

**Roca Redonda Island formation due to development of an extensional transform zone,
northern Galápagos Archipelago**

Heidi Berkenbosch¹

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¹ School of Oceanography, Box 357940, University of Washington, Seattle, Washington,
98195-7940

Non-Technical Summary

The Galápagos Islands are a group of volcanoes that were formed by a mantle hotspot underneath a tectonic plate; a similar mechanism formed the Hawaiian Islands. The hot magma rising from the mantle plume underneath the plate is lighter in density than the overlying crust. The magma pushes up against the thin oceanic crust, creating cracks, which it then leaks through until eventually a volcano (and eventually an island) is formed.

The Galápagos hotspot is located only 250 km south of an east-trending mid-ocean ridge spreading center and transform fault. A mid-ocean ridge forms between two tectonic plates as they slowly move apart. Magma flows up through the space between the plates to create new oceanic crust. North of the Galápagos the ridge jumps to the south, resulting in two parallel but offset lines. The section of ridge connecting the ends of each line is called a transform fault.

One theory holds that the northern islands of the Galápagos not formed by hotspot volcanism. Instead their formation is envisioned as follows: The plate beneath the northern Galápagos is under tension around the transform fault. The stresses create an extensional transform zone (ETZ), where the crust is being pulled apart. This zone, located between the hotspot and the mid-ocean ridge, has a large supply of magma pooled underneath it. The magma passively rises to the surface through the crack and creates the northern islands

This study tested the hypothesis that Roca Redonda Island was created by this extensional zone process because of its similarities to nearby Wolf and Darwin Islands that were formed along an ETZ. The seafloor northwest of Roca Redonda was mapped to see if there was evidence of a stress zone in that region. I looked for fractures, young (un-sedimented) lava flows, and seamounts. A relatively flat, sedimented seafloor would indicate absence of volcanism.

The maps and geophysical data generated in this study showed a seafloor very different from what previous maps suggested. There is one east-trending un-sedimented volcanic ridge, 600 m high and 15.8 km long ~165 km northwest of Roca Redonda. Most of the seafloor has rough volcanic areas with some small seamounts and thin (~5 m) sediment cover. Raised blocks covered by ~50 m of sediment break this terrain. Alignment of the volcanic structures does not indicate that an ETZ formed in this region. However, the sediment on the raised blocks is very similar to the sediment of the seafloor 10 km to the west, a region without any volcanic terrain. This study concludes that although no ETZ is present some volcanic process is occurring that results from interactions between the mid-ocean ridge and the hotspot.

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Abstract

Much of the complex geology of the Galápagos Islands remains unresolved. An example is the Wolf-Darwin Lineament (WDL), thought to result from stresses produced by a transform fault 250 km north of the islands. This lineament formed when an extensional transform zone (ETZ), not normally observable at mid-ocean ridge transform faults, filled with magma from the adjacent Galápagos Spreading Center (GSC) and mantle plume. Previous bathymetry data suggested that an incipient ETZ 55 km west of the WDL might have influenced the formation of Roca Redonda Island. A 1300 km² area northwest of Roca Redonda was mapped to confirm the existence of features that would be consistent with an ETZ. High-resolution bathymetry and backscatter data were collected using a Simrad EM300 multibeam mapping system; a 3.5 kHz subbottom profiler collected single-beam bathymetry and reflectivity data simultaneously. EM300 data were edited and processed using Caris® and Fledermaus® software. The mapped region contains one west-trending 15.7-km-long segmented ridge 600 m high; a region of small seamounts was mapped in the southern portion of the study area. Rough volcanic terrain comprises 34% of the mapped area, whereas uplifted (?) sedimented blocks having the same orientation (277°) as the GSC cover 66%. Although the volcanic and tectonic features mapped during the survey are not oriented in the direction that would be expected for an incipient ETZ (331°), their apparent young age indicates that some volcanic process is occurring in the region other than what would be expected from usual hotspot processes alone.

Introduction

The Galápagos Islands (Fig. 1) straddle the equator in the Pacific Ocean approximately 1000 km west of Ecuador. Island formation is due to a hotspot located 150- 250 km south of the Galápagos Spreading Center (GSC), which lies between the Cocos and Nazca plates (Fig. 1). The geology of the Galápagos Islands is puzzling and complex. Generally, the seamounts and islands in the east are older than those in the west, ranging from ~0.5 Ma for Fernandina to 3.4 Ma for Española (White et al. 1993). This conforms expected volcanic ages from a system with a stationary hotspot and plate motion to the east. However, location and age show no linear relationship when considering the Wolf-Darwin Lineament (WDL), Pinta, Marchena, and Genovesa Islands, which are collectively called the northern islands (Fig. 1). The continued activity of some of the older islands further complicates the geology of the Archipelago. Only Wolf, Darwin, Pinta, Santa Fe, and Española Islands are considered inactive. Theories about which volcanoes represent the young, intermediate, and mature stages of Galápagos volcanism are mainly based on geochemical evidence, in contrast to Hawaii, where faster erosion better exposes geological evidence of these stages (White et al. 1993; Standish et al. 1998).

The Hawaiian Islands are also the result of hotspot formation due to magma actively pushing its way to the surface. At a hotspot, mantle magma is relatively light in density and therefore buoyant compared to its surroundings that it exerts enough upward pressure on overlying lithosphere to create fractures (Macdonald and Abbott 1970). This magma then rises through the fractures to erupt at the seafloor surface where it cools and hardens. Subsequent eruptions overlay these cooled flows and the process continues, eventually resulting in the creation of a shield volcano (Macdonald and Abbott 1970). Shield volcanoes characteristically have slopes of only a few degrees (Skinner and Porter 2000). In the Galápagos they are described as having an “inverted soup bowl” shape with a region of higher slope mid-way to the top, which then decreases again into a gently sloping summit (McBirney and Williams 1969; Geist et al. 2005).

In contrast to Hawaiian hotspot processes, formation of the northern islands in the Galápagos is thought to be caused by plume-ridge interaction precipitated by the transform fault (Fig. 1) at 91° W (Harpp and Geist 2002). Models demonstrate that a stress zone is created in the inside corner of the intersection between a mid-ocean ridge and a transform fault (Fig. 2), such as occurs at the 91° W transform along the GSC (Fujita and Sleep 1978; Gudmundsson

1995). This stress zone creates an extensional region (Fig. 3) that causes fractures and fissures to form oriented along the WDL (Gudmundsson 1995). These fissures are present at any mid-ocean ridge transform fault but they are usually not visible. However, in the Galápagos hotspot and ridge combine to create a pool of magma underlying the fracture zone. According to Harpp and Geist (2002), as the crust opens due to extension from transform fault stresses magma passively upwells to the surface, thus illuminating the fractures. This process of passive magmatic migration is thought to produce the volcanoes and seamounts of the northern islands, and provides an explanation for the lack of a linear relationship between their age and location (Harpp and Geist 2002). The 40° orientation of the WDL with respect to the spreading direction of the GSC designates it as an extensional transform zone (ETZ). An ETZ (Taylor et al. 1994) is a type of plate boundary characterized by overlapping en echelon volcanic systems and/or faults that strike 30°- 75° to the direction of plate spreading.

