Forensic geomorphology of Volcan Ecuador, Galapagos: Collapse, lateral eruption or both?

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Non Technical Summary

Shield volcanoes such as Hawaii, The Canary islands, and the Galapagos are known to erode rapidly after they become extinct. This erosion can lead to massive landslides both on land and in the water. Most volcanoes in the world are known to have had some kind of collapse, which is occasionally associated with landslides. Volcan Ecuador is a volcano that is located on the northwestern tip of Isabela Island has experienced a collapse sometime in the last 100000 yBP that caused the volcano to lose it westernmost half. The goal of this project was to determine the volume of material that was transported to the sea during the collapse of this volcano, and from that information, further characterize the type of collapse that occurred. I would also like to determine the probability that a tsunami occurred as a result of this collapse. Using a mapping system on board the R/V Thomas G. Thompson in January 2006, data were collected which were then put into ArcGIS so that they could be used to reconstruct both the volcano and the submarine slope prior to eruption. The volume difference of the bathymetry was found by using the software to subtract the current bathymetry image from the prior reconstructed bathymetry image. The volume difference of the reconstructed volcano and the current remnant was determined by calculating the volume for each volcano and then subtracting the two. The volume calculations show that the landslide debris lobe that was mapped off the coast is only equivalent to 58% of the material missing from the volcano, but is greater than the volume of the material eroded from the upper submarine slope. The conclusion is that the volume of the landslide off the coast originated from the upper slope instead of from the volcano above. The material that is missing from the volcano is believed to have slid off into the ocean to depths of 3000 m.

Acknowledgements

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I would also like to send thanks to Gabrielle Rocap, Seelye Martin, Roy Carpenter, Mark Holmes and Llyd Wells for their magnificent comments on both my papers and my presentations. Their comments have allowed me to do my best on this project and its presentation to you.

Abstract

Shield volcanoes such as Hawaii, the Galapagos, and the Canary islands are known to decay rapidly once they become extinct. The decay can result in huge landslides that involve large sub aerial and submarine portions of the island. Volcan Ecuador, located on the westernmost tip of Isabela Island in the Galapagos Archipelago, was apparently subjected to a massive collapse approximately 100,000 yBP. The goal of this study was to determine the volume of the material that was transported during this collapse, to further characterize the type of sector collapse that occurred, and to assess the probability that the collapse triggered a tsunami. Using a high-resolution multi-beam mapping system on board the *R/V Thomas G. Thompson* in January 2006, data were collected which were then used to create a digital bathymetric model (DBM). The volume of the inferred landslide was determined by reconstructing the submarine flank prior to collapse and subtracting it from the DBM. In similar fashion, the volume missing from the volcano was estimated by subtracting the volume of the current volcano from the volume of the digitally reconstructed volcano. Comparison of the missing volume from the volcano to the inferred volume of the landslide suggests that only 58% of the missing volume can be accounted for. The 'missing' material could have been ejected into the atmosphere (in the case of an eruption) or have been carried away by the strong currents (in the case of a sub aerial/submarine landslide). Alternatively, the pre-collapse model of the volcano could have been substantially in error. The most likely explanation is that the 'collapse' involved both a lateral eruption and a massive landslide.

Introduction

The Galapagos Islands are located off the northwest coast of South America and are a chain of hot spot produced volcanoes. Recent radiometric dating studies of Espanola show that some of the islands have been present for at least the last 3.3 million years (Bailey 1976). The oceanic crust that the islands are built on is not older than 10 million years (Simkin 1984). The spacing and locations of the volcanoes in the Galapagos Islands all seem to lie along and parallel to a northwesterly axis as seen in Fig. 1. Most volcanic eruptions occurring in the Galapagos have created a line of vents along this axis rather than a central vent (Simkin 1984). Fig. 1 also shows the location of the islands and their corresponding volcanoes.

A sector collapse occurs when a flank or the dome of a volcano becomes unstable and subsequently collapses as a release of stress. There are two types of sector collapses, lateral and vertical; both are common in oceanic islands. Vertical collapses are usually associated with explosive eruptions and the effusion of lava, and most are characterized by the formation of ring faults, which control the vertical collapse of the volcanic edifices into the magma chamber (Williams and McBirney 1979; Gudmundsson 1988a). Lateral collapses are bounded by listric faults and lack ring faults connected to the associated magma chamber (Marti et al. 1997). A number of things such as volcanic spreading (Borgia 1994), dike intrusions (McGuire et al. 1990; Elsworth and Voight 1995), accumulation of eruptive products on steep slopes (Murray and Voight 1996), earthquakes (Montalto et al. 1996; McGuire 1996), magma chamber inflation and deflation (Lo Giudice and Rasa 1992), and also changing sea levels (Firth et al. 1996) could cause the stress that leads to the collapse. The Canary Islands, oceanic islands like the Galapagos Islands, have been studied and are now understood to have had large lateral sector collapses in the past. Relatively small lateral collapses at high velocity are capable of generating significant tsunamis upon entering the sea (Satake 2001). These tsunamis have propagated to the east coast of North America where they led to the devastation of large cities and harmed many people in coastal areas (Marti et al. 1997).

Volcan Ecuador is just one of the six volcanoes on Isabela Island, which is located on the far northwest corner of the island and has a height of 775 meters. Isabela Island, the largest island in the Galapagos archipelago, has the largest number of volcanoes of all the islands, with most of its volcanoes being radially symmetric. Isabela Island is a relatively active island with an eruption at Sierra Negra back in October 2005. Volcan Ecuador no longer has the radially symmetric appearance that the other five volcanoes on Isabela Island have. It appears to be missing its entire western half as seen in Fig. 2. The best explanation for this halving of the volcano is a lateral sector collapse.

Sector collapse is known elsewhere in the Galapagos, in places such as the southwest flank of Cerro Azul volcano and other places also include the west face of Pinta and the west face of Santa Fe. Although sector collapses in the Galapagos are not as common as in Hawaii, Volcan Ecuador is a particularly dramatic example, and catastrophic collapse events appear to be a common feature of volcanic evolution in the Galapagos, and perhaps in the evolution of oceanic volcanoes generally (Geist et al. 2003).

Geist et al. (2003) states that it is most likely that the entire western half of Volcan Ecuador most likely slid to the abyssal depth of over 3000 m. Bathymetric mapping has imaged a debris lobe common to landslides and has been identified as the volume deposited on the lower slope in Fig. 3. It is probable that at least some of the material lost in the collapse has been deposited mostly into the ocean off the west coast of the island within the last 100,000 years (Geist et al. 2003). The collapse of this volcano, under the right conditions, could have led to the production of a sizable tsunami, which could then possibly propagate across the water and devastate the entire eastern coast of Australia and New Zealand (after Satake 2001). The purpose of this project is to determine the volume of the debris lobe identified in Fig. 3 and then to compare that to the volume that is missing from the sub-aerial volcano. This comparison will then aid in the definition of the processes that led to the dissection of the volcano; collapse, lateral eruption, or both.

