Processes of sediment transport across the Galapagos Platform: A geophysical study of Canal Isabela

Running head: Sediment transport in Canal Isabela

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Non-technical summary

The Galapagos Islands are situated on a hot spot, an area in the Earth's crust that has magma close to the surface. Magma eventually pushes to the surface, forming volcanoes and warming the area. This warming causes the crust to become lighter than surrounding crust and due to the hot spot the warm crust is lifted up to form a platform with hot spot-formed volcanoes. This process has also formed other island chains such as the Hawaiian Islands and Kerguelen Platueau. Volcanically active, these islands erode slowly once past the hot spot and produce some of sediment in the process. This weathered and eroded sediment travels from the platform and eventually into the deep sea. This study was used to collect data that would show how sediment transport takes place between Isabela and San Salvador Islands in Canal Isabela. Sediment transport is important because this transfer process plays a major role in the transport of nutrients, the recycling of carbon, and the movement of pollutants, all important on a global scale in understanding how individual ecosystems function. Canal Isabela begins on the Galapagos Platform at depths of 500 m but quickly descends to oceanic depths of approximately 2200 m. Bathymetric tracklines, designed to follow and map contours and details of the Canal area and sub-bottom profile tracklines, which take a series of "snapshots" of vertical seafloor profiles designed to map the channel characteristics were produced. In January 2006 Canal Isabela was studied while on *R/V Thomas G. Thompson* cruise TN-189-2. The area mapped was approximately 100 km^2 and was completed with 17 tracklines totaling 200 km in length. Along with completing the survey lines, a box core that is a metal box used for grabbing sediment from the seafloor, was taken in order to search for evidence for sediment transport via different mechanisms. Due to the lumpy bottom and shape of channel slopes shown by bathymetric profiling data, Canal Isabela is likely influenced mainly by submarine landslides and not by turbidity (density driven) flows of sediment from terrestrial sources.

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Abstract

Submarine canyon systems provide major pathways by which sediment and other particulate matter is transported from continents and oceanic platforms to the deep sea. This transfer process plays a dominant role in the transport of nutrients, the recycling of carbon, and the movement of pollutants. Examination of existing (1947) Galapagos Islands bathymetry maps suggest that Canal Isabela, between San Salvador and Isabela Islands, is the site of a major canyon whose role in the movement of particulate matter across the Galapagos Platform had not been studied. It was thought that this canyon is the site of one or more turbidity current channels, whose geometry would permit calculation of turbidity flow volumes, speeds, and recurrence intervals. A geophysical survey of Canal Isabela was executed aboard *R/V Thomas G. Thompson* in January 2006. A Simrad EM300 multibeam system and 3.5 kHz sub-bottom profiling were used to map and characterize geologic and geomorphic features of the canyon system. Data were obtained along 210 km of track, resulting in a full coverage sea floor image covering ~100 km^2. Swath mapping and subbottom profiles show conclusively that large submarine landslides, not turbidity currents, are the dominant process moving sediments from the Islands to the Platform and thence to oceanic basins. Seafloor imagery shows the existence of previously unknown volcanic cones on the canyon floor; these edifices are aligned with similar features on adjacent islands. Two of these cones, now partially destroyed by faulting or landslides, form a dam across the northern outlet of the canyon system, thereby trapping much of the material.

Introduction

The Galapagos Islands (Fig. 1) are a volcanically active archipelago containing numerous shield volcanoes and are influenced by a hot spot that continues to shape morphology. As its volcanoes continue to erupt, the underlying oceanic crust stays hotter and less dense than the surrounding crust, over time causing the entire Archipelago to become a raised platform topped with islands (McBirney and Williams 1969). In this case, the Galapagos platform has a role similar to a continental shelf, enabling active sediment transport from the platform to the abyssal depths. . The transfer process of sediment transport plays a dominant role in the transport of nutrients, the recycling of carbon, and the movement of pollutants. There are many cases of other volcanically formed island systems with similar plateaus allowing for sediment transport from their plateaus.

