

Fire and Ice: The Geoheritage of Tasmania's Cradle Mountain–Lake St. Clair National Park

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Tasmania's Cradle Mountain–Lake St. Clair National Park displays rugged alpine scenery carved by Australia's biggest Pleistocene glaciers (Fig. 1). It is an integral part of the much larger Tasmanian Wilderness World Heritage Area—1.5 million hectares of wilderness that contains seven national parks and encompasses 20% of the island state (Fig. 2). Most World Heritage Areas are inscribed because they meet one or two of UNESCO's ten criteria for outstanding universal value; the Tasmanian Wilderness satisfies seven, a tally only one other World Heritage Area can match (Tasmania Parks and Wildlife Service, 2025a). Cradle Mountain–Lake St. Clair National Park was included because of its exceptional natural beauty and its outstanding examples of major stages in Earth's history.

You can immerse yourself in the park's beauty and exquisite geology for days while traversing the 65-km-long Overland Track from Cradle Mountain to Lake St. Clair, which is hailed as one of the world's great walks (Tasmania Parks and Wildlife Service, 2025b). For those with less time or stamina, the mountain's north face, looming over Dove Lake—the Overland Trail's starting point—exemplifies the geologic attributes that justified World Heritage status. The bedrock geology's simple, three-part architecture (Fig. 1) can be appreciated from the Dove Lake parking area or the moderate 6-km walk around the lake. It consists of folded and metamorphosed Precambrian and early Paleozoic sedimentary rocks overlain by nearly flat-lying conglomerate of the Upper Carboniferous–Permian Wynyard Formation, all capped by Jurassic dolerite. Together, these three elements narrate seminal chapters in the history of the Gondwana supercontinent, from its origins in the breakup of Rodinia to the Phanerozoic's largest glacial episode to the massive Karoo–Ferrar Large Igneous Province (LIP), an event that heralded the beginning of the supercontinent's protracted dismemberment.

THE BASEMENT ROCKS: FROM RODINIAN BREAKUP TO GONDWANAN ACCRETION

Tasmania's oldest exposed rocks are Mesoproterozoic (1450–1300 Ma) siliciclastic metasediments. Those are unconformably overlain by a Neoproterozoic (730–640 Ma) sequence that include two diamictites (glacial tills) that resemble the South Australian diamictites constituting the type sections for the Sturtian and Marinoan glacial episodes. That similarity has led researchers to conclude

that Tasmania and South Australia were neighbors already by Cryogenian (720–635 Ma) time (e.g., Calver and Walter, 2000). However, these “Snowball Earth” glacial episodes likely spanned the globe, so similarity in glacial records doesn't require proximity during the Cryogenian. In fact, detrital zircon records of contemporaneous South Australian and Tasmanian sandstones are distinct, with that of Tasmania's Oonah Formation more closely resembling time-equivalent sandstones in East Antarctica and Death Valley, California. That similarity, plus matching carbon isotope records in the overlying Tasmanian and Death Valley dolomites, caused Mulder et al. (2018) to place Tasmania between East Antarctica and western Laurentia (modern North America), far from the rest of modern-day Australia, in their reconstruction of Rodinia.

The volcanoclastic Oonah sediments and a ca. 730 Ma syndepositional dolerite they contain both suggest the basin belongs to a series of rifts that sundered Rodinia, setting the stage for the assembly of Gondwana. The picture that emerges is of Tasmania parting ways with Laurentia just prior to Snowball Earth and only later uniting with Australia.

That picture is reinforced by the characteristics of Tasmania's Middle Cambrian Tyennan Orogeny (515–505 Ma). It is synchronous with the Ross–Delamerian Orogeny, which entailed subduction beneath the 5000-km-long paleo-Pacific margin of the newly formed Gondwana supercontinent, including Tasmania's present-day neighbor South Australia (Bradshaw, 2023). But the Tyennan Orogeny is distinctly different, recording thrusting of an allochthonous Cambrian volcanic arc onto northwestern Tasmania's Proterozoic craton (Mulder et al., 2018). Tasmania appears to be an exotic terrane accreted to the Australian margin at the leading edge of Gondwana during the Middle Cambrian (Cayley, 2011; Bradshaw, 2023).

