AGU100 ADVANCING EARTH AND SPACE SCIENCE

Geophysical Research Letters

RESEARCH LETTER
10.1002/2018GL077237

Key Points:
- Olivine basalt, hyaloclastite erratics, and detrital zircon at Earth's southernmost moraine (Mount Howe) indicate magmatic activity 25–17 Ma
- The source, indicated by a magnetic anomaly (-740 nT) ~400 km inland from the West Antarctic Rift margin, expands the extent of Miocene lavas
- Data corroborate lithospheric foundering beneath the southern Transantarctic Mountains based on location of volcanism (duration <5 my)

Supporting Information:
- Supporting Information S1
- Table S1
- Table S2
- Table S3

Correspondence to:
K. J. Licht,
klicht@iupui.edu

Citation:
Licht, K. J., Groth, T., Townsend, J. P., Hennessy, A. J., Hemming, S. R., Flood, T. P., & Studinger, M. (2018). Evidence for extending anomalous Miocene volcanism at the edge of the East Antarctic craton. *Geophysical Research Letters*, *45*, 3009–3016. https://doi.org/10.1002/2018GL077237

Received 24 JAN 2018
Accepted 18 MAR 2018
Accepted article online 26 MAR 2018
Published online 6 APR 2018

Evidence for Extending Anomalous Miocene Volcanism at the Edge of the East Antarctic Craton

K. J. Licht[1], T. Groth[1], J. P. Townsend[2], A. J. Hennessy[1], S. R. Hemming[3], T. P. Flood[4], and M. Studinger[5]

[1]Department of Earth Sciences, Indiana University-Purdue University Indianapolis, Indianapolis, IN, USA, [2]HEDP Theory Department, Sandia National Laboratories, Albuquerque, NM, USA, [3]Department of Earth and Environmental Sciences, Columbia University, Lamont-Doherty Earth Observatory, Palisades, NY, USA, [4]Geology Department, Saint Norbert College, De Pere, WI, USA, [5]NASA Goddard Space Flight Center, Greenbelt, MD, USA

Abstract Using field observations followed by petrological, geochemical, geochronological, and geophysical data, we infer the presence of a previously unknown Miocene subglacial volcanic center ~230 km from the South Pole. Evidence of volcanism is from boulders of olivine-bearing amygdaloidal/vesicular basalt and hyaloclastite deposited in a moraine in the southern Transantarctic Mountains. $^{40}Ar/^{39}Ar$ ages from five specimens plus U-Pb ages of detrital zircon from glacial till indicate igneous activity 25–17 Ma. The likely source of the volcanism is a circular −735 nT magnetic anomaly 60 km upflow from the sampling site. Subaqueous textures of the volcanics indicate eruption beneath ice or into water at the margin of an ice mass during the early Miocene. These rocks record the southernmost Cenozoic volcanism in Antarctica and expand the known extent of the oldest lavas associated with West Antarctic Rift system. They may be an expression of lithospheric foundering beneath the southern Transantarctic Mountains.

Plain Language Summary Little is known about the geology of Antarctica's ice-covered interior, so unexpected volcanic rocks collected from Earth's southernmost glacial moraine provide valuable insights about what is under some of that ice. Analysis of five samples shows that volcanism occurred 20.6–17 million years ago, likely under Antarctica's early ice sheet. The source was a volcanic center only 230 km from the South Pole and 400 km from the nearest tectonic boundary. The volcanic source was identified from a geophysical survey that shows a circular magnetic anomaly 60 km upstream from the moraine where the cobbles were found. In addition to these volcanic rocks, three sand-sized zircon crystals were found in glacial sediments and are 25–19 million years old. These are the youngest zircon grains ever found in the Transantarctic Mountains and also indicate igneous activity. It is unusual to have such volcanism and igneous activity within a plate. Recent work has identified a reversal in Earth's layers here that brings warm rocks, normally deeper in the Earth, closer to the surface. Our samples provide physical evidence in support of this otherwise inaccessible anomaly.

1. Introduction

The geology of the Antarctic interior remains poorly characterized because ice covers 99.8% of the bedrock (Burton-Johnson et al., 2016). In contrast to remote sensing studies that have provided indirect information about Antarctic's subglacial topography, crustal architecture, and magnetic anomalies on regional to continental scales (e.g., Block et al., 2009; Studinger et al., 2006), sampling of bedrock has mostly been limited to the exposures in mountain ranges and nunataks. Palmer et al. (2012) showed that nunatak moraines can be valuable repositories of previously unknown bedrock buried beneath the ice sheet. The erratics and detrital minerals transported by ice and finally deposited in moraines can be used to make inferences about unexposed geologic terrains (e.g., Goodge et al., 2010; Welke et al., 2016).

In this paper we describe the texture, chemistry, and age of hyaloclastite and amygdaloidal/vesicular basalt erratics from Earth's southernmost moraine, located at the base of Mount Howe. We integrate this information with other geochronological and geophysical data sets to infer the likely subglacial source of these rocks. The results have valuable implications for models linking uplift of the Transantarctic Mountains (TAM) with the West Antarctic Rift system (WARS). Many mechanisms have been proposed to explain the high elevation of the TAM (e.g., Bialas et al., 2007; Fitzgerald, 2002; Stern & ten Brink, 1989), but none has found widespread acceptance (Shen et al., 2018). Recently, Shen et al. (2018) described new evidence for lithospheric

