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A new volcanic province: an inventory of subglacial volcanoes in West Antarctica

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Abstract

The West Antarctic Ice Sheet overlies the West Antarctic Rift System about which, due to the comprehensive ice cover, we have only limited and sporadic knowledge of volcanic activity and its extent. Improving our understanding of subglacial volcanic activity across the province is important both for helping to constrain how volcanism and rifting may have influenced ice-sheet growth and decay over previous glacial cycles, and in the light of concerns over whether enhanced geothermal heat fluxes and subglacial melting may contribute to instability of the West Antarctic Ice Sheet. Here, we use ice-sheet bed-elevation data to locate individual conical edifices protruding upwards into the ice across West Antarctica, and we propose that these edifices represent subglacial volcanoes. We use aeromagnetic, aerogravity, satellite imagery and databases of confirmed volcanoes to support this interpretation. The overall result presented here constitutes a first inventory of West Antarctica's subglacial volcanism. We identify 138 volcanoes, 91 of which have not previously been identified, and which are widely distributed throughout the deep basins of West Antarctica, but are especially concentrated and orientated along the >3000 km central axis of the West Antarctic Rift System.

West Antarctica hosts one of the most extensive regions of stretched continental crust on the Earth, comparable in dimensions and setting to the East African Rift System and the western U.S.A.'s Basin and Range Province (see Fig. 1 and e.g., Behrendt et al., 1991; Dalziel, 2006; Kalberg et al., 2015). Improved knowledge of the region's geological structure is important because it provides the template over which the West Antarctic Ice Sheet (WAIS) has waxed and waned over multiple glaciations (Naish et al., 2009; Pollard and DeConto, 2009; Jamieson et al., 2010), and this provides a first-order control on the spatial configuration of the WAIS' ice dynamics (Studinger et al., 2001; Jordan et al., 2010, Bingham et al., 2012). The subglacial region today is characterised by an extensive and complex network of rifts, which likely initiated at various times since the Cenozoic (Fitzgerald, 2002; Dalziel, 2006; Siddoway, 2008; Spiegel et al., 2016), and which in some locations may still be active (Behrendt, et al., 1998; LeMasurier, 2008; Lough et al., 2013; Schroeder et al., 2014). Collectively, this series of rifts beneath the WAIS has been termed the West Antarctic Rift System (WARS), and is bounded by the Transantarctic Mountains to the south (Fig. 1).

In other major rift systems of the world, rift interiors with thin, stretching crust are associated with considerable volcanism (e.g., Siebert and Simkin, 2002). However, in West Antarctica, only a few studies have identified subglacial volcanoes and/or volcanic activity (e.g., Blankenship et al., 1993; Behrendt et al., 1998; 2002; Corr and Vaughan, 2008; Lough et al., 2013), with the ice cover having deterred a comprehensive identification of the full spread of volcanoes throughout the WARS. Improving on this limited impression of the WARS' distribution of volcanism is important for several reasons. Firstly, characterising the geographical spread of volcanic activity across the WARS can complement wider efforts to understand the main controls on rift volcanism throughout the globe (Ellis and King, 1991; Ebinger et al, 2010). Secondly, volcanic edifices, by forming "protuberances" at the subglacial interface, contribute towards the macroscale roughness of ice-sheet beds, which in turn forms a first-order influence on ice flow (c.f., Bingham and Siegert, 2009). Thirdly, volcanism affects geothermal heat flow and, hence, basal melting, potentially also impacting upon ice dynamics (Blankenship et al., 1993; Vogel et al., 2006). Fourthly, it has been argued that subglacial volcanic sequences can be used to recover palaeoenvironmental information from Quaternary glaciations, such as palaeo-ice thickness and thermal regime (e.g. Smellie, 2008; Smellie and Edwards, 2016).

In this contribution, we present a new regional-scale assessment of the likely locations of volcanoes in West Antarctica based on a morphometric (or shape) analysis of West Antarctica's ice-bed topography. Volcano shape depends on three principal factors: (1) the composition of the magma erupted, (2) the environment into which the magma has been erupted, and (3) the erosional regime to which the volcano has been subjected since eruption (Hickson, 2000; Grosse et al., 2014; Pederson and Grosse, 2014). Magma composition in large continental rifts generally has low-medium silica content with some more alkaline eruptions (Ebinger et al., 2013). In West Antarctica, where most knowledge of volcanoes is derived from subaerial outcrops in Marie Byrd Land, volcanoes are composed of intermediate alkaline lavas erupted onto a basaltic shield, with smaller instances being composed entirely of basalt and a few more evolved compositions (trachyte, rhyolite; LeMasurier et al., 1990; LeMasurier, 2013). We therefore consider it likely that many structures in the WARS are also basaltic. Regarding the environment of eruption, subaerial basaltic eruptions typically produce broad shield-type cones protruding upwards from the surrounding landscape (Grosse et al., 2014). Under subglacial conditions, monogenetic volcanoes often form steeper-sided, flat-topped structures made up of phreato-magmatic deposits draped on pillow lava cores and overlain by lava fed deltas known as tuyas (Hickson, 2000; Pederson and Grosse, 2014; Smellie and Edwards, 2016). Larger, polygenetic volcanic structures, give rise to a range of morphometries reflecting the multiple events that cause their formation, but many also have overall “conical” structures similar to stratovolcanoes or shield volcanoes (Grosse et al, 2014; Smellie and Edwards, 2016).

In the WARS the macrogeomorphology is dominated by elongate landforms resulting from geological rifting and subglacial erosion. We propose here that, in this setting, the most reasonable explanation for any “cones” being present is that they must be volcanic in origin. We define “cones” as any features that have a low length-width ratio viewed from above; thus for this study we include cones even with very low slope angles. Thus we use cones in this subglacial landscape as diagnostic of the presence of volcanoes. We note that identifying cones alone will by no means identify all volcanism in the WARS. For example, volcanic fissures eruptions, a likely feature of rift volcanism, will yield ridge forms, or “tindars” (Smellie and Edwards, 2016) rather than cones. Moreover, in the wet basal environment of the WAIS, the older the cone the more likely it will have lost its conical form from subglacial erosion. Therefore, cones present today are likely to be relatively young – though we cannot use our method to distinguish whether or not the features are volcanically active.

Methods

Our underpinning methodology was to identify cones that protrude upwards from a digital elevation model (DEM) of Antarctica’s subglacial topography, and to assess the likelihood that each cone is a volcanic edifice. We undertook our analysis on the Bedmap2 DEM (Fretwell et al., 2013) domain encompassed by the WARS, which incorporates all of West Antarctica, the Ross Ice Shelf, and the Transantarctic Mountains fringing East Antarctica that flank the WARS (Elliott, 2013). Importantly, while Bedmap2 represents the state-of-the-art knowledge of West Antarctica’s subglacial landscape, it is derived from variable data coverage, the vast majority of the data being sourced from airborne radar sounding acquired along one-dimensional tracks. Along the radar tracks the horizontal spacing of bed-elevation data points can reach a few m, but between tracks the spacing is often several km. The DEM itself is presented as a 1 km gridded product, though the raw data were initially gridded at 5 km (Fretwell et al., 2013). Therefore, while the DEM cannot capture the fine-scale topography now routinely acquired by satellite and airborne altimetry, and which has been exploited for multiple morphometric analyses (e.g., Pederson and Grosse, 2014; Lindback and Pettersson, 2015; Ely et al., 2016), it nevertheless presents a workable starting point for identifying volcanic edifices. We consider how some of the DEM's limitations can be overcome in our analysis below.