The long axis of Isabela Island, which is composed of four active volcanoes, in conjunction with Roca Redonda 28 km to the northwest, runs parallel to the WDL (Fig. 1) and is therefore along the same orientation of extension predicted by the Gudmundsson (1995) model (Fig. 3). Furthermore, a bathymetric map created by W. Chadwick of Oregon State University, indicates an area of seamounts extending along the same orientation to the northwest of Roca Redonda (Fig. 4). Although Harpp and Geist (2002) state that the ETZ is bounded by the WDL in the west and the transform fault in the east, it is possible that the influence of the transform fault at 91° W extends further to create an incipient ETZ.

The characteristics of Roca Redonda suggest its formation may be due to passive magmatic upwelling processes, rather than active hotspot growth. Roca Redonda has been classified as a young (K-Ar age of 53 ± 54 ka) and growing shield volcano created by and at the leading edge of the Galápagos hotspot (White et al. 1993; Standish et al. 1998; Geist et al. 2005). It is thought to represent the most juvenile phase of Galápagos volcanism, comparable to a stage of evolution between the submerged Loihi seamount and subaerial Kilauea volcano of Hawaii (Standish et al. 1998). The subaerial portion of Roca Redonda has near-vertical walls composed of 20- 25 lava flows that are mantled by a thick subsurface talus apron. Palagonite tuff is exposed about 10 m below the summit and there is no caldera. These observations suggest that the exposed lavas once filled the crater of a palagonite tuff cone, which has subsequently been eroded (Standish et al. 1998). $^{87}\text{Sr}/^{86}\text{Sr}$ and $^{143}\text{Nd}/^{144}\text{Nd}$ ratios of Roca Redonda lavas occur at

the enriched end of the Galápagos assembly, indicating a high plume component (Standish et al. 1998). Backscatter and bathymetry show volcanic slumping with an identified partial sectorial collapse towards the west and another predicted to occur towards the south (Cando, M., Arreaga, P., Toulkeridis, T., and de la Torre, G. unpubl.). Numerous subaqueous fumaroles, with a possible magmatic component, vent fluids 1-2° C above ambient seawater within 30 m of water depth, indicating that Roca Redonda remains active (Standish et al. 1998). There have been no mapping efforts to locate hydrothermal venting sites on the marine flanks of the volcano deeper than 30 m.

Beyond these descriptive elements, comparisons can be drawn between Roca Redonda and remaining Galápagos volcanoes. A straight ridge, typical of hotspot volcanism, connects Roca Redonda to Wolf Volcano, the northernmost of Isabela Island's volcanoes (Geist, D., pers. comm.). Conversely, the nearly vertical walls of Roca Redonda are much more like Wolf and Darwin Islands and not the "upside-down soup bowl" shape typical of Galápagos shield volcanoes (McBirney and Williams 1969; Geist et al. 2005). As previously stated Roca Redonda has no caldera and is the only island outside of the northern islands that is not on the platform.

The interpretation of Roca Redonda's growth influences the way we regard formation of the other islands of the Archipelago because it is viewed as representing the youngest evolutionary phase of Galápagos hotspot volcanism. Geochemical aging is inconsistent with this view as it indicates that the Galápagos platform developed first and the volcanoes formed on top of it (Geist, D., pers. comm.). Why isn't Roca Redonda on the platform? Additionally, the $^{208}\text{Pb}/^{204}\text{Pb}$, $^{207}\text{Pb}/^{204}\text{Pb}$, and $^{206}\text{Pb}/^{204}\text{Pb}$ ratios from WDL lavas span a range of compositions comparable to that of the rest of the Archipelago, indicating that a high geochemical plume component is not necessarily indicative of hotspot formation (Harpp and Geist 2002).

Roca Redonda could either be a volcano created by the hotspot, or it could be a volcano created by the magmatic inflation of an extensional transform zone, or it could be a combination of these two processes. If there were an incipient ETZ, then evidence of the tensional stress zone would be expected in a line extending northwest from Roca Redonda that parallels the WDL. As mentioned above a bathymetry map of the Galápagos suggests seamounts occur along the described line (Fig. 4). There are also two broader elongate bedforms extending south towards Roca Redonda from the WDL (Fig. 4) that may indicate an interaction between the two island groups. However, this map was created by combining digitized hydrographic maps, ship track

data available up to 1994, and US Navy DBDB5 data and has a resolution of 1000 m. Considering that digitized hydrographic maps have low resolution and questionable accuracy, no ship tracks have recorded over the region northwest of Roca Redonda, and the DBDB5 database has 5-minute intervals between data points, the current bathymetry map is likely to have inaccuracies. This study gathered seafloor data from an area northwest of Roca Redonda to image and analyze for evidence of regional stress with or without magmatic inflation.

Methods

Mapping and data collection took place on the *R/V Thomas G. Thompson* on 19 and 20 January 2006. Backscatter and bathymetry data were collected using a Simrad EM300 mapping system operating at 30 kHz and having a swath width approximately 2 times that of the water depth. This research project was only able to gather data from a small portion of the vast unmapped area north of Roca Redonda because ship time was limited to less than 21 hours. Track lines were chosen to cover regions of potential volcanic terrain, the possible seamounts that parallel the WDL, and the western bedform mentioned above, as indicated by Chadwick's map (Fig. 4, Table 1). Total length of the track line was 300 km covering an area of 1300 km² and the ship cruised at 14.8 km h⁻¹ (8 kts) to minimize water flow noise across the transducer array. A sound velocity profile to calibrate the EM300 was determined from a CTD cast to 2300 m depth at station HB-1 (Table 1). EM300 data were edited and gridded using Caris® software and then transferred to Fledermaus® software for processing, visualization, and analysis. ArcMap® was used to add presentation details. All images were processed with 6x vertical exaggeration and a lighting angle of 315°.

Subbottom profiling data and bathymetry were collected using a Knudsen 320R transceiver with maximum output power of 10 kW and a nominal frequency of 3.5 kHz. This instrument employs 12 Massa TR-109A units resulting in a beam width of approximately 30 degrees. The data were recorded on an EPC 9800 thermal graphic recorder. Normal settings had a 1000 m depth window, an output power of 5 kW, and chirp pulse length of 6 or 12 msec.

Results

Multibeam sonar revealed seafloor quite different from Chadwick's bathymetry map (Fig. 5). Most notably the north-south aligned bedform that would have appeared in the north

central region of the map was not found. Instead a 600 m high, 15780 m long, and 3700 m wide ridge (Fig. 5) was found at the lower portion of the bedform region. This ridge, herein named the Peidl ridge, is oriented in an east-west direction at 277° , nearly the same orientation as the GSC (280°). Its ridge crest is broken into two sections with a depressed region between them (Fig. 5). The western section curves slightly to the right and the eastern section curves slightly to the left. Additionally, the potential seamounts expected on the western edge of the mapped region were not found. There are, however, 3 small seamounts in the southwest region of the map (Fig. 5, 6). The northern most of these (Fig. 5) is 251 m high and has a roughly circular $\sim 7.4 \text{ km}^2$ base. The central seamount (Fig. 5) reaches 306 m high and has a round base of $\sim 13.4 \text{ km}^2$. The southern seamount (Fig. 5) is more elongate with a $\sim 4.4 \text{ km}^2$ base and a 374 m peak. Bathymetry data also show shallow canyons $\sim 65 \text{ m}$ deep to the north of Peidl Ridge aligned in the same direction as the GSC (Fig. 5). With the exception of Peidl Ridge the mapped region slopes from 2250 m depth in the north to 2900 m depth in the south.