Methods

On 21 January 2006 the *R/V Thompson* began running track lines that were positioned off the northwestern coast of Isabela Island. The track lines were determined by plotting, using the depth readings from an enlarged Fig. 3, with the knowledge that the EM300 Simrad high resolution multi-beam mapping system (EM300) would have 2.5 times the depth as the length of the swath width (Glickson, D. pers. comm.). Track lines are plotted on Fig 4. At station HH14, there was a CTD cast so that a sound velocity profile could be collected to aid in the calibration of the EM300 and can be seen in Fig. 5. The ship then navigated along the track lines formed between the sample stations that are found in Table 1. The data collection also included information from the subbottom profiler system. The subbottom profiler system consisted of a Knudsen 320R transceiver, which is a chirp sonar system, having a maximum output power of 10 kW that sweeps through a band of frequencies between 2-7 kHz with a nominal frequency of 3.5 kHz.

This particular system employs a total of 12 Massa TR-109A units in a 3x4 array, resulting in an effective beam width of about 30 degrees. The data were displayed in real time on a computer monitor and were also recorded on an EPC 9800 thermal graphic recorder. The normal settings were a 1000 m or 500 m depth window, an output power of 5 kW, and a chirp pulse length of 6 or 12 msec. Data collection was all that was achieved while on the ship due to technical issues with processing software.

After data collection the collected data was cleaned by a process of using Caris software to open and view the information received by the EM300 and clearing out data that seems to be outlying and artificial. The process is done best by knowing roughly the bathymetry of the area within your study and being able to recognize when something doesn't fit in. After the data have been cleaned a grid of some resolution is created, which is then exported out of Caris as a .xyz file. A 100 m-grid resolution was chosen to start with and then after analysis a higher resolution grid of 50 meters was created. The file was then opened in Fledermaus, where it was then exported as an ASCII file. The ASCII file was then opened in ArcMAP where it was used to create various images that can be used to determine the volume of the material missing from Volcan Ecuador.

The first thing was to create a bathymetric map using the data that has been processed in ArcMAP, which can be seen in Fig. 6. From this bathymetric data a tool called "modify feature" was used to recreate the landslide debris lobe, which can be seen in Fig. 7. Also, as seen in Fig. 3, there is a volume that has been eroded from the upper slope. The modify feature tool was also used to flatten out this hill slope so that is does not include this erosional feature, Fig 8. The volume of the debris lobe was determined by using the program to subtract the pre-slide bathymetry from the current bathymetry.

A difference image was created and this image can be seen in Fig 9. The volume of the erosional feature was determined in the same way and its difference image can be seen in Fig. 10.

A 50-m resolution digital elevation model (DEM) of topographic lines of Volcan Ecuador was found on the internet (Fig. 11), and the topography of the volcano was then reconstructed to what it most likely looked like prior to collapse (Fig. 12). The former topography was determined by using the surrounding volcanoes and their inverted soup-bowl shapes as guides. The reconstruction of the volcano and its inverted soup-bowl shape did not include a caldera. It also was reconstructed so that only the western side of the volcano was recreated and the eastern half stayed exactly as it is today. Due to complications in the programming, the volumes of the slide and the volume missing from the volcano were determined in slightly different ways. The volume missing from the volcano was determined by using the program to determine the volume above 0 meters for both the current topographical image and the reconstructed topographical image. The two numbers were then subtracted to determine the difference, which is equivalent to the volume that is missing from the volcano. The two difference volumes were then compared to determine how much if any of the volume missing from the volcano correlates to the suspected debris lobe volume.

Results

In Fig. 9 the white and light grays are representative of the depth differences between the two images and correspond to an approximate thickness of 250 meters. The difference gave me a number that is equivalent to the integrated depth in meters of the difference. This number, 1.96×10^6 m, was then multiplied by the cell size to determine the volume, which is 50 m x 50 m. The debris lobe has a total volume of $4.9x10^9$ m^3. In Fig. 10 the black and dark grays are representative of the depth differences between the two images and also correspond to an approximate thickness of 250 meters. The integrated depth of this image is $1.23x10^6$ m. The volume then missing from the erosional slope is $3.1x10^9$ m^3. The volume missing from the volcano, which was determined by subtracting the total volumes of both the current and reconstructed volcanoes, gave a number of $8.5x\ 10^9$ m^3.

Discussion

The volume of the material missing from the erosional slope is 63% of the total volume determined in the debris lobe. This could mean that the majority of the debris lobe did not originate from what is missing from the volcano, but is instead mostly composed of the material that slid from the erosional surface on the upper slope. The other 37% of the debris lobe could be accounted for by the continued activity of the volcano and the recent lava flows which have obscured the seafloor.

The total volume of the debris lobe is only 58% of the total mass that is missing from the volcano. The volume of the landslide has been determined to be significantly less than the volume missing from the reconstructed volcano. This in turn could mean a few different scenarios could have taken place during the collapse or lateral eruption of the sub-aerial volcano. First, during the collapse of the western flank of the volcano, there could have been a large ash explosion which was carried off by the winds to the north, south, or even off to the east. A more likely explanation is that when the volcano collapsed, the collapse was more of a lateral collapse along a listric fault, causing the mass to go sliding off into the abyssal depths as proposed by Geist et al. (2003). The debris lobe is best defined as a lateral collapse along the submarine slopes of the steep platform after the collapse of Volcan Ecuador. Another explanation as to why the two volumes differ significantly is that the reconstruction of the volcano could have been in large human error for what was once actually there, and would therefore have a volume that is too large. A different recreation of the prior topography, especially one that includes a large caldera could lead to a smaller difference in volume. This could more accurately account for the material missing from the volcano.

The collapse of Volcan Ecuador could have occurred over many years and at a very slow rate, or it could have occurred all at once. If the collapse happened over a long period of time such as the slow creep of Kilauea's southern flank, there would be little to no effects on the sea surface and therefore no production of a tsunami. On the other hand, if the collapse occurred rather quickly due to some kind of stress that might have caused the mass to slide along an existing fault line, the disturbance to the sea surface would have been significant causing a rather large tsunami to be created. To be able to determine if there was a tsunami, further research would want to focus on the other Galapagos Islands for signs of inundation, along with looking in places such as Australia, Tahiti, and New Zealand.

Conclusion

The data shows that the mapped debris lobe only reflects 58% of the total volume missing from the volcano as reconstructed using ArcMAP, but reflects more than the volume of the material missing from the erosional surface. The conclusion then is that the debris lobe more accurately reflects the amount missing from the erosional surface above than from the volcano. The extra volume that is not accounted for by the erosional surface is accounted for by the continued activity on the submarine flanks, which have covered the slide and in turn have increased it volume. With 42% of the total mass missing from the volcano still unaccounted for, the conclusion is that the lateral collapse either sent the material off into the abyssal depths, or could have erupted in a large ash cloud that was carried off by the wind or submarine currents.