We defined a cone as an upwards protuberance from the DEM whose elongation ratio (width versus length) < 1.5. Over the domain, but excluding non-grounded ice (primarily the Ross Ice Shelf) where the subglacial topography is poorly characterised, we first extracted cones protruding at least 100 m from the surrounding terrain. The bed elevation uncertainties within the DEM prevent reliable identification of smaller edifices. Elevation profiles across each cone were then extracted from Bedmap2 at multiple angles with respect to the current ice flow direction (taken from Rignot et al., 2011). Where radar profiles directly traversed a cone, we further cross-checked the shape of the bed directly from the raw data. This is part of our procedure for accounting for any artefacts in Bedmap2, which involves corroborating our identified volcanoes with auxiliary datasets. To assess the likelihood that the Bedmap2-extracted cones were (a) not merely interpolation-induced artefacts, and (b) likely represent volcanoes, we implemented a scheme wherein points were awarded where auxiliary data ground-truthed the bed DEM and/or gave greater confidence in a volcanic interpretation. The assessment criteria are as follows, with points awarded for each and data-source references given in Table 1:

(1) Whether a cone is found within 5km of the nearest raw ice-thickness data.

(2) Whether a cone is overlain by an upward-protruding prominence in the surface of the ice draped over it. This criterion takes advantage of the fact that, under the right balance between ice thickness and ice-flow speed, subglacial topographic prominences can be expressed at the ice surface (e.g., De Rydt et al., 2013).

(3) Whether a cone is discernible as a feature at the ice surface in visible satellite imagery. Various recent studies have demonstrated that subglacial features can be outlined by visible expressions in surface imagery (e.g., Ross et al., 2014; Chang et al., 2015; Jamieson et al., 2016).

(4) Whether a cone is associated with a clear concentric magnetic anomaly. This depends on the potential volcano having a pillow-lava core, rather than being composed solely of tuff. This is consistent with the thickness of ice overlying the cones and the erodibility of tuff/tephra deposits. Strong geomagnetic anomalies have long been suggested as evidence of subglacial volcanism in the WARS (eg: Behrendt et al., 1998; Behrendt et al., 2002).

(5) Whether a cone is associated with a concentric free-air and/or Bouguer anomaly.

Each cone was assigned a final confidence factor value of between 0 and 5 by summing up the points from the five indicators described above (Table 1).

Results

Our morphometric analysis of subglacial West Antarctica recovers a total of 178 conical structures located beneath the grounded WAIS and along the WARS (Fig. 2; Table 2). Of these, 80% are located within 15 km of the raw ice-thickness data measurements (Fretwell et al, 2013), and 30% are identified from the DEM at sites where volcanoes, either active or inactive, have previously been identified (LeMasurier et al., 1990; LeMasurier 2013; Wardell et al 2014). Many cones were crossed directly by radio-echo sounding flightlines, allowing verification of their profiles (e.g., Fig. 3) – thus while there is, inevitably, some smoothing in the Bedmap2 interpolation, the major features of interest are largely captured. One of our confidence tests for volcanic interpretation of cones also takes into account proximity to the raw ice thickness measurements, further discounting DEM interpolation as a disproportionate influence on the results.

The identified cones range in height between 100 and 3850 m, with an average relief of 621 m, including 29 structures > 1 km tall that are mainly situated in Marie Byrd Land and the central rift zone. The basal diameter of the cones ranges between 4.5 and 58.5 km, with an average diameter of 21.3 km. Most of the cones have good basal symmetry with 63% of the long to short axis ratios being < 1.2. Table 3 presents a more in depth statistical analysis of the morphology of these features and compares them to a global volcanic database (Grosse et al., 2014). Figure 4 shows 1:1 cross sections of three of the newly identified cones along with three prominent shield volcanoes for comparison.

78% of the cones achieve a confidence score (from our 5-point scheme) > 3, and we therefore consider it reasonable to interpret these 138 cones henceforth as subglacial volcanoes. (We note that 98% of the 47 previously identified volcanoes in West Antarctica (visible at the surface and listed by LeMasurier et al., 1990) achieved a confidence score > 3.) The volcanoes are distributed across subglacial West Antarctica, but are especially concentrated in Marie Byrd Land (1 cone per 11200±600 km^2); and along a central belt roughly corresponding to the rift's central sinuous ridge (Behrendt et al., 1998) with 1 cone per 7800±400 km^2. For comparison the overall volcanic edifice concentration along the East African Rift is roughly 1 volcano per 7200 km^2, rising to 1 volcano per 2000 km^2 in the densest regions (Global Volcanism Program, 2013).

Discussion

Morphometry as a tool for identifying subglacial volcanoes

We consider here three main implications that arise from our findings. Firstly, our approach demonstrates that it is possible to use morphometry on Antarctica's subglacial DEM, crucially together with relevant auxiliary information, to identify potential subglacial volcanic edifices beneath West Antarctica. Secondly, it highlights that subglacial West Antarctica – and, in essence, the WARS – comprises one of the world's largest volcanic provinces (c.f., LeMasurier and Thompson, 1990; Smellie and Edwards, 2016), and it provides basic metrics concerning the locations and dimensions of the main volcanic zones. Thirdly, it serves to highlight the wide spread of subglacial volcanism beneath the WAIS, which may impact upon its response to external forcing through affecting coupling of the ice to its bed, and may have implications for future volcanic activity as ice cover thins.

To our knowledge, our study here is the first to apply morphometry to identify volcanic edifices on the continental scale beneath Antarctica. The extent of this volcanism has only previously been inferred from geophysical studies (Behrendt et al., 2002). Morphometry has been used widely elsewhere in volcanology, for example to catalogue volcanic parameters such as height, base width and crater width (e.g. McKnight and Williams, 1997; Pedersen and Grosse, 2014), or to reconstruct eroded volcanic edifices (Favalli et al., 2014). It has been applied to resolve volcanic characteristics in subaerial, submarine (e.g. Stretch et al., 2006) and extraterrestrial (e.g. Broz et al., 2015) settings. However, in all such cases volcanic morphometry has been applied to DEMs assembled from evenly-distributed elevation measurements derived from sensors viewing unobscured surfaces. For subglacial Antarctica, having confidence that the subglacial DEM that has been constructed from non-random elevation measurements has sufficient resolution for the applied interpretation is key. Recent years have witnessed increasing glaciological recovery of subglacial information from morphometry. For example, seeding centres for glaciation of the WAIS (Ross et al, 2014) and the East Antarctic Ice Sheet (Bo et al., 2009; Rose et al., 2013) have been identified by the preponderance of sharp peaks, cirque-like features, and closely-spaced valleys relative to other parts of the subglacial landscape. Elsewhere, landscapes of "selective linear erosion", diagnostic of former dynamism in now-stable regions of ice, have been detected from the presence of significant linear incisions (troughs) into otherwise flat higher surfaces (plateaux) (Young et al., 2011; Jamieson et al., 2014; Rose et al., 2014). All of these studies have in common that they have closely considered auxiliary evidence to the morphometry, and hence have not relied on the surface shape alone, in coming to interpretations concerning landscape formation. We have shown here that such a combined approach is also valid for locating and mapping numerous previously unknown volcanic edifices across the ice-shrouded WARS.

Extent and Activity of Subglacial Volcanism

We have identified at least 138 likely volcanic edifices distributed throughout the WARS. This represents a significant advance on the total of 47 identified volcanoes across the whole of West Antarctica, most of which are visible at the surface and are situated in Marie Byrd Land and the Transantarctic Mountains (LeMasurier et al., 1990). The wide distribution of volcanic structures throughout the WARS, along with the presence of clusters of volcanism concentrated within the Marie Byrd Land dome, is markedly similar to the East African Rift System, which is also > 2000 km in length and flanked by the Ethiopian and Kenyan domes (Fig 1b; Siebert and Simkin, 2002; Ebinger, 2005). Morphologically, the volcanoes have volume-height characteristics and basal diameters that closely match those of rift volcanoes around the world (Figure 5 and Table 3). Bearing in mind that data paucity beneath the Ross Ice Shelf precluded meaningful analysis of a significant terrain also considered to be part of the WARS, the total region that has experienced volcanism is likely to be considerably larger than that we have identified here.

