

# Enigmatic boulder trains, supraglacial rock avalanches, and the origin of “Darwin’s boulders,” Tierra del Fuego

**Edward B. Evenson**, Dept. of Earth and Environmental Sciences, Lehigh University, Bethlehem, Pennsylvania 18015, USA; **Patrick A. Burkhardt\***, Dept. of Geography, Geology, and the Environment, Slippery Rock University, Slippery Rock, Pennsylvania 16057, USA; **John C. Gosse**, Dept. of Earth Sciences, Dalhousie University, Halifax, Nova Scotia B3H 4J1, Canada; **Gregory S. Baker**, Dept. of Earth and Planetary Sciences, University of Tennessee, Knoxville, Tennessee 37996, USA; **Dan Jackofsky**, Esso Australia, Victoria 3006, Australia; **Andres Meglioli**, Environmental Resources Management, 6455 South Yosemite Street, Suite 900, Greenwood Village, Colorado 80111, USA; **Ian Dalziel**, Institute for Geophysics, Jackson School of Geosciences, University of Texas, Austin, Texas 78713, USA; **Stefan Kraus**, Instituto Antartico Chileno, Punta Arenas, Chile; **Richard B. Alley**, Dept. of Geosciences, Pennsylvania State University, University Park, Pennsylvania 16802, USA; **Claudio Berti**, Dept. of Earth and Environmental Sciences, Lehigh University, Bethlehem, Pennsylvania 18015, USA

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## ABSTRACT

Charles Darwin considered himself to be a geologist and published extensively on many geologic phenomena. He was intrigued with the distribution of erratic boulders and speculated upon their origins. In his accounts of the voyage of the *HMS Beagle*, Darwin described crystalline boulders of notable size and abundance near Bahía San Sebastian, south of the Strait of Magellan, Tierra del Fuego. Influenced by Charles Lyell’s reflections upon slow, vertical movements of crust, submergence, and ice rafting to explain drift, Darwin proposed that the boulders of Bahía San Sebastian were ice-rafted. Benefiting from 170 years of subsequent study of the glacial history of Tierra del Fuego, petrography, and terrestrial cosmogenic nuclide measurements, we revisit the origin of “Darwin’s Boulders” at Bahía San Sebastian. We suggest that they, as well as another train of boulders to the west, at Bahía Inútil, represent rock falls of Beagle-type granite from the Cordillera Darwin onto glacial ice flowing into the Bahía Inútil–Bahía San Sebastian lobe. These supraglacial rock avalanche deposits were subsequently elongated into boulder trains by glacial strain during transport and then deposited upon moraines. The cosmogenic nuclide exposure dates support the correlation of Andean glaciations with the marine oxygen isotope record and the glacial chronologies recently proposed for Tierra del Fuego.

## INTRODUCTION

Influenced by Adam Sedgewick and Charles Lyell’s *Principles of Geology* (v. 1, 1830), Charles Darwin became established as a geologist as a result of his voyage on the *HMS Beagle*. In his writings, he portrayed himself so: “I, a geologist, have ill-defined notion of land covered with ocean...” (Darwin notebook M, no. 40, 1838, p. 39–40). Darwin belonged to the Geological Society of London (GSL) and was elected secretary in 1838. He provided us with the first geological map of southern South America. Over his career, he published more than 20 geologic articles, and in 1859, was awarded the Wollaston Medal—the highest honor of the GSL—in recognition of his contributions. In fact, his push to disseminate the geological work, including the three geology volumes of the *Beagle* voyage, delayed the publication of *On the Origin of Species* until 1859 (coincidentally when the Wollaston Medal was awarded).

Darwin’s records as naturalist on the *HMS Beagle* reveal his curiosity concerning landscape evolution. For instance, his interpretation of atolls “forming as land sunk” and his measurements of raised marine terraces in South America attest to his interest in monitoring landscape change. Darwin’s thinking was profoundly influenced by Lyell’s obsession with large-scale, slow, vertical movements of the crust, especially as manifested in his theory of submergence and ice rafting to explain drift. In turn, Lyell profited greatly from Darwin’s observations, including uplift of the Pacific coast of Chile during the Talcahuano earthquake. Lyell celebrated these observations because they supported his idea of uniformitarianism—that continued small changes, as witnessed in the field, could account for dramatic changes of Earth’s surface over geologic time.

