Geomorphology of Two Seamounts Offshore Ascension Island, South Atlantic Ocean

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***Abstract*- Ascension Island is an intra-plate volcanic island in the South Atlantic Ocean, located 80km west of the Mid-Atlantic Ridge (MAR) and 50km south of the Ascension Fracture zone. The onshore lithologies show a magma chamber evolution from basic to felsic and physical textures suggest deposits erupted within the past several hundred years. The subaerial portion of the island accounts for less than 1% of the volcano's total volume and the 60km basal diameter lies in 3200 meters water depth. It lies on a 5- to 6-million-year-old portion of the South American Plate, between magnetic anomalies 3 and 4. The volcano emplacement may have caused significant crustal loading.**

Ascension Island's offshore geology has not been studied in much detail, in part because of its remoteness. During a July 2002 engineering survey, high-resolution data were acquired for portions of the island's eastern slope, which includes two seamounts. These seamounts have significantly different geomorphology.

A prominent northwest-trending ridge deepens from the Ascension volcano to the slopes of what was regarded as the northern seamount for the duration of the survey. The seamount rises to within 800m of the ocean surface and deepens to 3800m. Its basal diameter is approximately 16km and it is nearly conical in relief. Geomorphic features suggest it is the result of several flank eruptions. Detailed imagery delineates areas of exposed rock, rock debris, channelized deposits, and sediment ponds. Channel systems, probably created by slope failures, emanate near the central portion of the seamount, forming a radial pattern. Steep slopes outline numerous semi-circular terraces, giving the seamount a stepped appearance. These terraces appear to truncate against the northwest trending ridge, suggesting that seamount eruptions postdate a majority of the Ascension eruptions. The ridge is likely an extension of a regional northwest trending structure, a possible conduit from the Ascension mantle chamber to the seamount. This shoal does not appear to be a seamount by definition, but rather an eruptive center on the flanks of the Ascension volcano.

Along the southern slope north-south trending ridges appear at the base of the Ascension volcano. These structures probably formed as a result of MAR extensional tectonics or by dike intrusion that accommodated extension and crustal loading. Graben-like depressions between these structures suggest that they are fault controlled. High-resolution acoustic imagery suggests a relationship between the north-south trending structures and a prominent northeast-southwest elongate seamount. The base of the seamount is in 3200m water depth, it rises to 1540m, and its dimensions are 9km by 19km. Geomorphology suggests that this seamount is a Peléean dome. It is relatively flat-topped, covered locally by sediment, and has a central craggy ridge trending the length of the dome. A debris apron flanks its steep, rocky slopes and there are indications that pyroclastic flows may have emanated from the northern side. The dome probably erupted from one of the north-south trending structures.

I. INTRODUCTION

A. Regional Setting

Ascension Island is an intra-plate volcanic island [11] located in the southern Atlantic Ocean at 7.95°S and 14.37°W (Fig. 1). It is approximately 80km east of the Mid-Atlantic Ridge (MAR) and 50km south of the Ascension Fracture Zone (AFZ), which is the first right-lateral offset of the MAR south of the equator (Fig. 2). The proposed origin of the Ascension volcano is a hot spot located about 225km to the southeast of the volcano's present location [15]. This hot-spot may have been the origin for two "proto-Ascension" seamounts, labeled 1 and 2 on Fig. 2, that were translated west by seafloor spreading.

Fig. 1 The location of Ascension Island.

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14. ABSTRACT

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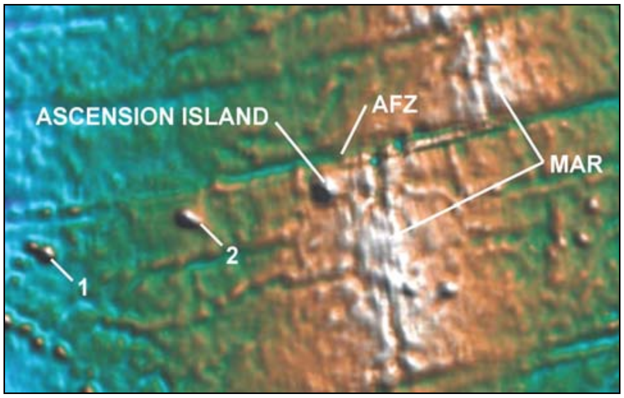

Fig. 2. The Ascension volcano, the AFZ, and the MAR. Note the two seamounts labeled 1 and 2, which may be "proto-Ascensions." Sun-illuminated bathymetry from [25].

The location of the Ascension hot spot has been inferred from geophysical and geochemical anomalies. Recent geophysical investigations suggest that the region along the MAR south of the AFZ may not dominated by an extensive hot spot, but rather by the melting of mantle heterogeneities originating from less than 200km deep [2].

The MAR is a relatively slow seafloor-spreading center and current estimates report a spreading rate of 35mm per year along a complex region that extends approximately 1000km south of the AFZ to the Bode Verde Fracture Zone (BVFZ) [2]. The central rift trends approximately N10°W where it intersects the N78°E trending AFZ [1]. South of this intersection and north of the BVFZ, [2] have identified three ridge offsets that separate the MAR into four second-order spreading segments. The Ascension volcano and the northern seamount of this paper lie within the northernmost second-order segment, labeled A1. This segment is approximately 90km long and is characterized by a well-defined rift valley with over 1000m of relief and significant seismicity.