The activity of the WARS has been the subject of a longstanding debate with one side advocating a largely inactive rift (LeMasurier, 2008) and others suggesting large-scale volcanism (Behrendt et al., 2002). The arguments in favour of an inactive rift are based on the anomalously low elevation of the WARS compared to other active continental rifts (LeMasurier, 2008; Winberry and Anandakrishnan, 2004) and the relative absence of basalt pebbles recovered from boreholes (LeMasurier pers. comm., 2015). Conversely, high regional heat fluxes (Shapiro and Ritzwoller, 2004; Schroeder et al., 2014), geomagnetic anomalies (Behrendt et al., 2002), and evidence of recent subglacial volcanism (Blankenship et al., 1993; Corr and Vaughan, 2008) suggest the rift is currently active. This study provides evidence of a large number of subglacial volcanoes, with their quasi-conical shield volcano type geometries still intact. The largely uneroded nature of the cones suggests that many may be of Pleistocene age or younger which supports the argument that the rift remains active today.

From this study, we are not able to determine whether the different volcanoes are active or not; however, the identification of multiple new volcanic edifices, and the improved regional sense of their geographical spread and concentration across the WARS, may guide future investigation of their activity. Several previous studies have suggested that the Marie Byrd Land massif is supported by particularly low-density mantle, possibly comprising a volcanic “hotspot” (Hole and LeMasurier, 1994; Winberry and Anandakrishnan, 2004). Tephra layers recovered from the Byrd Ice Core near the WAIS divide suggest multiple Marie Byrd Land volcanoes were active in the Late Quaternary (Wilch et al., 1999), while recent seismic activity in Marie Byrd Land has been interpreted as currently active volcanism (Lough et al., 2013). In the Pine Island Glacier catchment, strong radar-sounded englacial reflectors have been interpreted as evidence of a local eruption that occurred ~2000-2400 years ago (see Figure 3 and Corr and Vaughan, 2008) while, on the opposite rift flank in the Transantarctic Mountains, Mount Erebus comprises a known active volcano located above another potential volcanic hotspot (Gupta et al., 2009). Volcanism across the region also likely contributes to the elevated geothermal heat fluxes that have been inferred to underlie much of the WAIS (Shapiro and Ritzwoller, 2004; Fox Maule et al., 2005; Schroeder et al., 2014). The deployment of broadband seismics to recover mantle structure beneath the WAIS is now showing great promise (e.g., Heeszel et al., 2016), and our map of potential volcanic locations could help target further installations directed towards improved monitoring of the continent's subglacial volcanic activity.

Implications for Ice Stability and Future Volcanism

The wide spread of volcanic edifices and possibility of extensive volcanism throughout the WARS also provides potential influences on the stability of the WAIS. Many parts of the WAIS overlie basins that descend from sea level with distance inland, lending the ice-sheet a geometry that is prone to runaway retreat (Alley et al., 2015; Bamber et al., 2009). Geological evidence points to the likelihood that the WAIS experienced extensive retreat during Quaternary glacial minima (Naish et al., 2009) and concurrently contributed several metres to global sea-level rise (O'Leary et al., 2013). Currently the WAIS may be undergoing another such wholesale retreat, as ice in the Pacific-facing sector has consistently been retreating from the time of the earliest aerial and satellite observations (Rignot, 2002; McMillan et al., 2014; Mouginot et al., 2014). We do not consider it likely that volcanism has played a significant role in triggering the current retreat, for which there is compelling evidence that the forcing has initiated from the margins (Turner et al. submitted), but we do propose that subglacial volcanism has the potential to influence future rates of retreat by (1) producing enhanced basal melting that could impact upon basal ice motion, and (2) providing edifices that may act to pin retreat.

On the first of these possibilities, some authors have suggested that active subglacial volcanism, through providing enhanced basal melting that might "lubricate" basal motion, could play a role in WAIS instability (Blankenship et al., 1993; Vogel et al., 2006; Corr and Vaughan, 2008). A possible analogy is provided by subglacial volcanism in Iceland, where subglacial eruptions have been known to melt basal ice, flood the basal interface, and induce periods of enhanced ice flow (e.g., Magnússon et al., 2007; Einarsson et al., 2016); however, in Iceland's ice caps the ice is considerably thinner than in the WAIS and hence more prone to subglacial-melt-induced uplift. Nevertheless, there is evidence to suggest that changes to subglacial water distribution can occur beneath the WAIS, and that they can sometimes have profound impacts on ice-dynamics: examples are ice-dynamic variability over subglacial lakes (e.g., Siegfried et al., 2016), or the suggestion that subglacial water pulses may have been responsible for historical occurrences of ice-stream piracy (e.g., Anandakrishnan and Alley, 1997; Vaughan et al., 2008). Much recent attention has focussed on drainage of subglacial lakes comprising plausible triggers of such dynamic changes, but subglacial eruptions may represent another pulsed-water source whose occurrence has rarely, if ever, been factored into ice-sheet models. Even inactive or dormant volcanism has the potential to influence ice flow by increasing heat flux to the subglacial interface; this may generate a basal melt cavity and enhance ice flow (Bourgeois et al., 2000; Schroeder et al., 2014).

On the other hand, volcanic edifices, whether active or not, stand as significant protuberances which may act geometrically as stabilising influences on ice retreat. Numerical models used to project potential rates of WAIS retreat show that, once initiated, ice retreat will continue unabated as long as the ice bed is smooth and downslopes inland, but that any increase in roughness or obstacle in the bed can act to delay or stem retreat (Ritz et al., 2015; Nias et al., 2016). We have identified here a number of volcanic edifices sitting within the WAIS' deep basins; these edifices, which likely owe their existence to volcanism, could represent some of the most influential pinning points for past and future ice retreat.

Looking ahead, the thinning and potential removal of ice cover from the WARS volcanic province could have profound impacts for future volcanic activity across the region. Research in Iceland has shown that with thinning ice cover magma production has increased at depth as a response to decompression of the underlying mantle (Jull and McKenzie, 1996; Schmidt et al., 2013). Moreover, there is evidence that, worldwide, volcanism is most frequent in deglaciating regions as the overburden pressure of the ice is first reduced and then removed (Huybers and Langmuir, 2009; Praetorius et al., 2016). Unloading of the WAIS from the WARS therefore offers significant potential to increase partial melting and eruption rates throughout the rifted terrain. Indeed, the concentration of volcanic edifices along the WARS could be construed as evidence that such enhanced volcanic activity was a feature of Quaternary minima. This raises the possibility that in a future of thinning ice cover and glacial unloading over the WARS, subglacial volcanic activity may increase, and this in turn may lead to enhanced water production contributing to further potential ice-dynamical instability.

Conclusions

By applying morphometric analysis to a digital elevation model of the West Antarctic Rift System, and assessing the results with respect to auxiliary information from ice-surface expressions to aerogeophysical data, we have identified 138 subglacial volcanic edifices spread throughout the rift. The volcanoes are widely distributed in the broad rift zone with particular concentrations in Marie Byrd Land and along the central WARS axis. The results demonstrate that the West Antarctic Ice Sheet shrouds one of the world's largest volcanic provinces, similar in scale to East African Rift System. The overall volcano density beneath West Antarctica is found to be one edifice per 18500±500 km^2, with a central belt along the rift's central sinuous ridge containing one edifice per 7800±400 km^2. The presence of such a volcanic belt traversing the deepest marine basins beneath the centre of the West Antarctic Ice Sheet could prove to be a major influence on the past behaviour and future stability of the ice sheet.

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Figure Captions

Fig. 1. a. Location of the main components of the West Antarctic Rift System and confirmed volcanoes (red circles; after LeMasurier et al., 1990; Smellie and Edwards, 2016). b. Location of Holocene volcanoes (Red Circles) in the Ethiopia/Kenya branch of the East African Rift (red shaded area). The majority of this activity is aligned along the rift axis with occasional flank volcanism. Data from Siebert and Simkin(2002); Global Volcanic Program (2013).

Fig. 2. Location map of conical edifices (circles) identified from Bedmap2 (greyscale background) across the West Antarctic Rift System. The data are tabulated in Table 2. Circle colour represents the confidence factor used to assess the likelihood of cones being subglacial volcanoes, and circle size is proportional to the cone's basal diameter. Circles with black rims represent volcanoes that have been confirmed in other studies (LeMasurier et al., 1990; Smellie and Edwards, 2016), generally those that have tips that protrude above the ice surface.