Here we report another example of Darwin’s predilection for interpreting landscape anomalies with inductive reasoning. One-hundred-seventy years later, we share his fascination with the gigantic granitic boulders on the Atlantic coast of Tierra del Fuego. Under Lyell’s influence, Darwin invoked the submergence–ice-rafting hypothesis to explain them, which was further supported by reports of icebergs transporting boulders. His ice-rafting hypothesis is herein superseded by one involving supraglacial transport of rock avalanche debris from one coast of Tierra del Fuego to the other, where they were abandoned upon a coastal till plain. Nevertheless, Darwin’s request to delay the voyage of the *HMS Beagle* in order to document the unusual boulders has led to a clearer understanding of

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\*corresponding author: patrick.burkhardt@sru.edu

Cordillera Darwin glaciodynamics and should serve to encourage geologists to explore unexpected encounters that fall beyond the defined tasks at hand.

## DARWIN'S INTERPRETATION OF TIERRA DEL FUEGO ERRATICS

Darwin was long intrigued by erratic boulders, noting their locations and speculating on their origins in numerous papers (Darwin, 1839a, 1839b, 1839c, 1841a, 1841b, 1845, 1848, 1849, 1855). He dedicated one article (Darwin, 1842) exclusively to South America. The boulders at Bahía San Sebastian were discussed in several papers (Darwin, 1839a, 1842, 1848), and his description (1841a, p. 419) that enticed this investigation reads,

...great boulders of various and peculiar crystalline rocks, which have undoubtedly travelled from the south-west coast, lie scattered over the whole of the eastern part of Tierra del Fuego. One enormous block of syenite near St. Sebastian Bay was barn-shaped, and had a girth of 47 feet.

Darwin consistently attributed erratics to ice rafting (1839a, 1839b, 1839c, 1841, 1842, 1845, 1848, 1849, 1855). On more than one occasion, Darwin made reference to observations by Charles Lyell of how sediment-laden icebergs off the coast of Newfoundland would deposit debris onto the sea floor. Later, Darwin observed calving glaciers in Tierra del Fuego that produced icebergs containing boulders, writing in his second-edition account of the *Voyage of the Beagle* (1845, p. 234) that “some of the icebergs were loaded with blocks of no inconsiderable size, of granite and other rocks, different from the clay-slate of the surrounding mountains.” Further, in his 1841 paper (1841a, p. 430), Darwin wrote,

As one of the two methods of conveying erratic boulders, namely, that by icebergs from glaciers, is now in action on the South American shores, we are naturally led to conclude, that this was the chief agent in the enormous amount of transport formerly effected over a more extended area.

Another reason Darwin universally applied the concept of long-distance ice rafting was the report by the crew of the schooner *Eliza Scott* of an iceberg far out at sea carrying a large

erratic block, estimated at 12 ft high by 6 ft wide. In “Note on a rock seen on an iceberg...” (1839b), Darwin elucidated why this sighting was significant:

Every fact on the transportation of fragments of rock by ice is of importance, as throwing light on the problem of “erratic boulders,” which has so long perplexed geologists.

Darwin also deduced from his study of marine invertebrate-bearing, “step-formed” surfaces of eastern South America, and observations of uplift associated with the 20 February 1835 Chilean earthquake, that the east and west coasts of South America had been elevated from beneath the sea. His observations of calving glaciers producing debris-bearing icebergs, sighted great distances from possible sources, combined with his firm belief in land emergence, gave him a mechanism to explain emplacement of erratics, which he inferred were deposited too far from mountains to permit direct glacial deposition.

