A Positive Test of East Antarctica–Laurentia Juxtaposition Within the Rodinia Supercontinent

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The positions of Laurentia and other landmasses in the Precambrian supercontinent of Rodinia are controversial. Although geological and isotopic data support an East Antarctic fit with western Laurentia, alternative reconstructions favor the juxtaposition of Australia, Siberia, or South China. New geologic, age, and isotopic data provide a positive test of the juxtaposition with East Antarctica: Neodymium isotopes of Neoproterozoic rift-margin strata are similar; hafnium isotopes of ~1.4-billion-year-old Antarctic-margin detrital zircons match those in Laurentian granites of similar age; and a glacial clast of A-type granite has a uraniun-lead zircon age of ~1440 million years, an epsilon-hafnium initial value of +7, and an epsilon-neodymium initial value of +4. These tracers indicate the presence of granites in East Antarctica having the same age, geochemical properties, and isotopic signatures as the distinctive granites in Laurentia.

The supercontinent Rodinia is thought to have existed about 1 billion years ago (Ga) (*1–3*). Its breakup formed the nucleus of supercontinents that existed during the Phanerozoic and thus represents the starting point for understanding their subsequent evolution. The breakup of Rodinia also coincided generally with primary changes in seawater composition, the emergence of macroscopic biota, and the occurrence of Proterozoic glacial cycles, reflecting important linkages between geological and biological evolution. Reconstruction of Rodinia's pre-breakup paleogeography has been controversial because sea-floor spreading data are lacking before the Jurassic, and continental paleomagnetic data become increasingly fragmentary and are subject to overprinting with older age.

Laurentia has a central position in nearly all Rodinia reconstructions because it is surrounded by >14,000 km of late Precambrian rifted margin. What conjugate piece rifted from Laurentia's western (present coordinates) margin has long been debated, and proposed links include Australia, Siberia, South China, and Tasmania (*4*). One of the most prominent models, the southwest United States–East Antarctica (SWEAT) hypothesis, postulates a connection between the southwestern U.S. (Laurentia) and East Antarctica based on correlation of Neoproterozoic rift-margin stratigraphy, continuation of Paleoproterozoic provinces (Yavapai-Mazatzal), and extrapolation of Mesoproterozoic foldbelts (Grenville Orogen) (*1–3*). SWEAT fell into disfavor because (i) Grenville-age basement is globally widespread, making Grenville Orogen correlations nonunique; (ii) basement provinces are discontinuous (*4*); and (iii) paleomagnetic data are lacking for many Rodinia fragments, including East Antarctica, during the time period of assembly and breakup. Reconstructions using paleomagnetic data, for example, place East Antarctica either next to, or distant from, the southwestern margin of Laurentia (*5*). Although some paleomagnetic data allow a fit between Laurentia and a composite Austral-East Antarctica during the period from ~1050 to 720 million years ago (Ma) (*6–9*), other data appear contradictory (*10*) and additional paleopoles of appropriate age and geologic setting are needed to resolve existing disparities. Thus, although it is generally agreed that Rodinia was assembled between about 1.3 and 0.9 Ga, uncertainty remains about its paleogeography in general, and specifically about its western Laurentian conjugate margin.

As a test of the SWEAT model, we provide geological, geochronological, and isotopic data from Antarctica that address a key piece in the Rodinia puzzle. One of the most distinctive elements of Laurentian crust is a belt of ~1.4-billion-year-old rapakivi granites that extends from the Fennoscandian shield in Baltica across Laurentia to the southwestern U.S. If the SWEAT model for Rodinia is correct, traces of this belt, as well as Archean and Paleoproterozoic crust that hosts it, should be evident in East Antarctica. Indeed, isotopic data from the Transantarctic Mountains (TAM) suggest that crustal provinces in Antarctica are similar in age and character to those in western Laurentia (*11*). Here we present detrital-zircon Hf isotope compositions and Nd isotope data from rift-margin strata, and age and isotopic data from a rapakivi granite boulder in Pleistocene moraine, which demonstrate that these distinctive Laurentian basement belts extend into Antarctica.

Upper Neoproterozoic to Lower Cambrian (~670 to 520 Ma) siliciclastic rift- and passive-margin strata in the central TAM (Fig. 1A) contain up to 22% detrital zircon ~1.4 billion years old (*12*). The detrital zircons have an age profile similar to that of A-type Mesoproterozoic granites in Laurentia (Fig. 1B) (*13*, *14*). However, this detritus cannot have a direct source in Laurentia, because by the time of Gondwanaland amalgamation in the Early Cambrian, any fragment of Rodinia juxtaposed with present-day western Laurentia must have drifted away (*6*), and because the sediment was transported outboard from the interior of East Antarctica (*15*). Therefore, the persistent signature of this distinctive ~1.4-billion-year-old detritus in autochthonous units of Antarctica indicates that the central East Antarctic shield must contain an igneous geologic province of this age.