The southern seamount of this paper lies on the boundary between the A1 and A2 segments. The A2 segment is more complicated in structure: two ridge axes can be defined from magnetic modeling, the segment appears to be magmatically inflated, and there is low seismicity. A discontinuity separating the A1 and A2 segments right-laterally offset the MAR axis about 20km. The off-axis trace of this discontinuity forms a discordant zone that disrupts the ridge parallel seafloor fabric in a NE-SW trending fashion, approximately 45° to the direction of seafloor spreading.

Regional trends adjacent to the Ascension volcano pedestal include ridges oriented N60°W and N55°E [1], the latter of which may be related to the discordant zone separating the A1 and A2 second-order spreading segments. These trends are reflected in structures onshore Ascension Island as well as on the two seamounts east of the Ascension volcano [15].

Sediment primarily accumulates in local depressions along the steep, rugged MAR terrain. Seafloor sediments thicken away from the MAR and range from 250m to 340m near the Ascension volcano [27]. They continue to thicken to the west and are anonymously thick locally within the AFZ, to about 0.53km.

Seismicity near the Ascension volcano is concentrated on the MAR, the AFZ, and on the ridge-transform intersection. Minor earthquakes occur nearly every other day and all are centered outside the Ascension volcano. A recent study by [8] recorded a range of earthquake magnitudes from 0.4 to 4.2. They were shallow events, with hypocenters ranging in depth from 500m to 2500m. Many events lacked body-wave energy, which suggests an anomalously slow energy release resulting in strong surface waves.

B. Ascension Island Geology

The subaerial portion of Ascension Island has an area of approximately 98km^2, accounting for approximately 1% of the volcano's total volume [15]. It rises 879m above sea level to its highest elevation at Green Mountain. The base of the volcanic edifice lies in about 3200 meters water depth and the basal diameter is approximately 60km. The volcano is on a 5-6 Ma portion of the South American Plate, between magnetic anomalies 3 and 4 [27].

The onshore volcanic rocks comprise a transitional to mildly alkaline basalt-hawiite-mugearite-benmoreite-trachyte-rhyolite series lava flows, trachytic domes, scoria cones, and pyroclastic deposits [11]. By volume, 43% of the rocks are mafic, 43% are trachyte and rhyolite, and 14% are pyroclastic flows (pumice and scoria).

Geochronologic ages from onshore rocks indicate that felsic lithologies are significantly older than mafic deposits. Felsic rocks range in age from 1.2 Ma to 0.56 Ma, mafic volcanic rocks range from 0.47 Ma to 0.12 Ma, and basaltic dikes are 0.80 Ma [11]. There have been no historic eruptions since the island was permanently inhabited in 1815. However, physical textures suggest that the most recent deposits erupted less than 500 years ago. Offshore lithologies have not been studied [28], in part because of the volcano's remoteness.

Trace element comparisons from Ascension Island and other South Atlantic volcanic islands suggest they have different magma sources and the magma chambers have been isolated for several hundred million years [28]. The isotopic combinations for Ascension Island are also significantly distinct from MAR basalt samples and therefore must have a different source region. Geochemical evidence suggests the source area for the Ascension Island volcanics is an ancient subducted slab with considerable sedimentary rocks that was diluted by the upper mantle.

Trace element characteristics and radiogenic isotope compositions differentiate four distinct basalt and hawaiite rock types that erupted at different island localities, suggesting heterogeneity in the magma source region. Strontium trace element ratio values from granitic xenoliths found within lava and pyroclastic flows suggest there was a hydrothermally altered pre-existing volcanic basement that may have assimilated during felsic magma differentiation. Furthermore, strontium ratios from felsic rocks suggest that the magma chamber was contaminated by seawater [11].

Fault orientations on Ascension Island include north-south, east-west, northwest, and northeast [15]. Northeast trending faults on Green Mountain are normal faults and the sense of motion is not discernable in other fault trends. The east-west trending faults do not show strike slip components even though they are parallel to the AFZ.

All onshore structural trends have controlled volcanic eruptions. Faults in the northwest and southwest controlled flows in their respective locations. East-west faults controlled flows to the eastern portion of the island [15]. The youngest pyroclastic and lava flows have erupted from faults, which suggests the fractures are deep-seated and recently active. Fault orientations may reflect regional structures but have apparently developed radially around the island as a result of intrusive uplift.

The volcanic edifice may be a substantial load on the underlying lithosphere. Regional bathymetry shows a 200m deep moat in the south and west of the volcano [13], which may be the result of subsidence. Geothermal well explorations noted the presence of hyaloclastites from 1000m to 1790m below present day sea level. These normally form in shallow water and may indicate 1.2km to 2.0km of subsidence that is possibly the result of lava accretion.

A steep gravity gradient indicates lateral density variations within the volcano. Reference [13] reports that the lithosphere responded to the Ascension volcano load by flexure equivalent to an elastic plate 3±1km thick (Fig. 3A). This flexure may be attributed to the combined effects of bending stresses by the high curvature beneath the island, localized heating of the lithosphere during emplacement of the island, and crustal thickening. Flexure of this extent would indicate a weak lithosphere.