References

Bailey, K., 1976, Potassium-Argon ages from the Galapagos Islands. Science, **192**.

Borgia, A., 1994, Dynamic basis of volcanic spreading: Journal of Geophysical Research, **99**.

Elsworth, D., and Voight, B., 1995, Dike intrusion as a trigger for large earthquakes and failure of volcano flanks: Journal of Geophysical Research, **100**.

Firth, C., Stewart, I., McGuire, W.J., Kershaw, S., and Vita-Finzi, C., 1996, Coastal elevation changes in eastern Sicily: Implications for volcano instability at Mount Etna, in McGuire et al., eds., Volcano Instability on the Earth and other planets: Geological Society [London] Special Publication, **100**.

Geist, D., w. White, F. Albarede, K. Harpp, R. Reynolds, J., Blichert-Toft, M. Kurz. 2003. Volcanic evolution in the Galapagos: The dissected shield of Volcan Ecuador. Geochemistry Geophysics Geosystems, **3**

Gudmundsonn, A., 1988a, the formation of collapse calderas: Geology, **16**.

Kurz, M., D. Fornari, D. Geist, and Shipboard Scientific Party. 2001. Cruise report Leg-4 R/V Roger Revelle

Lo Giudice, E., and Rasa, R., 1992, very shallow earthquakes and brittle deformation in active volcanic areas: the Etnean region as an example: Tectnophysics, **202**.

Marti, J., M. Hurlimann, G. Ablay, A. Gudmundsson. 1997. Vertical and Lateral Collapses on Tenerife (Canary Islands) and other volcanic ocean islands. Geology **25**.

McGuire, W.J., Pullen, A.D., and Saunders, S.J., 1990, Recent dyke-induced large scale block movement at Mount Etna and potential slope failure: Nature, **343**.

McGuire, W.J., 1996, Volcano instability: A review of contemporaneous themes, in McGuire et al., eds., Volcano Instability on the Earth and other planets: Geological Society [London] Special Publication, **100**.

Montalto, A., Vicinguerra, S., Menza, S., and Patane, G., 1996, Recent seismicity of Mount Etna: Implication for the development of Galapagos-type shield volcanoes, Bull. Volcanol., **61**.

Murray, J.B., and Voight, B., 1996, Slope stability and eruption prediction on the eastern flank of Mount Etna, in McGuire et al., eds., Volcano Instability on the Earth and other planets: Geological Society [London] Special Publication, **100**.

Sakate, K., 2001, Tsunami modeling from submarine landslides. Proceedings of the International Tsunami Symposium, Seattle, July 2001.

Simkin, T. 1984. Geology of the Galapagos Islands *In*: Perr R. (ed) Galapagos, Oxford: Pergamon.

Williams, H., and McBirney, A.R., 1979, Volcanology: San Francisco, California, Freeman, Cooper & Co.

Table 1. Way points for tract lines. HH14 was the location of the CTD cast

Label	Latitude	Longitude
HH1	00° 01.58'	-91° 38.95'
HH2	-00° 06.21'	-91° 31.73'
HH3	00° 01.53'	-91° 38.72'
HH4	-00° 06.43'	-91° 32.18'
HH5	00° 00.91'	-91° 39.53'
HH6	-00° 07.16'	-91° 33.13'
HH7	-00° 07.92'	-91° 33.83'
HH8	00° 00.32'	-91° 40.27'
HH9	-00° 00.27'	-91° 40.80'
HH10	-00° 08.43'	-91° 34.77'
HH11	-00° 09.50'	-91° 36.05'
HH12	-00° 00.87'	-91° 41.62'
HH13	-00° 01.76'	-91° 42.85'
HH14	-00° 10.30	-91° 37.35'

Figure Captions

Figure 1. A picture of the Galapagos Islands. The major volcanoes are labeled together with their respective elevations in meters. The islands are also named on this image.

Figure 2. An image of Volcan Ecuador on Isabela Island, which shows the western flank of the volcano missing. Arrow is drawn indicating north.

Figure 3. A Picture of bathymetric profile map, which was altered to point out the volume deposited on the lower slope, the volume eroded from the upper slope and the volume missing from Volcan Ecuador. The image is after that taken from the DRIFT Leg-4 Cruise Report (Kurz et al, 2001).

Figure 4. Track lines as determined from the points in Table 1.

Figure 5. Sound velocity profile as collected by the CTD on board the Thomas G. Thompson.

Figure 6. Current bathymetric image as processed using ArcMap.

Figure 7. Pre-slide bathymetric image as processed using ArcMap's "modify feature" tool. Use to reposition the contours so that they exclude the debris lobe.

Figure 8. Pre-slide bathymetric image as processed using ArcMap's "modify feature" tool. Use to reposition the contours so that they exclude the erosional surface.

Figure 9. Difference image created using ArcMap. Created by calculating the difference between the Fig 7 and Fig. 11.

Figure 10. Difference image created using ArcMap. Created by calculating the difference between the Fig 8 and Fig. 11.

Figure 11. Current bathymetric image created from data obtained from the EM300 system and analyzed in ArcGIS.

Figure 12. Current topographic image with DEM obtained from the website http://rslultra.star.ait.ac.th/~souris/ecuador.htm.

Figure 1.