Fig. 3. The upper panel shows an echogram from NASA's Icebridge mission (Leuschen et al., 2014) that shows generally good agreement between a cone on the echogram and on the Bedmap2 data. The lower panel shows an echogram from Corr and Vaughan (2008) with basal topography picking out two cones; the dark layer above the bed is tephra believed to have erupted around 2000 years ago.

Fig. 4. Cross sections of three cones from this study (numbers 21, 60 and 91; see Figure 2 and Table 2 for more details and locations) and three prominent shield volcanoes, namely Mauna Kea (Hawaii), Erta Ale and Marsabit (East African Rift).

Fig. 5. Volume/height chart of the cones from this study (crosses) superimposed over data from volcanoes worldwide (Grosse et al., 2014). The cones closely fit the morphology data for shield volcanoes, as would be expected for basalt-dominated rift volcanism.

Table 1: *Classification scheme used in assessing confidence that a cone extracted from Bedmap2 (Fretwell et al., 2013) can be interpreted as a volcano. Full scores are given in Table 2.*

Confidence assessment criterion	**Dataset / source**	**Confidence score**		
		0	**0.5**	**1**
1)Distance to nearest raw ice-thickness measurement	Figure 3 in Fretwell et al. (2013)	> 15 km	5 to 15 km	< 5 km
2)Expression in ice-surface DEM overlying identified subglacial cone	Bedmap2 ice-surface DEM (Fretwell et al., 2013)	No expression	Associated but off-centre anomaly	Direct overlying anomaly
3)Expression in MODIS imagery of ice surface overlying identified subglacial cone	MODIS Mosaic of Antarctica (Scambos et al., 2007)	No expression	Weak expression	Nothing visible
4)Magnetic anomaly data	ADMAP (Kim et al., 2007)	No anomaly	Weak anomaly	Clear anomaly
5)Gravity anomaly data	Studinger et al. (2002) Damiani et al. (2014) Scheinert et al. (2016)	No anomaly	Weak anomaly	Clear anomaly

Table 2: *Tabulation of subglacial cone coordinates, dimensions, and volcanic-interpretation confidence factors (see Table 1). The final column identifies whether the cone was a previously recognised volcano (Yes) or a new discovery (No). Most of the previously identified volcanoes are catalogued in LeMasurier et al., 1991.*

Number	Height (m)	Average Diameter (km)	Elongation Ratio	Volume (km3)	Latitude	Longitude	Volcano Confidence Factor						Previously identified
							1	2	3	4	5	Sum	
1	800	26	1.08	106	-74.00	-80.38	0.5	1	1	0.5	0.5	3.5	Yes
2	600	14	1.15	23	-75.60	-81.60	1	1	0	1	0.5	3.5	No
3	300	7.5	1.14	3	-76.13	-83.53	1	0.5	0	1	0.5	3	No
4	300	18.5	1.18	20	-76.80	-85.27	1	0	0	1	0.5	2.5	No
5	650	24.5	1.04	77	-74.47	-86.40	0.5	0.5	0.5	0.5	0.5	2.5	No
6	350	17.5	1.19	21	-76.74	-87.50	1	0	0.5	1	0.5	3	No
7	250	17	1.27	14	-76.97	-87.89	1	0	0	1	0.5	2.5	No
8	950	29	1.07	157	-77.37	-88.10	1	0	1	0.5	0.5	3	No
9	300	19.5	1.05	22	-77.40	-89.38	1	0.5	1	0.5	0.5	3.5	No
10	350	15.5	1.07	17	-77.32	-90.34	1	0.5	1	0.5	0.5	3.5	No
11	600	32.5	1.17	124	-74.27	-89.58	0.5	0.5	0	0.5	0.5	2	No
12	550	36	1.06	140	-74.07	-91.18	0.5	0	1	0.5	0.5	2.5	No
13	450	27.5	1.20	67	-72.90	-91.30	0	1	0.5	0.5	0.5	2.5	No
14	500	22.5	1.25	50	-74.05	-92.90	1	1	0.5	1	0.5	4	No
15	1400	22.5	1.25	139	-73.73	-93.68	0.5	1	1	1	0.5	4	Yes
16	1450	19.5	1.29	108	-70.03	-125.97	1	1	1	1	0.5	4.5	Yes
17	1300	27	1.25	186	-73.89	-94.64	0.5	1	1	1	0.5	4	Yes
18	400	20	1.11	31	-78.03	-92.95	1	1	0	0.5	0.5	3	No
19	325	18.5	1.18	22	-78.21	-93.20	1	1	0	0.5	0.5	3	No
20	200	9.5	1.11	4	-78.20	-93.82	1	0.5	0	0.5	0.5	2.5	No
21	600	20.5	1.16	49	-78.15	-94.62	1	1	0	0.5	0.5	3	No
22	375	18.5	1.06	25	-78.68	-95.65	1	0	0.5	0.5	0.5	2.5	No
23	250	19	1.11	18	-78.52	-96.16	1	0.5	1	1	0.5	4	No
24	700	26.5	1.30	96	-78.13	-96.36	1	0.5	0	0.5	0.5	2.5	No
25	450	22.5	1.25	45	-78.00	-97.16	1	1	0	0.5	0.5	3	No
26	250	13.5	1.25	9	-78.67	-97.68	1	1	0	1	1	4	No
27	500	24.5	1.13	59	-74.97	-96.54	0.5	1	1	1	0.5	4	No
28	400	16.5	1.36	21	-74.86	-97.42	1	1	0	1	0.5	3.5	No
29	550	16	1.13	28	-75.07	-99.54	1	1	1	1	0.5	4.5	Yes
30	820	20.5	1.16	68	-74.73	-99.04	1	1	1	1	0.5	4.5	Yes
31	650	29	1.15	107	-75.07	-99.54	0.5	1	1	1	0.5	4	Yes
32	750	31	1.07	141	-74.03	-98.83	0.5	0	0	1	0.5	2	No
33	950	26	1.17	126	-74.21	-100.19	1	1	1	0.5	0.5	4	No
34	900	30	1.14	159	-74.51	-99.94	1	0	1	0.5	0.5	3	Yes
35	300	15.5	1.21	14	-74.72	-100.09	1	0	1	0.5	0.5	3	No
36	325	11.5	1.30	8	-75.24	-96.95	1	1	1	0.5	0.5	4	No
37	500	34	1.13	113	-72.19	-97.70	0	1	1	1	0.5	3.5	Yes
38	1025	40.5	1.19	330	-72.54	-97.61	0	0	0.5	1	0.5	2	Yes
39	400	20.5	1.16	33	-72.51	-98.38	0	1	1	1	0.5	3.5	Yes
40	525	28	1.15	81	-72.42	-99.23	0.5	1	1	1	0.5	4	Yes
41	325	20.5	1.16	27	-72.47	-99.94	0	1	1	1	0.5	3.5	Yes