Contrary to the lithospheric flexure model, a more recent geophysical investigation [14] suggests that Ascension Island formed adjacent to the MAR and gravity anomalies are primarily attributed to an over-thickened oceanic crust directly above the volcanic edifice (Fig. 3B). Additionally, the moat around the island previously attributed to crustal flexure is likely a result of crustal accretion during the earliest volcanic stages. However, additional gravity modeling confirmed that there has been some minor lithospheric flexure beneath the island and current research is underway to better understand this relationship with Ascension volcano subsidence.

In addition to evidence for subsidence, studies indicate that the island may have undergone minor uplift. Ascension Island translated west through seafloor spreading and sea level relative to fixed positions on the island should have risen with increasing water depth. However, wave cut platforms and paleo beach deposits indicate that there were decreases in sea level, which are probably the result of sea level fluctuations [17]. An alternative explanation for the apparent fall in sea level may be westward translation followed by intrusive uplift.

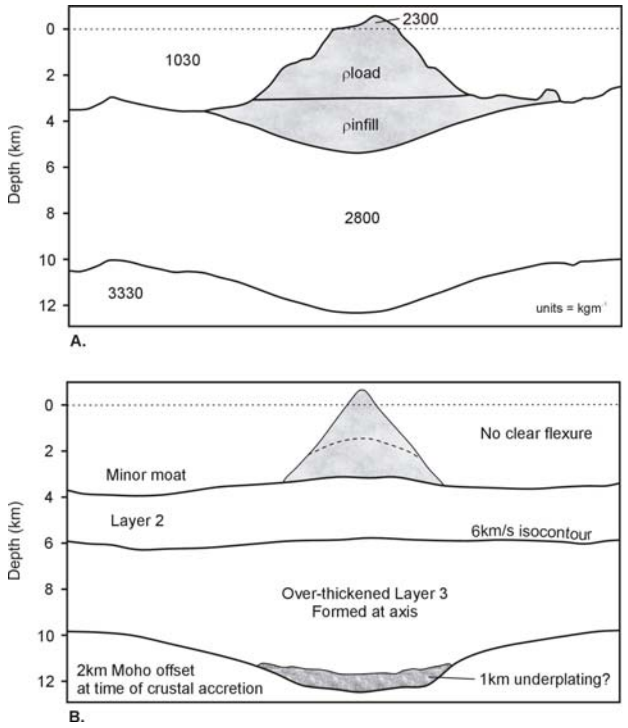

Fig. 3 Two opposing models for lithospheric flexure at the Ascension Volcano. A. Model showing flexure equivalent to an elastic plate 3±1km thick [13]. B. Model showing an over-thickened crust, with no lithospheric flexure [14].

C. Thales Survey

Thales GeoSolutions (Pacific), Inc. was contracted by Sound & Sea Technology to conduct a geophysical seabed survey for the Hydroacoustic Data Acquisition System (HDAS) project at Ascension Island, which will be part of the monitoring systems for the Comprehensive Test Ban Treaty. The survey was conducted for MCA Engineers, Inc. (MCA) on behalf of the Naval Facilities Engineering Service Center (NFESC). Survey operations took place between June 13 and July 29, 2002, from the survey vessel *R/V Baruna Jaya III* (Fig. 4). Routes were identified for two cable installations connecting underwater acoustics monitoring systems with a shore-based data acquisition and transmission facility at Ascension Island.

The offshore survey extended from shore to proposed locations for the acoustic monitoring arrays. One of these arrays is located approximately 27 km to the northwest of the landfall and the other is approximately 116 km to the south (Fig. 5). Data acquired in order to characterize the seabed and identify suitable cable routes includes single-beam bathymetry, multibeam bathymetry (two systems), sidescan sonar, multibeam backscatter imagery, and shallow seismic reflection profiles.

Areas of approximately 20km^2 were surveyed at each of the two proposed hydrophone locations, which were regarded as the northern and southern seamounts throughout the duration of the survey. Data collected at these deep-water localities includes multibeam bathymetry and multibeam backscatter intensity data that was acquired with a Simrad EM12D, a full ocean depth 13 KHz multibeam echosounder (MBES) designed to operate in water depths from 50m to greater than 11000m.

Fig. 4: The R/V Baruna Jaya III.