THE WYNYARD FORMATION: GONDWANA'S LATE PALEOZOIC ICE AGE

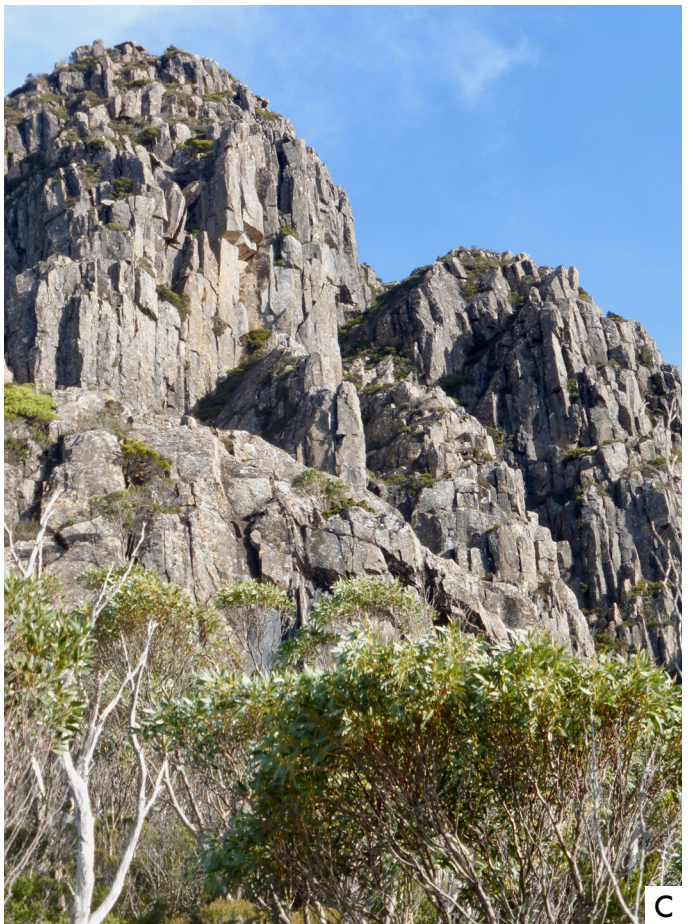
The Precambrian basement rocks that underlie Cradle Mountain were folded during the Tyennan Orogeny and then again in the Middle Devonian Tabberabberan Orogeny. This marked the last folding episode in Tasmania, as the overlying Late Carboniferous Wynyard Formation is nearly horizontal (Fig. 1; Fielding et al., 2010).

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CITATION: Abbott, L.D., 2026, Fire and ice: The geoheritage of Tasmania's Cradle Mountain–Lake St. Clair National Park: *GSA Today*, v. 36, p. 26–30, <https://doi.org/10.1130/GSATG122GH.1>

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Looking south to Cradle Mountain from Dove Lake. The mountain consists of three rock units. Folded Precambrian metasediments (A) underlie Late Carboniferous-Permian Wynyard Formation diamictites (B). Both Cradle Mountain (right) and its sub-peak Little Horn (left) are constructed from a thick sill of Jurassic dolerite (C) carved by Pleistocene glaciers. Photo credit: Lon D. Abbott.

The Wynyard Formation consists of diamictite deposited during the acme of the Late Paleozoic Ice Age (LPIA), the largest glacial episode in the last 600 million years. Peak glaciation occurred during the Late Carboniferous–Early Permian, when the South Pole lay in Antarctica and Tasmania was at ~75–80°S latitude (Henry et al., 2012).

By the late 1800s, geologists recognized that all the southern continents experienced simultaneous LPIA glaciation; Alfred Wegener used this fact in the early 1900s as evidence to support his continental drift hypothesis (Rosa and Isbell, 2021). Early workers thought the Wynyard Formation was deposited as continental moraines, but it is now interpreted as having been deposited on oceanic grounding-line fans that formed just outboard of tidewater glaciers. The Wynyard glacier(s) occupied a 40-km-wide trough in northwest Tasmania (Henry et al., 2012). The edge of that trough is visible at Cradle Mountain, as the Wynyard Formation underlies the Jurassic dolerite at Little Horn, a subsidiary peak, but it pinches out toward Cradle Mountain, leaving dolerite directly overlying folded basement (Fig. 1).

The LPIA had global effects, most notably by causing eustatic sea level to fluctuate on 1–10 m.y. timescales, which triggered cyclic deposition of shallow marine through coal swamp sequences on the vast coastal plains of then-tropical North America and Eurasia. These are the famous cyclothems, which have profoundly influenced human history because they produced the coal that fueled the industrial revolution (Abbott and Cook, 2023).