The subbottom profiler and bathymetry demonstrate two distinct types of terrain in addition to the ridge: smooth, uplifted blocks which cover 66% of the region and an undulating area covering 34% of the region (Figs. 5, 6, 7). In general the northern most, western-central, and eastern-south regions are composed of the latter while the remaining central region and eastern-south region are composed of the former (Fig. 6). North and south boundaries between these regions are aligned nearly parallel to the GSC. No fault features appear on the subbottom profiler record.

Backscatter data show low reflectivity over most of the region, particularly over the uplifted block regions (Fig. 8). The highest backscatter occurs over the entire length of Peidl Ridge, and high backscatter is also present at the southern seamounts and surrounding region (Fig.8). The regions of undulating terrain have intermediate levels of backscatter.

The subbottom profiler indicates sediment thickness of $\sim 5 \text{ m}$ over the regions of undulating terrain (Fig. 9B). The uplifted blocks are covered with $\sim 50 \text{ m}$ of layered sediment (Fig. 9B).

Discussion

The seafloor northwest of Roca Redonda has been altered from the flat surface that would be expected on seafloor a distance from both the GSC and the hotspot. Peidl Ridge is a product

of recent volcanism due to its high backscatter (Fig.8) that indicates insufficient time has passed for sediment to accumulate, as well as morphological features such as its ridge crest (Fig. 5). Genovesa Island, located to the east (Fig. 1), exhibits the ETZ by the broken en echelon pattern of its eastern submarine rift crest (Harpp et al. 2003). En echelon structures are consistent with passive upwelling of underlying mantle and not active magmatic processes (Harpp, K., pers. comm.). In contrast, a straight, continuous ridge crest has formed on Puna ridge off Kilauea volcano in Hawaii, which has a substantial active magma supply (Lonsdale 1989). Interestingly, Roca Redonda's northwest rift has a curved continuous ridge crest like many of the Galápagos rifts such as Fernandina Island's northwest rift (Glass 2006), although the reasons for this regional curvature are not understood. For Peidl Ridge to form in an east- west direction from passive magmatic upwelling there would have to be extension of the crust in a north- south direction.

Considering the moderate backscatter (Fig. 8) and the reduced sediment cover as compared to the surrounding blocks (Figs. 6, 9B) the undulating terrain and southern seamounts are likely due recent volcanism as well, although they may be older than Peidl Ridge. Some uplift may also have occurred with the sedimented blocks as they are raised from the surrounding seafloor (Fig. 6) and have shallow canyons between them (Fig. 5).

The expected seamounts along a line parallel to the WDL if an incipient ETZ were present were found to be artifacts of a poor resolution map. However, the southern seamounts and Peidl Ridge join Roca Redonda to make a line at 344° , one closer to angle of the transform fault at 354° than the WDL at 323° . Gudmundsson's (1995) model does not predict that extension would rotate to a higher angle further away from the transform fault (Fig. 2). Additionally, on a broader scale, a moat-like depression bounds the western and northern side of Fernandina Island and continues over the top of Isabela Island to wrap around to its northeastern side (Fig. 4). However, the volcanic features mapped in this study are in an area where the moat is disrupted to the north of Roca Redonda. Some process is creating the features mapped in this study to overcome the process that has made the moat. The orientation of Peidl Ridge and the southern seamounts and lack of expected seamounts to the west suggest that this area is not an extensional transform zone.

Further evidence for volcanic alteration can be seen when comparing the subbottom profile records of the study area to the record taken 10 km west (Fig. 9). To the west there is

only smooth seafloor, gently rising, that is covered with ~50 m of layered sediment (Fig. 9A). The distinct layers may be turbidites or they may have ash from the surrounding volcanoes layered with hemipelagic sediments. Within the study region the uplifted blocks also have ~50 m of layered sediment (Fig. 9B) although the layers are not as distinct. Potentially, the terrain within the study region, once like the terrain outside the study region, was volcanically altered such that some new undulating terrain was formed and other parts were uplifted. The volcanic activity could have altered the sediment on the uplifted blocks through diffuse venting of heated pore water. Considering that the boundaries between the different types of terrain and Peidl Ridge are oriented in the same direction as the GSC (Fig. 6), volcanic activity could have occurred along zones of weakness established during formation of the seafloor at the GSC.

There are multiple possibilities for the process at work in the region between the WDL and Roca Redonda. Earlier studies suggested that the WDL was a channel that connected the plume to the GSC. Geochemical determinations of the WDL did not support this hypothesis because the lavas did not change from having a high plume component in the south to having a high ridge component in the north (Harpp and Geist 2002). Perhaps this sort of plume- ridge interaction is occurring from Roca Redonda northward. The direction of the line connecting the volcanic features mentioned above may simply be the shortest route to the GSC. Another possibility is that an incipient transform fault is forming as opposed to an incipient ETZ.

Conclusions

This study concludes that, within the limits of the survey area, there is no evidence supporting the existence of an extensional transform zone extending from the volcanic axis of Isabela Island, through Roca Redonda Island, and parallel to the Wolf-Darwin Lineament. However, the shape and volcanic activity of Roca Redonda, the fact that it is not on the Galápagos platform, and the existence of such features in the survey area as Peidl Ridge, relatively fresh volcanic terrain, and uplifted crustal blocks, together suggest that some volcanic and tectonic process other than active hotspot volcanic growth is occurring. Further mapping efforts, particularly between the region mapped in this study and the WDL, would help to provide more evidence for the mantle plume- spreading ridge interactions occurring in the Galápagos Archipelago.

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Table 1- Location of stations comprising ship tracks 1-7 numbered from north to south. Waypoints start at most northern point and alternatively head south then north along each track to finish at the most southwestern point. Track lines are shown in Figures 1 and 4.

Station Number	Latitude	Longitude
HB1a	1 00.97' N	91 49.30' W
HB1b	0 47.34' N	91 43.27' W
HB1c	0 43.00' N	91 41.00' W
HB2a	0 41.60' N	91 43.10' W
HB2b	0 46.75' N	91 45.58' W
HB2c	0 59.35' N	91 51.00' W
HB3a	0 57.30' N	91 52.05' W
HB3b	0 44.80' N	91 47.20' W
HB3c	0 32.00' N	91 40.60' W
HB4a	0 31.50' N	91 42.70' W
HB4b	0 44.00' N	91 49.00' W
HB4c	0 52.70' N	91 52.60' W
HB5a	0 52.00' N	91 54.00' W
HB5b	0 41.87' N	91 50.30' W
HB5c	0 34.00' N	91 46.20' W
HB6a	0 33.00' N	91 48.15' W
HB6b	0 40.40' N	91 52.00' W
HB6c	0 51.30' N	91 56.10' W
HB7a	0 50.30' N	91 57.70' W
HB7b	0 38.75' N	91 53.52' W
HB7c	0 32.00' N	91 50.60' W

Figure Captions

Fig. 1- Map of the Galápagos Islands. White borders around islands indicate sea level and black contour outlines the Galápagos platform. GSC is the Galápagos Spreading Center, TF is the transform fault, and WDL is the Wolf-Darwin Lineament, which is also shown by the oblique black line. The oblique white line shows the orientation of the chain of volcanoes along the axis of Isabela Island. The maze-like black lines to the northwest of Roca Redonda show ship survey track lines. Dotted outline indicates area in Fig. 4.