The Kerguelen Plateau in the Indian Ocean is a platform with sediment transport and upwelling currents. A relationship between the strong bottom currents around the Kerguelan Plateau and the suspension of sediments flowing from the plateau (Dezileau et al. 2000) has shown that much of the sediment transport from the Plateau is due to interactions between Antarctic Bottom Water (AABW) and the strong Antarctic Counter-Current (ACC) as well as topographic features. Similar examples also exist in the Canary Islands (Wynn et al. 2002, Gee et al. 2001, Krastel et al. 2001), Japan (Klaus and Taylor 1991), Fiji Islands (Weaver et al. 2000), Vanuatu (Smith et al. 1997), and Hawaii (Garcia and Hull 1994). These locations all contain active sediment transport from their island platforms via ocean currents and wind and can be used as models for determining how these processes affecting Canal Isabela.

The volcanically active nature of the Galapagos Islands leads to creation of sediment material (Tasch 1978, McBirney and Williams 1969). This sediment created by volcanism is subsequently transported by currents and are small particles consisting of dust, dirt, and sand-sized grains (Christie and Fox 1990). In addition to volcanism and tectonics shaping the Galapagos region, strong currents around and between the Islands affect its morphology. The strong and direct magnitude of the southwest trade winds allows for constant wave action on the coasts and beaches, increasing weathering and transport. Shield volcanoes have been shown to have relatively slow weathering, whether they are active or not (Tasch 1978). Therefore, a small amount of sedimentary material is expected, especially in nearshore areas such as Canal Isabela (Christie and Fox 1990). The trade winds would also cause alongshore drift cells of sediment, which develop as a response to local wind-generated waves and are affected by local bathymetry and geomorphology. Sediment transported in these cells would become intercepted by an island margin canyon system and transported off the platform to the deep ocean, most likely in the form of turbidity (density) flows and landslides.

Submarine canyons and channels exist in many marine environments. These canyon systems provide major pathways by which sediment and other particulate matter is transported from continents and oceanic platforms to the deep sea. Canyon characteristics are shaped by sediment transport, often in the form of turbidity currents and submarine landslides (Shanmugam 2003). Monterey Canyon in California is an example of a channelized canyon constricting direction of sediment flow. This constriction works by forcing sediment in one direction, increasing its potential wave energy and accelerating erosion of the canyon (Kunze et al. 2002, Komar 1969). Turbidity flows, occasional density-driven sediment currents with average speeds of 20 cm s^{-1} but sometimes over 75 cm s^{-1} (She and Klinck 2000), are responsible for moving large amounts of sediment in submarine channels. Locally in Puget Sound, Hutnak (1996) concluded that turbidity flows were responsible for the majority of sediment transport in the region.

Submarine landslides are another density-driven flow responsible for shaping seafloor morphology. While turbidity currents are characterized by well-sorted fine grains moving with strong currents, landslides happen quicker and involve large amounts of sediment arriving on the seafloor poorly sorted (Martin 1995). Submarine landslides are often triggered by tectonics and are also more possible when channel flanks have slopes steeper than 20º (Karlin et al. 2004). Likewise, seafloor evidence of past density-driven flows includes deposits made by turbidity currents. These past turbidity current deposits are generally better stratified with distinct sediment layers, compared to debris piles resulting from submarine landslides (Table 1). Figure 2 from Puget Sound, WA shows an ideal profile of an area dominated by turbidity currents (Staly 2002). Channel walls are asymmetric, showing the influence of centrifugal and Coriolis forces shaping sediment deposition on the flanks. There is also layered sediment in the middle of the channel, showing an even distribution of sediment by turbidity currents.

Canal Isabela was chosen as my study area for its transition from platform depths of approximately 500 m to abyssal depths of approximately 2800 m within a short 50 km distance. The Canal is also confined between Isabela and San Salvador Islands, both of which provide likely sources of terriginous sediment. Analysis of 1947 bathymetry data (Defense Mapping Agency 1976) shows a braided system of broad channels trending northward off the platform into depths of 2000 m. This bathymetry is low resolution (Fig. 3), with approximately one sounding depth reading per 10 km. The purpose of this study is to determine if a channel system does exist between Isabela and San Salvador Islands, describe the main geomorphic and geologic features that form this channel, and to determine what, if any transport processes are active in the channel system.