To provide additional constraints, we analyzed the Hf isotope compositions of the ~1.4-billion-year-old Antarctic detrital zircons. Their initial epsilon-Hf (ε_{Hf}, the deviation from chondrite uniform reservoir evolution) values of –2 to +7 (table S1) closely match those from Laurentian A-type granites (Fig. 1C) (*14*). The Hf isotope compositions correspond to depleted-mantle model (or crustal extraction) ages of ~2.0 to 1.6 Ga. Crust of this type is not known from present rock exposures in Antarctica, but is well represented in the Proterozoic orogenic provinces of southwestern Laurentia (Penokean, Yavapai, and Mazatzal). Together, these detrital-zircon age and isotopic data indicate that rift-margin sediment deposited on the paleo-Pacific margin of East Antarctica had a crustal provenance of similar age and isotopic character as that known from Laurentia. Because the isotopic compositions of both the Laurentian granites and the Antarctic detrital zircons cluster tightly, it is difficult to determine which type, if any, of the Laurentian provinces best represents the source of Antarctic detrital zircons; however, many of the detrital zircons have Hf isotope compositions that overlap with those from granites intruding the Yavapai province. Thus, an extension of the Proterozoic belts in Laurentia, including 1.4-billion-year-old igneous rocks and their host terrains, probably exists as a crustal province in central East Antarctica. This interpretation is also consistent with the co-occurrence of ~1.8- to 1.6-billion-year-old zircons in the detrital populations.

We also compared the Nd isotope compositions of the Antarctic rift-margin strata with coeval successions in western Laurentia. Nd isotopes in Proterozoic (~1.1 to 0.6 Ga) strata of western Laurentia show that provenance varies substantially with age and location (*16*). Not surprisingly, sediments deposited in close proximity to the Wyoming craton contain large proportions of material derived from Archean crust. In the southwestern United States and northern Mexico, in contrast, such deposits were derived predomi-

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nantly from Paleoproterozoic crust, with variable proportions of material derived from Mojave versus Yavapai-Mazatzal provinces. Overall, sediment transport across this part of western Laurentia was dominantly east to west (present coordinates). Thus, the sedimentary provenance was almost exclusively within ~2.0- to 1.6-billion-year-old crust, presumably reflecting the fact that Paleoproterozoic rocks were the dominant exposed source material for ≥2000 km inboard from the western continental margin. Neoproterozoic (≥0.6 Ga) rift-margin siliciclastic rocks in the central TAM have ε_{Nd} = –16 to –20 (Fig. 1D and table S2), overlapping with sedimentary rocks of similar age and depositional setting along the southwestern margin of Laurentia. Therefore, although the sources for these autochthonous Antarctic and Laurentian rift-margin successions lie within their respective cratons, they were derived from isotopically equivalent Paleoproterozoic crust.

We also collected large clasts and matrix material from heterolithic Pleistocene moraines in the central TAM. One 24-cm granitoid clast (sample TNQ) is a coarse-grained, red, porphyritic, rapakivi-type muscovite-biotite granite with a weak foliation (Fig. 2A). This small boulder

