



Figure 1. The 1080 Ma Enchanted Rock Batholith is one of many late-stage, A-type intrusive rocks across the Llano Uplift that stitch together the several rock packages that were metamorphosed during the Grenville Orogeny. Credit: Jmbuytaert via Wikimedia Commons.

Central Texas' Llano Uplift: The Keystone for Reconstructing the Mesoproterozoic through Cambrian History of Southern Laurentia

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The Llano Uplift is an “island” of Mesoproterozoic crystalline rocks (Fig. 1) surrounded by an Early Paleozoic apron standing in Central Texas' vast expanse of Pennsylvanian through Cretaceous sedimentary rocks. Located less than 150 km north of San Antonio and a similar distance west of Austin, the 9000 km² Llano Uplift possesses a geoheritage unique in Texas. It contains an invaluable record of the Grenville Orogeny in southern Laurentia when that continent was surrounded by others,

becoming the center of the global Rodinian supercontinent at 1100 Ma. Researchers debate when plate tectonics began on Earth; the Grenville rocks of the Llano Uplift shed light on that debate. The distinctive isotopic fingerprint of the Uplift's Mesoproterozoic rocks also gives it a starring role in studies that decipher the shifting sediment dispersal patterns as the supercontinent broke up during the Neoproterozoic through Cambrian and the Great Unconformity was created.

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WHEN DID PLATE TECTONICS BEGIN?

When did plate tectonics begin on Earth? Few geoscience questions are as fundamental, and it might seem surprising that even now, 60 years after the plate tectonic revolution, it remains unresolved. But expert interpretations for the onset of plate tectonics span most of Earth history, from the Hadean (4200 Ma; Hopkins et al., 2008) to the Neoproterozoic (850 Ma; Hamilton, 2011; Stern, 2020). The answer to this question clearly has profound implications for our understanding of Earth history, but its import is broader still; it furthers our comprehension of how silicate bodies in our solar system and beyond behave (Palin et al., 2020, and numerous references therein).

Llano rocks were deformed and metamorphosed during a Mesoproterozoic orogenic event that unfolded between ca. 1300–1000 Ma and is known in North America as the Grenville Orogeny. The type area for the Grenville Orogeny lies in eastern Canada. The Llano Uplift stands at the opposite end of the belt and provides the southernmost large exposure of Grenville rocks, making it a key location for deducing what transpired during the orogeny and afterwards (Kyle et al., 2022). Tracts of contemporaneously deformed rocks exist on every continent and together comprise the Global Grenville Orogeny (Stern, 2020). This global orogeny is commonly interpreted, using the lens of plate tectonic theory, as recording a series of continent–continent collisions that sequentially assembled all the continental material then in existence into the global supercontinent Rodinia (e.g., Mosher, 1998; Li et al., 2008). Other workers conclude that the Grenville mountain-building episode differed in fundamental ways from Phanerozoic orogens and was instead the product of a “single-lid” tectonic regime, with Earth enveloped by a continuous lithospheric shell instead of today’s mosaic of tectonic plates (Stern, 2020, and references therein).

Stern (2020) pointed out that single-lid tectonics is the norm for the five tectonically active silicate bodies in our solar system; Venus, Mars, Io, and Europa all possess different forms of single-lid tectonics, with Earth constituting the only exception. He posited that Earth progressed through different phases of single-lid tectonics, and one brief phase of plate tectonics between ca. 2000–1800 Ma, before settling into a protracted single-lid regime in the Mesoproterozoic. This single-lid regime culminated in the Grenville Orogeny before the modern plate tectonic regime was established in the Neoproterozoic.