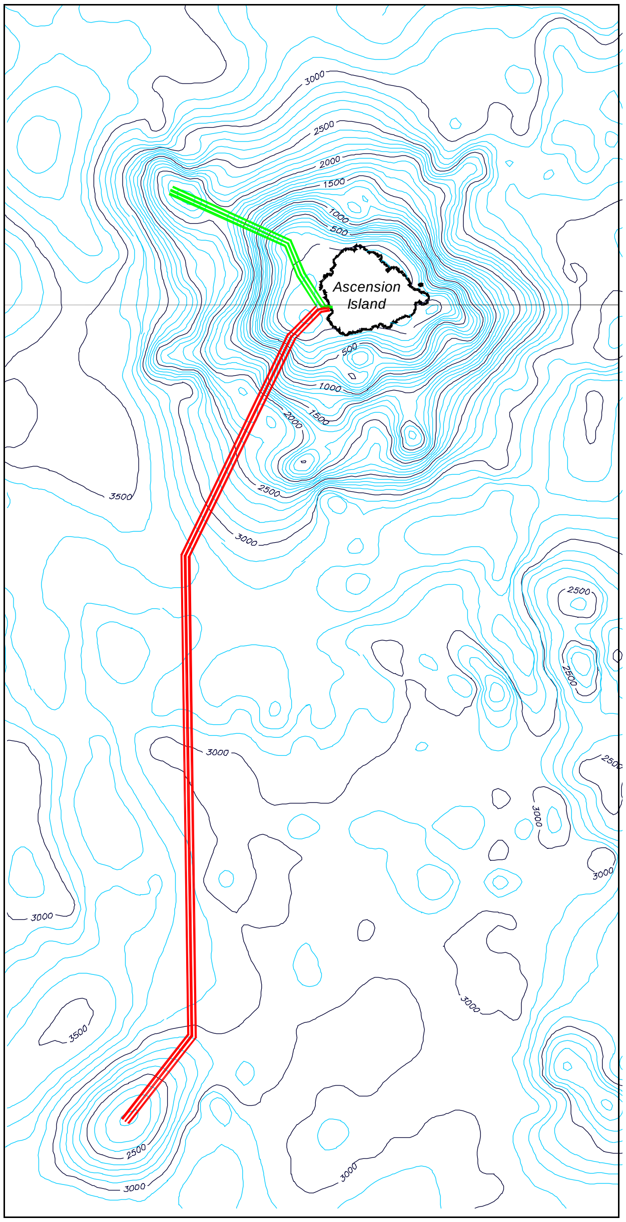

Fig. 5: Ascension Island with regional bathymetry generated from satellite altimetry [25]. The northern and southern survey corridors are shown in green and red respectively. Areas of approximately 20km^2 were surveyed at the end of each survey corridor.

During this survey, the EM12D collected data between 345m and 3650m water depths. Bathymetry data and backscatter imagery were processed onboard the *R/V Baruna Jaya III* immediately after data acquisition. The data presented in this report for the two seamounts is presently the highest resolution seafloor imagery acquired offshore Ascension Island.

II. NORTHERN SEAMOUNT

The northern seamount is located at 7° 50' S, 14° 35'W. It is a 549.9km^3 conical structure with a basal diameter of approximately 16km lying in about 3600m of water. A gently sloping saddle on its southeastern side separates the seamount from a prominent N60°W trending ridge that shoals on the Ascension volcano flank (Fig. 6). Regional bathymetry suggests that this ridge is a more extensive geomorphic feature than the survey data alludes.

The data suggests that this seamount is an eruptive center on the flanks of the Ascension volcano. The seamount's summit lies in about 800m of water. It is craggy and elongated in direct trend with the above-mentioned ridge. The volcano itself is perhaps the continuation and terminus for the northwest trending ridge system.

The seamount slopes are relatively steep with numerous channels radiating from the summit. The slopes appear to be constructed of successions of lobate flow units that give the slopes a hummocky appearance. These flows have a terraced appearance that appear to truncate against or overlap onto the Ascension volcano, suggesting that the seamount had several flank eruptions that are younger than the Ascension volcano's basal flows. A potential rotational slope failure is seen on the southwest side of the seamount with the head scarp about two-thirds of the way up the seamount. Lithologic and sediment units identified from multibeam backscatter imagery (Fig. 7) include rock, areas of scattered rock, rock partially covered by sediment, slope or channeled debris, and coarser and finer-grained sediments. Prominent narrow channels extending from the summit area of the volcano were probably produced by cold slope failures as loose volcanic material accumulated over time and became unstable. However, these channels could also have been formed by pyroclastic flows during eruptions. Backscatter imagery suggests these channels are filled with coarser-grained sediments.

Since the seamount appears to be younger than the Ascension volcano's basal flows and the youngest volcanic rocks on Ascension Island are mafic, the volcanic rocks on the seamount are potentially basalts. Sediment accumulations and channelized deposits are likely to be hyaloclastites and pelagic mud.

The northwest trending structure noted both in regional studies and onshore Ascension Island is also evident in the shape of the island pedestal. There is a well-defined northwest trending fault system on the island from which the most recent eruptions on Green Mountain occurred [15]. Studies of eruptions from northwest trending faults at other locations on the island suggest that these are deep-seated structures.

There is no evidence of faulting from the survey data; however, regional geology suggests that the northwest trending ridge as well as formation of the seamount may be fault controlled. A northwest trending fault system may penetrate the Ascension volcano magma chamber and serve as an eruptive conduit for the seamount.

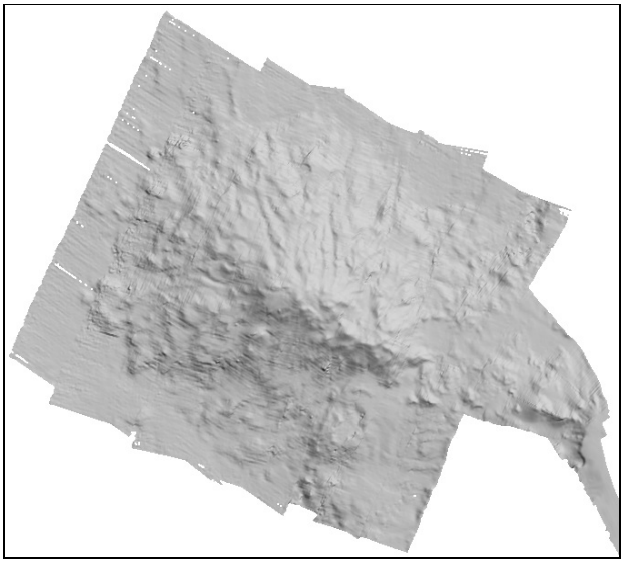

Fig. 6: Sun-illuminated bathymetry for the northern seamount.