Geology of the Galapagos website

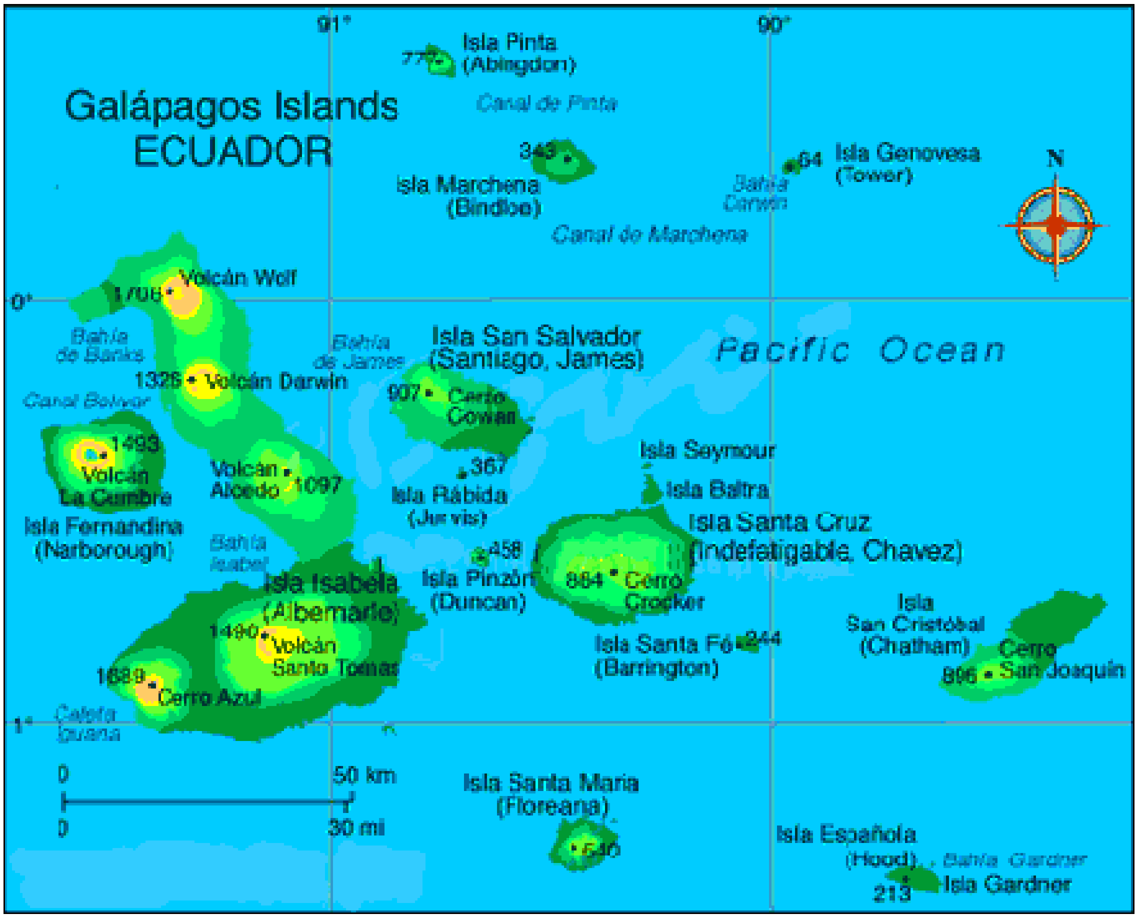

Figure 2

Geology of the Galapagos website

Figure 3

After Kurz et al. 2001

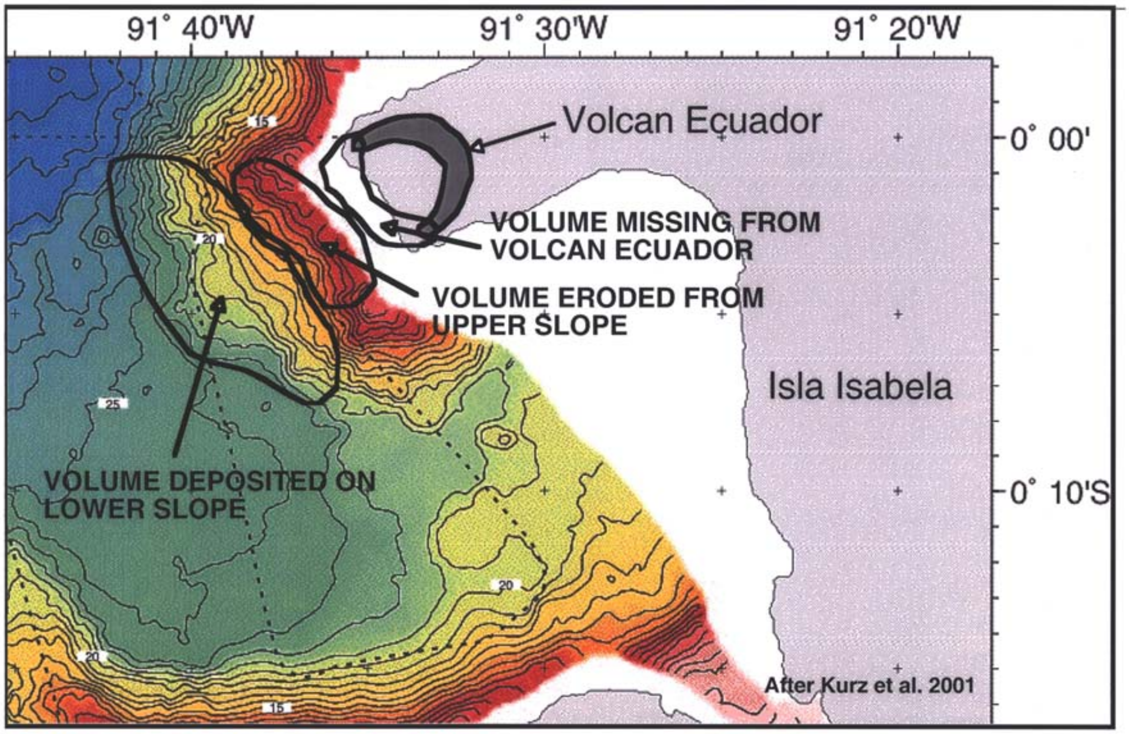

Figure 4

After Kurz et al. 2001