Fig. 2- Stress trajectories at the junction between an oceanic transform fault and adjacent ridge segments such as occurs at the Galápagos Spreading Center at 91°W. The ticks represent the direction of maximum compressive principal stress. Oblique extension fractures forming a curved fabric grow parallel with the compressive stress direction and are favored at the ridge-transform junction (after Gudmundsson 1995). Figure 3 shows ellipses based on this stress model and the resulting extensional zone.

Fig. 3- Conceptual diagram of the processes involved in creating the Wolf-Darwin lineament (after Harpp and Geist 2002). Yellow-orange tones indicate area of Galápagos mantle plume influence. Long south-directed arrows show spreading direction of the Nazca plate. Short southwest-directed arrows show extension necessary to accommodate plate spreading when strike-slip component of the transform fault is removed. Bold red lines show observed volcanic lineaments. Ellipses are from Gudmundsson's (1995) model for stresses resulting from transform fault- spreading center intersection (Fig. 2). Inset shows vector representation in velocity space of a model for strain partitioning through a combination of transform and extensional motions. GSC is the Galápagos Spreading Center and WDL is the Wolf-Darwin Lineament.

Fig. 4- Bathymetry map showing bedforms and seamounts of interest using 1000 m resolution grid compiled by W. Chadwick at Oregon State University from digitized hydrographic maps and ship track data up to 1994, and US Navy DBDB5 data (available at <http://newport.pmel.noaa.gov/~chadwick/Galápagos.html>). GSC is the Galápagos Spreading

Center, which also continues eastward from the southern end of the transform fault (TF) shown by the vertical black line. WDL is the Wolf-Darwin Lineament that is also shown by the oblique line. Ship track lines are shown in black. Lighting angle is from 315°. Survey tracks are shown between seamounts and bedform labels.

Fig. 5- Bathymetric image at 50 m resolution produced from Simrad EM300 swath data collected on cruise TN-189-1 of the *R/V Thomas G. Thompson*. Processing details are discussed in the text. Note the different color scale from Figure 4. Lighting angle is from 315°. Dotted outline shows region of Figure 6 and the red line shows portion track line from which the subbottom profile was taken. Red arrow indicates view direction for Figure 7. Black arrow at bottom center of figure indicates view direction for Figure 8. The other black arrow at the bottom of the figure indicates the direction to the tip of Roca Redonda's northwest rift. Seamounts are labeled north (N), central (C), and south (S). White lines indicate the two sections of ridge crest on Peidl Ridge. White squares are areas of no data.

Fig. 6- Schematic diagram of Figure 5 showing dominant types of seafloor terrain. Inset shows the orientation of the Galápagos Spreading Center (GSC), the transform fault (TF), the Wolf-Darwin Lineament (WDL) and the long axis of Isabela Island (IA). The boundaries of volcanic terrain regions are aligned parallel to the GSC, as is Peidl Ridge.

Fig. 7- Subbottom profile record along Line 3 (red line on Fig. 5) inserted vertically into bathymetry map of region indicated in Figure 5. The color scale is the same as Figure 4. The raised block appears to be covered by up to 50 m of interbedded turbidites or ash and hemipelagic sediments similar to sections mapped 10 km to the southwest of the survey area. Vertical exaggeration of bathymetry is 6x; lighting angle is from 315°. Horizontal lines on profile are at 5 m intervals.

Fig. 8- Backscatter map of study area produced using amplitude data from the Simrad EM300 system. Area of coverage is shown in Figure 5. This is an oblique view, looking north-northwest. High backscatter (black) represents strong reflectivity from rough, possibly fresh,

volcanic seafloor. Lower reflectivity indicates older weathered volcanics and sedimented seafloor.

Fig. 9- Subbottom profiler records comparing sedimentary sections within and outside the study area. (A) Record from 10 km west of the study area showing ~50 m thick sedimentary section consisting of what are probably interbedded turbidites or ash layers and hemi-pelagic sediment. Sea floor elevation is decreasing on approach to the survey site. (B) Record along Line 3 (see Fig. 5 for location) showing similar sediment covering uplifted blocks in study area. Acoustic stratigraphy suggests that sediments here have been disturbed or disrupted. See Figure 7 to compare this profile with surrounding seafloor.