Stern (2020) compiled a list of positive and negative indicators in support of the Mesoproterozoic single-lid hypothesis. As negative evidence, he claimed that the presence of ophiolites, blueschists/eclogites, and ultra-high pressure (UHP) metamorphic rocks are all clear signs of plate tectonic processes, and he argued that the Mesoproterozoic lacks evidence for any of them. Positive indicators for a single-lid regime are an abundance of Mesoproterozoic A-type granites and anorthosites, an unusually hot Mesoproterozoic lithosphere, and a paucity of passive continental margins at that time. The reasoning is that plate tectonics delivers abundant water to the

mantle, so magmas generated by plate tectonics should be “wetter” than the anhydrous A-type granites and anorthosites that dominate the Mesoproterozoic; plate tectonics cools the planet’s interior more than single-lid tectonics can, so higher geotherms should exist during single-lid episodes; and passive margins form in response to plate tectonic processes but not from single-lid tectonics, so the relative lack of identified Mesoproterozoic passive margins supports the single-lid hypothesis for the Grenville. Articulation of this list makes the hypothesis testable, so the hunt is on to find ophiolites, high pressure–low temperature metamorphic rocks, and low geothermal gradients in rocks of the Global Grenville Orogeny; their discovery would cast doubt on the hypothesis that the Grenville Orogeny was a product of single-lid tectonics instead of plate tectonics.

THE NATURE OF GRENVILLE TECTONISM: CLUES FROM THE LLANO UPLIFT

Given the global distribution of rocks that record the Grenville Orogeny, plenty of locations exist where the plate tectonic versus single-lid hypotheses can be tested. But most other Grenville-aged exposures are superimposed on older orogenic elements and/or have been overprinted by younger orogenic episodes, both of which obscure or complicate their Grenville histories. The Llano Uplift doesn’t suffer from either of these confounding scenarios, making it an especially high-fidelity tracer of Grenville-aged tectonism (Mosher and Gillis, 2025) and thus an ideal location to test the competing hypotheses.

Evidence gathered in the Llano Uplift tests presence versus absence for several of Stern’s (2020) single-lid indicators. The orogen contains multiply deformed Mesoproterozoic metasedimentary, metavolcanic, and metaplutonic rocks that were intruded by late-stage granitic plutons (Mosher et al., 2008). Paleozoic normal faults later segmented the Llano’s Mesoproterozoic rocks into eastern, central, and western regions, which display broadly similar tectonic histories but also possess important differences. The eastern segment possesses three rock packages thrust one atop the next, with the southwesternmost Coal Creek package on top. Coal Creek rocks are older than (1326–1275 Ma compared to 1288–1232 Ma) and geochemically and isotopically distinct from all other Llano Uplift rocks. The eastern segment also possesses the largest serpentinite body known from any Grenville-aged rock sequence. Mosher and colleagues interpreted the Coal Creek rocks as an exotic volcanic arc that was thrust atop the Laurentian continental margin during an arc-continent collision, with the serpentinite interpreted as an ophiolite marking the suture zone (Mosher et al., 2008; Mosher and Gillis, 2025). If that interpretation is correct, then Mesoproterozoic ophiolites do exist after all.

The western segment of the Llano Uplift possesses high-pressure eclogites that reached peak metamorphic conditions of ~775 °C and 2.4 GPa of pressure. Those conditions indicate the rocks reached depths exceeding 70 km and experienced a very low geothermal gradient of only ~10 °C/km (Mosher et al., 2008; Levine and Mosher, 2010). The Llano Uplift thus contains eclogites and documents

the existence of a cool mantle, both attributes whose Mesoproterozoic absence Stern (2020) argued support the single-lid hypothesis. Their presence, along with the ophiolite farther east, supports a plate tectonic rather than single-lid regime for the Grenville Orogeny. After all, low geothermal gradients are typical in Phanerozoic collision zones, where subduction of thick continental lithosphere cools the surrounding mantle. High-pressure rocks are also typically exposed in parts of those collision zones thanks to later uplift and exhumation driven by the buoyancy of the once-subducted continental crust. By contrast, the Llano's voluminous late-stage granitoids (Fig. 1) are all A-type granites (Smith et al., 1997), supporting Stern's (2020) contention that the Mesoproterozoic mantle was comparatively dry.

Viewed as a whole, the Llano Uplift rock assemblage appears to favor the hypothesis that plate tectonics operated during the Mesoproterozoic. In fact, its rock record is strikingly similar to that produced by the Cenozoic plate collision that raised the Alps. Figure 2 illustrates how that record is interpreted through a plate tectonic lens. Southward-directed subduction carried the Laurentian continental margin beneath an exotic island arc (the Coal Creek Domain) at 1150–1120 Ma, followed soon thereafter by collision with a southern continent during assembly of Rodinia (Mosher et al., 2008; Levine and Mosher, 2010). The identity of that southern continent is debated, with the Kalahari Craton (Dalziel et al., 2000) and the Amazon Craton (Tohver et al., 2002; Spencer et al., 2014) being the leading candidates.