Darwin applied this assumption to the boulders at Bahía San Sebastian (“Darwin’s Boulders”). In his account of the *Voyage of the Beagle* (1845, p. 236), his conviction about ice rafting was strengthened by the shared opinion of other geologists:

Few geologists now doubt that those erratic boulders which lie near lofty mountains have been pushed forward by the glaciers themselves, and that those distant from mountains, and embedded in subaqueous deposits, have been conveyed thither either on icebergs or frozen in coast-ice.

To Darwin, ice rafting was the only model to explain the erratic boulders of Tierra del Fuego because he found no other evidence for glaciation of the Atlantic coast. In “On the distribution of erratic boulders...” (1841b, p. 430), Darwin stated,

The boulders... are strewn on land, which certainly has been modelled by the action of the sea... this little inclination of the surface, with the absence of mounds or ridges on it, and the angularity of the fragments, are opposed to the notion that the blocks have been pushed to this great distance by glaciers. Hence I conclude... that the boulders were transported by floating ice.

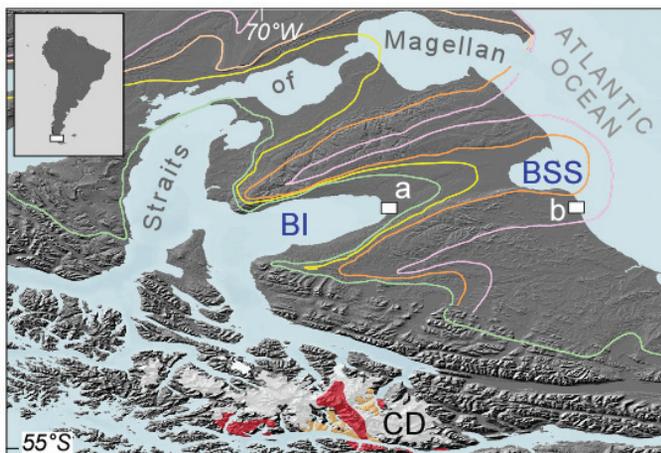


Figure 1. Digital elevation model of the Strait of Magellan region showing location of the erratic boulder trains: a—Bahía Inútil (BI); n—Bahía San Sebastian (BSS). See Figure 5 for detailed maps. The outer limits of four glacial drifts according to Meglioli (1992) are depicted by colored lines. CD—Cordillera Darwin. Shades within Cordillera Darwin depict the Beagle Granite (red), Darwin Granite (orange), and glacier ice fields (white).



Figure 2. Darwin's boulders (A) in the surf of the Atlantic Ocean and (B) upon till plains.

### REINTERPRETATION OF ORIGIN OF THE DISTAL TIERRA DEL FUEGO ERRATICS

Figure 1 depicts the Cordillera Darwin, the Strait of Magellan, and the location of the two boulder trains discussed in this paper. "Darwin's boulders" are located in the surf at Bahía San Sebastian (Fig. 2A) and on the elevated till plain (Fig. 2B) above a 20 m sea cliff at Punta Sinaí on the Atlantic coast of Tierra del Fuego. They consist of an isolated train of ~500 huge, angular, variably weathered boulders, all of which are medium-grained hornblende granodiorites. Outside of the train, large boulders are rare. The boulders lie on the terminal moraine of the Daniglacial advance of Caldenius (1932) or Rio Cullen Drift of Meglioli (1992), which is bracketed from older than 0.36 m.y. to younger than 1.07 m.y. (Meglioli, 1992; Rabassa et al., 2000; Kaplan et al., 2007).

Meglioli (1992) described a second train of gigantic boulders at the head of Bahía Inútil on the western coast of Grande Isle. Darwin was apparently unaware of the existence of the Bahía Inútil boulder train, which interestingly also consists of an isolated group of about 1000 huge, angular, granodioritic boulders. They lie upon the terminal moraine of the Finiglacial advance of Caldenius (1932) or the Bahía Inútil Drift of Meglioli (1992).