TASMANIAN DOLERITE: THE FERRAR LIP AND THE BEGINNING OF GONDWANA'S END

Like most of Tasmania’s mountains, Cradle Mountain is capped by polygonal columns of dolerite (Fig. 1), a shallow intrusive equivalent of basalt. More than 30,000 km² of Tasmania is covered by dolerite that injected as sills into the flat-lying Parmeener Supergroup, of which the Wynyard Formation is the lowermost unit (Ware et al., 2023). This is the largest expanse of dolerite on Earth, but it is just a small part of the vast Early Jurassic Karoo-Ferrar Large Igneous Province (LIP), which has an estimated volume of 2.5 million km³ and stretches over 5000 km across Gondwana (Fig. 3), from southern Africa, through Antarctica and Tasmania, to New Zealand and southeastern Australia (Courtillot and Renne, 2003; Ivanov et al., 2017).

The cause of LIP eruptions is debated (Hastie et al., 2014). Furthermore, LIP volcanism commonly precedes continental breakup events (Manu Prasanth et al., 2022), extreme environmental disruptions, and mass extinction events (Courtillot and Renne, 2003; Rampino et al., 2024). These correlations present three fundamental questions about LIPs and their effects on Earth’s climate and lifeforms that analysis of Tasmanian magmatism and its comparison with the eruptive history in southern Africa, then 5000 km away, can shed light on. They are:

1. Are LIPs generated by rising mantle plumes or in response to plate interactions?
2. Do mantle plumes drive continental breakup?
3. Are LIP eruptions the proximal cause of the world’s most extreme environmental disruptions and biggest mass extinction events?

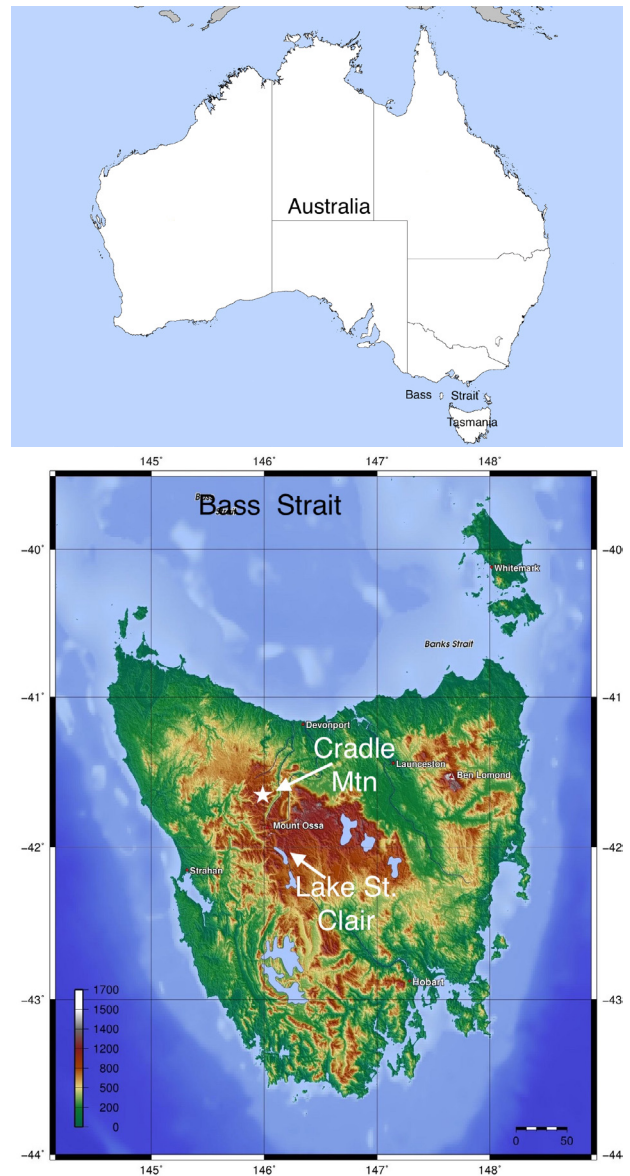


Figure 2. Topographic map of Tasmania, with Cradle Mountain and Lake St. Clair marked. The inset map of Australia shows Tasmania’s separation from the mainland of southeastern Australia by the Bass Strait, which is underlain by continental crust thinned by short-lived rifting during the Cretaceous. Credit: Zamonin via Wikimedia Commons; inset: Diceman-commonswiki via Wikimedia Commons

The unusual length of the Karoo-Ferrar LIP, combined with the fact that it immediately preceded the initial breakup of Gondwana and was broadly contemporaneous with a ca. 183 Ma, two-stage environmental and biotic crisis (Kemp et al., 2024; Abbott and Cook, 2024), makes it an ideal place to probe these questions.

