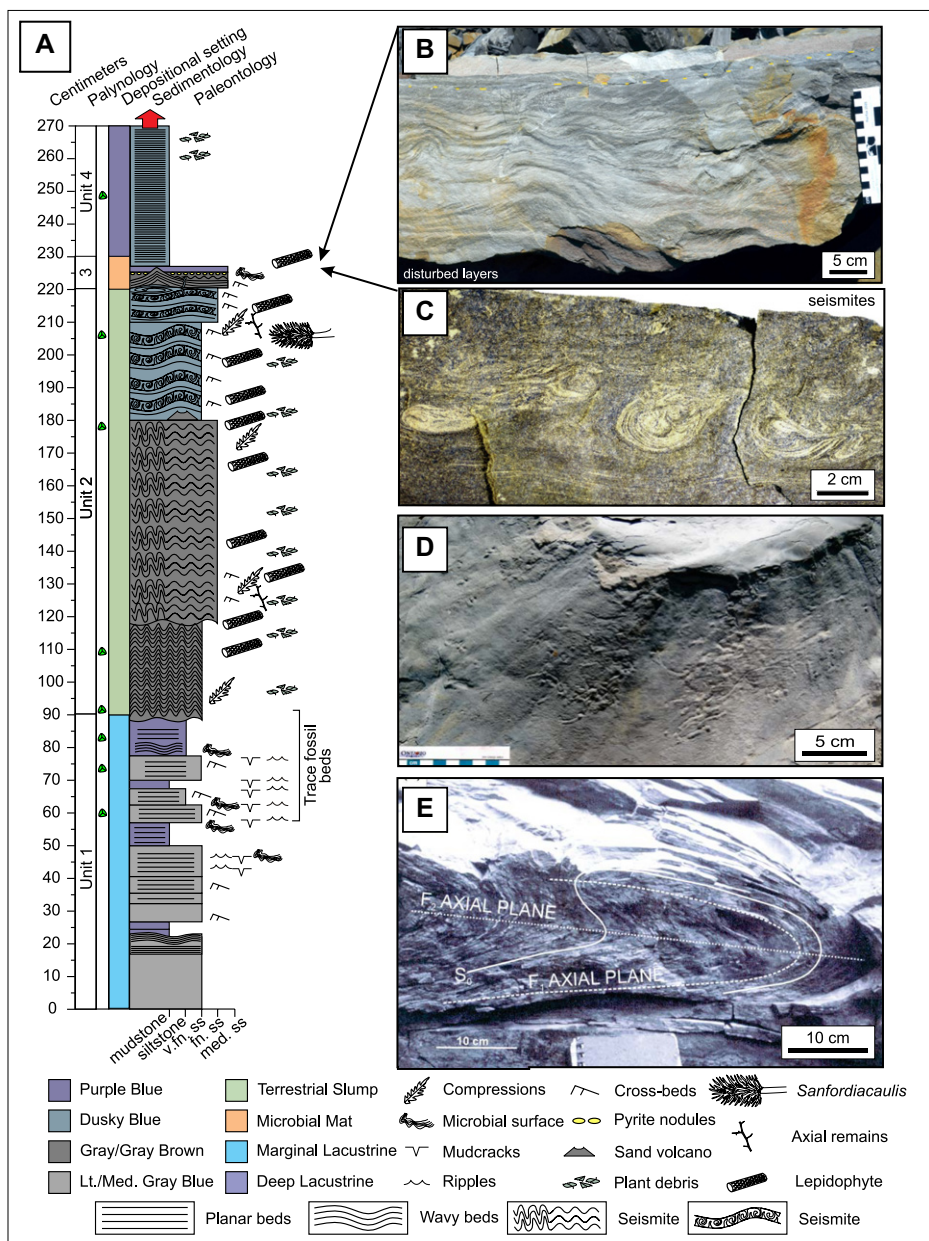


Figure 3. Lithostratigraphy and evidence of seismicity. (A) Composite stratigraphy of quarry succession. (B) Unit 2 soft-sediment liquefaction and deformation structures. (C) Unit 2 seismite ball-and-flame and deformation structures. (D) Surficial trails on margin of sand boil indicating sediment-water interface residency and post-earthquake bioturbation. (E) Deformational folding below sand boils showing sand dikes and slumped horizon with refolded fold. Image from Wilson (2006). v. fn. ss.—very fine sandstone; f. ss.—fine sandstone; med. ss.—medium sandstone.

and mud-filled petioles and the near absence of lateral axes, and photosynthetic laminae exhibit differential decay (Fig. S2). Soft-sediment deformation between articulated leaves displays a swirling pattern, indicating liquefaction as a burial mechanism.