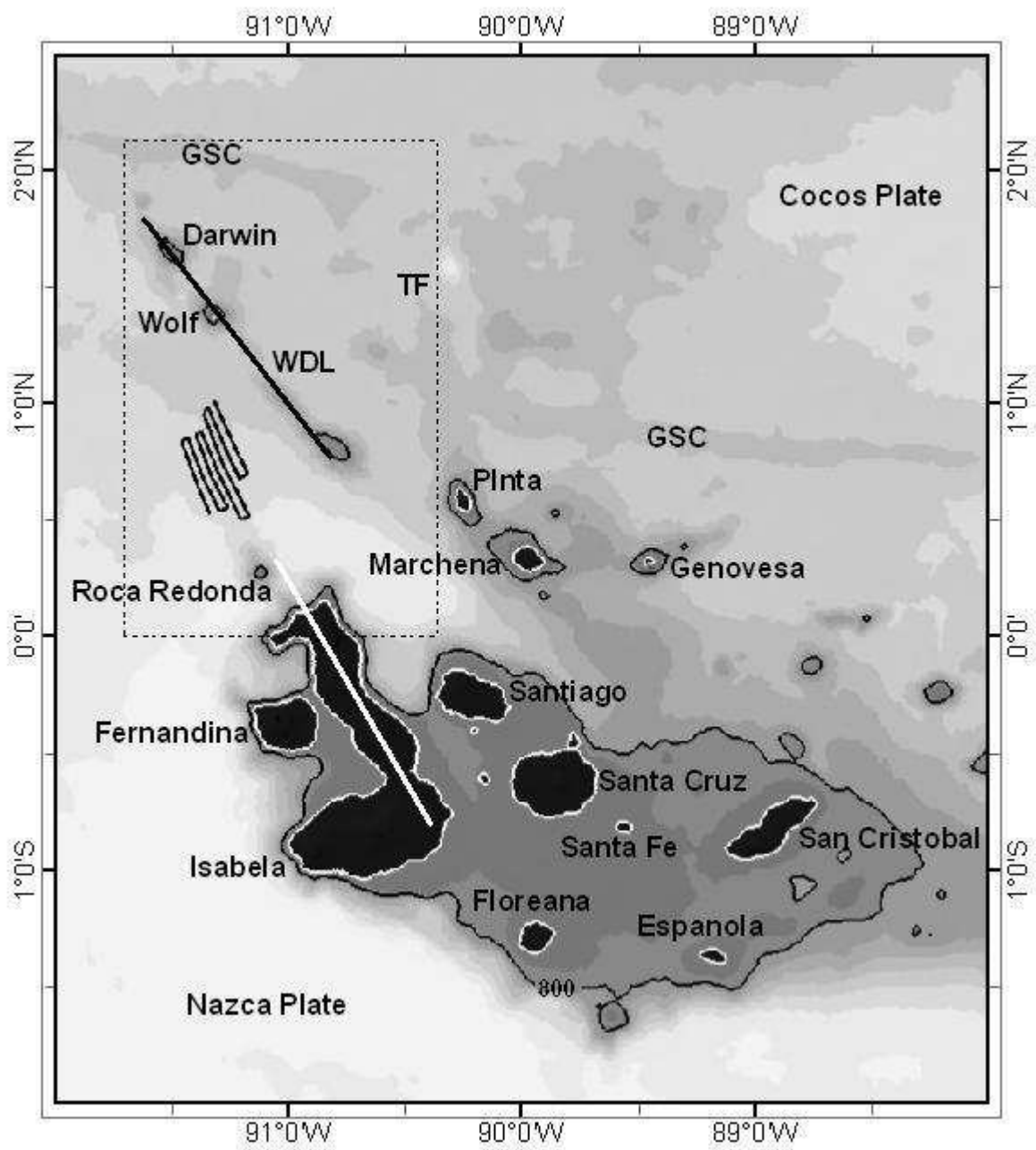


Fig. 1- Heidi Berkenbosch

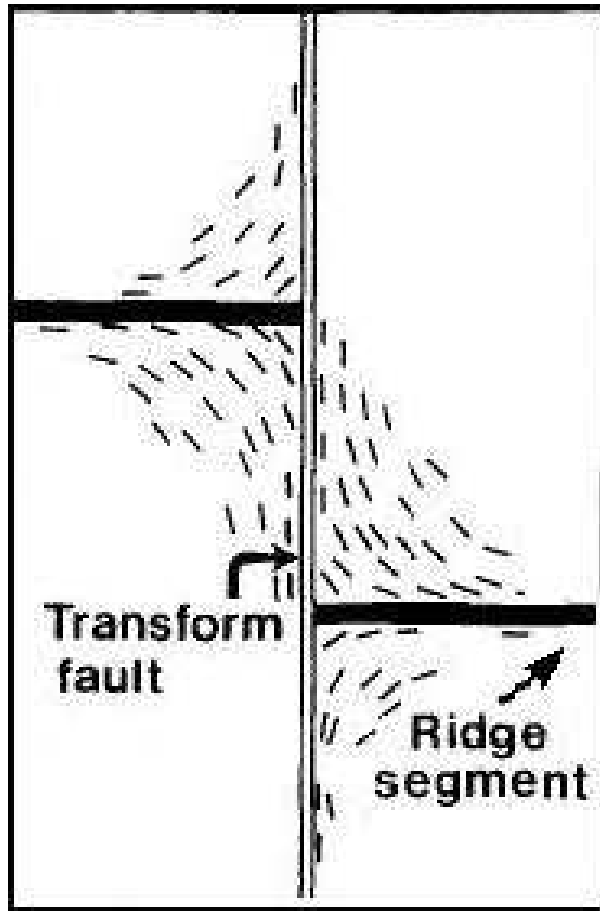


Fig. 2 – Heidi Berkenbosch