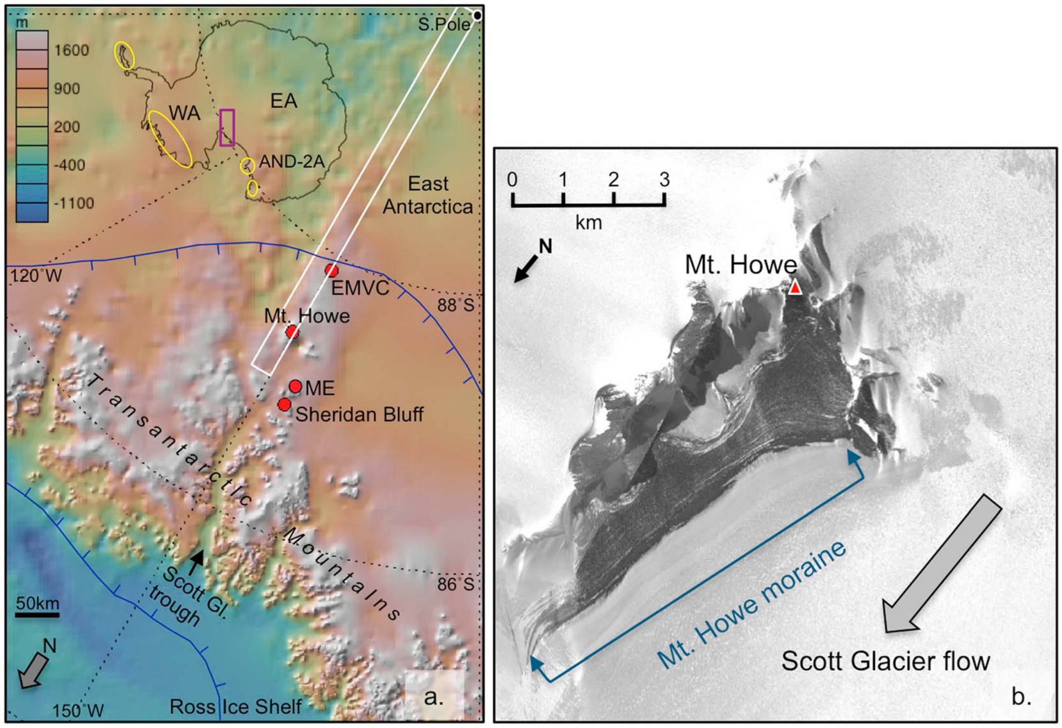

Figure 1. (a) Bedrock elevation of Scott Glacier area (GeoMapApp). White box shows location of magnetic survey shown in Figure 4. Mount Howe sampling area, ME = Mount Early, and Sheridan Bluff, locations of other Miocene volcanics; EMVC = early Miocene volcanic center. Inset map of Antarctica shows study area (purple box) and the regions with Cenozoic volcanism (yellow circles), including ANDRILL core (AND-2A). WA = West Antarctica, EA = East Antarctica. Hatched line (blue) highlights low-velocity (<4.37 km/s) area of uppermost mantle from Shen et al. (2018). (b) Digital Globe image showing the Mount Howe moraine adjacent to the Scott Glacier. White areas are snow covered, light gray are blue ice areas, and dark gray is either debris covered ice (moraine) or bedrock.

foundering beneath the southern TAM that provides a mechanism for TAM uplift and also an explanation for anomalous volcanism in this area. Consequences of delamination include basalt extrusion and silicic intrusion (Bird, 1979).

Major extension of the WARS began in the Cretaceous circa 105 Ma and continued into the Cenozoic, with basaltic volcanism beginning in the mid-Cenozoic (e.g. Behrendt et al., 1996; Siddoway, 2008). Most of the Cenozoic volcanics in Antarctica discovered thus far occur across West Antarctica and along the Antarctic Peninsula (e.g., van Wyck de Vries et al., 2017). They also cluster along some segments of the seaward margin of the TAM, as the McMurdo Volcanic Group (Figure 1; e.g., Kyle, 1990). Two outliers are Sheridan Bluff and Mount Early, isolated volcanic centers along the inland margin of the Scott Glacier (Figure 1). At these two sites, olivine basalts, including hyaloclastites and pillow basalts, were erupted in the early Miocene onto a striated bedrock surface (Stump et al., 1980). Volcanic textures and stratigraphic relationships were used to infer that glacial ice must have been present in the area of the Scott Glacier in the early Miocene, thus providing information about the early East Antarctic ice sheet history but leaving open the question about why volcanism occurred in this area. Our findings expand the extent of Miocene volcanism in the southern TAM and provide evidence related to the lithospheric foundering model (Shen et al., 2018).

2. Setting and Methods

2.1. Geological Study Site

As part of a larger study of the provenance of glacial till of the Scott Glacier, a suite of erratic volcanic clasts was discovered on the surface of the Mount Howe moraine, 290 km from the South Pole (Figure 1). This ~ 2-km × 8.5-km ice-cored moraine occurs in a blue ice area at the base of the Mount Howe nunatak. Bedrock exposures at Mount Howe consist of siliciclastic rocks and coals of the Permian Buckley

Formation, intruded by sills of Jurassic Ferrar Dolerite (Doumani & Minshew, 1965). The moraine is in a cirque-like embayment along the lateral margin of the Scott Glacier. Here subglacial and englacial material transported by the Scott Glacier is brought to the surface, emerging as debris-rich bands, similar to the process described by Bader et al. (2017). Sublimation of the ice exposes the debris and results in till accumulation on the surface of glacial ice over time. Debris thickness near the Scott Glacier margin is $<$1 cm and increases to $>$15 cm near the base of the nunatak. The catchment area for the Scott Glacier extends inland from Mount Howe ~115 km, and ice velocity is generally $<$10 m/year (Rignot et al., 2011).