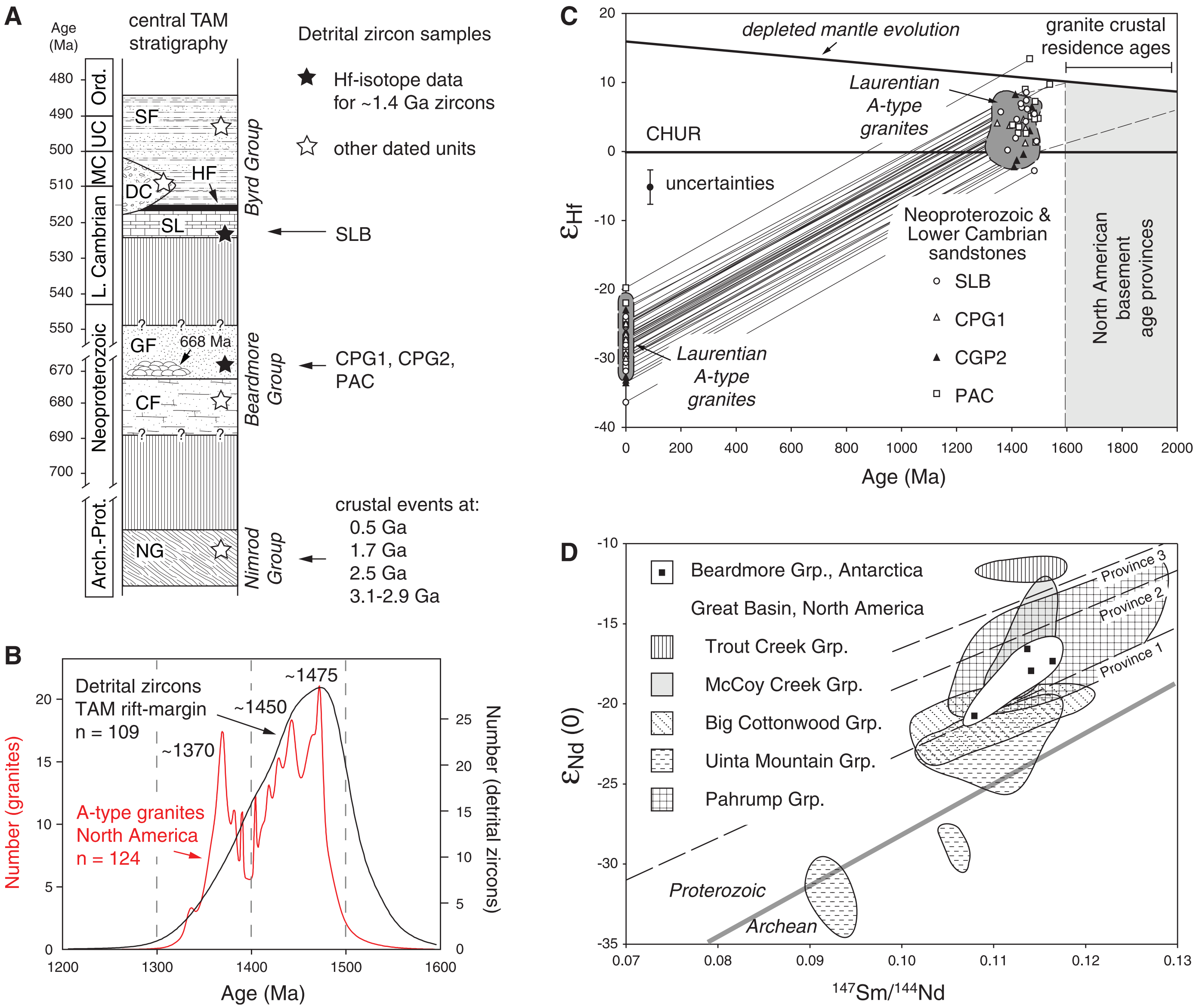

Fig. 1. Key features of Neoproterozoic and Lower Cambrian siliciclastic rocks from the central TAM margin of Antarctica. (**A**) Simplified stratigraphy of pre-Devonian sedimentary rocks overlying cratonic basement (Nimrod Group) in the Nimrod Glacier area (*15*). Stars indicate strata for which detrital-zircon age populations are known (*12*) and for which Hf isotope compositions were determined in ~1.4-billion-year-old detrital zircons (black stars). Formations are as follows: CF, Cobham; DC, Douglas Conglomerate; GF, Goldie; HF, Holyoake; NG, Nimrod Group (undivided); SF, Starshot; SL, Shackleton Limestone. SLB, CPG, and PAC are sample numbers. (**B**) Relative probability distribution of zircon U-Pb ages from Laurentian A-type granites [red (*14*)] and total detrital-zircon populations aged between ~1300 and 1600 Ma in Neoproterozoic to Lower Cambrian rift-margin sedimentary rocks in the central TAM [black (*12*)]. Curves are scaled to same height for comparison only; the smoothness of the detrital-zircon profile results from greater individual age uncertainty. (**C**) Age versus ε_{Hf} for detrital zircons from Antarctic rift-margin sedimentary rocks (table S1) and Laurentian granites [gray field (*14*)]. Uncertainties associated with individual detrital-zircon Hf isotope compositions are shown by an error bar (about ±2 ε_{Hf} units of total uncertainty for the laser-ablation inductively coupled plasma mass spectrometer method). CHUR, chondrite uniform reservoir. (**D**) Whole-rock ε_{Nd} versus $^{147}Sm/^{144}Nd$ isochron plot for Antarctic rift-margin siliciclastic rocks (table S2) compared to Neoproterozoic rift-margin successions in the Great Basin area of western North America (*16*). The gray line divides Archean from Proterozoic crustal sources; thin black lines are isochrons corresponding to different Laurentian basement provinces.