Of the three plausible mechanisms for emplacement of these distal erratics—iceberg rafting, stream-ice rafting, or direct deposition from glaciers—we support the latter. Overwhelming evidence for complete glaciation of Tierra del Fuego, from coast to coast, has been unchallenged for almost a century. It is unlikely that stream ice could have transported such large boulders over hundreds of kilometers while maintaining such a tight distribution, and there is no evidence of a capable fluvial environment in the immediate vicinity of either boulder train. On the basis of boulder size, angularity, lithology, and isolation, Meglioli (1992) proposed that the boulders originated as rock avalanches that were transported supraglacially, and Coronato et al. (1999) and McCulloch et al. (2005a) concurred. We supplement the observations that led to this interpretation and propose the bedrock source and timing of deposition of both boulder trains.

Multiple lines of evidence support a rock avalanche-supraglacial transport interpretation for the boulder trains. The

evidence includes the (1) great size, (2) angularity, (3) monolithologic composition, and (4) surficial positioning of the boulders, as well as the (5) restricted areal extents, (6) orientations, and (7) locations of the boulder trains on left lateral moraines (looking upstream) of the Bahía Inútil–Bahía San Sebastian ice lobe.

The maximum diameter of the majority of boulders in both trains ranges from 1 m to 16 m, but the size distribution is skewed toward the larger. While glaciers and icebergs can carry large boulders, it would be unlikely for iceberg rafting or subglacial processes to transport such clusters of numerous, extremely large boulders. It is well known, however, that landslides from competent, jointed rocks produce large boulders, which can be supraglacially transported the entire lengths of glaciers.

Almost all of the boulders are sharply angular and show no sign of subglacial abrasion (Fig. 3). The sides of many boulders are roughly planar, suggesting that some surfaces may be original fracture planes. Their angularity and lack of curved faces are indicative of rockfall and supraglacial—not subglacial—transport, and although transport by icebergs could also yield far-traveled angular boulders, we have essentially eliminated this interpretation.



Figure 3. Darwin's boulders are distinctively angular, lacking evidence for glacial abrasion.



Figure 4. Darwin's boulders, which are exposed in (A) sea cliffs and (B) stream valley cuts, lie upon the moraine surface (<2 m depth) and not within tills.

Both boulder fields have a limited areal extent, and boulders >1 m in diameter beyond the fringe are rare. Ice rafting would be unlikely to produce concentrations of 500–1000 boulders in the restricted areas occupied by these boulder trains. The boulder trains are not situated in steep-sided valleys, where currents might have concentrated icebergs.

The glacier lobes that extended eastward across Tierra del Fuego had accumulation zones in the Cordillera Darwin. Owing to a complex geological history, the cordillera comprises a wide range of lithologies, including arc volcanics, I- and S-type granitoids, sediments, metasediments, and high-grade metamorphic rocks. Subglacial tills deposited near the termini of the last (Bahía Inútil) and pre-ultimate (Bahía San Sebastian) glaciations are characterized by a wide range of lithologies; however, the erratics in both boulder fields are monolithological, essentially identical, hornblende granites, possessing a coarse tabular jointing pattern. On the basis of petrography and glacial reconstructions, the most likely origin of the erratics is the Beagle Granite in the Cordillera Darwin (Fig. 1) (Nelson et al., 1980). The singular composition of the erratics indicates that subglacial processes, which would commingle all lithologies present throughout the glaciated basin, were unlikely, and instead supports a supraglacial origin by rock avalanche from a subcatchment incising the Beagle Granite.

Careful examination of coastal (Fig. 4A) and stream exposures (Fig. 4B) demonstrates that the boulders lie on or within the upper 2 m of the underlying till units, indicating that the boulders were delivered to the surface of the glacier and subsequently deposited on top of the glacial drift in the last phases of glaciation (Bahía Inútil) or during the initial phase of deglaciation (Bahía San Sebastian). The geometries of both boulder trains were determined by GPS mapping of large boulders. At Bahía San Sebastian, we mapped all boulders larger than 3 m using real-time differential corrected GPS (horizontal precision,  $\pm 0.1$  m), and at Bahía Inútil, we mapped long and short axes of the train with a Garmin® handheld GPS (horizontal precision,  $\pm 5.0$  m). The Bahía Inútil boulder train forms an east-west ellipse (Fig. 5A). Similarly, with the exclusion of a small number of “outliers” to the north of the main concentration at Bahía San Sebastian, the train forms an east-west oriented ellipse that has a deflection (Fig. 5B),

which we believe relates to deformation of the underlying ice near the lobe terminus prior to deposition.