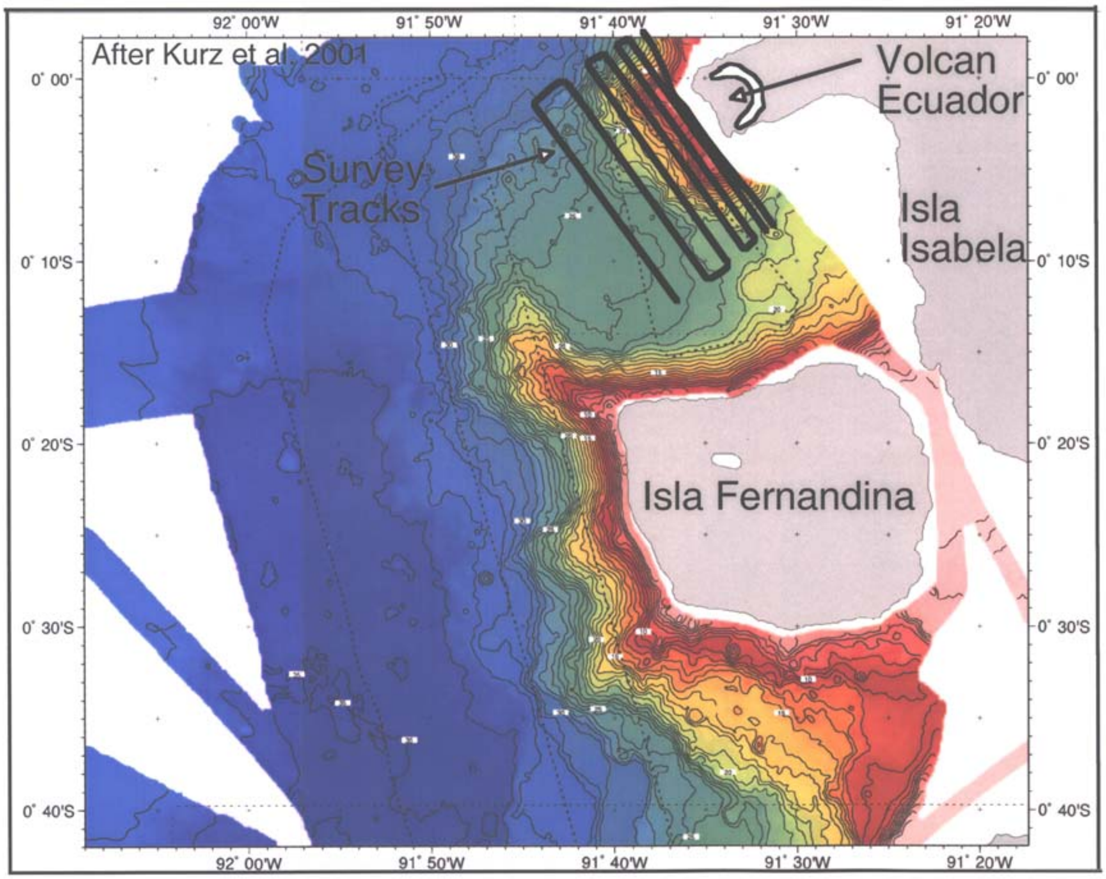

Figure 5

R/V Thompson   CTD Cast 18902901

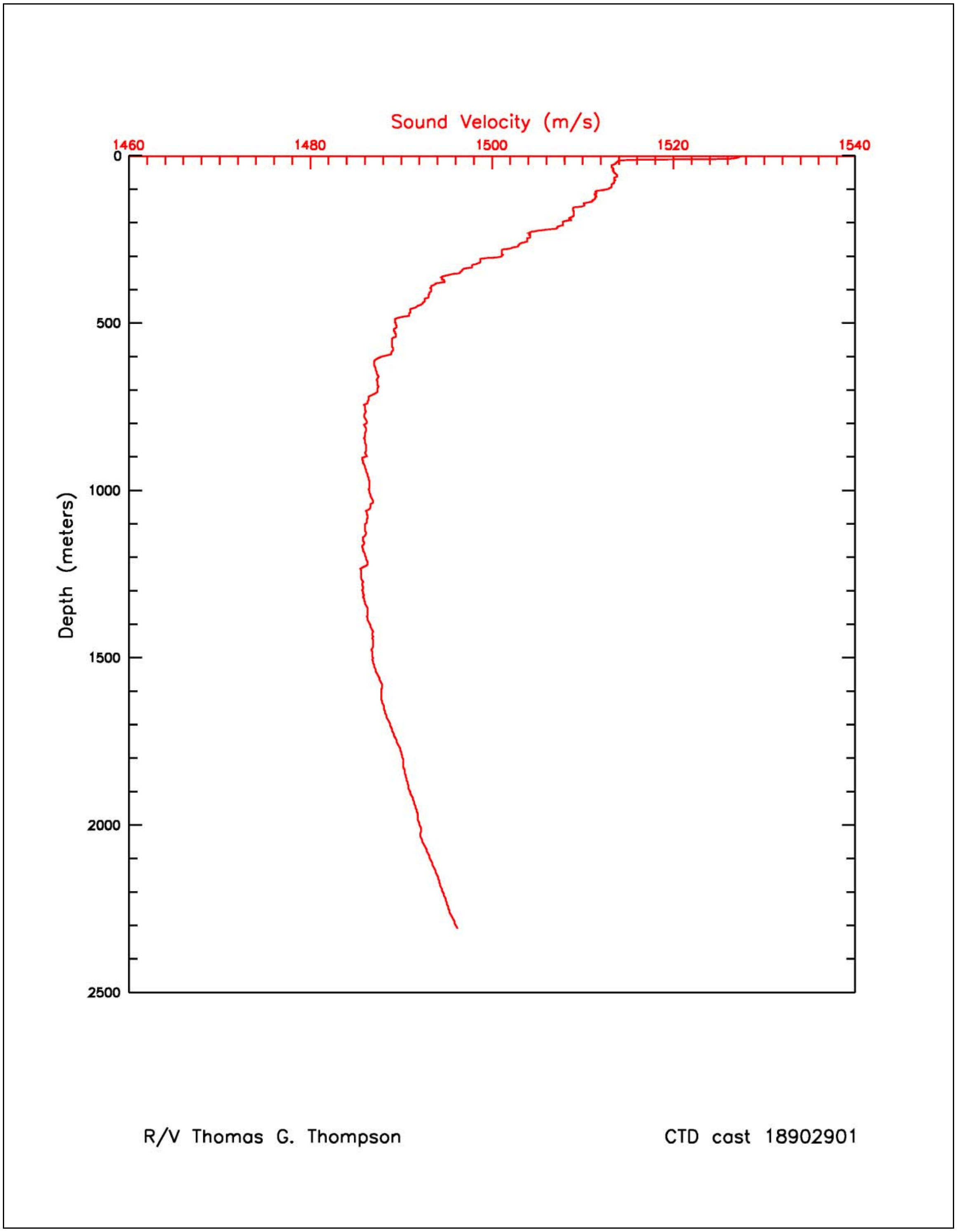

Figure 6

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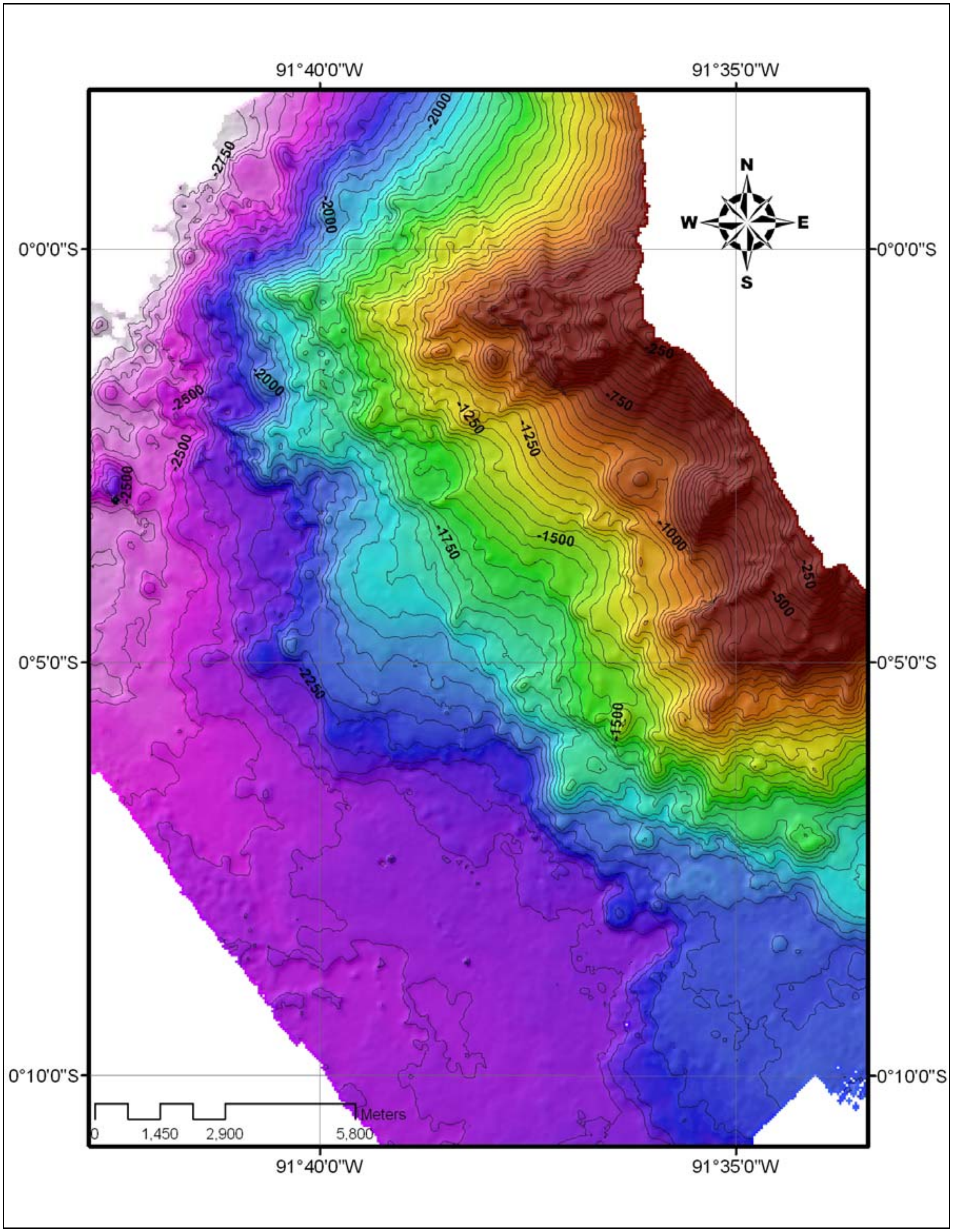