was glacially transported from the direction of the present-day polar ice cap and was collected near the upper Nimrod Glacier. This rock has high values of Zr (440 ppm), Y (90 ppm), Nb (23 ppm), Ce (180 ppm), and $K_2O + Na_2O$ [8.85 weight % (wt %)] (table S3), similar to A-type within-plate granites (*17*), including the Mesoproterozoic Laurentian suite (*13*, *18*). TNQ is strongly peraluminous (molar $Al_2O_3/(CaO + Na_2O + K_2O) = 1.01$), has a high Fe/(Fe + Mg) ratio of 0.83, and shows incompatible trace-element compositions overlapping those of 1.4-billion-year-old two-mica granites

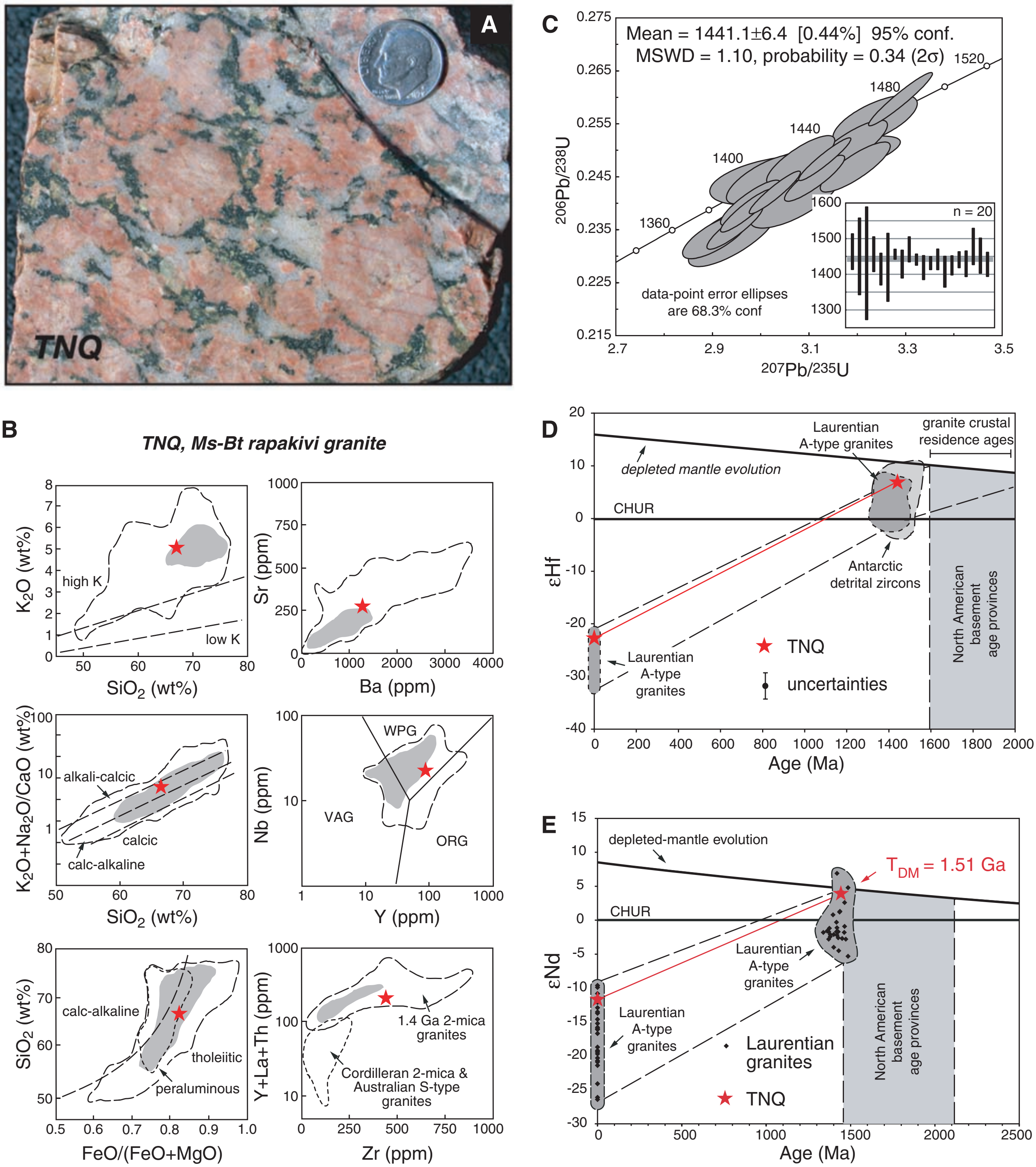

Fig. 2. Characteristics of granite boulder TNQ from a glacial moraine in the upper Nimrod Glacier area, Antarctica. (**A**) Photograph of cut slab, showing porphyritic rapakivi texture. (**B**) Geochemical characteristics of sample TNQ [red star (table S3)] compared to compositions of 1.4-billion-year-old granites in Laurentia (*18*); a dashed line bounds all analyses, and gray shading shows the densest data distribution. Ms-Bt, muscovite-biotite; ppm, parts per million. Fields for within-plate (WPG), volcanic-arc (VAG), and ocean-ridge (ORG) granites are shown. (**C**) Zircon U-Pb concordia diagram for sample TNQ (table S4). The inset shows individual SHRIMP ages included in the weighted-mean age calculation (all 20 analyses are included). MSWD, mean