2.2. Geochronological and Geochemical Analysis

Eleven cobbles of amygdaloidal/vesicular basalt and hyaloclastites were collected from across the moraine surface, and a subset was analyzed via thin section, whole rock geochemistry, and $^{40}Ar/^{39}Ar$ geochronology. This data set is complemented by data from a total field magnetic anomaly survey (Studinger et al., 2006) and detrital zircon geochronology studies of Mount Howe moraine till (Schilling, 2010).

Zeolite-free groundmass fragments were isolated from five samples for $^{40}Ar/^{39}Ar$ dating, which complement geochemical analyses on these samples. Potential sources of excess Ar, such as xenoliths and ultramafic nodules (Armstrong, 1978), were not observed and are not apparent from the character of the data. The fragments were irradiated for 8 hr with Cd shielding, in the TRIGA reactor at U.S. Geological Survey Denver, along with Fish Canyon sanidine-monitor standard (age of 28.201 ± .046 Ma; Kuiper et al., 2008). Samples were packaged in Ta tubes and incrementally heated with a 50-W diode laser at Lamont-Doherty Earth Observatory, and extracted argon from each step was measured on a VG5400 noble gas mass spectrometer. Ages were calculated from Ar isotope ratios corrected for mass fractionation, interfering nuclear reactions, procedural blanks, and atmospheric Ar contamination.

U and Pb isotopic compositions of zircon were analyzed by laser ablation multicollector inductively coupled plasma mass spectrometry at the Arizona LaserChron Center following the method of Gehrels et al. (2006). Zircon was ablated with a New Wave/Lambda Physik DUV193 Excimer laser (operating at a wavelength of 193 nm) using a spot diameter of 20 μm. All measurements were made in static mode, using 10^{11} ohm Faraday detectors for ^{238}U, ^{232}Th, ^{208}Pb, and ^{206}Pb, a 10^{12} ohm faraday collector for ^{207}Pb, and an ion-counting channel for ^{204}Pb. Ion yields are ~1.0 mv per ppm. Each analysis consisted of one 20-s integration with the laser off (for backgrounds), 20 one-second integrations with the laser firing, and a 30-s wait to flush out the previous sample. Common Pb correction was done by using the measured ^{204}Pb and assuming an initial Pb composition from Stacey and Kramers (1975). Every fifth measurement, a standard, a Sri Lanka zircon crystal (564 ± 4 Ma), was used to correct for the fractionation of Pb isotopes, generally ~2%. Uncertainty resulting from the calibration correction is generally 1–2% (2-sigma) for both $^{206}Pb/^{207}Pb$ and $^{206}Pb/^{238}U$ ages. Interpreted ages are based on $^{206}Pb/^{238}U$ (Gehrels et al., 2006).

For geochemical analysis, five representative samples showing the least alteration were coarsely crushed, and visible zeolites/sediment fragments were removed from the sample before powdering. Samples were analyzed by X-ray fluorescence (XRF) and inductively coupled plasma mass spectrometry in two labs: the XRF Laboratory at Michigan State University using a Bruker S4 Pioneer WDXRF or at Washington State's GeoAnalytical Lab where major and trace elements are run on the same sample material using a ThermoARL automated sequential wavelength XRF spectrometer (Johnson et al., 1999). Loss on ignition was determined by heating a sample aliquot at 900°C for 16 hr and comparing weights before and after heating.

3. Results

3.1. Petrography and Geochemistry

The 11 volcanic cobbles collected from the Mount Howe moraine fall into two categories based on hand specimen observation: amygdaloidal/vesicular basalts (n = 8), and hyaloclastites (n = 3; supporting information Figure S1). All thin sections show variolitic textures in the groundmass but varying degrees of vitrification (Figures S2a and S2b). All basalts are olivine bearing, and most show skeletal olivine in thin section (Figure S2c). Thin sections also reveal variable chemical weathering (syndepositional) between specimens, as indicated by altered feldspars and iddingsite. All the samples analyzed geochemically are basalts that cluster around the alkaline/subalkaline boundary and at the tholeiitic/calc-alkaline boundary.

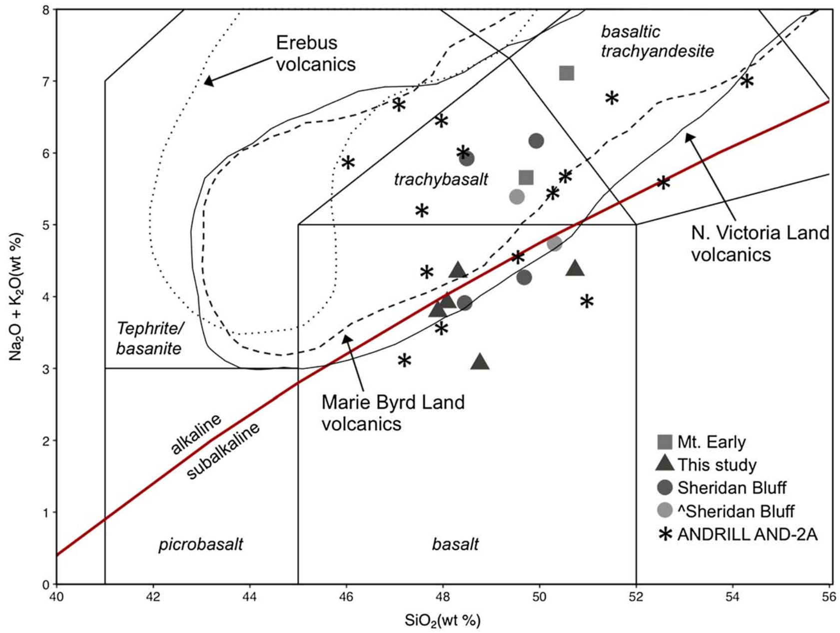

Figure 2. Total alkalis versus silica content (wt.%) showing samples from this study compared to a compilation from Panter et al. (2009) for ANDRILL core (AND-2A) samples. Major elements recalculated to 100%, volatile free, following LeBas et al. (1986). Samples from this study (triangles) are basalts (Table S1), and are most similar to northern Victoria Land volcanics. Two samples fall outside the known northern Victoria Land range but show similarities to volcanic clasts from the AND-2A core (Figure 1). Sheridan Bluff (circles) basalts and trachybasalts are from ^Stump et al. (1990) and S. Hart (Table S4). Data sources for comparative compositional fields: Erebus volcanics: LeMasurier and Thomson (1990) and Kyle et al. (1992); Marie Byrd Land volcanics: LeMasurier and Thomson (1990) and Rocchi et al. (2006).