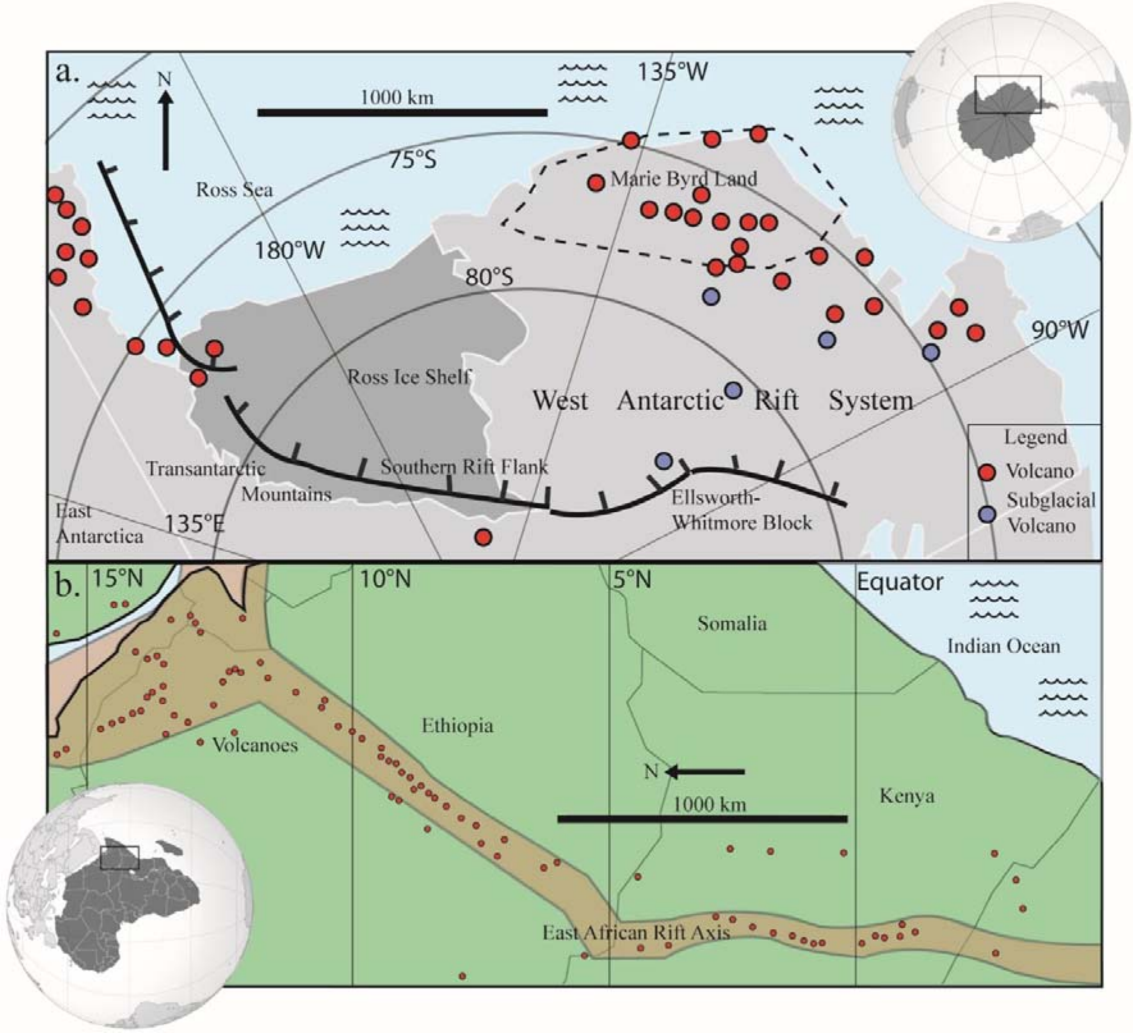
42	550	33.5	1.16	121	-72.32	-101.07	0.5	1	1	0.5	0.5	3.5	Yes
43	225	11.5	1.30	6	-73.87	-103.30	0	0.5	1	1	0.5	3	No
44	675	26.5	1.12	93	-75.45	-103.29	1	1	1	0.5	1	4.5	No
45	350	9.5	1.38	6	-78.41	-101.96	1	0	0	0.5	0.5	2	No
46	575	23	1.19	60	-79.65	-101.80	1	0.5	0	1	0.5	3	No
47	275	12	1.18	8	-80.03	-101.60	1	0.5	0	0.5	0	2	No
48	250	13	1.17	8	-80.15	-101.46	1	0.5	0	0.5	0	2	No
49	175	21.5	1.15	16	-80.17	-103.39	0.5	0.5		0.5	0.5	2	No
50	325	22	1.20	31	-78.87	-102.91	1	0.5	0.5	0.5	0	2.5	No
51	225	27	1.16	32	-80.40	-105.61	0.5	1	0	1	0.5	3	No
52	1175	23	1.19	122	-78.74	-104.24	1	1	1	0.5	1	4.5	No
53	125	15	1.14	6	-77.61	-103.56	1	0.5	0.5	0.5	1	3.5	No
54	225	11.5	1.30	6	-82.05	-111.42	1	0.5	1	1	0.5	4	No
55	175	23	1.19	18	-77.43	-105.77	1	1	1	1	0.5	4.5	No
56	150	9	1.25	2	-77.70	-74.55	1	0.5	0	0.5	0	2	No
57	275	13.5	1.25	10	-78.46	-107.77	1	0.5	1	0.5	0	3	No
58	175	11	1.44	4	-76.72	-106.61	1	1	1	1	0.5	4.5	No
59	150	12.5	1.27	5	-76.87	-106.38	1	1	1	1	1	5	No
60	1200	33.5	1.16	264	-79.15	-111.05	1	0	1	1	1	4	No
61	450	14.5	1.23	19	-79.60	-111.45	1	0	0	1	0.5	2.5	No
62	200	6	1.40	1	-80.42	-114.00	1	0.5	0	1	0	2.5	No
63	425	10	1.22	8	-75.22	-106.92	0	0.5	0.5	0.5	0.5	2	No
64	450	18	1.12	29	-75.71	-108.40	1	0	1	0.5	1	3.5	No
65	375	14.5	1.23	15	-76.11	-107.68	1	0	1	0.5	1	3.5	No
66	400	17	1.27	23	-76.38	-109.78	1	0.5	1	1	1	4.5	No
67	325	10.5	1.33	7	-74.60	-110.62	0.5	1	1	0.5	0.5	3.5	No
68	400	19	1.24	28	-74.81	-110.57	1	1	1	0.5	0.5	4	No
69	350	14	1.33	13	-75.00	-110.43	0.5	1	1	0.5	0.5	3.5	No
70	750	30	1.14	132	-74.89	-111.26	1	1	1	0.5	0.5	4	No
71	2300	51.5	1.15	1197	-75.60	-110.70	1	1	1	0.5	1	4.5	Yes
72	3200	58.5	1.13	2149	-76.52	-112.02	1	1	1	1	1	5	Yes
73	250	15.5	1.07	12	-77.21	-111.92	1	0	0.5	0.5	1	3	No
74	1025	36	1.00	261	-77.72	-112.64	1	0.5	1	1	0.5	4	No
75	300	16	1.13	15	-77.67	-114.04	1	0.5	1	0.5	1	4	No
76	625	26	1.17	83	-77.80	-115.00	1	1	1	0.5	1	4.5	No
77	650	12	1.18	18	-78.08	-115.37	1	0	0.5	0.5	0	2	No
78	400	10.5	1.33	9	-78.11	-115.93	1	1	0.5	0.5	0	3	No
79	350	13.5	1.25	13	-78.93	-115.69	1	0	0.5	1	1	3.5	No
80	325	20.5	1.28	27	-79.68	-113.53	1	1	0	1	1	4	No
81	200	6	1.40	1	-80.38	-115.11	1	0.5	0	1	1	3.5	No
82	125	4.5	1.25	0	-80.38	-115.11	1	0.5	0	1	1	3.5	No
83	150	10	1.22	3	-80.34	-116.40	1	1	0	1	1	4	No
84	1750	31.5	1.10	341	-80.30	-117.49	1	1	1	1	1	5	No
85	800	20	1.22	63	-80.37	-118.90	1	0.5	1	1	1	4.5	No
86	750	18.5	1.31	50	-80.73	-117.56	1	1	1	1	1	5	No
87	150	10.5	1.33	3	-80.81	-118.65	1	1	0	1	1	4	No
88	225	13	1.36	7	-80.87	-120.70	1	0	0	1	1	3	No
89	100	9	1.25	2	-80.27	-117.62	1	1	0	0	0	2	No