square of weighted deviates. (**D**) ε_{Hf} versus age for zircons in TNQ (determined by multicollector inductively coupled plasma mass spectrometry, table S5) compared to Laurentian 1.4-billion-year-old granites (dark gray field) and detrital zircons from Antarctic-margin rift sediments (light gray field; Fig. 1C). (**E**) Whole-rock ε_{Nd} versus age for TNQ (determined by thermal ionization mass spectrometry, table S6) compared to Laurentian 1.4-billion-year-old granites (*19*–*22*).

in southwestern Laurentia (Fig. 2B). Zircons from this granite are prismatic and clear, with broad growth bands observable in cathodoluminescence and no visible inherited cores, which is consistent with an origin from high-temperature Fe-rich melts (*13*). Its sensitive high-resolution ion microprobe (SHRIMP) U-Pb zircon age is 1441 ± 6 Ma (Fig. 2C and table S4). Zircons from TNQ have an average ε_{Hf} initial [$\varepsilon_{Hf(i)}$] value of +7.1 (Fig. 2D and table S5), which matches those of Laurentian A-type granites, particularly those of the central Yavapai province (*14*). TNQ has an $\varepsilon_{Nd(i)}$ value of +3.9 (Fig. 2E and table S6), yielding a depleted-mantle model age of 1.51 Ga, which corresponds to values reported for ~1.4-billion-year-old Laurentian granites (*19*–*22*). Sample TNQ thus demonstrates that the ice-covered East Antarctic shield near its paleo-