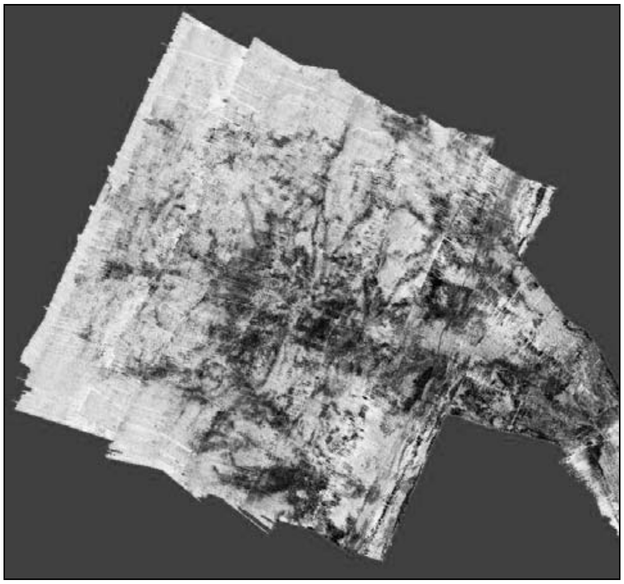

Fig. 7: Multibeam backscatter image of the northern seamount.

A summit caldera is conspicuously absent on the seamount. The lack of calderas or other collapse structures on the Davidson, Guide, Pioneer, Gumdrop and Rodriguez seamounts located in the northeastern Pacific led [4] to believe that these lacked shallow storage reservoirs, at least during their later eruptive stages. The lack of a summit caldera on the seamount may further suggest that eruptions occur from a conduit and not from a magma chamber directly below the seamount.

Since there is no seismic activity in the vicinity of the Ascension volcano [8], it is possible that the potential magma conduit has annealed and there may be no potential for future volcanic activity at this locality. However, given the recent onshore fault controlled volcanic events, it is plausible that this seamount may erupt in the future.

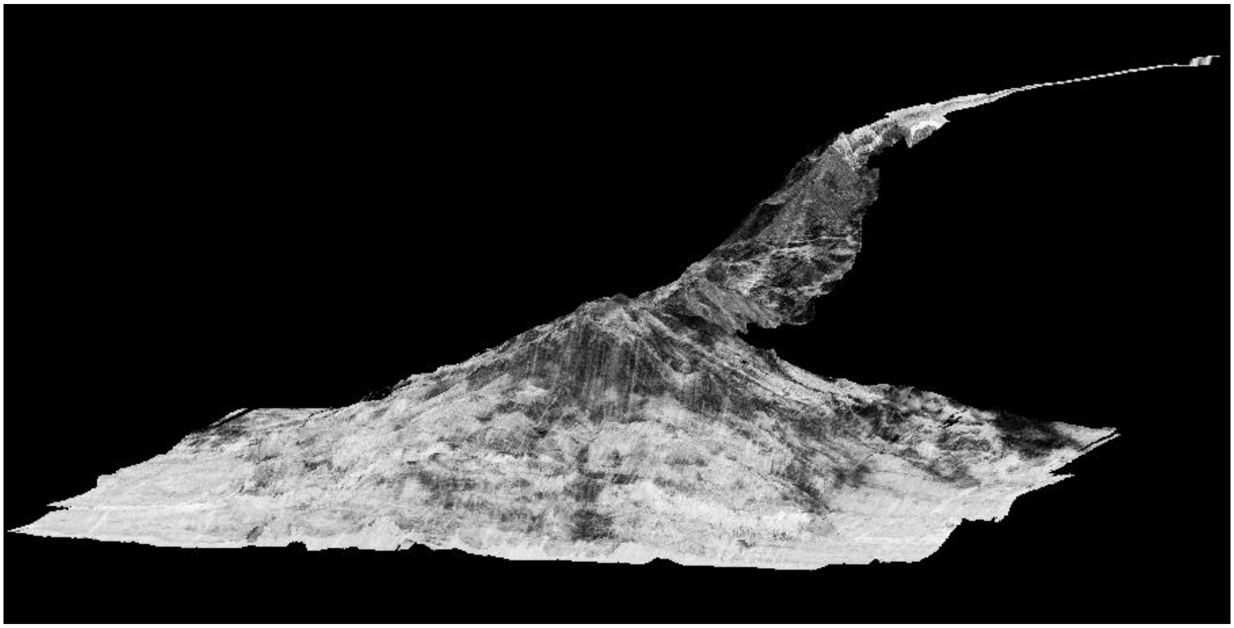

Fig. 8: Multibeam backscatter imagery, draped over bathymetry data, crating 3D perspective view of the northern seamount. Looking southeast.

III. SOUTHERN SEAMOUNT

The southern seamount is located at 8° 57’S and 14° 38’W, approximately 116km southwest of Ascension Island and 100km west of the MAR. The base of the 204.1km^3 seamount is in approximately 3200m of water. It is approximately 19km by 9km, oval shaped in plane view, with a somewhat truncated eastern end (Fig. 9). It is steep sided and has a relatively smooth upper surface with prominent crags along its central axis. These crags may be cooling features formed by off gassing and dewatering as the lava cooled. The summit of the seamount rises to a water depth of 1500m and the greatest relief from the surrounding seafloor is exhibited in the southwestern portion. As with the northern seamount, a summit caldera is conspicuously absent, suggesting the absence of shallow magma storage.