Their chemistry is similar to silica-poor northern Victoria Land volcanics from the ANDRILL AND-2A core collected in southern McMurdo Sound (Figure 2; Panter et al., 2009). The Mount Howe samples are also geochemically similar to volcanic clasts from Mount Early and Sheridan Bluff (Figure 2). All samples are classified as within-plate basalts when plotted on trace element discrimination diagrams using Zr,Y, Ti, and Nb and as continental basalts using the La/10-Y/15-Nb/8 discrimination diagram (Rollinson, 1993). Amygdaloidal volcanics have both zeolite and quartz filled vesicles that constitute 10–20% (by volume) of the rocks. Two samples feature large vugs that contain laminated silt, and one specimen has numerous parallel pipe vesicles 1–4 cm long (Figure S1).

Hyaloclastite erratics are rounded and highly vesicular and contain subangular to subrounded unaltered amygdaloidal basalt fragments (up to 5 cm) in an orange-brown palagonite (hydrous alteration of volcanic glass) matrix with glass and euhedral-subhedral olivine crystals up to 2 mm. The hyaloclastite specimens are highly porous and friable. Even gentle handling dislodges fragments of palagonite. Phases identified from the palagonite by X-ray diffraction are dominantly feldspars and olivine but also include zeolites such as chabazite and phillipsite (Figure S3).

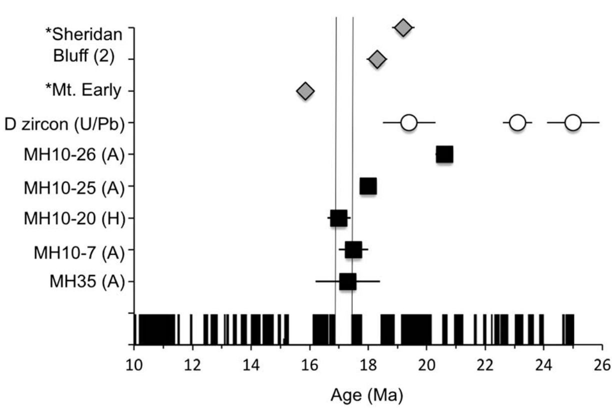

Figure 3. Rank plot of Ar-Ar ages on basalts from Mount Howe (squares), detrital zircon U-Pb ages from Mount Howe till (circles), and K-Ar ages from Sheridan Bluff and Mount Early (diamonds) from *Stump et al. (1980). Vertical lines highlight the age range of the magnetic reversal that overlaps with four samples analyzed. A = amygdaloidal basalt, H = hyaloclastite clast. The magnetic reversal (white) that overlaps with the Ar-Ar ages is 17.399–16.807 Ma (geomagnetic timescale of Huestis & Acton, 1997).

3.2. Geochronology

The zeolite-free groundmass from five samples produced $^{40}Ar/^{39}Ar$ plateau ages ranging from 17 ± 0.4 to 20.6 ± 0.3 Ma (Figures 3 and S4 and Table S2). For the hyaloclastite specimen, the age is on groundmass from an amygdaloidal basalt fragment within the hyaloclastite matrix. The assumption used in all of the step heating spectra is that the initial argon was atmospheric. Alternative ways to evaluate ages (i.e.,

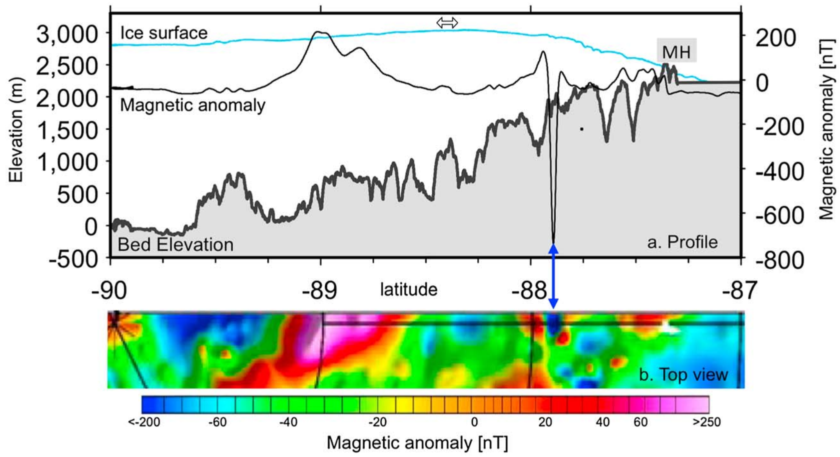

Figure 4. (a) Profile view of ice surface and bedrock elevation along with magnetic anomaly along −150°. Double arrow shows position of ice divide. (b) Top view of total field magnetic anomaly in box shown on Figure 1 (modified from Studinger et al., 2006). Blue arrow highlights early Miocene volcanic center.

isochrones) were explored and described in Figure S5; they do not result in significant changes to our interpretation. Only three of the >600 detrital zircon grains measured from Mount Howe till have late Oligocene/early Miocene U-Pb ages: 19.4 ± 0.9, 23.1 ± 0.5, and 25.0 ± 0.9 Ma (Figure 3 and Table S3). Of the ~4,000 detrital zircon grains we have previously analyzed from the Ross Embayment (Licht et al., 2014), these are the only three grains <90 Ma. The rocks from which they are derived are not known, and no zircon grains were found in the Mount Howe basalt thin sections; therefore, these detrital zircon grains were derived from an as yet undiscovered host rock. Because zircon may be metamorphically altered, we measured the Th/U ratio for all three grains and found values of >0.5, which indicate primary magmatic origin rather than recrystallization due to metamorphism (Hoskin & Black, 2000).