SEDIMENT DISPERSAL PATTERNS BEFORE AND AFTER THE GREAT UNCONFORMITY

Although scientists disagree whether the Rodinian supercontinent was assembled by plate tectonic or single-lid processes and where some cratonic pieces fit into the Rodinian puzzle, everyone agrees that the supercontinent existed and that plate tectonics was operating during the Neoproterozoic, when it broke apart. Breakup of Rodinia coincided with formation of the Great Unconformity, which separates Phanerozoic (commonly Cambrian) sedimentary rocks above from Precambrian ones (commonly crystalline basement) below. John Wesley Powell coined the term during his first descent of the Colorado River through Grand Canyon (Powell et al., 1875), but because the boundary is seen globally, the term's geographic usage has expanded accordingly.

The global ubiquity of the Great Unconformity marks it as a singular event in Earth history, so naturally many geoscientists have searched for a global explanation. One prominent idea is that during the Cryogenian (720–635 Ma) Snowball Earth episode, the unconformity was formed by glacial erosion of 3–5 km of rock, resulting in widespread exposure of crystalline basement (e.g., Keller et al., 2019). Others argue that no single event is responsible for development of the global Great Unconformity, which is instead an amalgam of many smaller unconformities that developed during the assembly and breakup of

Rodinia (e.g., Peak et al., 2021). Whatever the cause(s) for its development, geoscientists are keenly interested in tracking the evolution of sediment dispersal patterns through its formation and aftermath. The Llano Uplift plays a prominent role in tracing that evolution across the Laurentian portion of Rodinia (Fig. 3).

Grenville-aged detrital zircons are abundant in Neoproterozoic (1000–541 Ma) and Early Cambrian (541–521 Ma) sandstones across western Laurentia (today's American West). But the supply was abruptly cut off ca. 521 Ma as the Sauk Sea (Sloss, 1963) transgressed across Laurentia throughout the Middle Cambrian (521–497 Ma). So how and why did that sediment dispersal network change?

By pairing Hf-isotope analysis with detrital zircon geochronology, researchers have been able to locate more specifically where in the Grenville Orogen those zircons came from (Fig. 3). That's because Grenville rocks from the Appalachian Mountains possess low $\epsilon_{\text{Hf}}(0)$ zircon values (< -20) and Llano Uplift igneous rocks have high $\epsilon_{\text{Hf}}(0)$ values (> -20). The reason for this difference is that the zircon-producing magmas in the Appalachians incorporated more preexisting Precambrian crust than did the Llano ones (Hantsche et al., 2021).

Rodinia began to break up ca. 780 Ma (Spencer et al., 2014) during the Neoproterozoic's Tonian Period. The abundant Grenville-aged detrital zircons that filled the few western Laurentian Tonian sedimentary basins that still survive possess low $\epsilon_{\text{Hf}}(0)$ values, indicating that the Tonian drainage network headed in the Appalachians, not the Llano Uplift (Fig. 3A; Hantsche et al., 2021). That situation changed in the Cryogenian, with high $\epsilon_{\text{Hf}}(0)$ zircons sourced from the Llano Uplift dominating in sedimentary basins from present-day Colorado to the Grand Canyon, to Death Valley and beyond (Fig. 3B; Hantsche et al., 2021; Holland et al., 2024).

The advent of this new Llano Uplift source of detrital zircons is consistent with (U-Th)/He dating of zircons from Llano Uplift crystalline rocks that documents more than 6 km of Llano exhumation between 800 and 750 Ma (Kyle et al., 2022). A likely reason for that exhumation is that Llano rocks were uplifted and exposed on a rift flank during the breakup of Rodinia. By the Middle Cambrian, the Sauk Sea was well on its way to inundating Laurentia, drowning the Llano rocks and all other sources of Grenville-aged zircons; only a trickle of them reached the extensive sand bodies that accumulated on its shores (Fig. 3C). The exception is in the Llano Uplift itself, where the Hickory Sandstone, the ca. 500 Ma sandstone that unconformably overlies the Uplift's Mesoproterozoic crystalline rocks, is full of Grenville-aged zircons derived from the north, likely in response to gentle flexural uplift of the Transcontinental Arch (Kyle et al., 2022).