Methods

Data for this study were collected 20-28 January 2006 on R/V *Thomas G. Thompson* as part of cruise TN189-2 (Fig 1). Based the existing 1947 data (Defense Mapping Agency 1976), a contour map (Fig. 3) was designed and tracklines plotted for the Simrad EM300 (EM300) and 3.5 kHz subbottom surveys. EM300 survey lines were parallel to the channel axis in order to obtain the best swath coverage (Fig. 4). These data also defined the overall morphology of the channel and determined slopes of the channel flanks. The channel slopes were then used to infer slope stability. A second set of tracklines (Fig. 5) was completed normal to the inferred channel axes in order to collect 3.5 kHz subbottom profiles, which were used to map and analyze bottom features. These data provided evidence of landslide activity and was also influential in determining the spade box core location. Due to time restrictions the simultaneous EM300 and 3.5 kHz surveys were confined to the outer area of Canal Isabela, where the morphology transitions from platform to abyssal depths over an approximate distance of 50 km. The total survey consisted of 17 tracklines covering approximately 100 km^2.

A Conductivity Temperature Depth (CTD) cast was taken to measure the sound velocity profile of the water column; this reading was used to calibrate the EM300 system and to provide accurate depth readings for the survey. While surveying the *R/V Thompson* traveled at 8 knots and swath-widths were roughly 2.5 times as wide as the average water depth in each location, with swath overlap of 10% (Glickson, D., pers. comm.). Raw data from the EM300 mapping was imported into CARIS software, which was used to correct for erroneous readings due to system malfunctions, for tides and, for heave and pitch of *R/V Thompson*. Fledermaus mapping software was then used to create different views of the study area. The result is a bathymetric map of the Canal with an approximate 50 m grid resolution.

Survey of the region with the 3.5 kHz subbottom profiler was used to verify the presence of sediment and to accurately locate the channel axis. After completing the 3.5 kHz site survey, a location (Fig. 5) was chosen due to high amounts of sediment in that area of the channel, and a spade box core sample was taken. This box core sample was examined based on properties and sizes of the sediments and for signs of turbidites and layering in the sediment record, which would show past turbidity currents (Table 1). Features of the sample were examined using relative grain size analysis and these data recorded using a digital camera and a tape measure to record any distinct layers or sediment characteristics (Table 2).

Results

Both the 3.5 kHz subbottom profiles and the EM300 swath imagery revealed many surprises regarding the geology and geomorphology of Canal Isabela. The seafloor in the survey area is much more complex, in terms of morphology and sediment transport processes, than was expected from even a detailed examination of the existing bathymetric data (Fig. 2)

3.5 kHz Data

Two of the 3.5 kHz profiles serve to illustrate the complexity of the main channel system. Figure 6 shows the record from Line 2 (Fig. 5), obtained from the western part of the survey area. The main channel system here is approximately 5.0 km wide (at the tops of the bounding walls, and has a floor width of about 1.2 km. The flanks of the channel are steep, ranging from 18° to 20° and appear to be generally quite smooth. The floor of the channel, at a depth of 1230 m, is characterized by strong, complex, hyperbolic reflectors; some appear to be about 10 m high. The smoothness of the southern wall is interrupted at a depth of about 1225 m by a large ‘shoulder’ having a width of 700 m.

The 3.5 kHz record from Line 6 (Fig. 7) was obtained across the channel system at the eastern end of the survey area (Fig. 5). Here the walls are even smoother and steeper (~22°) than those seen to the west along Line 2. The width of the 640-m-deep channel at the tops of the bounding slopes is 2.5 km (half as wide as along Line 2) and the width of the valley floor is 700 m, about the same as at the western end of the survey area. The echo characteristics of the channel floor show strong reflectors, with hyperbolic echoes. The geometry of the reflectors suggests a slightly smoother surface than the channel floor beneath Line 2.

The 3.5 kHz data collected along the other lines throughout the survey area (Fig. 5) show channel morphologies and geometries similar to those described from Lines 2 and 6. The channel becomes much less distinct in certain areas, especially in the region from Line 6 eastward for about 4.5 km. Here the southern flank of the channel system consists of a very rough sea floor, with individual features having reliefs of up to 45 m. A prominent bounding southern wall is absent.