SEISMIC EVIDENCE

The prominent SSD features of the Hiram Brook Member are indicative of seismicity coeval with the emplacement of the marginal lake plants. Convolute-bedding, load-casts, pouches, and ball-and-flame structures (Fig. 3) are ubiqu-

itous, and small sand boils (Fig. S1) occur. In laterally equivalent rocks, 6.6 km away along Highway 1 (Erb Settlement locality; Fig. 1A; N 45.6674694°, W 65.6276806°), unequivocal seismic evidence is exposed at various scales (Wilson, 2006). Here, sand boils are clustered across an upper sandstone contact. Conical sand boils, up to several decimeters, stand in relief and vary in diameter from ~5–40 cm. Individual boils are superposed in at least four events (Figs. 4A and 4B), with surficial grazing trails traversing their sides (Fig. 3E). Underlying beds are refolded and distorted (Figs. 4C and 4D).

DISCUSSION

North American Mississippian rocks are dominated by marine carbonates and siliciclastics, with these concentrated in the Michigan and outlining the Midcontinent basins (Peters et al., 2018). In contrast, non-marine deposits comprise a very small percentage of that record, and Lower Mississippian (Tournaisian and Viséan) deposits, more common in the Maritimes Basin, comprise <6% of surficial and subsurface deposits. Regardless of geography or depositional environment, plant fossils are extremely rare in these rocks. When present, isolated compressions (e.g., Knaus, 1995; Gensel and Pigg, 2010), charcoal (Hu et al., 2024), and palynomorphs (Richardson and Ausich, 2004) occur in coastal plain, deltaic, and nearshore facies. To our knowledge, Canada's Horton Formation preserves the only fully continental succession in which Tournaisian plants are reported (e.g., Falcon-Lang, 2004). The conditions under which *Sanfordiacaulis* was preserved are an anomaly in the stratigraphic record.

Coseismic activity is a factor in the fossilization of upright trees in coastal plain settings (Gastaldo et al., 2004), and this biostratigraphic mode is likely responsible for sites where whole plants (roots, stems, crowns) were transported and preserved in nearshore settings (e.g., Giesen and Berry, 2013). However, Unit 2 is interpreted as a cohesive slump with a copse of trees in a fully terrestrial lacustrine-delta lobe of the Hiram Brook Member (Keighley, 2008). The continental nature of these facies is atypical of Carboniferous coseismic preservation and is the earliest example of this taphonomic mode of whole-tree preservation under which an unexpectedly novel tree from an "upland" or "extrabasinal" (sensu Thomas and Cleal, 2017; i.e., non-basinal-wetland vegetation) has been revealed (Gastaldo et al., 2024).

Seismic evidence, confined mainly to Unit 2, indicates that marginal lake sediments underwent structural collapse, transferring soil, leaf litter, and standing vegetation en masse into a Tournaisian-age rift lake. To date, no roots have been observed, as this horizon of the slump block remains buried. The rapid displacement of subaerial plants, entrained on a translational or rotational sediment raft (e.g., Sudd = islands of trees; Ridley, 1930) and buried by subsequent mass-flow events, allowed for preservation of articulated trees. Trees in outcrop display a preferred orientation, the trunks of which are parallel aligned, indicating the cluster was toppled in life position and remained anchored to a soil as it settled to the sediment-water interface. The capping sandstone retains a seismically induced topography, in which convolute-bedding is extensive, and through which sand boils erupted.

Sand boils (Figs. 4A and 4B), along with refolded folds (Figs. 3D and 4C) in underlying slumped beds, result from liquefaction of satu-