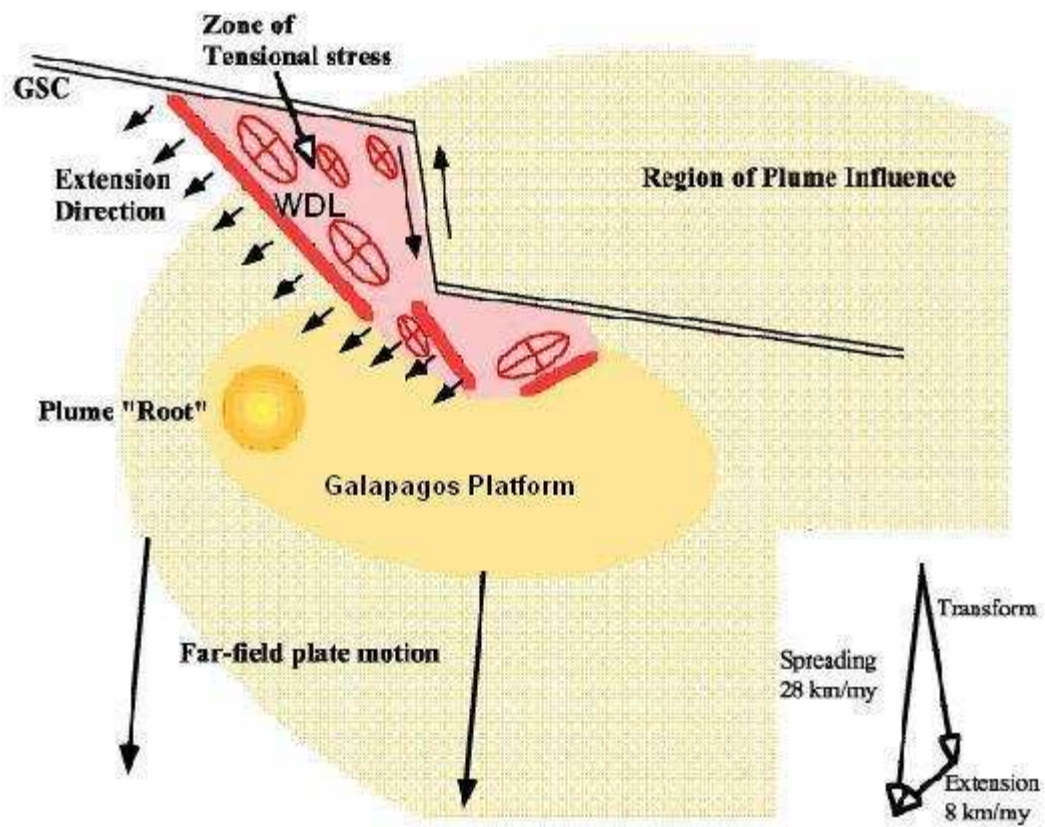


Fig. 3- Heidi Berkenbosch

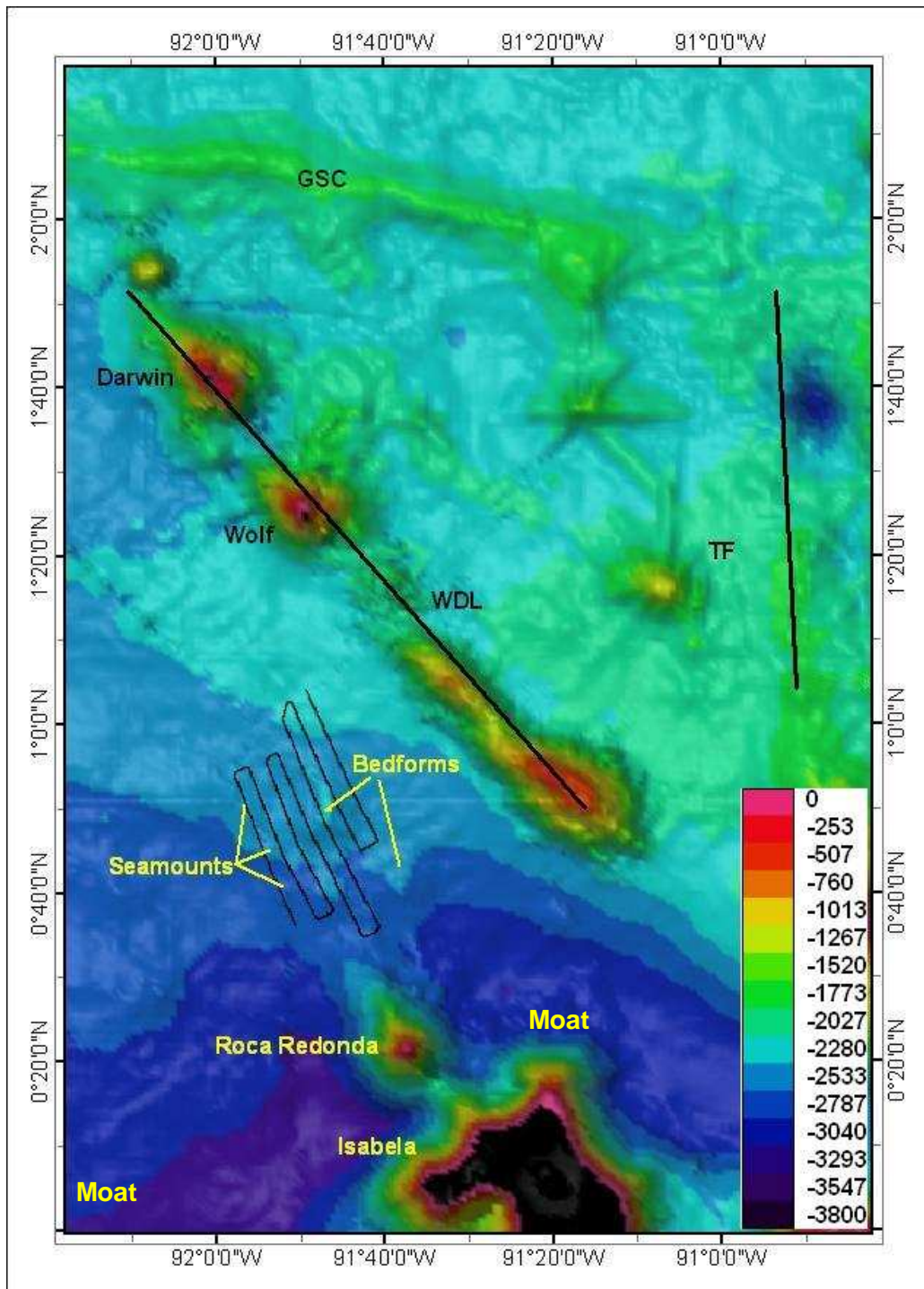


Fig. 4- Heidi Berkenbosch

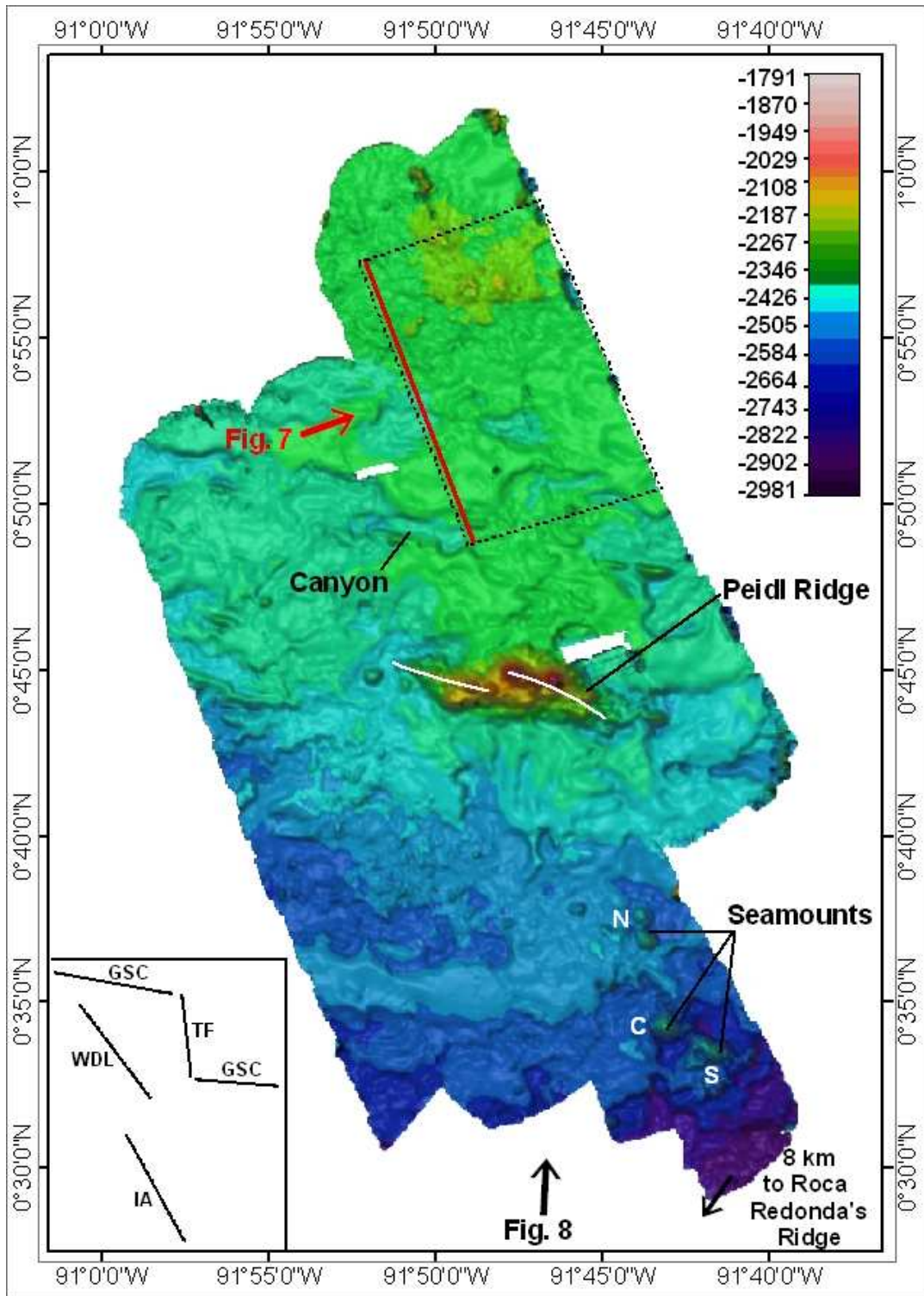