Sediment Sample

The spade box core sample obtained from the channel axis along 3.5 kHz Line 6 (Fig. 5) contained 23 cm of indistinctly-layered sediment ranging from olive gray fine clay in the top centimeters followed by alternating layers of olive gray silty clay and sandy clay to the bottom of the core which consisted of olive black sandy silt (Table 1).

EM300 Swath Bathymetry/Imagery

The EM300 swath data provide a detailed regional morphological context that not only yields many clues to the geomorphology of Canal Isabela but also permits additional interpretive insights for the 3.5 kHz data. Figures 8 and 9 show the results of the EM300 processing; the former is a vertical (plan) view and the latter shows the imagery in an isometric view. Both are helpful from an interpretive standpoint. A simplified bathymetry contour map (Fig. 10) was also prepared to help illustrate the gross morphology of the channel system and the oceanic basin to the west.

The imagery and bathymetry show the floor of Canal Isabela to be extremely complex, not at all the simple channel/valley system that was envisaged from the older 1947-era bathymetry. In general, the channel in this portion of Canal Isabela is bordered on the north by the steep flanks of Isla San Salvador and on the south by a series of cone-like structures (in the east and west) and a large field of hummocky topography in the central region.

At the eastern end of the survey area two conical features, both previously unmapped, were discovered 4.6 and 8 km south of Cabo Nepean on San Salvador Island (Figs. 8 and 9). Both cones are about 200 m high, rising to depths of 350 and 450 m. The northernmost of these cones forms the southern flank of the main channel system, as is shown by the 3.5 kHz line which crosses it (Fig. 7). A moat-like feature appears to partially surround the southernmost of these two cones. Both features exhibit arcuate depressions on their southern flanks (Figs. 8 and 9).

To the west of these two cones the channel is delineated by a 650-m-deep basin that is about 1.5 km wide (Fig. 9). The portion of the Platform lying south of this basin is characterized by an extensive zone of hummocky topography, seen in profile form on the 3.5 kHz data. Relief, as mentioned previously, is as much as 45 m. The average depth of this hummocky region is about 600 m.

West of the basin the gradient of the channel is interrupted by a 'saddle' having a depth of 550 m lying between two submarine cones (Fig. 8-10). The southernmost of the cones appeared as a discreet 100 km sounding on the 1947 era bathymetry (Fig. 2). The two submarine cones, whose peaks reach depths of 250 m and 150 m lie in a roughly southwesterly line between Punta Boquerizo on San Salvador Island and Punta Alfaro on Isabela Island.

West of the cone and saddle structure the channel descends steeply into a small t-shaped basin at a depth of 700 m formed by spurs extending from the flanks of Isla Isabela and Isla San Salvador. These spurs look rather subdued on the simplified bathymetry chart of Figure 10. The EM300 imagery, however, shows them to be sharp ridges, with morphology resembling half cones. The spurs restrict the outlet of the t-shaped basin to a narrow (~250 m) chute. West of the spur ridges the morphology shows a slope of 15° to 20° descending to depths of 1650 m.

The southern flank of Isla San Salvador is cut by two distinct canyons that incise the shelf. One of these is south of Cabo Nepean, and the other is just to the east of the prominent cone that was mapped south of Punta Boquerizo. This latter canyon is almost directly north of the saddle structure described previously.

Discussion

Not surprisingly, the 3.5 kHz data provide a much better insight into the sediment transport processes than do the swath mapping data. The EM300 swath imagery, on the other hand, provides a visual geomorphic context without which the subbottom profiling information would be difficult to interpret.

Sediment Transport

The 3.5 kHz records over the channel system beneath Canal Isabela show acoustic stratigraphy on the valley floor that is indicative of landslide deposits (Table 1). The strong hyperbolic reflectors, having a relief of several meters, indicate that the deposits responsible for this acoustic signature are poorly sorted, with sizes probably ranging from silt to boulders. This echo character also suggests that the deposits consist of closely spaced large piles of debris. The steep ~20° slopes of the flanks of structures bounding the main channel support the interpretation of landslides. A slope of 18° to 20° is the angle of repose for 'normal' saturated marine sediment (Holmes, M., pers. comm.). None of the 3.5 kHz data suggested the presence of turbidity current deposits, either on the valley flanks or on the valley floors.