One important attribute that distinguishes a place as a valuable geoh heritage site is the significance its rock record has for answering the most profound questions that the

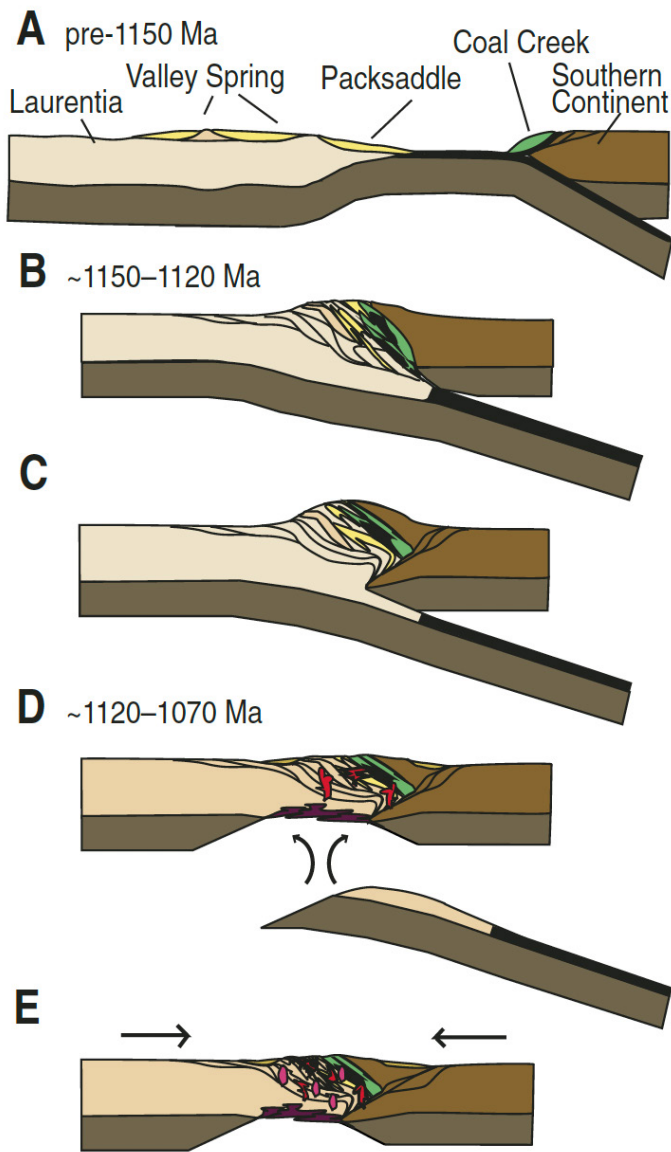


Figure 2. A plate tectonic reconstruction of the events that affected southern Laurentia during the Grenville Orogeny. (A) Southward-directed subduction of Laurentian oceanic lithosphere beneath the Coal Creek volcanic arc and a southern continent began before 1150 Ma. (B) and (C) Arc-continent collision, followed soon thereafter by continent-continent collision thrust the Coal Creek Packsaddle, and Valley Spring domains of the Llano Uplift toward the NE, stacking the Coal Creek atop the pile and the Valley Spring domain at the base. This stacking sandwiched ophiolitic rocks along the suture zone and subjected Laurentian continental crustal rocks to high-pressure metamorphism at depth. (D) Further convergence led to development of a SW-verging retrowedge to form a doubly-vergent orogen similar to that of the Cenozoic Alpine Orogeny. Breakoff of the subducted slab led to lithospheric thinning and intrusion of late-stage granites (red). (E) Uplift caused by the buoyancy of the deeply buried continental crust produced exhumation and erosion that exposed the deepest portions of the orogen on Earth's surface by the Cambrian. From Mosher et al. (2008).