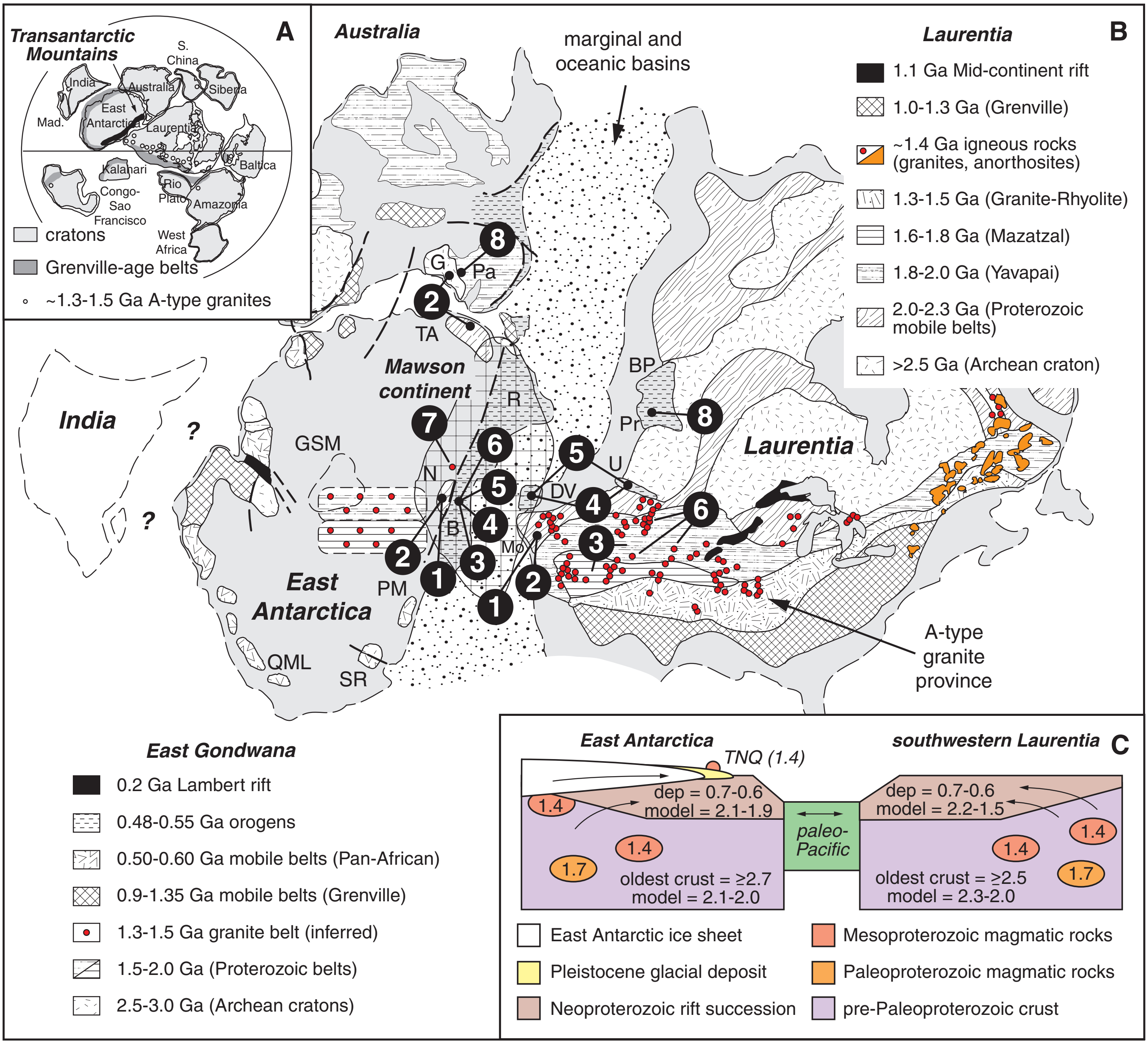

Fig. 3. Proposed paleogeographic relations of Laurentia and East Antarctica. (**A**) General Rodinia reconstruction at ~800 to 750 Ma consistent with SWEAT (*1*–*3*, *40*). Mesoproterozoic orogenic belts (dark gray) are thought to be associated with Rodinia assembly. The TAM margin of East Antarctica is shown in black. (**B**) Paleogeographic reconstruction of central Rodinia, emphasizing the postulated fit of East Antarctica–Australia and western Laurentia before rift separation, based on geologic, age, and isotopic correlations discussed in the text: 1, Nd isotope basement model ages; 2, ~1.7-Ga orogenesis and magmatism; 3, 1.8- to 1.4-Ga detrital-zircon provenance; 4, Nd isotope signature in rift-margin sediment; 5, ~0.7-Ga rift-margin sedimentation; 6, ~1.4-Ga Laurentian Hf isotope signature; 7, glacial clast of ~1.4-billion-year-old rapakivi A-type granite; 8, sediment with Gawler age and Hf signature. Also shown are Neoproterozoic and Lower Cambrian marginal-basin deposits (stippled) and the postulated extension of Proterozoic Laurentian crustal provinces into the East Antarctic shield (shown as patterned rectangles with round corners), including the ~1.4-Ga trans-Laurentian igneous province (small red circles). Crustal elements in present-day India, southern Africa, and Queen Maud Land that were assembled during Pan-African growth of Gondwana are of uncertain position in Rodinia (*40*, *41*). B, Beardmore Group; BP, Belt-Purcell basin; DV, Death Valley; G, Gawler Range; GSM, Gamburtsev Subglacial Mountains; Mo, Mojave Province; N, Nimrod Group; Pa, Pandurra Formation; PM, Pensacola Mountains; Pr, Prichard Formation; R, Ross Orogen; SR, Shackleton Range; TA, Terre Adélie; U, Uinta Mountains. (**C**) Schematic diagram showing common crustal features of the Antarctic and Laurentian margins. Numbers refer to crustal or magmatic ages (in billions of years).

Pacific margin contains Mesoproterozoic igneous crust, which further explains the large populations of detrital zircons of this age in Neoproterozoic craton-margin strata. Its age, geochemical composition, and isotopic signature indicate not only that it is the same age as the A-type granite province in Laurentia, but that it has a crustal source identical to that of the Proterozoic provinces of Laurentia. This clast thus represents a piece of rock in Antarctica with demonstrable ties to Laurentia.

Although there are as yet no known and exposed ~1.4-billion-year-old igneous bodies in East Antarctica, the high proportions of detrital zircons of this age, coupled with the discovery of a distinctive glacial clast that matches all known characteristics of the Laurentian A-type magmatic suite, suggest that a Mesoproterozoic igneous belt is present in Antarctica beneath the East Antarctic ice sheet. We fit this East Antarctic igneous source to the end of the Laurentian magmatic belt (Fig. 3).