The spade box core collected from 3.5 kHz survey Line 6 (Figs. 5 and 7) shows indistinct layering that exhibits some signs of at least three sequences of graded bedding (Table 2), in which coarser sediment grades upward into finer material. These sediments could have been deposited by a turbidity flow, or they could have resulted from fall-out from a landslide plume. The echo character of the channel floor deposits at the coring site is strongly suggestive of landslide debris. Local topography is very hummocky and shows no evidence of turbidity flows.

The configuration of the channel system also plays an important role in how sediments are moved across the Platform. The EM300 imagery (Figs. 8 and 9) and the bathymetry contour map (Fig. 10) show the channel system to be complex and discontinuous. EM300 and 3.5 kHz data show the presence of a system of unconnected channels extending along the northern part of Canal Isabela, indicating that there is no continuous pathway by which turbidity currents could carry sediment across the Platform and into the deep basin to the north (Figs. 8-10).

The channel between Cabo Nepean and the volcanic cone (Figs. 8-10) trends westward into a 650-m-deep basin about 1.5 km wide and 6 km long. This basin lies at the foot of a steep (>20°) slope that forms the flank of Isla San Salvador. The 3.5 kHz records indicate large amounts of landslide debris at the foot of this slope (Fig. 7). Exit from this depression is blocked by a saddle (depth 550 m) extending between the two volcanic cones that were mapped between Punta Boquerizo and Punta Alfaro (Fig. 10). This constructional saddle forms an effective barrier that confines any sediment being transported westward across the Galapagos Platform to a 650-m-deep basin. West of this saddle the valley morphology resumes, extending westward into a T-shaped catchment basin at a depth of 700 m formed by sharp ridges extending north and south from Isabela and San Salvador. A narrow 300-m-wide exit channel provides and outlet from this perched basin. After passing through this narrow outlet between the two ridges, sediment would pass across slopes of 10-15º into the 2200-m-deep oceanic basin.

Two large previously unknown canyons were mapped on the southern margin of Isla San Salvador (Figs. 8-10). These canyons might provide important pathways for sediment from the near shore to the deep Platform by intercepting material being moved by alongshore transport. One canyon appears to feed sediment into the 650 m deep basin, the other channels sediment onto and to the west of the constructional saddle between the two volcanic cones (Figs. 8-10).

The complete dominance of landslide deposits, together with the absence of a distinct channel system having a continuous downward gradient, indicates that most sediment transport in this portion of Canal Isabela is occurring in a vertical rather than a horizontal direction. The apparent lack of a mechanism and morphology to permit sediment to move readily into the deep basin north of Canal Isabela might also explain the lack of sediment cover in that area (Neibauer 2006).

Volcanic Processes

Perhaps the most surprising result of this study was the number of volcanic features that were mapped on the floor of Canal Isabela (Figs. 8 and 9). The four prominent submarine cones that were imaged (three previously unknown) are aligned in two semi-parallel rows trending generally north-south, about 9 km apart. The two cones south of Cabo Nepean (Fig. 10) both show evidence of southward-directed flank collapse (Figs. 8 and 9). This morphology is very similar, though on a much smaller scale, as that of Volcan Ecuador on the northwest tip of Isla Isabela (Hall 2006). These collapses could be a source of landslide debris onto the platform.

The southernmost of these two cones shows a moat-like depression partially encircling it on its western flank. Such a moat could be caused by asymmetric subsidence (tilting) of the edifice, by current scour, or as a result of landsliding. Highly fluidized landslides can sometimes produce a 'plunge-pool' depression and the base of the slope down which they travel. Without bottom samples and additional modeling using the EM300 data it is not possible to distinguish between these possibilities.

The two cones lying between Punta Boquerizo and Punta Alfaro (Fig. 10) are somewhat larger than the pair to the east. These cones are connected by a submarine ridge that forms the channel-blocking saddle mentioned previously. The alignment of these cones with the prominent points of land and with two similar subaerial volcanic cones on Punta Boquerizo suggests that there may be some sort of fissure system between the two islands. That might also the explanation for the two smaller cones south of Cabo Nepean (Fig. 10). Such fissures could have formed as Isla San Salvador moved away from the Galápagos hot spot and volcanic activity became concentrated on the structures of Isla Isabela. Without detailed sampling and petrologic analysis the age of these cones cannot be determined.