The geomorphology of the seamount suggests that it either erupted from successive lava sheet flows or is a lava dome type structure. Along the northwest to southwest end of the seamount, slopes are relatively smooth and a terraced appearance is on the southwest flank. This along with the steep leading edges may suggest lava sheet flows. Surface lava flows and their morphology are controlled by variables such as lava viscosity, effusion rate, cooling rate, and underlying slope [24]. A relation in submarine lava flows exists between the rate of eruption and controls on flow morphology, where higher eruption rates tend toward smoother lava flows [7] and low angle flows may have steep leading edges.

Alternatively, the seamount may be a lava dome type structure. Lava domes typically represent extremely sluggish, thick, extrusions of viscous magma. As lava extrudes, the outer surface cools and the interior remains viscous for an extended period of time. The surface becomes rough and blocky as a result of fragmentation of the cooler, outer crust during growth of the dome. Each successive increment of lava pushes earlier erupted material outward.

The southern seamount may represent a Peléean type dome (Fig. 11). These type domes are characterized by lava spines that form along the crest and steep sides that are flanked by cold slope debris from collapsed pinnacles. Incandescent rocks from within the core may be exposed on leading edges, forming explosive block-and-ash pyroclastic flows.

The craggy median of the seamount may have formed during dome growth and/or as cooling features. Debris slopes are present on all sides of the seamount and prominent linear features on the northern side of the dome, evident in sun-illuminated bathymetry, suggest very rapid movement that may be a result of explosive fragmentation of magma. These linear features have a “wishbone” appearance, emanating from a central point.

Lithologic and sediment units identified from multibeam backscatter imagery include rock, scattered rock, rock covered in sediment, slope debris, and finer-grained sediment. No samples were collected and therefore the seamount’s true lithologies remain unknown. Sediments are probably pelagic mud.

The seafloor between the Ascension volcano edifice and the southern seamount is characterized by a series of north by northwest trending ridges and intervening depressions that are probably grabens (Fig. 12). The spacing between ridges is roughly 3km. A second north by northeast trending structure is also present, which appears to truncate the northwest ridges that continue to the south.

The north by northwest trending ridges and grabens could have form through extensional tectonic processes at the MAR or by shallow dike intrusion. The ridges appear to be parallel to the MAR, which is less than 100km to the east. It is possible that these ridge and grabens formed on the MAR and were translated west during seafloor spreading.

The north trending ridges could have resulted form hypabyssal dike intrusion. Dike intrusion is common in rift zones and results as an accommodation to extension [18]. They intrude perpendicular to the direction of least compressive stress and may be influenced by the combined effects of mass loading and the regional stress field. Dikes intrude within 2km to 4km of the surface, the depth of which is due to the combined effects of neutral buoyancy (where magma and crustal densities are equivalent) and decreased tensile strength of rocks in the shallow crust. A graben forms above and parallel to the dike and the width is proportional to the depth and size of the dike. Thin skin normal faults die down toward the top of the dike.

As mentioned, previous geophysical studies have shown that the young, buoyant lithosphere responded to the Ascension load by flexure, which has been attributed to the combined effects of bending stresses by the high curvature beneath the volcanic edifice, localized heating of the lithosphere during emplacement, and crustal thickening. This flexure combined with the regional stress field would have produced extension directly beyond the crustal loading, which may have been accommodated by dike intrusion.

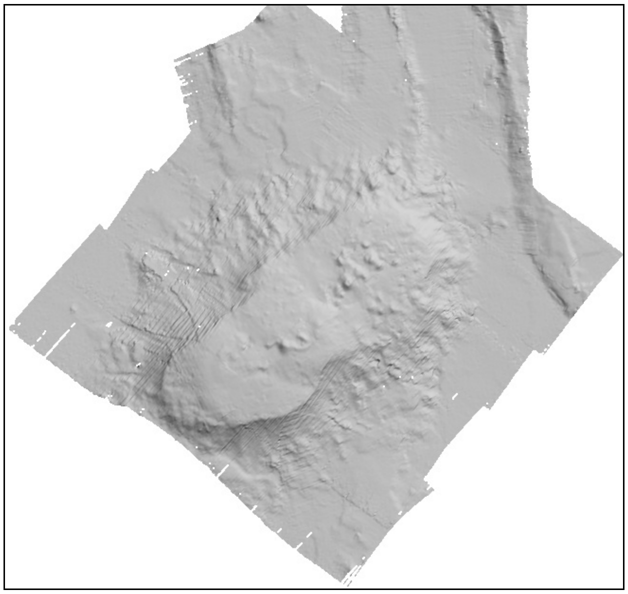

Fig. 9 Sun-illuminated bathymetry for the southern seamount.