In each train, boulders were deposited atop an extended section of the lateral, verging-on-end moraine. This pattern is fully consistent with the glaciological expectation for transport

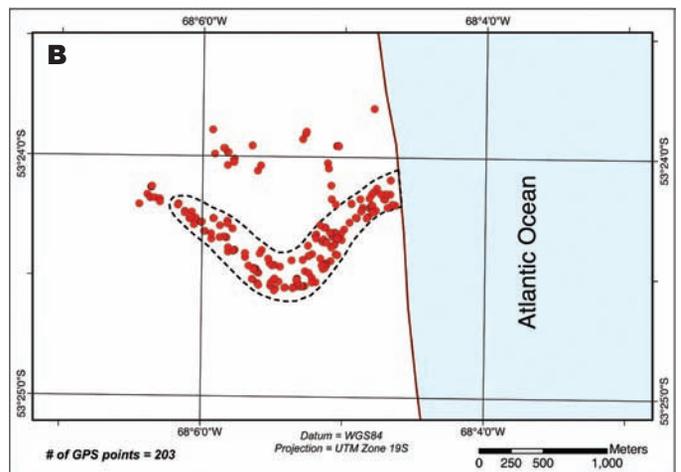
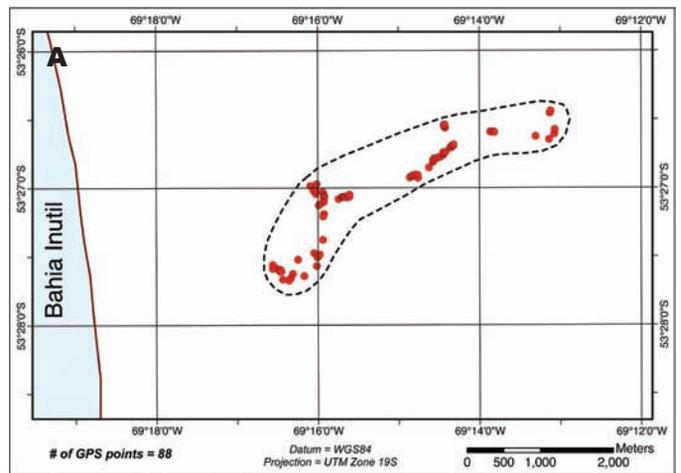


Figure 5. Boulders at (A) Bahía Inútil and (B) Bahía San Sebastian (Darwin's boulders) exist as trains whose distributions support emplacement through supraglacial transport and deposition.

of supraglacial boulders from a debris fall. End moraines form only in the ablation zone (e.g., Denton et al., 2005), demonstrating that a component of ice-flow velocity was toward the moraine. Because the moraine is longer than the ice-lobe width at its upglacier end, flowlines must diverge toward the moraine, spreading any supraglacial materials along it. Such spreading may be enhanced by additional supraglacial processes of mass transport across the surface of the glacier (e.g., Anderson, 2000; Kowalczyk et al., 2002; Vacco, 2009). Thus, it appears that boulders were carried atop a glacier onto a tongue that had deposited a moraine, and then the boulders were dropped upon the moraine as flow balanced melting. Divergence of flowlines in the tongue spread the boulders along the moraine, probably enhanced by supraglacial mass-transport processes.

Darwin incorrectly interpreted the glacial drift at Bahía San Sebastian as “subaquatic” sediments, based on its proximity to the coast, the distance from any then-known glaciated region (the Andes), the fine-grained nature of the paleosol, and the lack of large boulders within the sediment (the soft Tertiary rocks of the Tierra del Fuego lowlands do not produce boulders). Although Darwin initially considered the possibility that glaciers could have extended from the Cordillera Darwin, he ruled it out on the basis of such vast distance. In fact, the boulder trains at Bahía San Sebastian and Bahía Inútil lie on moraine crests, albeit the former is older and more subdued. The mapping by Caldenius a century later (1932) would have made the eastward extent of the glaciers evident to Darwin.