90	150	10.5	1.33	3	-80.41	-118.65	1	1	1	1	0.5	4.5	No
91	550	29.5	1.19	94	-80.62	-120.12	1	0.5	1	1	1	4.5	No
92	250	12.5	1.27	8	-79.96	-120.20	1	1	1	1	0.5	4.5	No
93	150	10	1.22	3	-79.24	-119.18	1	1	0	1	0	3	No
94	100	8	1.00	1	-79.37	-119.00	1	1	0	0	0	2	No
95	125	7.5	1.14	1	-79.78	-115.18	1	0	0	0.5	0.5	2	No
96	100	8.5	1.13	1	-78.46	-120.28	1	0	0.5	1	1	3.5	No
97	1000	28.5	1.19	159	-77.54	-118.28	0.5	1	0.5	0.5	0.5	3	No
98	2600	49.5	1.11	1250	-76.96	-117.78	1	1	1	0.5	1	4.5	Yes
99	3850	58	1.11	2542	-76.07	-115.94	0.5	1	1	1	1	4.5	No
100	1350	27.5	1.29	200	-76.73	-125.76	1	1	1	1	0.5	4.5	Yes
101	1100	21	1.21	95	-76.93	-125.73	1	1	1	1	0.5	4.5	Yes
102	1050	20	1.11	82	-77.11	-125.89	0.5	1	1	0.5	0.5	3.5	Yes
103	2400	39	1.17	716	-77.32	-125.97	1	1	1	0.5	0.5	4	Yes
104	1100	22	1.20	104	-77.46	-126.85	0.5	1	1	0.5	0.5	3.5	Yes
105	550	29	1.15	91	-79.24	-128.12	0.5	0	1	0.5	0.5	2.5	No
106	600	17	1.27	34	-81.34	-125.35	1	0.5	0	1	1	3.5	No
107	150	11.5	1.30	4	-82.36	-127.50	1	1	1	1	1	5	No
108	600	25.5	1.13	77	-83.98	-133.02	1	0	1	0.5	0.5	3	No
109	500	39	1.11	149	-84.31	-131.87	1	0.5	1	0.5	0.5	3.5	No
110	125	11.5	1.30	3	-81.82	-128.45	1	0.5	1	1	1	4.5	No
111	100	8	1.29	1	-81.20	-129.58	1	1	0	0	0	2	No
112	550	42	1.15	190	-81.62	-130.38	1	0	1	1	1	4	No
113	275	28.5	1.19	44	-81.87	-130.76	1	0	0	1	1	3	No
114	350	29	1.07	58	-82.41	-134.85	1	1	1	0.5	0.5	4	No
115	150	10.5	1.33	3	-81.10	-132.52	1	0.5	1	1	1	4.5	No
116	400	31.5	1.25	78	-81.36	-133.60	1	1	1	0	0.5	3.5	No
117	100	6	1.40	1	-81.64	-134.55	1	0	0	0	1	2	No
118	250	15.5	1.07	12	-81.55	-135.48	1	0	1	1	0.5	3.5	No
119	550	21.5	1.15	50	-80.35	-131.14	1	1	1	0	1	4	No
120	250	11.5	1.30	6	-80.50	-134.03	1	0	1	1	1	4	No
121	950	36	1.12	242	-80.23	-134.29	1	0.5	1	1	0	3.5	No
122	250	30.5	1.03	46	-79.57	-132.88	1	0	0	0.5	0.5	2	No
123	325	23.5	1.24	35	-80.40	-136.32	0.5	0	1	1	1	3.5	No
124	400	29	1.00	66	-80.08	-138.89	0.5	0.5	0	1	0.5	2.5	No
125	275	32.5	1.10	57	-79.39	-137.82	0.5	0.5	1	1	0.5	3.5	No
126	125	17.5	1.19	8	-79.67	-138.15	0.5	0	1	0.5	0.5	2.5	No
127	250	19	1.11	18	-79.76	-139.69	1	0	0	0.5	0.5	2	No
128	400	24	1.18	45	-78.70	-137.18	0.5	1	0	0.5	0.5	2.5	No
129	300	10.5	1.33	6	-78.61	-137.87	0.5	0	1	0.5	0.5	2.5	No
130	600	25.5	1.13	77	-78.39	-139.25	1	0.5	1	1	0.5	4	No
131	425	39.5	1.08	130	-79.00	-142.10	1	0.5	0	0.5	0.5	2.5	No
132	700	31	1.00	132	-78.15	-140.91	1	0.5	1	0.5	0.5	3.5	No
133	675	22	1.00	64	-77.91	-140.89	1	1	1	0.5	0.5	4	No
134	2600	52.5	1.06	1406	-73.71	-126.54	0	1	1	1	0.5	3.5	Yes
135	400	28	1.15	62	-74.69	-127.78	0.5	1	1	0.5	0.5	3.5	No
136	200	4.5	1.25	1	-75.98	-128.21	0	1	1	1	0.5	3.5	Yes
137	1700	47.5	1.16	753	-76.11	-128.64	0	1	1	1	0.5	3.5	No