In addition to results presented here, additional lines of evidence support a Laurentia–East Antarctic fit (Fig. 3B). Crustal-age provinces defined by Nd isotopes in East Antarctica (*11*, *23*) are similar to those in southwestern Laurentia (*20*, *24*). Proterozoic Nd-model ages from granites in the TAM are like those of known crustal provinces of southwestern Laurentia at 2.1 to 2.0, 1.9 to 1.6, and 1.2 to 1.1 Ga. Model ages of 1.45 to 1.38 Ga in the central and southern TAM (*11*) indicate the presence of Mesoproterozoic crustal sources in basement that is hidden beneath the East Antarctic ice cap. These signatures, and exposed crustal rocks having U-Pb and Nd-model ages of 3.1 to 2.7 Ga (*23*, *25*, *26*), resemble the pattern in Laurentia of Archean crust (Wyoming province) juxtaposed with Proterozoic accretionary belts (*27*). Second, granulite-facies gneiss, Caledonian-type eclogites, and intermediate-composition granitoids in the central TAM record lower-crustal metamorphism and magmatism between 1730 and 1720 Ma (*26*). Paleoproterozoic orogenesis is contemporaneous with magmatic and metamorphic events elsewhere in present-day Antarctica (*28*) and Australia (*29*) that straddle the future rift margin. The ~1.7-billion-year-old activity in East Antarctica and southern Australia reflects a phase of continental assembly that is coeval with prolific crustal growth, accretion, and reactivation in Laurentia (*30*). Both East Antarctica and southwestern Laurentia contain older parent rocks (3.0 to 2.0 Ga) that were modified substantially by events ~1.7 Ga. Third, the Antarctic-margin siliciclastic rocks noted above contain large populations of ~1.8- to 1.6-billion-year-old detrital zircons, in addition to lesser Mesoproterozoic (1.2 to 0.9 Ga) and Archean contributions (*12*). These detrital-mineral age signatures indicate that Paleoproterozoic igneous and/or metamorphic rocks are a substantial crustal component within the composite East Antarctic shield, similar to southwestern Laurentia. Notably, the ~1.8- to 1.6-billion-year-old detrital populations overlap the age of magmatic crustal growth in the Yavapai and Mazatzal provinces of Laurentia (*30*). Last, siliciclastic rocks in the central TAM contain 668-million-year-old intercalated pillow basalts and gabbros (Fig. 1A), constraining the time of rift-margin sedimentation before Early Cambrian platform development (*31*). In western Laurentia, thermal subsidence analysis indicates that the transition from rift to drift sedimentation occurred at a similar time (*32*), reflecting passive margin growth by ~625 Ma. Earlier on this margin, 689- to 667-million-year-old volcanic rocks within widespread Neoproterozoic successions date the time of rift-margin extension, sedimentation, and glacial activity (*33*, *34*). Thus, the continental rift margins in East Antarctica and western Laurentia developed synchronously after ~700 Ma. It follows that the principal breakup of Rodinia did not take place between 800 and 750 Ma, but rather was initiated between ~720 and 660 Ma (*32*, *35*, *36*).

Our reconstruction of central Rodinia (Fig. 3B) connects southwest Laurentia and central East Antarctica as in the SWEAT configuration. It is based on similarities in crustal isotopic signatures, ages of basement igneous and metamorphic events, the age and isotopic character of rift-margin sedimentary successions, sedimentary provenance tracers, and the matching of modern glacial clasts to distinctive igneous sources. Specifically, we suggest that the hallmark Proterozoic provinces of southwestern Laurentia (Mojave, Yavapai, Mazatzal, and the ~1.4-billion-year-old granite belt they host) extend into central East Antarctica. A criticism of the SWEAT model, and our modification to it, is that alleged allochthonous crustal blocks in the TAM preclude geological correlation from the East Antarctic margin (*4*). However, these units, once thought to be Neoproterozoic accreted terranes (*23*), are now recognized as autochthonous Cambro-Ordovician molasse deposits that postdate Rodinia breakup (*12*, *15*, *31*). Thus, the rift-margin deposits we have discussed do not contradict the SWEAT model; rather, their provenance characteristics reinforce it.

Together, these independent lines of geologic, age, and isotopic evidence provide a positive test of the Rodinian connection between East Antarctica and southwest Laurentia (Fig. 3C). These two areas share similar crustal, rift-margin, and sedimentary histories, including Archean crustal growth, Paleoproterozoic magmatic and metamorphic events, Mesoproterozoic magmatism, and late Neoproterozoic craton-margin sedimentation. They also share distinctive isotopic signatures, including crustal model ages, sediment model ages, and isotopic values of ~1.4-billion-year-old igneous detritus, indicating that part of the East Antarctic shield is composed of a Paleoproterozoic terrain punctuated by geochemically and temporally distinctive ~1.4-billion-year-old A-type rapakivi granites. Although Rodinia reconstructions are difficult to prove, any robust model of global Neoproterozoic paleogeography must explain the close geological, age, and isotopic ties between East Antarctica and western Laurentia. Various alternative paleogeographic configurations have been suggested, but the SWEAT model most successfully identifies the former conjugate margin to western Laurentia.