4. Discussion

4.1. Timing and Source of Cenozoic Volcanism in the Region

Several data sets allow us to evaluate the timing and source of volcanic activity that produced the samples recovered from Mount Howe. Ages from four of the five dated basalts are similar and centered around 17.5 Ma (Figure 3). Previously studied basalts outcropping ~50 km downstream from Mount Howe at Sheridan Bluff (Figure 1) are 19.2 ± 0.4 and 18.3 ± 0.4 Ma; a sample from nearby Mount Early is 15.9 ± 0.3 Ma (Figure 3; Stump et al., 1980). Together, samples from Mount Howe, Sheridan Bluff, and Mount Early indicate a period of igneous activity in the range of ~25–16 Ma in the Scott Glacier catchment. Two detrital zircon grains are slightly older than any measured ages on basalts in this region. The zircon may represent a felsic expression of magmatism (Bird, 1979), though no felsic pebbles of Miocene age were found in the moraine. If the foundering model explains this magmatic activity, it suggests contact melting and recrystallization of the lower crust associated with the high temperatures from the rising asthenosphere. However, this explanation is in conflict with the Th/U ratios suggesting igneous origin. Regardless of the source of the zircon, the ages of the samples described here put these rocks among the oldest dated lavas associated within the entire WARS (Kyle, 1990).

In the search for a source of the Mount Howe erratics, we examined aeromagnetic data upstream of Mount Howe (Studinger et al., 2006). The profile data show an isolated, circular, high-amplitude negative anomaly (−740 nT) that is ~7 km in diameter (Figure 4). This anomaly is centered at −87.892°, −149.996° about 60 km inland, and upflow, from the moraine where the samples were collected (Figure 1). The shape, strength, and sign of the anomaly are consistent with reversely magnetized volcanic rocks (Studinger et al., 2006), and we suggest that this is the likely source of the early Miocene volcanic rocks found in the glacial deposits of the Mount Howe moraine. An early Miocene volcanic center (EMVC) at the site of the negative magnetic anomaly would mark the southernmost extent of Cenozoic volcanism identified on Earth. If it is the source of most of the Mount Howe basalts, the timing can be further refined to 17.399–16.807 Ma. This is based on the age of a magnetic reversal that overlaps with the central age of volcanic activity (Figure 3). Unfortunately, we could not confirm this possibility from the magnetic signature of our samples because they are erratics.

The magnetic anomaly is located along the margin of the East Antarctic craton, an inferred rift margin transfer zone, and along strike of an E-W oriented fault (Goodge & Finn, 2010; Studinger et al., 2006). Together these indicate that the EMVC may be associated with a weakness in the crust, similar to the Erebus Volcanic Province (Wilson, 1999), though its relationship to the WARS is not clear. The site also lies at the southern margin of a low velocity zone within the upper mantle described by Shen et al. (2018) in the southern TAM. They interpret this as a region of lithospheric foundering where the warm asthenosphere is shallow ($<$50 km), having replaced the cold lithosphere. One of the predicted consequences of this foundering is volcanism, and the age of the volcanic rocks from Mount Howe can provide constraints on the timing of the foundering. Shen et al. (2018) suggest that the process may have begun in the late Cretaceous when the TAM shows the onset of exhumation events (Fitzgerald, 2002) or in the Miocene, as rifting in the Ross Sea (Adare Trough and Terror Rift) progressed and lithospheric foundering developed beneath the southern TAM. Our geochronology data clearly support the latter interpretation, with evidence for the earliest magmatic activity indicated by the detrital zircon ages of 23.1 ± 0.5 and 25 ± 0.9 Ma. The duration of basaltic volcanism associated with foundering is on the order of $<$5 My.

4.2. Style of Eruption and Implication for Climatic Conditions

Glaciovolcanic eruptive sequences have been described elsewhere in Antarctica and show evidence of subaqueous/subglacial eruptions (e.g., Antibus et al., 2014; Smellie et al., 2011; Stump et al., 1980). Stump et al. (1980) described pillow lavas and hyaloclastites at Sheridan Bluff and Mount Early that were interpreted to indicate early Miocene subglacial eruptions. The EMVC identified in this study is ~ 110 km poleward of known exposures of Miocene volcanic rocks from Sheridan Bluff and Mount Early (Figure 1) and follow the trend of the axis of the upper Scott Glacier. Geochemical and geochronological analysis of Sheridan Bluff volcanics show a similar composition and crystallization age to the Mount Howe volcanic erratics (Figures 2 and 3; Stump et al., 1980); therefore, we infer that petrogenesis for the two groups was similar. We note that the presence of olivine in the Mount Howe basalts is consistent with volcanism associated with early stages of Miocene rifting suggested by Shen et al. (2018). Although the lack of stratigraphic information from the Mount Howe erratics prevents us from making a direct comparison about eruptive style, the thin section characteristics, combined with macroscopic properties, including laminated sediment infill of large vugs and hyaloclastite, are all consistent with subaqueous (subglacial) eruption in the early Miocene. We cannot completely rule out the possibility of subaerial eruption that came into contact with water. Subsequently, the rocks experienced little transport and were covered by ice until their eventual entrainment and transport to the Mount Howe moraine 60 km downstream. They were collected from an area of the moraine where rocks show minimal recent chemical weathering, consistent with surface exposure ages indicating that they have been on the moraine surface no longer than the last glacial cycle (Mathieson et al., 2012).