Fig. 5- Heidi Berkenbosch

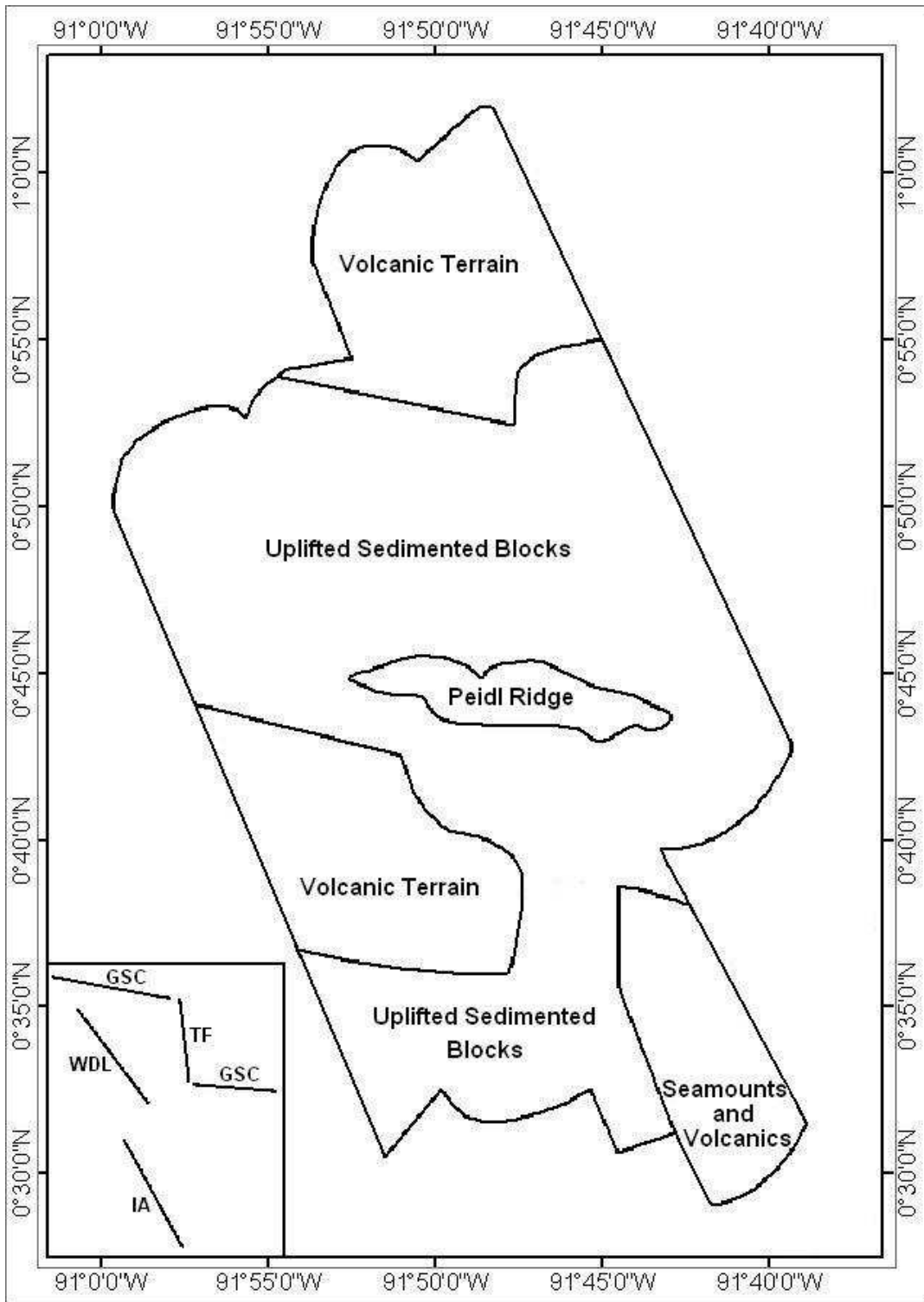


Figure 6- Heidi Berkenbosch

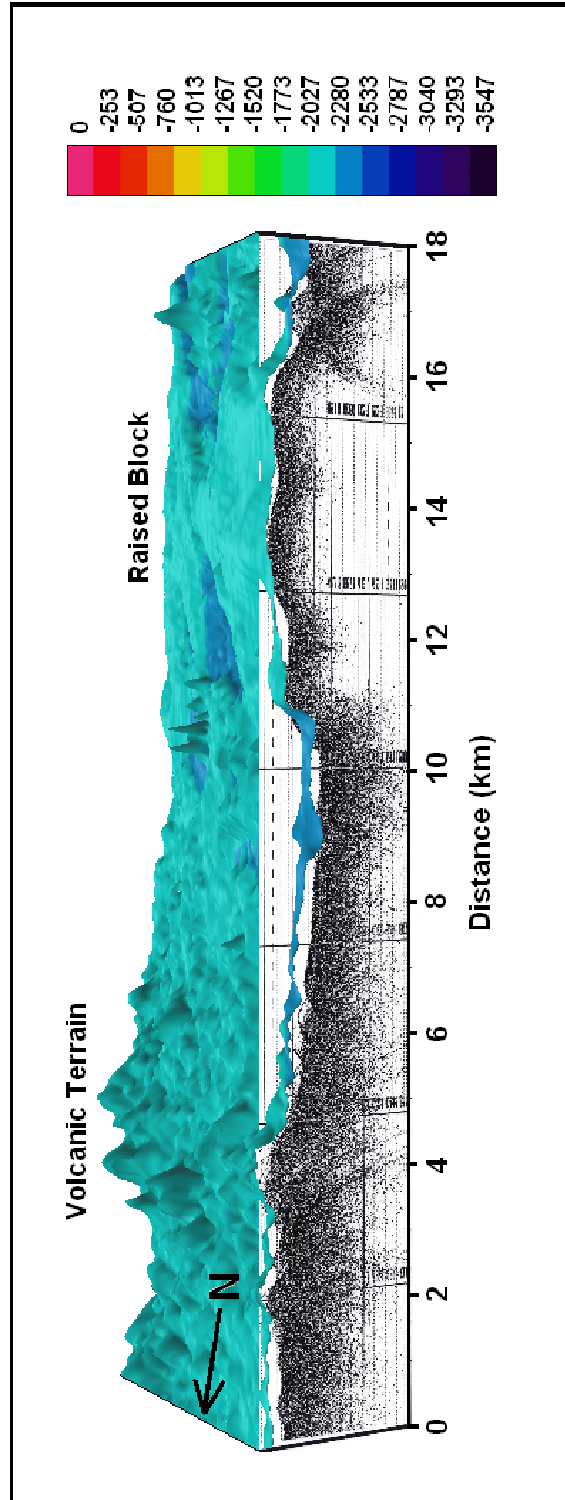