When considering the first question, plume models easily explain the huge LIP eruptive volumes but struggle to explain their geochemical details. No oceanic plumes possess the Karoo-Ferrar low-Ti basalts’ distinctive combination of $\delta^{18}\text{O}$ values indicative of a mantle source and trace element compositions associated with the upper crust (Hergt and Brauns, 2001). Lower mantle plume source areas don’t have a crustal signature, so plume models posit that plume-derived magma was contaminated during its ascent through the

crust. An alternative is that LIPs aren't sourced from plumes but rather from depleted upper mantle that acquired a crustal signature during refertilization by subduction zone-derived fluids. Hergt and Brauns (2001) tested these two hypotheses using Re-Os isochrons for seven Tasmanian dolerites. Osmium is a compatible element that is strongly enriched in the mantle. They reasoned that if rising plume magmas were contaminated during passage through the crust, the Re-Os isochron values of western Tasmanian dolerites should differ from those of eastern dolerites because western Tasmania is a Precambrian craton, whereas eastern Tasmania lacks a cratonic keel. They found no regional isochron differences, so concluded that Tasmanian dolerites are derived from refertilized upper mantle, not a plume.

Ivanov et al. (2017) also rejected the plume hypothesis based on high precision U/Pb geochronology for African, Antarctic, and Tasmanian dolerites. Previous U/Pb and $^{40}\text{Ar}/^{39}\text{Ar}$ dating had suggested that Tasmanian dolerites were several million years younger than the ~183 Ma Karoo rocks, suggesting a Karoo-Ferrar plume might have migrated eastward through time. But previous dating was not sufficiently precise to reach a definitive conclusion. The recent advent of ultra-high precision U/Pb dating of single zircon and baddeleyite crystals using isotope dilution thermal ionization mass spectrometry (ID-TIMS) made it possible to test for time-transgressive LIP behavior. Ivanov et al.'s (2017) ID-TIMS results for Tasmanian dolerites dated their emplacement to 182.90 ± 0.21 Ma. That value is statistically indistinguishable from ID-TIMS dates obtained previously from South African and Antarctic rocks (Svensen et al., 2012; Burgess et al., 2015), indicating magmatism was synchronous across the entire 5000 km length of the Karoo-Ferrar LIP. It also limited the Karoo-Ferrar LIP duration to <1 m.y. For a single plume head to stretch from Africa's Karoo to Tasmania (Fig. 3) in less than 1 m.y., the lateral spreading rate must exceed 5 m/yr, an order of magnitude faster than the 0.5 m/yr rate calculated for "ultrafast" plumes. Ivanov et al. (2017) found such a rate improbable and rejected the plume hypothesis. They argued instead that if the Phoenix Plate, which was subducting beneath Gondwana's Pacific-facing margin during the Jurassic, was subducting faster than ~20 cm/yr, the slab could retain fluids down to the mantle transition zone, where dewatering would produce Karoo-Ferrar melts. So, to them, neither the Karoo-Ferrar LIP nor the rifting of Gondwana were associated with a mantle plume.

Turning to the third question, the clustering of all high-precision U-Pb dates across the LIP from South Africa to Tasmania at 183 Ma strengthened the case that LIP eruptions were synchronous with, and likely triggered, the environmental crisis that began at the Pliensbachian-Toarcian stage boundary (~183 Ma) and was followed a few hundred thousand years later by the Toarcian Oceanic Anoxic Event, an event marked by ocean anoxia, a large negative carbon isotope excursion, 5 °C ocean warming, and enhanced terrestrial chemical weathering (e.g., Kemp et al., 2024). But it didn't confirm synchrony, because now age precision for the LIP was much higher than for the environmental crisis itself. Two studies of especially good Japanese exposures recording the two-stage crisis determined that it is indeed synchronous with Karoo-Ferrar eruption ages, making a causal link stronger still (Ikeda et al., 2018; Kemp et al., 2024).

The ID-TIMS U/Pb zircon ages are not the last word, though, on the duration of Karoo-Ferrar volcanism. The precision of