The most complete records of Antarctica's early Miocene climatic conditions come from the Cape Roberts and ANDRILL-2A marine cores in the McMurdo Sound region ($>$1,100 km from Mount Howe). Both sites record numerous fluctuations by temperate glaciers during this time (e.g., Barrett, 2007; Passchier et al., 2011). The nearest Neogene terrestrial glacial deposits to Mount Howe are Sirius Group sequences located at the head of Shackleton Glacier. They are interpreted to represent deposition by warm-based ice, likely thinner than the modern ice sheet (Hambrey et al., 2003). The age of the deposits is not well constrained but reported to be Miocene-Pliocene. As noted above Stump et al. (1980) interpreted the basalts at Sheridan Bluff and Mount Early to have been subglacially erupted and indicate the presence of an ice sheet since the early Miocene. Both of these terrestrial data sets are consistent with the idea of glaciation during the time of eruption at the EMVC upstream of Mount Howe. Without the context provided by outcrop exposures, we cannot say with certainty whether this was a subglacial eruption or an eruption into a glacial lake.

5. Conclusions

A suite of volcanic erratics from the southernmost moraine on Earth records Miocene volcanism only ~230 km from the South Pole. The erratics include (a) subalkaline/alkaline, olivine-bearing amygdaloidal/vesicular basalts whose chemistry indicates within-plate volcanism and (b) hyaloclastites containing basalt fragments, glass, and olivine. The textures indicate that subaqueous (likely subglacial) eruptions occurred 20.6–17 Ma. The volcanic center that likely produced these basalts is 60 km upstream of the Mount Howe moraine at the location of a subglacial, circular −740 nT magnetic anomaly (Studinger et al., 2006). Three detrital zircon grains from the moraine till also indicate Neogene igneous activity, with the oldest occurring 25 Ma. Together the samples from Mount Howe expand the known extent of volcanism southward into the East Antarctic interior by ~110 km. The data are consistent with the suggestion of lithospheric foundering beneath the southern TAM and provide evidence that the duration of volcanism was likely <5 My and that substantial crustal heating may have begun as early as 25 Ma.

Acknowledgments
This research was supported by two grants from NSF (OPP-0440885 and 0944578) and IUPUI's Undergraduate Research Opportunities Program. The first sample that inspired this project was spotted by mountaineer P. Braddock; we also thank field team members N. Bader, M. Kaplan, and M. Roberts. We are grateful to Kenn Borek Air, Ltd., and the U.S. Antarctic Program. We thank W. LeMasurier and K. Panter for constructive reviews, D. Wiens for helpful discussions, and S. Hart for unpublished data from Sheridan Bluff rocks. Analytical assistance was provided by T. Vogel; R. Conrey; University of Arizona LaserChron Center; and J. Mosely and J. Mickey (IUPUI). Sandia National Laboratories is a multimission laboratory managed and operated by National Technology and Engineering Solutions of Sandia, LLC, a wholly owned subsidiary of Honeywell International, Inc., for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-NA0003525. Data supporting the conclusions are in tables and supporting information.

References

Antibus, J. V., Panter, K. S., Wilch, T. I., Dunbar, N., McIntosh, W., Tripati, A., et al. (2014). Alteration of volcaniclastic deposits at Minna Bluff: Geochemical insights on mineralizing environment and climate during the Late Miocene in Antarctica. *Geochemistry, Geophysics, Geosystems*, *15*, 3258–3280. https://doi.org/10.1002/2014GC005422

Armstrong, R. L. (1978). K-Ar dating: Late Cenozoic McMurdo Volcanic Group and dry valley glacial history, Victoria Land, Antarctica. *New Zealand Journal of Geology and Geophysics*, *21*(6), 685–698. https://doi.org/10.1080/00288306.1978.10425199

Bader, N. A., Licht, K. J., Kaplan, M. R., Kassab, C., & Winckler, G. (2017). East Antarctic ice sheet stability since the mid-Pleistocene recorded in a high-elevation ice cored moraine. *Quaternary Science Reviews*, *159*, 88–102. https://doi.org/10.1016/j.quascirev.2016.12.005

Barrett, P. J. (2007). Cenozoic climate and sea level history from glacimarine strata off the Victoria Land coast, Cape Roberts Project, Antarctica. In M. J. Hambrey, P. Christoffersen, N. F. Glasser, & B. Hubbart (Eds.), *Glacial processes and products: International Association of Sedimentologists special publication 39* (pp. 259–287). Malden, MA: Blackwell.

Behrendt, J. C., Saltus, R., Damaske, D., McCafferty, A., Finn, C. A., Blankenship, D., & Bell, R. E. (1996). Patterns of late Cenozoic volcanic and tectonic activity in the West Antarctic Rift system revealed by aeromagnetic surveys. *Tectonics*, *15*, 660–676. https://doi.org/10.1029/95TC03500

Bialas, R. W., Buck, W. R., Studinger, M., & Fitzgerald, P. G. (2007). Plateau collapse model for the Transantarctic Mountains West Antarctic Rift System, Insights from numerical experiments. *Geology*, *35*(8), 687–690. https://doi.org/10.1130/G23825A.1

Bird, P. (1979). Continental delamination and the Colorado Plateau. *Journal of Geophysical Research*, *84*, 7561–7571. https://doi.org/10.1029/JB084iB13p07561