The rather chaotic zone between these two pairs of island could also have been formed, at least partially, by volcanic processes. The possibility that the rough seafloor here is mantled by landslide debris has already been discussed. Another explanation, building on the possibility of volcanic conduits or fissures between the two islands, is that some of this chaotic topography has been formed by sea floor eruptions. Sequences of pillow basalts on the flanks of mid-ocean ridges exhibit very similar topography (Holmes, M., pers. comm.).

The EM300 imagery suggests that there might at one time have been another pair of volcanic cones between the two islands. The structures that form a partial dam across the western outlet of the main channel system (Figs. 8 and 9) appear to be half-cones. Tectonic activity, possibly due to differential movement between the two islands, may have resulted in a fracturing and massive collapse of these cones. There is some evidence of very large slump or slide deposits in the deep basin just to the west of these features.

The spade box core collected from 3.5 kHz survey line 6 (Fig. 7) shows layering, which could be from turbidity currents or landslides. There are at least three sequences of coarser sediment grading upward into finer material. This suggests that a process that provides sorting has deposited the sediments. Its layers suggested a density flow of some kind, most likely from a landslide due to the 3.5 kHz imagery (Fig. 7) from the same area. A solution is that the sediments were laid out by a turbidity flow; the observed layering could be the result of fallout from a plume created by a submarine landslide. Based on Line 6 (Fig. 7), this layering is most likely from the latter. Local topography is very hummocky and shows no evidence of turbidity flows.

Conclusions

The purpose of this study was to determine if a channel system exists in Canal Isabela between Isabela and San Salvador Islands, to describe the main geomorphic and geologic features forming this channel, and to determine what, if any, transport processes are active in the channel system. From the foregoing Discussion the following conclusions can be made:

• Landslides are the dominant sediment transport mechanism in the northern part of Canal Isabela. No evidence of turbidity current channels or turbidity current deposits was seen in the geophysical data.

• There is no continuous channel system allowing sediments derived from the shelf and slope areas of the adjacent islands (Isabela and San Salvador) to be transported across the Platform via turbidity currents to the deep basin north of the Canal. The gradient of the main channel is interrupted by a saddle between two constructional volcanic cones. Material contributed by landslides to this portion of Canal Isabela mostly remains on the Platform.

• Two submarine canyons on the southern margin of Isla San Salvador provide conduits for transporting sediment from the near shore onto the Platform.

• Three previously unknown volcanic cones were mapped in Canal Isabela. The linear alignment of the cones suggests that they were formed along two north-trending zones of fissures between Isla Isabela and Isla San Salvador.

• A ~ 42 km^2 zone of hummocky sea floor south of Isla San Salvador could be due to extensive landslides from the northern flank of Isabela, or it could be due to submarine lava flows that have been extruded between the chains of volcanic cones. No bottom sampling was conducted in this area.

Beneficial future study would involve more sediment coring in other locations in Canal Isabela, and also longer cores in order to see if the layering trend continues. Surveying of the outer regions of this area would likely provide more clues to processes affecting Canal Isabela.

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Table 1. Comparative anatomy of turbidity flows and landslides in submarine canyon/channel systems.

	Turbidity Flow	Landslide
Channel floor Morphology	Flat; might be sloped, depending on channel axis curvature (plan view)	Hummocky, lumpy
Channel floor Subbottom reflectors	Parallel to sub-parallel reflectors representing layered sands and muds	Clustered hyperbolic reflectors representing rough bottom and large “point” sources
Channel flanks Morphology	Slopes variable; gently undulating due to sediment accumulation	Usually smooth slopes with angles> 20º
Channel flanks Subbottom reflectors	Levee deposits several meters thick, usually higher on one flank than the other	Hard with no subbottom reflection; large slump or slide bodies might be present

Table 2. Description of box core AC-BC2. See Fig. 5 for core location

Depth in core (cm)	Lithologic description
0-2	Olive gray fine clay
3-7	Olive gray silty clay
8-9	Olive gray sandy clay
10-13	Olive gray silty clay
14-17	Olive gray sandy clay
18	Olive gray fine clay
19-21	Olive gray sandy clay
22-23	Olive black sandy silt

Figures

1. Complete view of Galapagos Islands, showing the ship track for R/V Thomas G. Thompson cruise TN-189-2 in January 2006. The black box denotes the study area, shown in greater detail in Figs. 2, 4, and 5. Canal Isabela is the passage between three of the largest of the Galapagos Islands. The study area at the northern end of the Canal covers the transition in water depths from those of the platform (~500 m) to those of the deep ocean (~2500 m).