Since Caldenius’ surficial mapping of the Andes (1932), many studies have increased our knowledge of the glacial dynamics of Tierra del Fuego. Meglioli (1992) conducted the most recent detailed glacial sediment mapping throughout all of Tierra del Fuego and southern Patagonia, relying on morphology, stratigraphy, geochronology (his and others), weathering rind development, and pedogenesis. The ages of the pre-ultimate glacial drifts were not well established due to the limited number of  $^{40}\text{Ar}/^{39}\text{Ar}$  datable volcanic tuff layers interstratified within the tills, and correlations of drifts of five different lobes were based mostly upon relative position. Numerical modeling of the last glacial maximum (Bahía Inútil Lobe; Jackofsky, 2000), constrained by gradients of the lateral and interlobate moraines, provided a means of establishing the position of the paleo-equilibrium line altitude for the eastern Cordillera Darwin, and ice sheet models have provided a better constraint on the advance and retreat of the Patagonian Ice Fields and adjacent regions.

In the past decade, significant attention has been placed on the chronology of the ultimate and pre-ultimate drifts using terrestrial cosmogenic nuclides (TCN). Significant contributions to knowledge of the glacial history have been advanced by Kaplan et al. (2007, 2008), Glasser et al. (2008), and Rabassa (2008), who used combinations of radiocarbon (mostly on peat and lacustrine organics and marine macrofossils) and TCN exposure ages on boulders to date the ultimate and pre-ultimate glaciations. To this foundation, we add the following TCN

ages: (i) nine ages on the terminal moraine of the ultimate glaciation of the Bahía Inútil lobe; (ii) four ages on a recessional moraine of the same lobe, but at an elevation below a post-glacial lake (McCulloch et al., 2005b), suggesting that the ages reflect the time of glacial lake drainage; (iii) nine ages on the Bahía San Sebastian boulder train that reproduce problematic exposure ages reported by Kaplan et al. (2007) that were considered too young for the stratigraphic position of the moraine according to previous maps and that are accordingly interpreted to be evidence of rapid exhumation of the drift; and (iv) other ages to constrain the timing of the penultimate glaciation, which was tentatively correlated to marine oxygen isotope stage 6 (OIS-6) glaciation (Meglioli, 1992). Unlike the areas to the north, these TCN dates indicate a significant OIS-4 ice expansion in southern Patagonia and Tierra del Fuego, which is consistent with ice extents in other parts of the mid-latitude southern hemisphere (e.g. Barrows et al., 2001), where the OIS-4 paleo-margin extends beyond the last glacial maximum. Table 1 lists these data; details of the chemistry, analysis, and ages are provided in the GSA Data Repository<sup>1</sup>.

Overall, our new TCN exposure ages generally confirm earlier work of Kaplan et al. (2007, 2008) and McCulloch et al. (2005b) in documenting a rich, but sometimes puzzling, glacial history in the vicinity of Darwin’s boulders and the Bahía Inútil boulder train. Excluding outliers, which suggest either inheritance or shielding, our Bahía Inútil dates average  $22.2 \pm 0.9$  k.y., while our Bahía San Sebastian dates reveal anomalously young ages (74.4 to 38.1 k.y.) for moraines previously interpreted to be  $\sim 1$  m.y., thus requiring significant reworking. The combined data set is most consistent with a last glacial maximum age for the deposition of the Bahía Inútil boulder train, and an older age for deposition of Darwin’s boulders (likely OIS-6 or older).