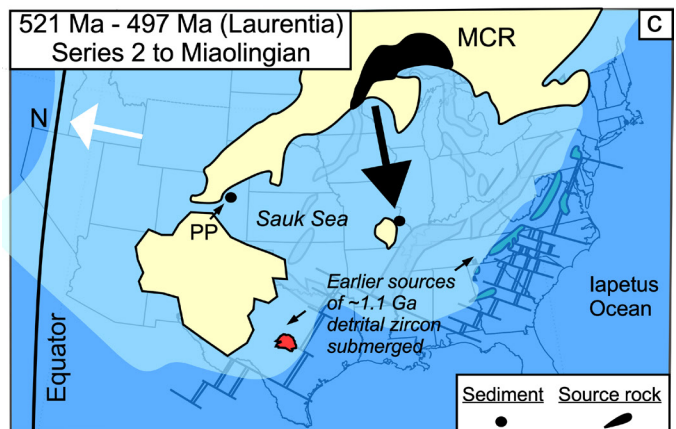
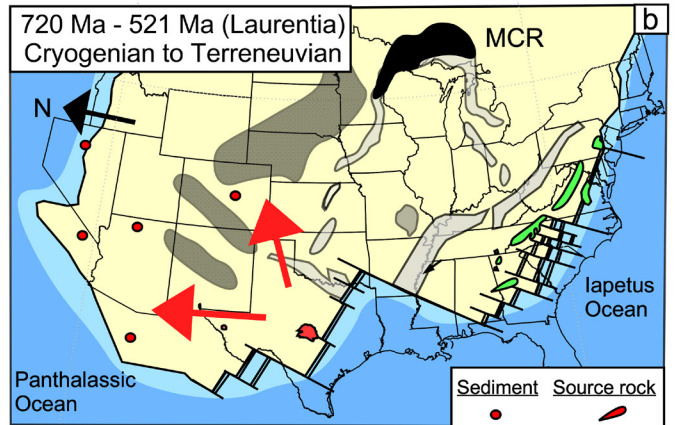
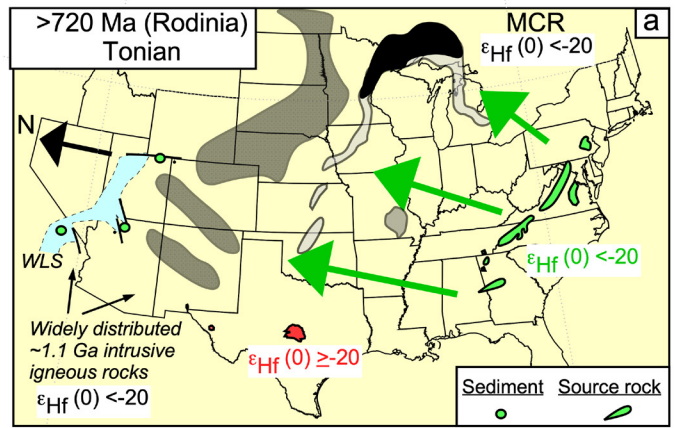


Figure 3. Evolution of the Neoproterozoic through Cambrian sediment dispersal network of southern Laurentia from combined U-Pb dating and $\epsilon_{\text{Hf}}(0)$ -isotopic analysis of detrital zircons. (A) Abundant Grenville-aged zircons possessing low (<-20) $\epsilon_{\text{Hf}}(0)$ isotopic values were shed from the Appalachian Mountains (green arrows) to Tonian-aged depocenters in western Laurentia (green dots). MCR = Mid-continent rift, WLS = Western Laurentian Seaway. (B) The dominant source of Grenville-aged sediment shifted to the Llano Uplift (red arrows) in response to rift-flank uplift there as Rodinia rifted apart between 720 and 521 Ma during the Cryogenian through Early Cambrian (Terreneuvian Epoch), as recorded by detrital zircons in Colorado, the Grand Canyon, Death Valley, and elsewhere (red dots). (C) Transgression of the Sauk Sea in the Middle and Late Cambrian drowned nearly all sources of Grenville-aged detrital zircons, including the Llano Uplift. PP = Pikes Peak Batholith. From Hantsche et al. (2021).

study of Earth history serves up. The Llano Uplift fits the bill; its rocks provide clues that help address such fundamental questions as: When did plate tectonics begin? And how did sediment dispersal patterns change during formation of the Great Unconformity?

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