Figure 7

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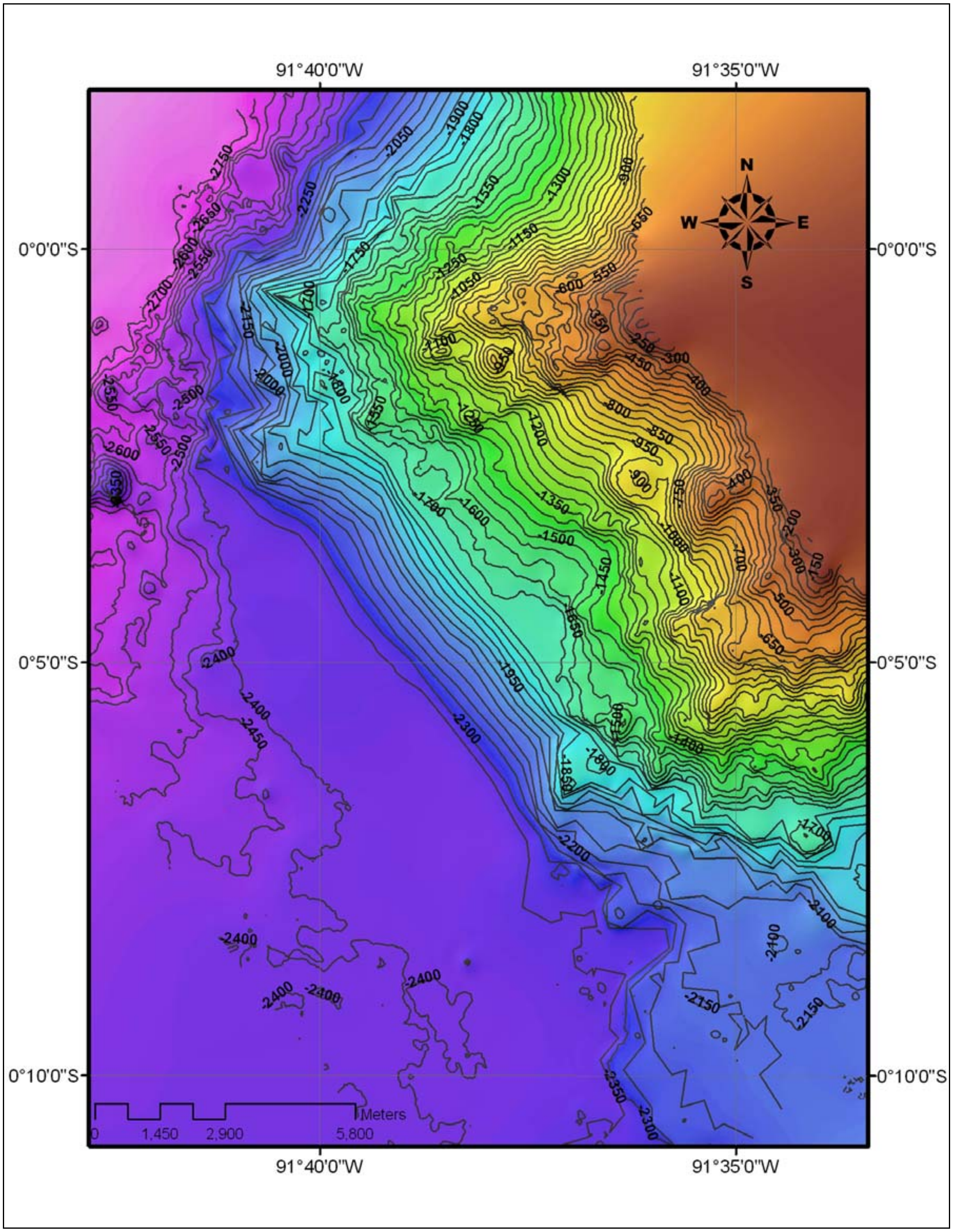