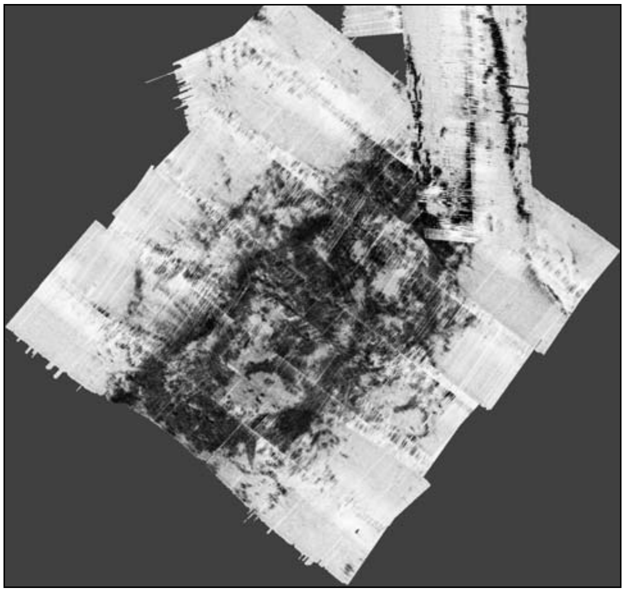

Fig. 10 Multibeam backscatter image of the southern seamount.

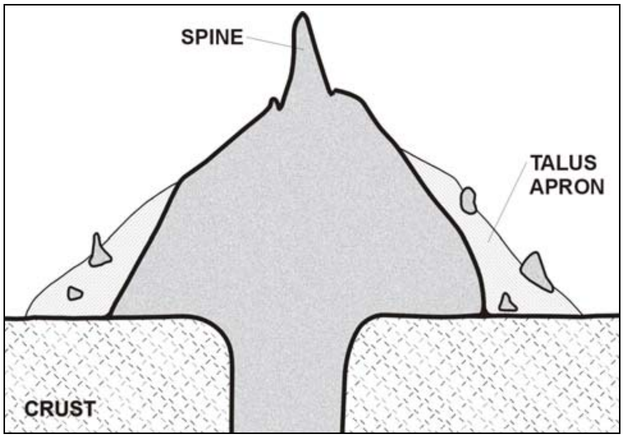

Fig. 11: Cartoon showing a typical Peléean type lava dome.

The north by northeast trending structures are probably remnants from the discontinuity that separates second-order spreading segments A1 and A2. Cross cutting relationships suggest that the north by northeast trending structures formed prior to the north by northwest trending ridges. The north by northeast trending structures may have also formed as a result of dike intrusion. There is approximately a 25º difference between the two structures.

The north by northeast trending structures are to the south of the above-described area and found throughout the southernmost survey area. The area between rock ridges that the survey route traverses before reaching the seamount is an approximately 5km wide depression that is probably a graben. The northeastern most portion of the seamount is either cut by one of these structures or covers it. Signatures on the multibeam backscatter image suggest the latter is case and the seamount may possibly be related to this or another structure directly to the north of the central portion of the seamount.

Regional bathymetry derived from satellite altimetry suggests the seafloor deepens to the west of the seamount and survey data shows that the seafloor deepens into the potential graben where the northeastern portion of the seamount lies. The seamount probably erupted through one of the north by northwest trending structures. The structure responsible for the dome's extrusion could either have been one that the seamount intersects on its northeastern portion or one that may be directly to the north of its summit. The lava surface probably cooled quickly while the hot interior flowed downhill, dragging the blocky, cooled surface to the southwest. Lava would have continued to intrude the seamount along an interior conduit to the downhill area that remained molten, ultimately giving this portion shallower bathymetry. Alternatively, the lava dome may have erupted from a north trending structure directly below the dome's summit and flowed to the northeast into the 5km wide graben previously described.

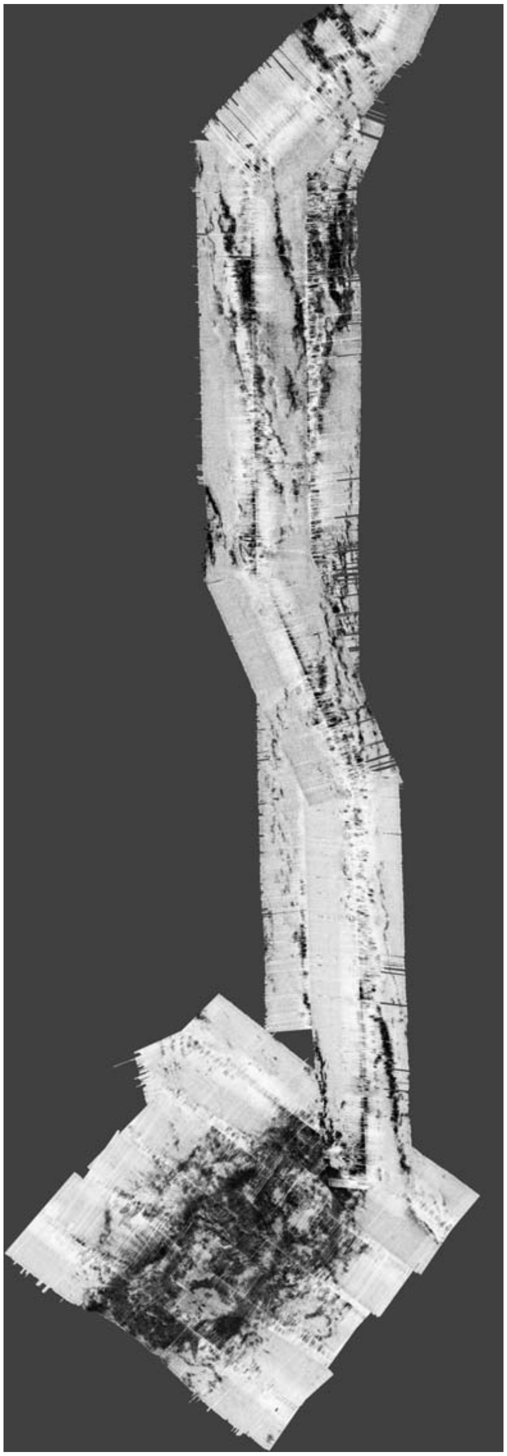

Fig. 12: Multibeam backscatter imagery, showing the area between the Ascension volcano and the southern seamount. High-backscatter (dark) linear features are rock ridges.