Our configuration also explains relations between Laurentia and Australia. For example, the Mesoproterozoic Belt–Purcell basin of Laurentia contains detrital zircons with ages of 1610 to 1490 Ma, including a ~1590-million-year-old population that is unknown from Laurentia and inferred to have a western source (*37*, *38*). As shown in Fig. 3B, these rocks are now adjoined to redbeds of the Pandurra Formation in South Australia, which have detrital zircons with ages of 1595 to 1585 Ma as well as overlapping Hf isotope signatures (*39*). It appears that the Pandurra and Belt successions represent proximal and distal deposits, respectively, that share a common western source in a Mesoproterozoic igneous terrain of present-day South Australia.

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Anticrack Nucleation as Triggering Mechanism for Snow Slab Avalanches

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Snow slab avalanches are believed to begin by the gravity-driven shear failure of weak layers in stratified snow. The critical crack length for shear crack propagation along such layers should increase without bound as the slope decreases. However, recent experiments show that the critical length of artificially introduced cracks remains constant or, if anything, slightly decreases with decreasing slope. This surprising observation can be understood in terms of volumetric collapse of the weak layer during failure, resulting in the formation and propagation of mixed-mode anticracks, which are driven simultaneously by slope-parallel and slope-normal components of gravity. Such fractures may propagate even if crack-face friction impedes downhill sliding of the snowpack, indicating a scenario in which two separate conditions have to be met for slab avalanche release.

Dry snow avalanches occur in two fundamentally different modes. Loose snow avalanches fan out from one point, entraining granules of snow of low cohesion by collisions. Slab avalanches originate from the extended failure of a weak subsurface layer in cohesive snow and release a large volume of the overlying snowpack (the slab) at once (Fig. 1). An apparently different type of snow instability is a sudden settling, which may occur even on horizontal terrain and may spread over large areas, often producing an audible "whumpf" sound (*1*–*3*). In practice, such whumpfs are considered clear warning signs of high avalanche hazard (*4*).

Snow is one of the most brittle materials (*5*), and the established view is that slab avalanches release by propagation of shear cracks along the weak layer (*6*, *7*). According to this viewpoint, the crack driving force is provided by the slope-parallel component of gravity. Hence, the critical crack size r_c should increase with decreasing slope angle, and fracture propagation should be impossible on flat or weakly inclined terrain. This prediction is in sharp contrast with recent experimental findings in which weak layers were artificially notched (*8*, *9*). In these experiments, critical lengths for fracture propagation, typically of a few decimeters, were found to remain constant or slightly increase with slope angle between 0° and 40° (*9*).

This discrepancy can be resolved by considering the propagation of mixed-mode anticracks that are driven by both shear and nonshear (compressive) components of the gravitational force. A mode I anticrack is a fracture mode in which the displacement field is equal in magnitude but opposite in sign to that of a classical mode I crack (*10*). In standard materials, this is not physically possible because of material interpenetration. Therefore, anticracks require loss of cohesion to be accompanied by a reduction in specific volume, clearing the space for inward displacement of the crack faces. The concept was originally introduced to characterize localized dissolution of limestone on closed, subplanar, cracklike structures (*10*), superheated ice (*11*), and in the context of earthquakes occurring under high pressure in deep subduction zones (*12*). The concept has natural applications in the analysis of failure processes in loosely packed cohesive granular materials, such as the self-sustaining progression of porosity collapse in granular sandstone under compressive tectonic loading (*13*). In snow, weak layers often have strongly anisotropic microstructures, the collapse of which may lead to a substantial reduction in specific volume (Fig. 2). It is therefore natural to apply the anticrack concept to weak-layer failure in slab avalanche release. Because the loading on a slope is not purely compressive but has important shear components, we speak of mixed-mode (mode I/II) anticracks.

We envisage a three-layer configuration consisting of a rigid collapsible layer embedded be-

Fig. 1. Crown face of a slab avalanche of exceptional size observed at Glacier du Vallonnet, France, 4 April 2007. The avalanche triggered spontaneously during precipitation. The thickness of the released slab exceeded 2 m. [Reprinted with permission of www.data-avalanche.org and A. Duclos (photo)]

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