Figure 8

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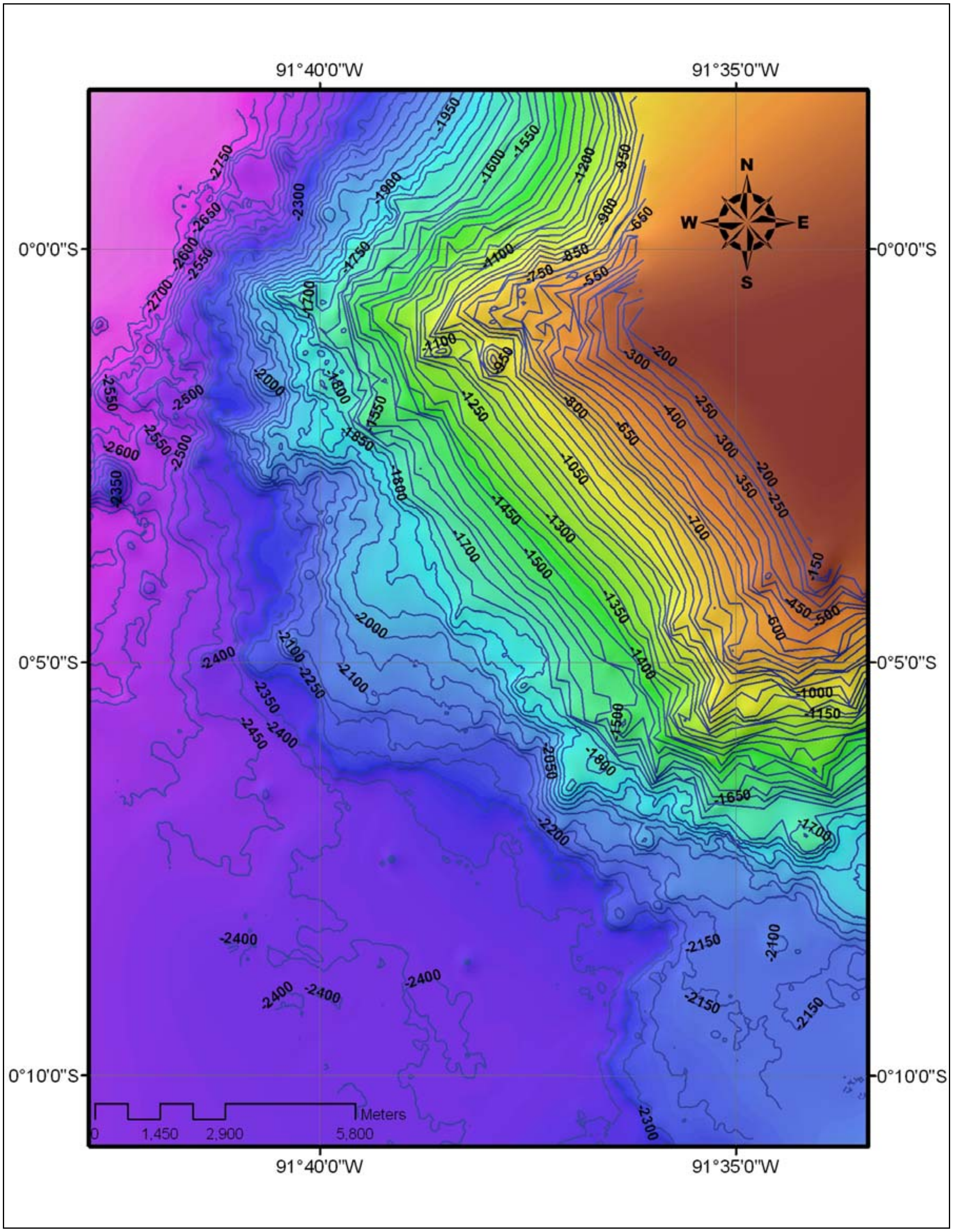

Figure 9

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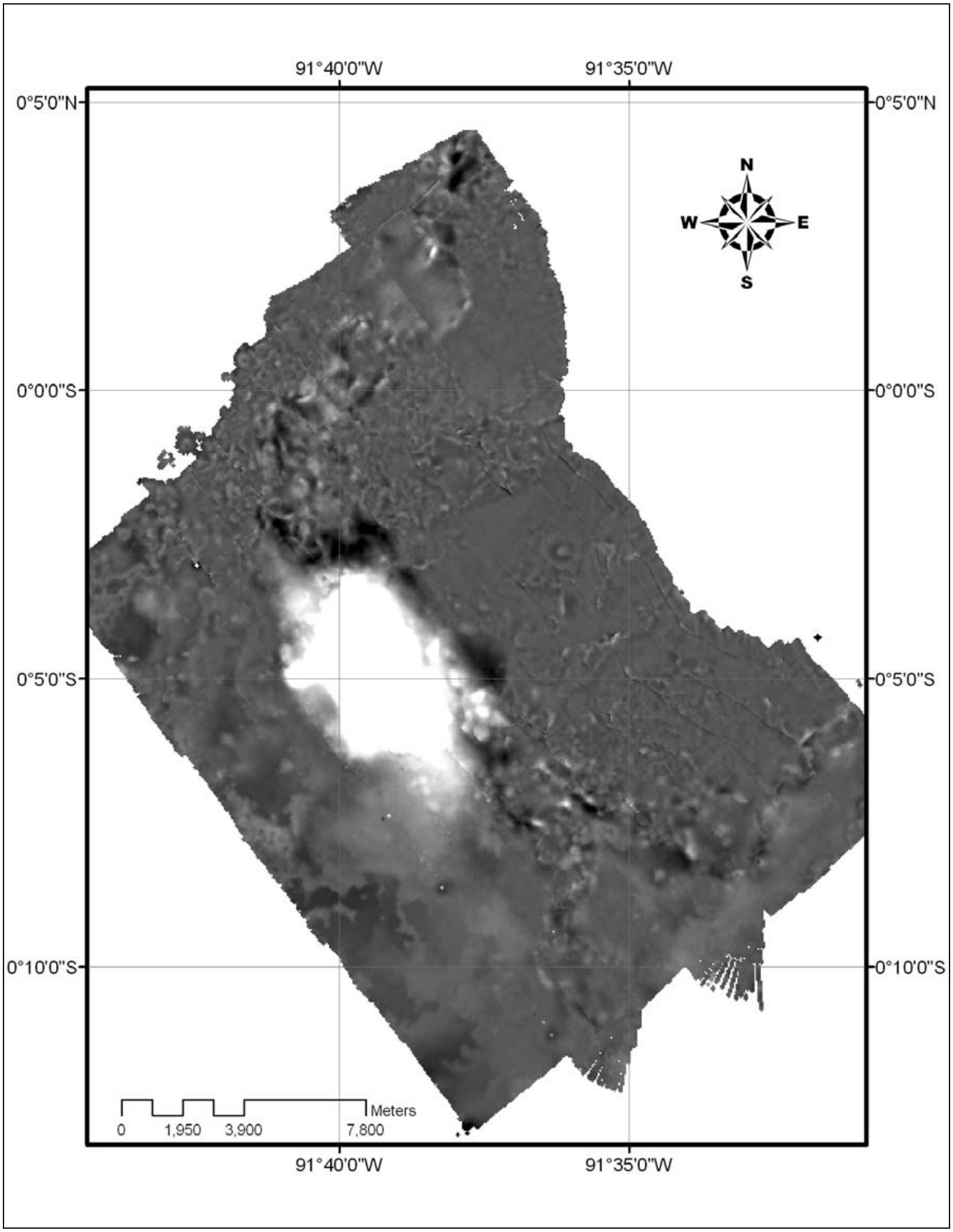