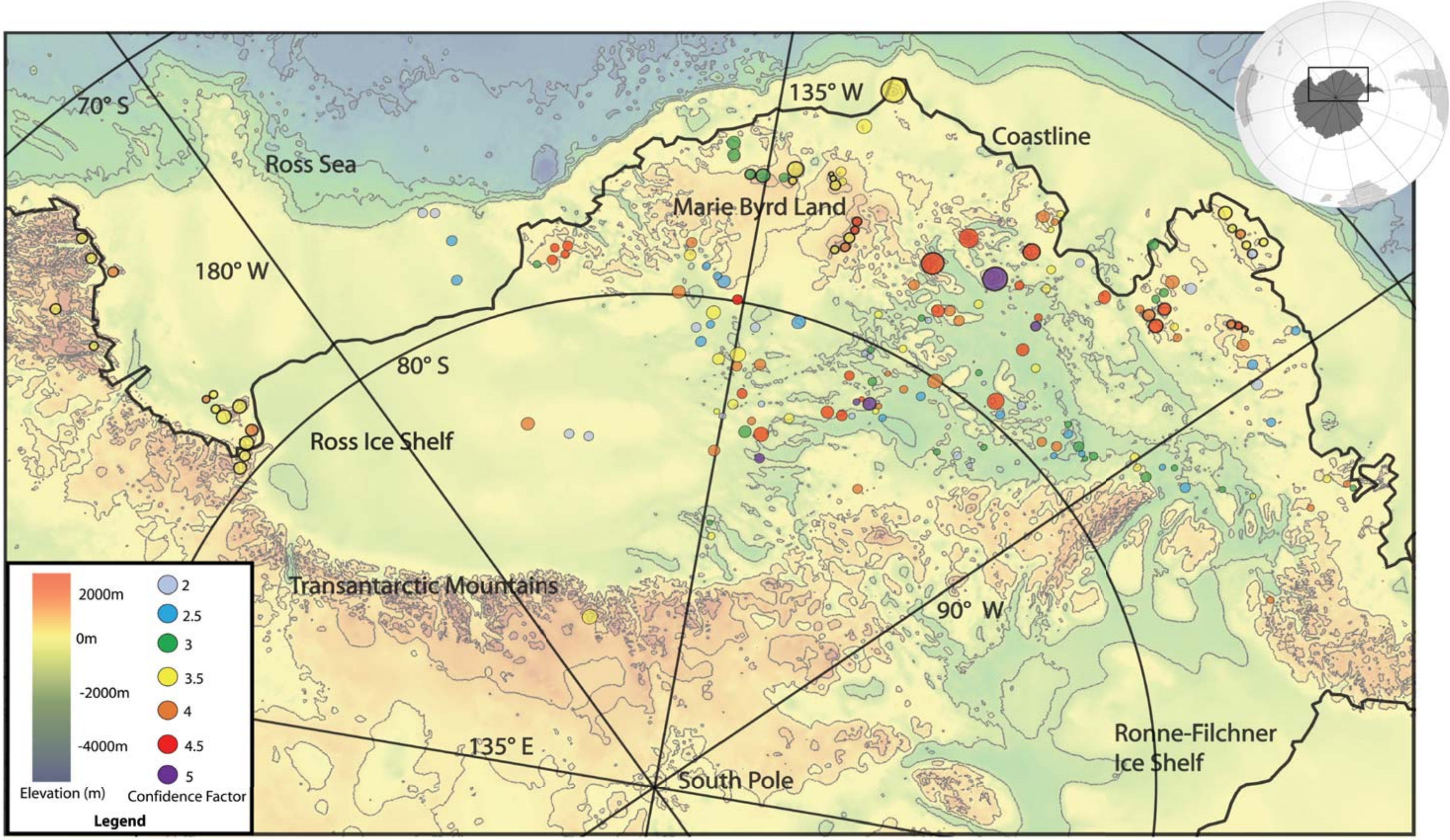
138	325	16	1.13	16	-75.80	-128.57	0	1	1	1	0.5	3.5	No
139	1500	19.5	1.17	112	-75.98	-129.11	0	1	1	1	0.5	3.5	Yes
140	450	5.5	1.20	3	-75.90	-129.29	0	1	1	1	0.5	3.5	No
141	1800	36	1.06	458	-75.98	-132.31	0.5	1	1	0.5	0.5	3.5	Yes
142	900	21	1.00	78	-76.24	-132.63	0.5	1	1	0.5	0.5	3.5	Yes
143	400	5	1.00	2	-76.22	-133.14	0	1	1	0.5	0.5	3	No
144	600	13	1.17	20	-76.27	-135.11	0	1	1	0.5	0.5	3	Yes
145	950	18.5	1.18	64	-76.27	-136.12	0	1	1	0.5	0.5	3	Yes
146	800	9.5	1.11	14	-75.88	-137.95	0	1	1	0.5	0.5	3	No
147	275	19.5	1.17	21	-75.62	-138.08	0	1	1	0.5	0.5	3	No
148	600	8.5	1.13	9	-78.09	-153.87	1	1	1	1	0.5	4.5	No
149	450	21.5	1.15	41	-78.13	-155.26	1	1	1	1	0.5	4.5	No
150	775	23	1.19	80	-77.88	-153.60	1	1	1	1	0.5	4.5	No
151	275	16.5	1.06	15	-77.89	-154.81	1	1	1	1	0.5	4.5	No
152	100	7	1.33	1	-78.19	-157.00	0	1	1	0.5	0.5	3	No
153	125	18	1.25	8	-82.11	-154.71	0	0	1	0.5	0.5	2	No
154	100	16.5	1.06	5	-81.96	-157.64	0	0	1	0.5	0.5	2	No
155	150	24	1.18	17	-81.53	-163.39	1	1	1	0.5	0.5	4	No
156	225	15	1.00	10	-78.00	-165.52	0	0.5	0.5	1	0.5	2.5	No
157	100	12	1.18	3	-77.18	-164.77	0	0.5	0.5	1	0.5	2.5	No
158	1400	34	1.13	318	-85.96	-163.98	0.5	1	1	0.5	0.5	3.5	Yes
159	400	10.5	1.33	9	-78.39	167.56	0.5	1	1	1	0.5	4	Yes
160	325	16.5	1.20	17	-78.50	166.04	0	1	1	1	0.5	3.5	Yes
161	1600	29	1.07	264	-78.61	165.08	0	1	1	1	0.5	3.5	Yes
162	2050	39.5	1.14	628	-78.73	163.67	0	1	1	1	0.5	3.5	Yes
163	2250	33	1.13	481	-77.78	168.67	0	1	1	1	0.5	3.5	Yes
164	1800	29.5	1.19	307	-77.70	166.83	0	1	1	1	0.5	3.5	Yes
165	1250	21	1.10	108	-77.49	166.78	0	1	1	1	0.5	3.5	Yes
166	425	22.5	1.14	42	-77.23	167.68	0	1	1	1	0.5	3.5	Yes
167	350	20.5	1.16	29	-77.18	166.94	0	1	1	0.5	0.5	3	Yes
168	750	16.5	1.20	40	-74.58	164.22	1	1	1	1	0.5	4.5	Yes
169	600	26.5	1.21	83	-73.80	169.69	0.5	1	1	1	0.5	4	Yes
170	950	33.5	1.09	209	-73.42	164.70	0	1	1	1	0.5	3.5	Yes
171	1550	34.5	1.16	362	-72.78	169.89	0	1	1	0.5	0.5	3	Yes
172	750	17.5	1.19	45	-71.93	170.41	0	1	1	1	0.5	3.5	Yes
173	500	25.5	1.13	64	-76.45	-165.16	0	0.5	0.5	0.5	0.5	2	No
174	450	34.5	1.09	105	-76.37	-166.16	0	0.5	0.5	0.5	0.5	2	No
175	450	13.5	1.25	16	-76.12	-72.41	0.5	1	1	1	0.5	4	Yes
176	400	9.5	1.38	7	-73.68	-78.91	0	1	1	0.5	0.5	3	No
177	550	20	1.22	43	-73.70	-79.43	0.5	1	1	1	0.5	4	Yes
178	300	17	1.27	17	-74.67	-78.72	0.5	1	1	1	0.5	4	Yes
Average	621	21.3	1.18	121	-77.56	-120.28	.69	.69	.71	.74	.57	3.40	

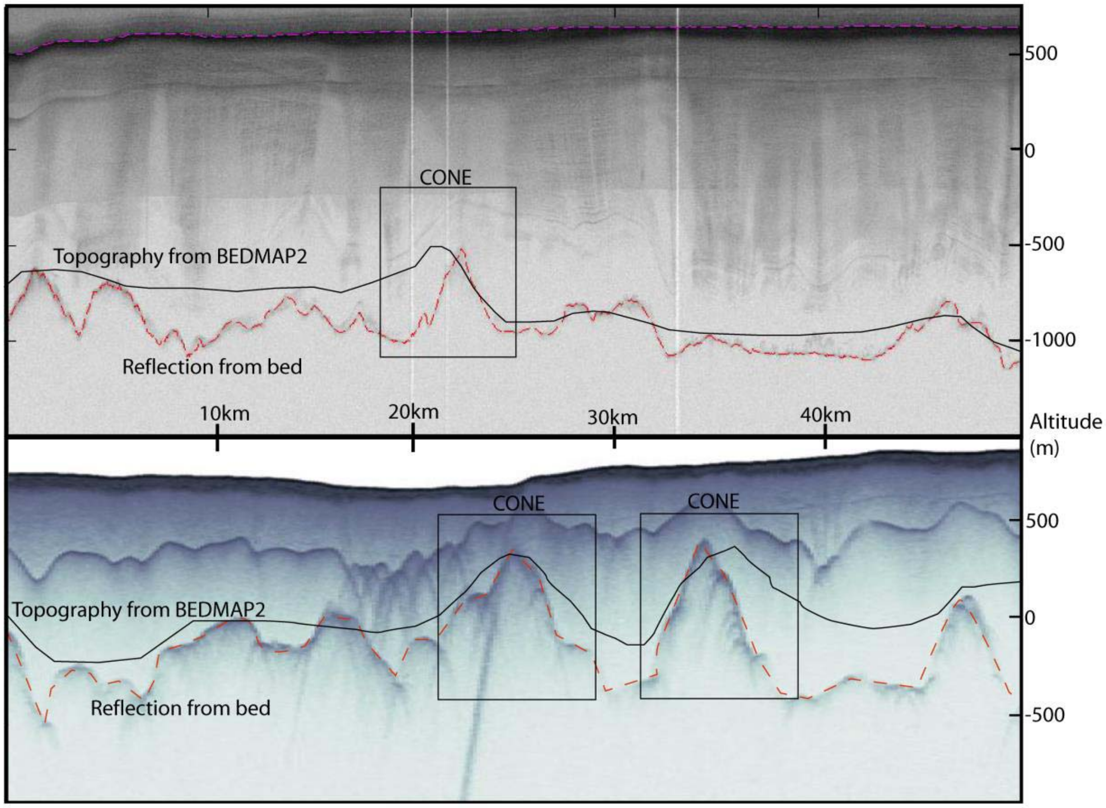
Table 3: Statistical comparison of the morphologies of the cones identified in this study identified as volcanoes (a) with those from a global database of shield volcanoes (b; Grosse et al., 2014). The two are similar apart from the long-short axis ratio; our cones are, on average, more circular than shield volcanoes elsewhere. This could be linked to specific glaciovolcanic eruption mechanisms, but is most likely a data bias due to our detection methods excluding more elliptical edifices.