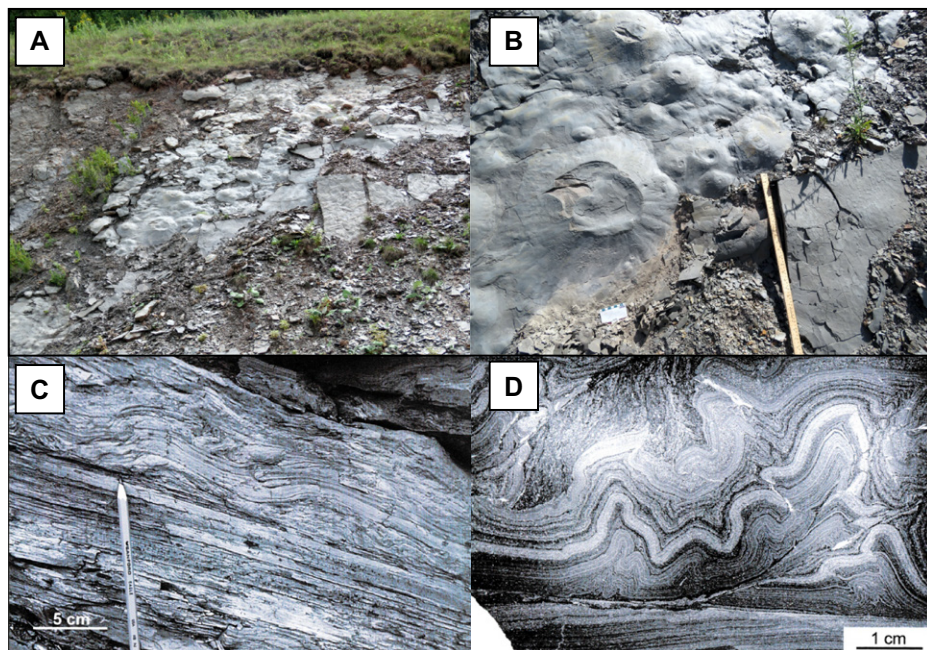


Figure 4. Sand boils and subjacent sedimentary structures. (A, B) Superposed and cross-cutting relationships of sand boils, Erb Settlement locality, indicating contemporaneous seismic events. Scale in cm. (C) Lower detachment surface of high-strain zone in Highway 1 outcrop near the Erb Settlement, 7.5 km SW of Sussex (N 45.679995°, W 65.589527°). (D) Thin section showing the lower contact of a high-strain zone from same outcrop. Images C and D used with permission from Wilson (2006).

rated sand during earthquakes (Montenat et al., 2007). Today, these are visible directly after seismic events with moment magnitudes >6.3 Mw (Reid et al., 2012) and aftershocks as low as 4.3 Mw (Sims and Garvin, 1995). Affected areas can extend for several square kilometers (Greene et al., 1991). The cross-cutting relationships of sand boils along the Erb Settlement outcrop attest to this and indicate episodic earthquake activity during lake sedimentation. Sand boils are covered by a fine-grained clastic drape, the base of which also truncates deformed bedding in the slump as an intraformational unconformity. The upper surfaces of all sand boils preserve bioturbation structures (Fig. 3D), confirming invertebrate activity at the sediment-water interface. Hence, sufficient time elapsed between sand-boil eruption, clastic draping, and for invertebrate colonization.

Although relevant geotechnical properties cannot be measured directly, some can be inferred. Organic-rich mud of the underlying Frederick Brook Member possessed a high water content and smectite (St. Peter and Johnston, 2009), known to lower shear strength. We propose that biogenic methane generated from these carbon-rich sediments also increased pore-water pressures and reduced effective stress, possibly equivalent to pore-water pressure alone (Gillott, 1968). This intrinsic weakness of the organic mud may have led to sediment failure on very shallow gradients, especially if these were shaken by frequent seismic activity. An angle of

repose for these sediments below 3° is plausible (Fig. S3; ASTM, 1985), and dewatering of this sediment via tremors would act to stabilize the lake-bottom accumulation (Bartetzko and Kopf, 2007; Sammartini et al., 2021). Most slumps that originated during this time conform to bedding-parallel slab failures.

Fossiliferous rift-lake deposits are an anomaly in the stratigraphic record. This is particularly true for the Mississippian of North America, where terrestrial deposits are mainly of coastal plain and deltaic origin (Peters et al., 2018). The occurrence of an interior rift-basin setting is even more unusual. Acadian seismicity in the Maritimes likely was as frequent as seen today in East African rift systems. For example, Lake Tanganyika experienced 421 earthquakes >4.5 Mw between 2020 and 2024 (<https://www.usgs.gov/programs/earthquake-hazards/>). There are no reports of either sand boils or cohesive block slumping during this interval; these structures occur infrequently. The probability of such a slump in which rooted, non-woody trees are transferred to the lake bottom and preserved is an even more improbable occurrence. Encountering evidence of this taphonomic phenomenon is even more improbable when considering that the trees are confined to an area of >125 m² in the Sanford Quarry.

CONCLUSIONS

Clear geological evidence of seismicity in a fully continental setting is directly associated

with the wholesale deposition and preservation of intact trees in a Tournaisian rift lake. Earthquake magnitudes were, at a minimum, 4.6 Mw and likely stronger based on a field of sand boils capping the fossiliferous interval. An array of soft-sediment deformational structures—ball-and-flame, load-casts, and convolute-and-contorted bedding—envelop plant fossils that represent not only the forest-floor litter but elements of the forest itself. This is the first example of an extremely improbable, evidenced as probable, event where non-woody intact trees are preserved due to sediment failure of marginal lake sites as a consequence of seismicity.

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