Figure 10

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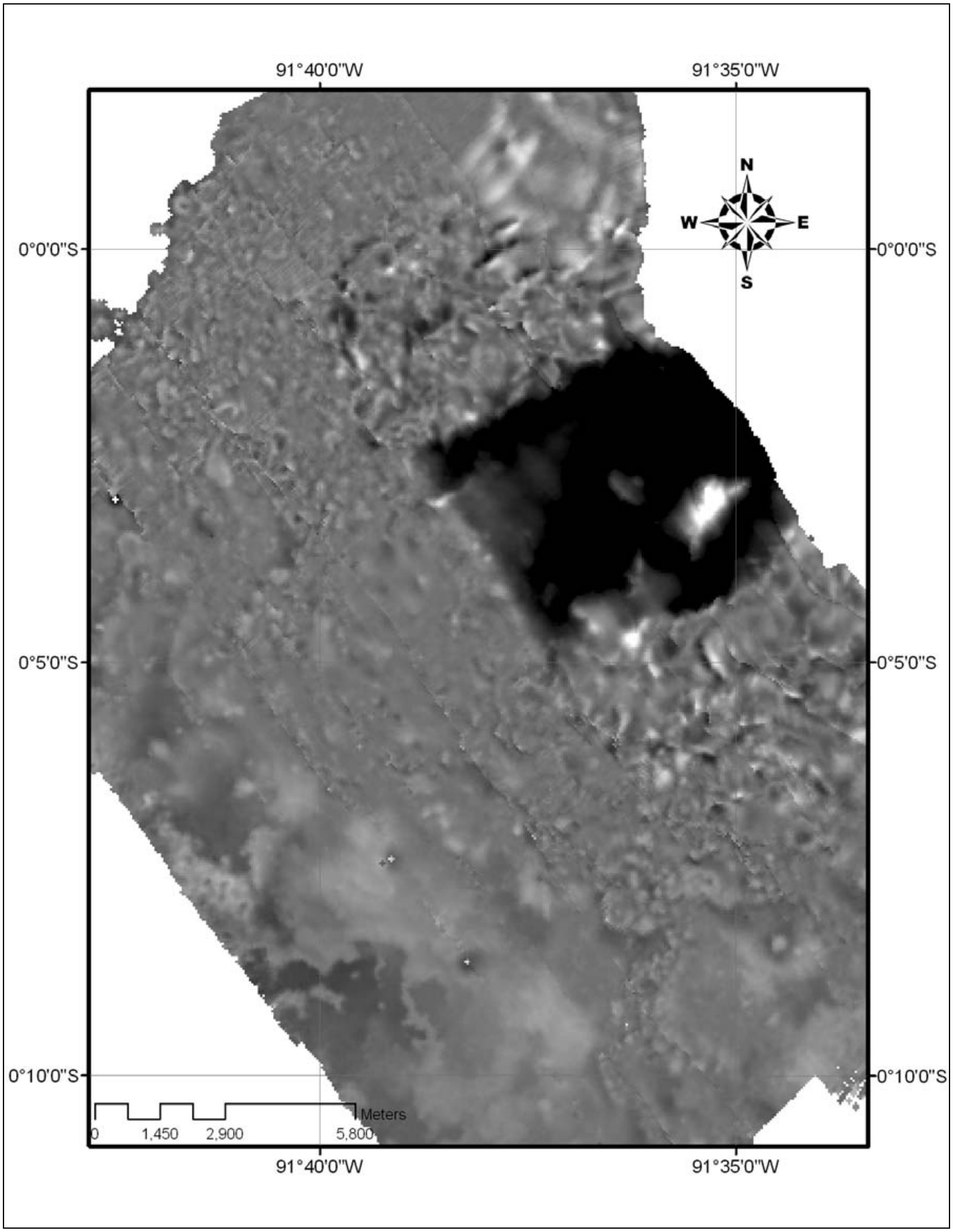

Figure 11

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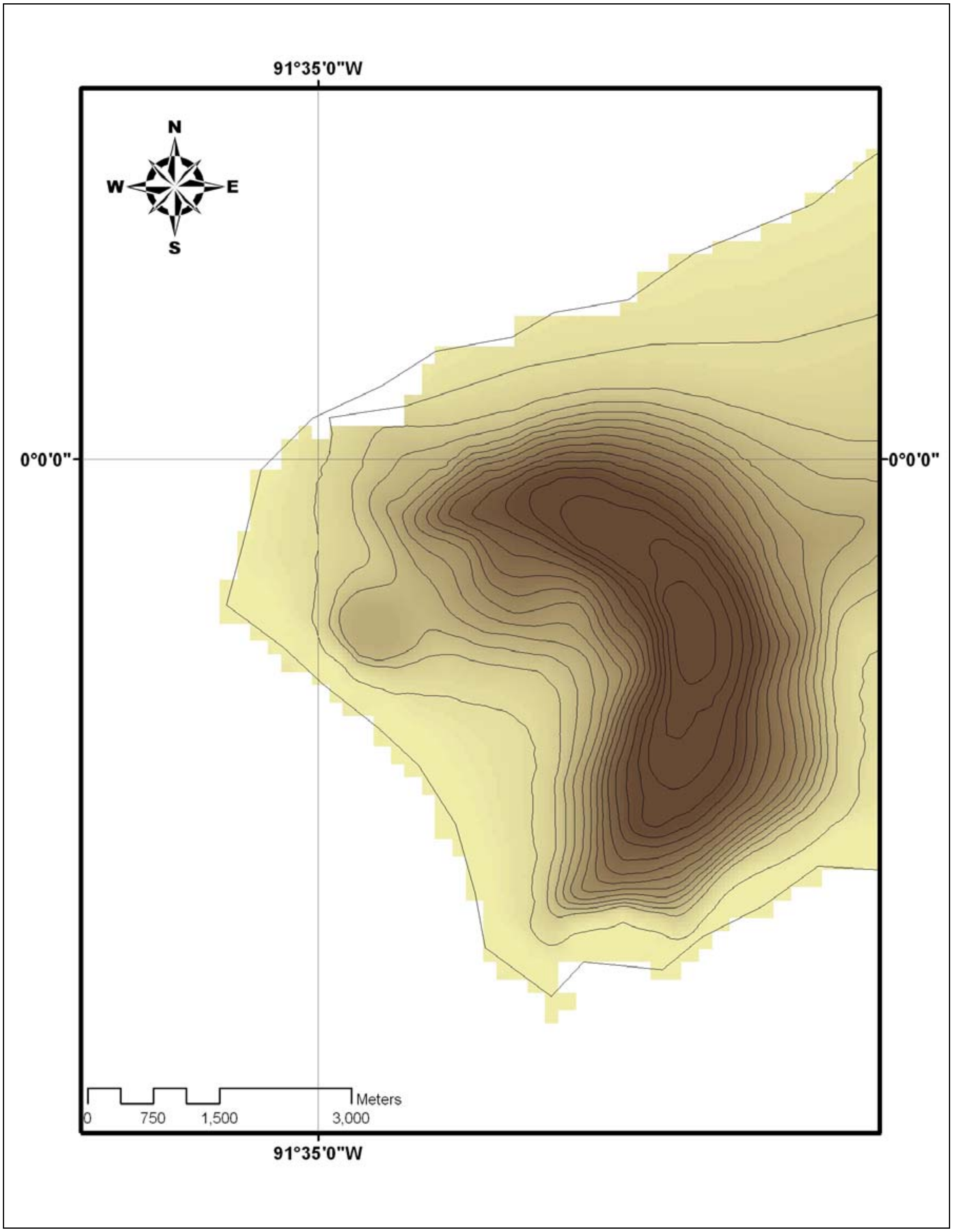

Figure 12

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