Block, A., Bell, R. E., & Studinger, M. (2009). Antarctic crustal thickness from satellite gravity: Implications for the Transantarctic and Gamburtsev Subglacial Mountains. *Earth and Planetary Science Letters*, *288*(1-2), 194–203. https://doi.org/10.1016/j.epsl.2009.09.022

Burton-Johnson, A., Black, M., Fretwell, P. T., & Kaluza-Gilbert, J. (2016). An automated methodology for differentiating rock from snow, clouds and sea in Antarctica from Landsat 8 imagery: A new rock outcrop map and area estimation for the entire Antarctic continent. *The Cryosphere*, *10*(4), 1665–1677. https://doi.org/10.5194/tc-10-1665-2016

Doumani, G. A., & Minshew, V. H. (1965). General geology of the Mount Weaver area, Queen Maud Mountains, Antarctica. *Antarctic Research Series*, *6*, 127–139. https://doi.org/10.1029/AR006p0127

Fitzgerald, P. G. (2002). Tectonics and landscape evolution of the Antarctic plate since the breakup of Gondwana, with an emphasis on theWest Antarctic Rift System and the Transantarctic Mountains. *Royal Society of New Zealand Bulletin*, *35*, 453–469.

Gehrels, G., Valencia, V., & Pullen, A. (2006). Detrital zircon geochronology by laser-ablation multicollector ICPMS at the Arizona Laserchron Center. In T. Loszewski & W. Huff (Eds.), *Geochronology: Emerging Opportunities, Paleontological Society Papers 12* (pp. 67–76).

Goodge, J., Fanning, M., Brecke, D., Licht, K., & Palmer, E. (2010). Continuation of the Laurentian Grenville province across the Ross Sea margin of Antarctica. *Journal of Geology*, *118*(6), 601–619. https://doi.org/10.1086/656385

Goodge, J. W., & Finn, C. A. (2010). Glimpses of East Antarctica: Aeromagnetic and satellite magnetic view from the central Transantarctic Mountains of East Antarctica. *Journal of Geophysical Research*, *115*, B09103. https://doi.org/10.1029/2009JB006890

Hambrey, M. J., Webb, P.-N., Harwood, D. M., & Krissek, L. A. (2003). Neogene glacial record from the Sirius Group of the Shackleton Glacier region, central Transantarctic Mountains, Antarctica. *Geological Society of America Bulletin*, *115*(8), 994–1015. https://doi.org/10.1130/B25183.1

Hoskin, P. W. O., & Black, L. P. (2000). Metamorphic zircon formation by solid state recrystallization of protolith igneous zircon. *Journal of Metamorphic Geology*, *18*, 423–439.

Huestis, S. P., & Acton, G. D. (1997). On the construction of geomagnetic timescales for non-prejudicial treatment of magnetic anomaly data from multiple ridges. *Geophysics Journal International*, *129*(1), 176–182. https://doi.org/10.1111/j.1365-246X.1997.tb00947.x

Johnson, D. M., Hooper, P. R., & Conrey, R. M. (1999). XRF analysis of rocks and minerals for major and trace elements on a single low dilution Li-tetraborate fused bead. *Advances in X-Ray Analysis*, *41*, 843–867.

Johnson, J. S., & Smellie, J. L. (2007). Zeolite compositions as proxies for eruptive paleoenvironment. *Geochemistry, Geophysics, Geosystems*, *8*, Q03009. https://doi.org/10.1029/2006GC001450

Kuiper, K. F., Deino, A., Hilgen, F. J., Krijgsman, W., Renne, P. R., & Wijbrans, J. R. (2008). Synchronizing rock clocks of Earth history. *Science*, *320*(5875), 500–504. https://doi.org/10.1126/science.1154339

Kyle, P. R. (1990). McMurdo Volcanic Group western Ross embayment. In W. E. LeMasurier & J. W. Thomson (Eds.), *Volcanoes of the Antarctic plate and southern oceans, Antarctic research series* (Vol. 48, pp. 19–25). Washington, DC: American Geophysical Union. https://doi.org/10.1029/AR048p0018

Kyle, P. R., Moore, J. A., & Thirlwall, M. F. (1992). Petrologic evolution of anorthoclase phonolite lavas at Mount Erebus, Ross Island, Antarctica. *Journal of Petrology*, *33*(4), 849–875. https://doi.org/10.1093/petrology/33.4.849

LeBas, M. J., Le Maitre, R. W., Streckeisen, A., & Zanettin, B. (1986). Chemical classification of volcanic rocks based on the total alkali-silica diagram. *Journal of Petrology*, *27*, 745–750.

LeMasurier, W. E., & Thomson, J. W. (Eds) (1990). *Volcanoes of the Antarctic plate and southern oceans, Antarctic research series* (Vol. 48, pp. 19–25). Washington, DC: American Geophysical Union. https://doi.org/10.1029/AR048

Licht, K. J., Hennessy, A. J., & Welke, B. M. (2014). The U/Pb detrital zircon signature of West Antarctic ice stream tills in the Ross Embayment, with implications for LGM ice flow reconstructions. *Antarctic Science*, *26*(06), 687–697. https://doi.org/10.1017/S0954102014000315

Mathieson, C., Kaplan, M. R., Winckler, G., Schaefer, J., Licht, K. J., Bader, N., & Dits, T. (2012). *Cosmogenic dating of moraines in the central Transantarctic Mountains to evaluate past behavior of the East Antarctic Ice Sheet*. Paper presented at 2012 Fall Meeting, AGU, San Francisco, CA, Abstract PP23C-2071.