## CONCLUSION

On the voyage of the *HMS Beagle*, Charles Darwin was struck by the observation of numerous large boulders near Bahía San Sebastian in Tierra del Fuego. In the context of field observations and the preponderant thinking of the day, he interpreted their occurrence as resulting from ice rafting of boulders entrained into icebergs. In his view, emergence of the coastline by vertical uplift then lodged the boulders into their current locations. Darwin and his contemporaries, however, did not recognize the now well-established field evidence for the eastward extent of Andean glaciers that flowed through the Strait of Magellan and the Bahía Inútil–Bahía San Sebastian lobes to the Atlantic Ocean. In light of the accumulated evidence since Darwin’s time, including our observations, we maintain that the boulder trains of Bahía San Sebastian and Bahía Inútil are the vestiges of Andean rock avalanches, transported supraglacially, and spread by ice flow into linear trains upon moraines. We utilized terrestrial cosmogenic nuclide techniques to date the exposure age of the boulders, constraining the ages of the land surfaces upon which they lie, and placing them into the record of Andean glaciations.

<sup>1</sup>GSA Supplemental Data item 2009287, summary of terrestrial cosmogenic nuclide ages for boulders of Bahía Inútil–Bahía San Sebastian ice lobe, with discussion, is available at [www.geosociety.org/pubs/ft2009.htm](http://www.geosociety.org/pubs/ft2009.htm); copies can also be obtained by e-mail to [GSAToday@geosociety.org](mailto:GSAToday@geosociety.org).

TABLE 1. SUMMARY OF TERRESTRIAL COSMOGENIC NUCLIDE (TCN) EXPOSURE AGES FROM BOULDERS IN OR NEAR THE BAHÍA SAN SEBASTIAN OR BAHÍA INÚTIL BOULDER TRAINS

	Nuclide	Sample ID	Elev. (m)	Age (ka)	Unc (ka)	Age (ka)	Unc (ka)
				$\epsilon = 0 \text{ mm/ka}$		$\epsilon = 1.7 \text{ mm/ka}$	
<b>TCN ages of Bahía Inútil Boulder Train</b>							
Terminal or recessional above shorelines*	$^{10}\text{Be}$	BI-B1	80	26.0	4.4	27.0	4.7
	$^{10}\text{Be}$	BI-B2	75	24.3	4.0	25.1	4.3
	$^{10}\text{Be}$	BI-B3	85	22.4	3.3	23.1	3.5
	$^{10}\text{Be}$	BI-B4	80	24.8	4.3	25.7	4.6
	Mean/SE			24.4	0.9	25.2	0.9
Terminal or recessional above shorelines†	$^{10}\text{Be}$	TF-04-04	90	21.8	3.4	22.5	3.6
	$^{10}\text{Be}$	TF-04-04	90	18.2	2.1	18.7	2.3
	$^{10}\text{Be}$	TF-04-05	90	21.4	4.2	22.1	4.3
	$^{10}\text{Be}$	TF-04-06	101	20.1	3.1	20.7	3.2
	Mean/SE			20.4	0.9	21.0	1.0
Terminal above shorelines (distal-proximal)	$^{10}\text{Be}$	CBI-T51-99-15	160	21.0	2.5	21.6	2.7
	$^{10}\text{Be}$	CBI-T51-99-16	160	22.7	2.6	23.5	2.8
	$^{10}\text{Be}$	CBI-T51-99-17	160	26.0	2.8	26.9	3.1
	$^{10}\text{Be}$	CBI-T51-99-18	160	66.0	7.2	72.8	8.9
	$^{10}\text{Be}$	CBI-T51-99-13	145	21.2	2.6	21.8	2.8
	$^{10}\text{Be}$	CBI-T51-99-14	145	23.7	2.9	24.5	3.1
	$^{10}\text{Be}$	CBI-T51-99-20	140	17.8	2.1	18.3	2.2
	$^{10}\text{Be}$	CBI-T51-99-19	135	23.1	2.6	23.8	2.8
	$^{10}\text{Be}$	CBI-T51-99-21	135	22.3	2.7	23.0	2.9
	Mean/SE			22.2	0.9	22.9	0.9
Recessional below shoreline	$^{10}\text{Be}$	CBI-T52-99-10	65	8.3	1.0	8.4	1.0
	$^{10}\text{Be}$	CBI-T52-99-11	65	9.4	1.1	9.5	1.2
	$^{10}\text{Be}$	CBI-T52-99-12	65	8.9	1.1	9.1	1.2
	$^{10}\text{Be}$	CBI-T54-99-08	60	14.1	1.7	14.3	1.7
	Mean/SE			8.9	0.4	9.0	0.4
<b>TCN ages for Bahía San Sebastian Boulder Train</b>							
Southeast of Bahía San Sebastian†	$^{10}\text{Be}$	RC-04-01	16	21.9	6.6	22.6	7.0
	$^{10}\text{Be}$	RC-04-02	22	27.1	4.2	28.2	4.6
	$^{10}\text{Be}$	RC-04-03	21	20.0	3.4	20.6	3.6
	$^{10}\text{Be}$	RC-04-04	23	27.3	9.0	28.4	9.7
	$^{10}\text{Be}$	RC-04-05	17	26.9	6.8	27.9	7.4
	$^{10}\text{Be}$	RC-04-06	12	13.5	1.6	13.8	1.7
	$^{10}\text{Be}$	RC-04-07	21	51.4	12.3	55.5	14.4
	Mean/SE			22.8	1.2	23.6	1.3
	$^{36}\text{Cl}$	ARG-00-Tdf-039	34	18.7	9.0		
	$^{36}\text{Cl}$	ARG-00-Tdf-043	34	27.1	9.0		
	Mean/SE			22.9	5.9		
<b>TCN ages for the penultimate drift</b>							
	$^{10}\text{Be}$	CRG-T3 <sub>1</sub> -99-22		74.0	8.1	82.7	10.3
	$^{10}\text{Be}$	CRG-T3 <sub>2</sub> -99-24		74.4	8.2	83.2	10.3
	$^{36}\text{Cl}$	CRG-T3 <sub>2</sub> -99-23		55.2	2.7		
	$^{36}\text{Cl}$	CRG-T4 <sub>1</sub> -99-25		40.8	1.6		
	$^{36}\text{Cl}$	CRG-T4 <sub>1</sub> -99-26		38.1	1.8		