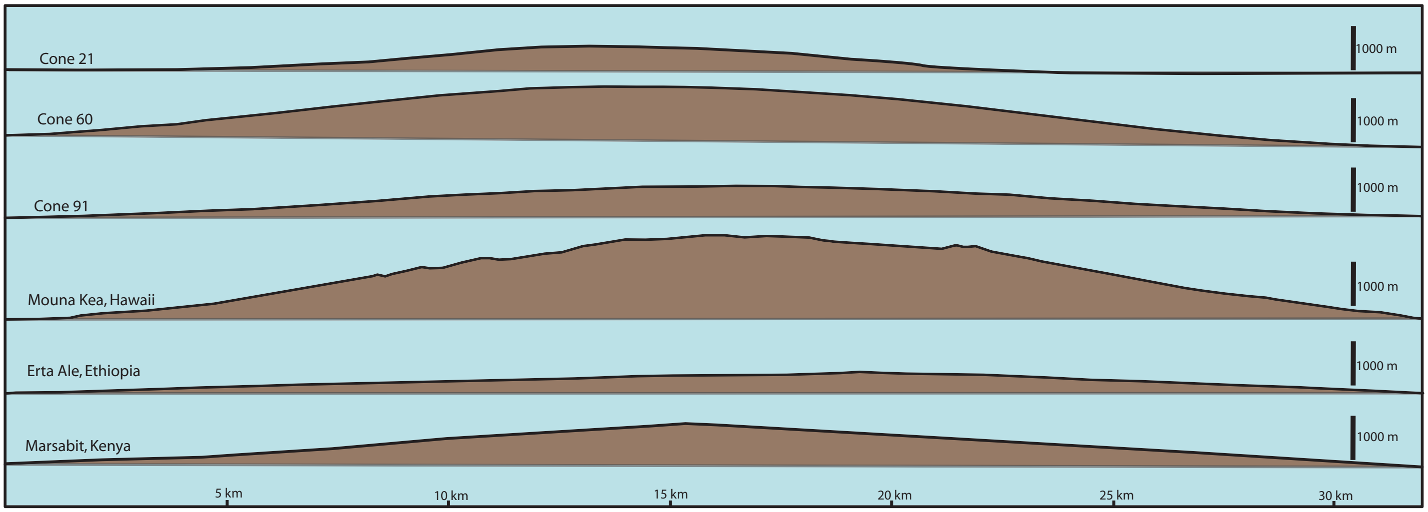
	Height (m)		**Average Diameter (km)**		**Axis Ratio**		**Volume (km^3)**		**Confidence Factor**
	a.	b.	a.	b.	a.	b.	a.	b.	a.
Average	701	940	21.9	17.1	1.19	2.11	144	150	3.75
Standard Deviation	641	670	10.7	11.6	0.09	0.81	345	371	0.56
Median	475	810	20.5	15.3	1.17	1.98	42	31	3.5
Minimum	100	100	4.5	2.3	1.00	1.13	0.5	0.2	3
Maximum	3850	3030	58.5	63.3	1.44	5.23	2542	3086	5

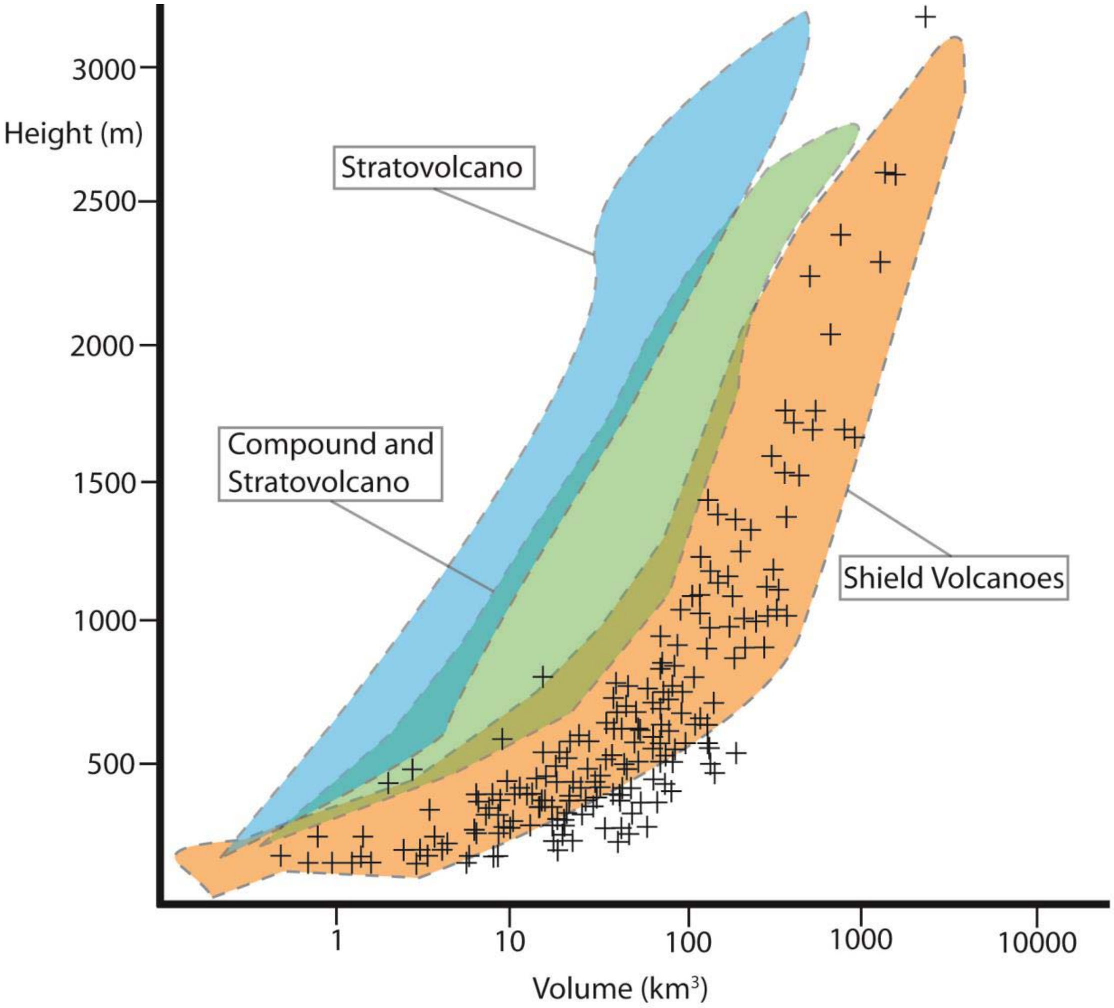


a.
N
1000 km
135°W
75°S
Ross Sea
Marie Byrd Land
180°W
80°S
90°W
Ross Ice Shelf
West Antarctic Rift System
Legend
Volcano
Subglacial Volcano
Transantarctic Mountains
Southern Rift Flank
Ellsworth-Whitmore Block
East Antarctica
135°E
b.
15°N
10°N
5°N
Equator
Somalia
Indian Ocean
Ethiopia
Volcanoes
N
1000 km
Kenya
East African Rift Axis


70° S
Ross Sea
180° W
135° W
Coastline
Marie Byrd Land
80° S
Ross Ice Shelf
Transantarctic Mountains
90° W
135° E
South Pole
Ronne-Filchner
Ice Shelf
2000m
0m
-2000m
-4000m
Elevation (m)
2
2.5
3
3.5
4
4.5
5
Confidence Factor
Legend


CONE
Topography from BEDMAP2
Reflection from bed
500
0
-500
-1000
10km
20km
30km
40km
Altitude (m)
CONE
CONE
Topography from BEDMAP2
Reflection from bed
500
0
-500


Cone 21
1000 m
Cone 60
1000 m
Cone 91
1000 m
Mouna Kea, Hawaii
1000 m
Erta Ale, Ethiopia
1000 m
Marsabit, Kenya
1000 m
5 km
10 km
15 km
20 km
25 km
30 km



3000
Height (m)
2500
2000
1500
1000
500
1
10
100
1000
10000
Volume (km³)
Stratovolcano
Compound and Stratovolcano
Shield Volcanoes