Palmer, E. F., Licht, K. J., Swope, R. J., & Hemming, S. R. (2012). Nunatak moraines as a repository of what lies beneath the East Antarctic ice sheet. In E. T. Rasbury, S. R. Hemming, & N. R. Riggs (Eds.), *Mineralogical and geochemical approaches to provenance*, *Geological Society of America Special Paper 487* (pp. 97–104). Boulder, CO: Geological Society of America. https://doi.org/10.1130/2012.2487(05

Panter, K. S., Talarico, F. M., Bassett, K., DelCarlo, P., Field, B., Frank, T., et al. (2009). Petrologic and geochemical composition of the AND-2A Core, ANDRILL Southern McMurdo Sound Project, Antarctica. *Terra Antarctica*, *15*, 147–192.

Passchier, S., Browne, G., Field, B., Fielding, C. R., Krissek, L. A., Panter, K., et al. (2011). Early and middle Miocene Antarctic glacial history from the sedimentary facies distribution in the AND-2A drill hole, Ross Sea, Antarctica. *Geological Society of America Bulletin*, *123*(11-12), 2352–2365. https://doi.org/10.1130/B30334.1

Rignot, E., Mouginot, J., & Scheuchl, B. (2011). Ice flow of the Antarctic ice sheet. *Science*, *333*(6048), 1427–1430. https://doi.org/10.1126/science.1208336

Rocchi, S., LeMasurier, W. E., & Di Vincenzo, G. (2006). Oligocene to Holocene erosion and glacial history in Marie Byrd Land, West Antarctica, inferred from exhumation of the Dorrel Rock intrusive complex and from volcano morphologies. *Geological Society of America Bulletin*, *118*(7-8), 991–1005. https://doi.org/10.1130/B25675.1

Rollinson, H. (1993). *Using geochemical data: Evaluation, presentation, interpretation*. New York, NY: John Wiley & Sons.

Schilling, A. (2010). Reconstructing past Antarctic ice flow paths in the Ross Embayment, Antarctica using sand petrography, particle size and detrital zircon provenance (Master's thesis). Indianapolis, IN: Indiana University. Retrieved from Scholarworks https://scholarworks.iupui.edu/bitstream/handle/1805/2133/Thesis%20Andrea%20J.%20Schilling.pdf?sequence=4

Shen, W., Wiens, D. A., Stern, T., Anandakrishnan, S., Aster, R. A., Dalziel, I., et al. (2018). Seismic evidence for lithospheric foundering beneath the southern Transantarctic Mountains, Antarctica. *Geology*, *46*(1), 71–74. https://doi.org/10.1130/G39555.1

Siddoway, C. S. (2008). Tectonics of the West Antarctic Rift system: New light on the history and dynamics of distributed intracontinental extension. In A. K. Cooper, et al. (Eds.), *Antarctica: A keystone in a changing world—Proceedings of the 10th International Symposium on Antarctic Earth Sciences* (pp. 91–114). Washington, DC: The National Academies Press. https://doi.org/10.3133/of2007-1047.kp09

Smellie, J. L., Rocchi, S., Gemelli, M., Di Vincenzo, G., & Armienti, P. (2011). A thin predominantly cold-based Late Miocene East Antarctic ice sheet inferred from glaciovolcanic sequences in northern Victoria Land, Antarctica. *Palaeogeography, Palaeoclimatology, Palaeoecology*, *307*(1-4), 129–149. https://doi.org/10.1016/j.palaeo.2011.05.008

Stacey, J. S., & Kramers, J. D. (1975). Approximation of terrestrial lead isotope evolution by a two-stage model. *Earth and Planetary Science Letters*, *26*, 207–221. https://doi.org/10.1016/0012-821X(75) 90088-6

Stern, T. A., & ten Brink, U. (1989). Flexural uplift of the Transantarctic Mountains. *Journal of Geophysical Research*, *94*, 10,315–10,330. https://doi.org/10.1029/JB094iB08p10315

Studinger, M., Bell, R. E., Fitzgerald, P. G., & Buck, W. R. (2006). Crustal architecture of the Transantarctic mountains between the Reedy Glacier and South Pole from aerogeophysical data. *Earth and Planetary Science Letters*, *250*, 182–199.

Stump, E., Borg, S. G., & Sheridan, M. F. (1990). A.26. Sheridan Bluff. In W. E. LeMasurier & J. W. Thomson (Eds.), *Volcanoes of the Antarctic plate and southern oceans, Antarctic research series* (Vol. 48, pp. 136–137). Washington, DC: American Geophysical Union.

Stump, E., Sheridan, M. F., Borg, S. G., & Sutter, J. F. (1980). Early Miocene subglacial basalts, the East Antarctic Ice Sheet, and uplift of the Transantarctic Mountains. *Science*, *207*(4432), 757–759. https://doi.org/10.1126/science.207.4432.757

van Wyck de Vries, M., Bingham, R. G., & Hein, A. S. (2017). A new volcanic province: An inventory of subglacial volcanoes in West Antarctica. In M. Siergert, S. S. R. Jamieson, & D. A. White (Eds.), *Exploration of subsurface Antarctica: Uncovering past changes and modern processes*, *Special Publications* (Vol. 461, pp. 461–467). London: Geological Society of London. https://doi.org/10.1144/SP461.7

Welke, B., Licht, K., Hennessy, A., Hemming, S., Pierce-Davis, E., & Kassab, C. (2016). Applications of detrital geochronology and thermochronology from glacial deposits to the Paleozoic and Mesozoic thermal history of the Ross Embayment, Antarctica. *Geochemistry, Geophysics, Geosystems*, *17*, 2762–2780. https://doi.org/10.1002/2015GC005941

Wilson, T. J. (1999). Cenozoic structural segmentation of the Transantarctic Mountains rift flank in southern Victoria Land. *Global and Planetary Change*, *23*(1-4), 105–127. https://doi.org/10.1016/S0921-8181(99)00053-3