Note: See GSA supplemental data item 2009287 for AMS and chemical data, age calculation method, and TCN data interpretation. Erosion rates are as suggested by McCulloch et al. (2005), but measurement of  $^{10}\text{Be}$  in quartz and  $^{36}\text{Cl}$  in biotite from a single granite boulder (CBI-T51-99-16) requires much less erosion to resolve age disparity (see Table DR2A). Unc—uncertainty.

\*McCulloch et al., 2005a. †Kaplan et al., 2007.

In June of 1833, Charles Darwin delayed the progress of the *HMS Beagle* to better observe the boulders at Bahía San Sebastian, and in doing so, prompted the eventual satisfactory explanation for their existence. While our interpretations, after nearly two centuries of continuing field mapping and sophisticated material analyses, have revealed inaccuracies in Darwin's geologic thoughts about the boulders, we revere his exquisite, detailed recordings of natural occurrences, as well as his pursuit of rational explanations based upon observable phenomena. "Darwin's Boulders" are not ice-rafted blocks, but rather glacially transported detritus of alpine avalanches; yet, his accounts of them beckoned us to reexamine the deposits, thus reinforcing his intent to explain landscapes within the constraints of physical evidence.

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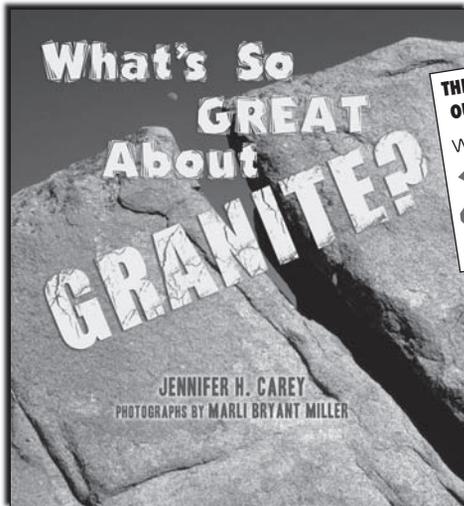
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