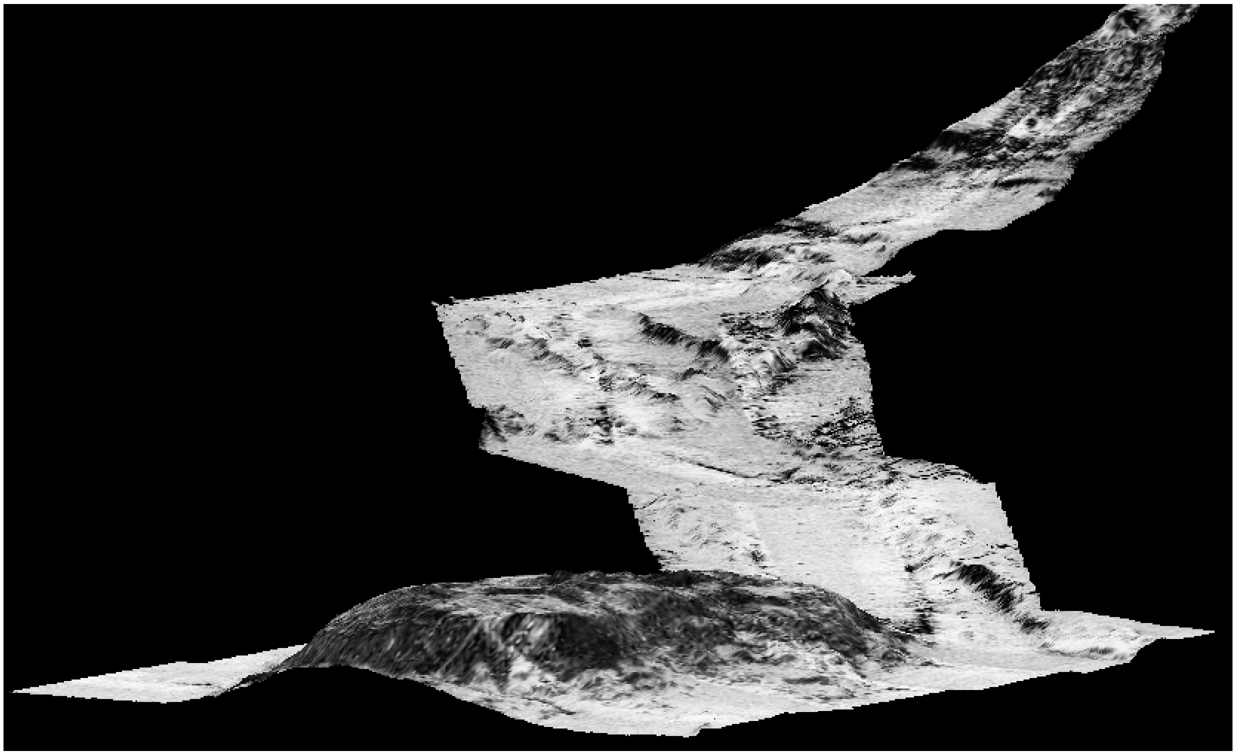

Fig. 13: Multibeam backscatter imagery, draped over bathymetry data, crating 3D perspective view of the southern seamount. Looking northeast.

IV. CONCLUSIONS

This survey has imaged two seamounts that were constructed under similar conditions yet demonstrate widely deferring morphology. They are relatively close in proximity, are in similar water depths and are within the same tectonic setting. The northern seamount is a large conical structure composed mostly of flank eruptions and a well-developed debris channel system. The southern seamount is composed of either a combination of sheet flows or as a Peléean type lava dome.

The seamounts were formed in similar water depths and therefore the different styles of construction may be attributed to differences in magma viscosity and the effusion rate of eruptions. The differences in viscosity and effusion rate can only be attributed to the two seamounts having different magma sources. This idea is consistent with the belief that permanent magma chambers are not commonly found along slow-spreading ridges such as the MAR. Instead, small magmatic bodies rise in the crust to feed locally axial volcanoes [10].

The northern seamount's close proximity to the Ascension volcano, the correlation of the summit with the northwest trending ridge, and the overlapping relationships deposits with the basal portion of the Ascension volcano suggests that the seamount originated as Ascension flank eruptions. Due to the orientations of the southern seamount to the ridge and graben structures that so closely parallel the MAR, it can be concluded that the southern seamount probably originated from MAR volcanic processes as apposed to hot-spot related processes suggested for Ascension Island.

Direct sampling at both seamounts followed by geochemical comparisons may lead to a better understanding of the seamount's differences, their formation, and potentially to ridge-hot spot interactions in general.

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