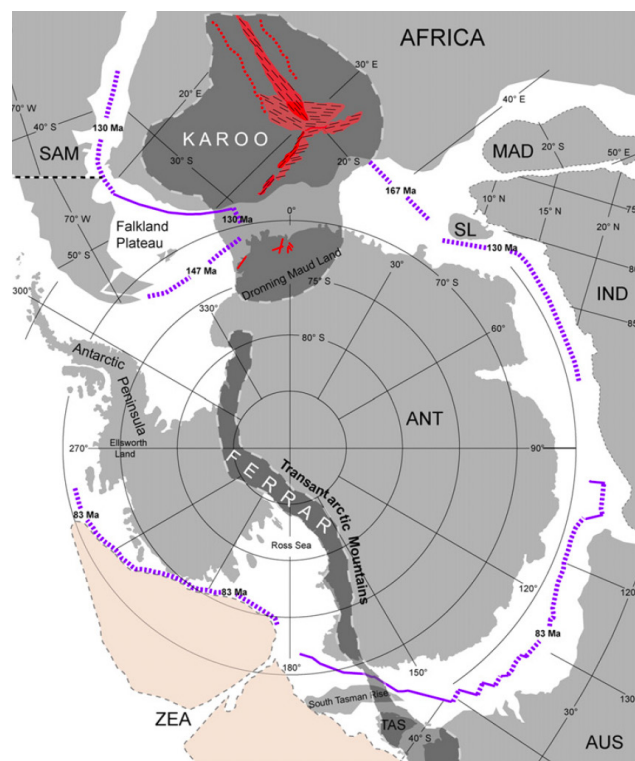


Figure 3. Positions of the continents in southern Gondwana at ~180 Ma. The inferred extent of Karoo-Ferrar LIP magmatism, from southern Africa, through Antarctica to Tasmania and southeastern Australia, is shown in dark gray. Major dike swarms in southern Africa and Antarctica's Dronning Maud Land analyzed by Hastie et al. (2014) are in red. Oceanic rifts that dismembered Gondwana are shown by purple hatched lines with the age of the oldest known seafloor anomalies shown in millions of years. The Weddell Sea opened between Africa and Antarctica at 147 Ma and the first seafloor to separate Western Australia from Antarctica formed at 83 Ma. The solid purple lines are transform faults that were active during Gondwana breakup. ANT = Antarctica, AUS = Australia, IND = India, MAD = Madagascar, SAM = South America, SL = Sri Lanka, TAS = Tasmania, ZEA = Zealandia. From Hastie et al. (2014).

$^{40}\text{Ar}/^{39}\text{Ar}$ dating has improved apace with that for U/Pb of zircon; Ware et al. (2023) reported $^{40}\text{Ar}/^{39}\text{Ar}$ ages on plagioclase from four Tasmanian dolerites that range from 184.27 ± 0.24 to 182.69 ± 0.54 Ma. The plagioclase and zircon ages broadly agree, reinforcing confidence that the Karoo-Ferrar LIP is the proximal cause of the contemporaneous environmental crisis. But the plagioclase dates indicate Tasmanian magmatism lasted 1.6 ± 0.4 My—longer than the duration suggested by zircon dates. Ware and colleagues (2023) argued that the conditions necessary for zircon crystallization were not met in the dolerites' mafic magma chambers until the final cooling stage—thus zircons merely date the end of the magmatic event. In contrast, plagioclase crystallizes throughout the solidification process, making it the most reliable recorder of the magmatic event's duration.

TASMANIA CHOOSES AUSTRALIA: GONDWANA'S FINAL DEMISE

The first cracks in Gondwana began to form between Antarctica and Africa ~167 Ma, soon after eruption of the Karoo-Ferrar LIP, and oceanic crust began to form in the Weddell Sea by 147 Ma (Fig. 3; Hastie et al., 2014). Incipient continental rifting between Antarctica and Australia started then, propagating from west to east, reaching a point just west of Tasmania by the end Jurassic. But by 118 Ma, Australia and Antarctica had only separated by ~180 km (Veevers, 2012).

The rift west of Tasmania went dormant during the Early Cretaceous. Active rifting shifted to the north, thinning the crust beneath the future Bass Strait, which separates Tasmania from the mainland (Fig. 2), until it shut off in the middle Cretaceous. The locus of rifting then returned to the spreading center west of Tasmania, keeping it attached to the Australian plate as slow rifting continued through the Cretaceous and early Cenozoic (O'Sullivan et al., 2000). Tasmania finally parted ways with Antarctica at 34 Ma, when faster spreading produced the final dismemberment of Gondwana (Veevers, 2012).

The combination of Tasmania's comparatively high latitude (42°S) and the 1500 m altitude of its highest peaks produced Australia's largest Pleistocene glaciers. The Central Plateau, home to Cradle Mountain (Fig. 2), was covered by a 7000 km² ice cap ~1 Ma and progressively smaller ice masses formed during six subsequent glaciations, culminating in 1085 km² of ice cover during the Last Glacial Maximum (LGM) at 20 ka (Colhoun et al., 2011).

During the LGM, Cradle Mountain's north face glacier terminated at Dove Lake and the Derwent glacier terminated at Lake St. Clair. These and other LGM glaciers carved the final scenic flourishes into a landscape shaped by repeated episodes of fire and ice that spanned Gondwana's long history, resulting in geologic scenery worthy of World Heritage recognition.

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