Fig. 7- Heidi Berkenbosch

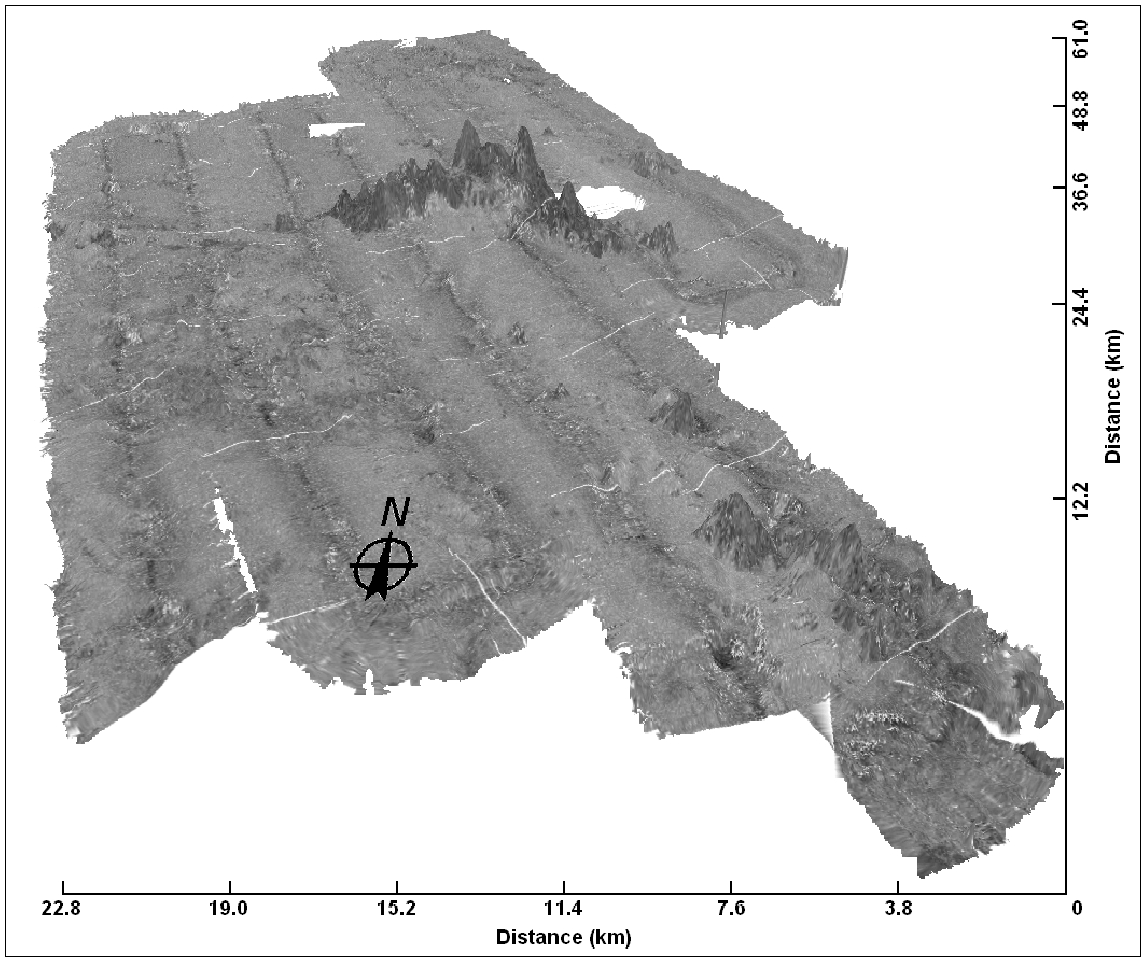


Fig. 8 – Heidi Berkenbosch

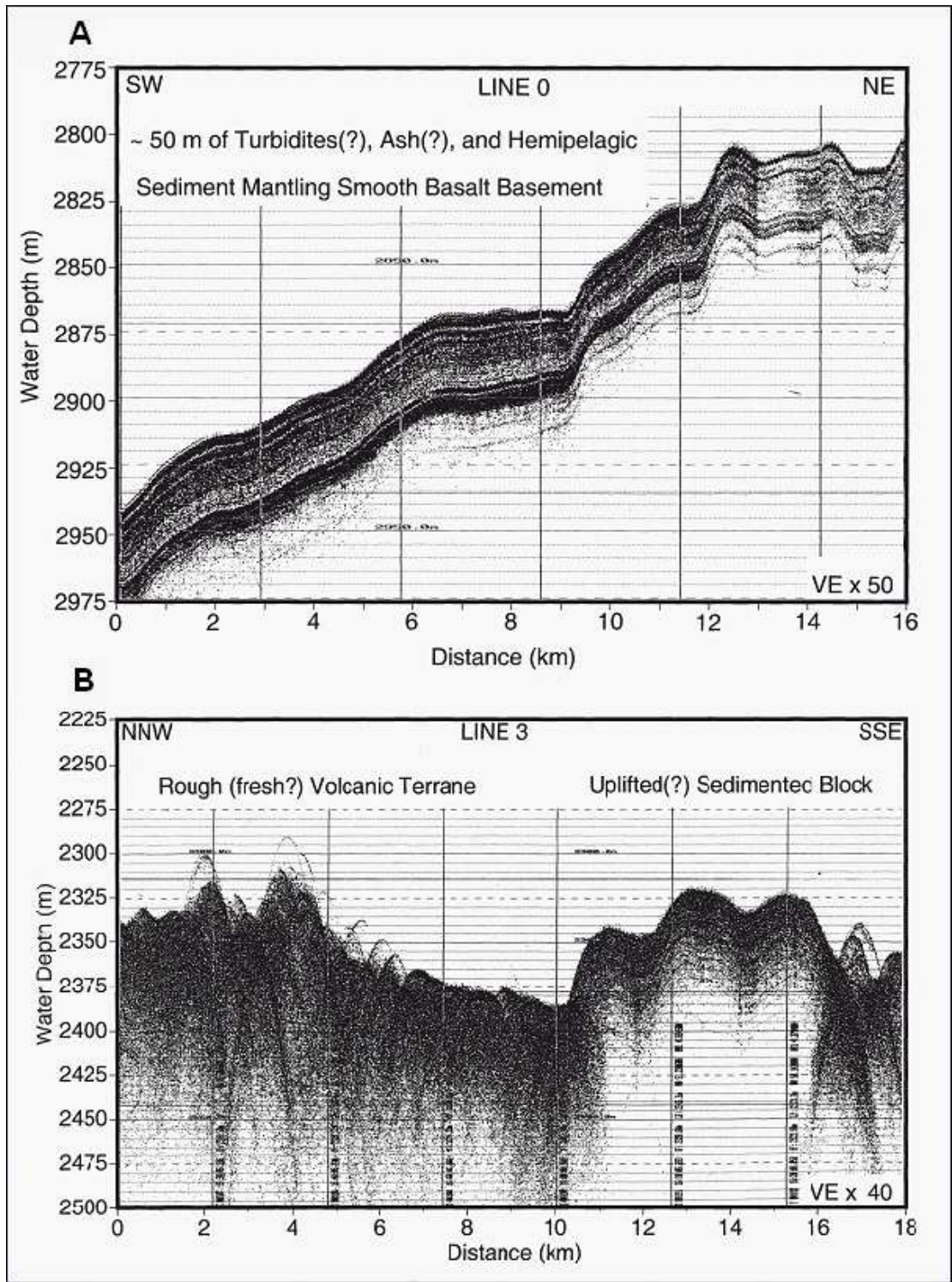


Figure 9- Heidi Berkenbosch