2. A 3.5 kHz profile from Puget Sound, WA of an ideal turbidity current (after Staly 2002). The angles drawn show the geometry created between the uneven slope angles. These angles can be used to calculate turbidity flow speeds. The characteristics of a channel formed by turbidity currents have sides that are uneven due to centrifugal and Coriolis forces acting on the sediments traveling through. Vertical exaggeration easily shows the difference in size between slopes. This difference is due to Coriolis and centrifugal forces pushing materials more favorably against one slope than the other.

3. Bathymetric map of the study area at the northen end of Canal Isabela. Contours are in fathoms and were drawn using the 1947 era depth notations on Defense Mapping Agency (1976) chart 22545. This map was used to derive the axes of what appeared to be a branched channel system on the floor of Canal Isabela. The geophysical survey described in the text was laid out in such a way as to map and characterize this inferred channel system to determine the sediment transport processes (if any) that are active in the canyon(s).

4. Simrad EM300 survey tracklines parallel to the axis of the channel in order to obtain the best swath coverage. Depths of this survey ranged from 500-2000 m away from the platform. Swath widths were approximately 2.5 times as wide as the average depth and swath paths overlapped by 10% in order to obtain the most complete and accurate data of the region. These data also

defined the overall morphology of the channel and determined slopes of the channel flanks. The channel slopes were then used to infer slope stability.

5. 3.5 kHz Survey tracklines normal to the axis of the channel, which were used to map and analyze bottom features. Both surveys were run simultaneously and covered approximately 100 km^2 and total length of the 17 tracklines was 210 km. These data provided evidence of landslide activity and was also influential in determining the spade box core location; the box core was collected during Line 6 of the 3.5 kHz survey. Refer to Table 2 for characteristics of the spade box core sample.

6. A 3.5 kHz subbottom profile from line 2 of the survey (Fig. 5). Line 2 is located at the northern corner of the survey area where the channel area has subsequently trailed to depths of approximately 1150 m. vertical exaggeration of the image distorts the channel flanks but their flanks measure 18-20º, borderline values for landslides to dominate the scene. Other evidence of landslide activity comes from the pile of debris in the center of the channel. These piles were seen throughout and are clearly caused by submarine landslide activity.

7. A 3.5 kHz subbottom profile from line 6 of the survey (Fig. 5). Line 6 is located in the southern portion of the survey in an area dominated by landslides as shown by EM300 data. This is also where the spade box core AC-BC2 was sampled at approximately 650 m depth. The steep slopes of channel flanks in this profile measure approximately 22º, making submarine landslides highly possible. There is a pile of debris in the center of the channel as well as possible piles of debris coming from the sides of channel flanks.

8. A 50 m gridded EM300 planar of Canal Isabela with no vertical exaggeration. Depths range from 500 m to 2200 m. On the right is a shallow area dominated by submarine landslides with some channels running throughout. This area also has several small shield volcanoes. In the

center of the figure is a basin created by several shield volcanoes trapping sediment. To the left of this feature is a smooth oceanic basin averaging 2200 m depth.

9. A 50 m grid EM300 isometric profile of Canal Isabela viewed from the left side of the Canal. The sediment basin formed by several shield volcanoes can be seen, as well as the missing half of one of the cones that has sense fallen into the oceanic basin to the left of the Canal. Evidence for the landslide-dominated front half of the Canal is also seen, due to mounds of sediment debris.

10. A planar view bathymetric contour of Canal Isabela region. The right side of the profile is relatively smooth because this half is on the Galapagos Platform. On the left half the contour lines become closer showing the rapid drop in depth as the Platform descends to oceanic depths. Also shown in this contour map are the volcanoes and their approximate heights.

Figure 1-Allison Cougan

TN189 Cruise Track (Leg-2)

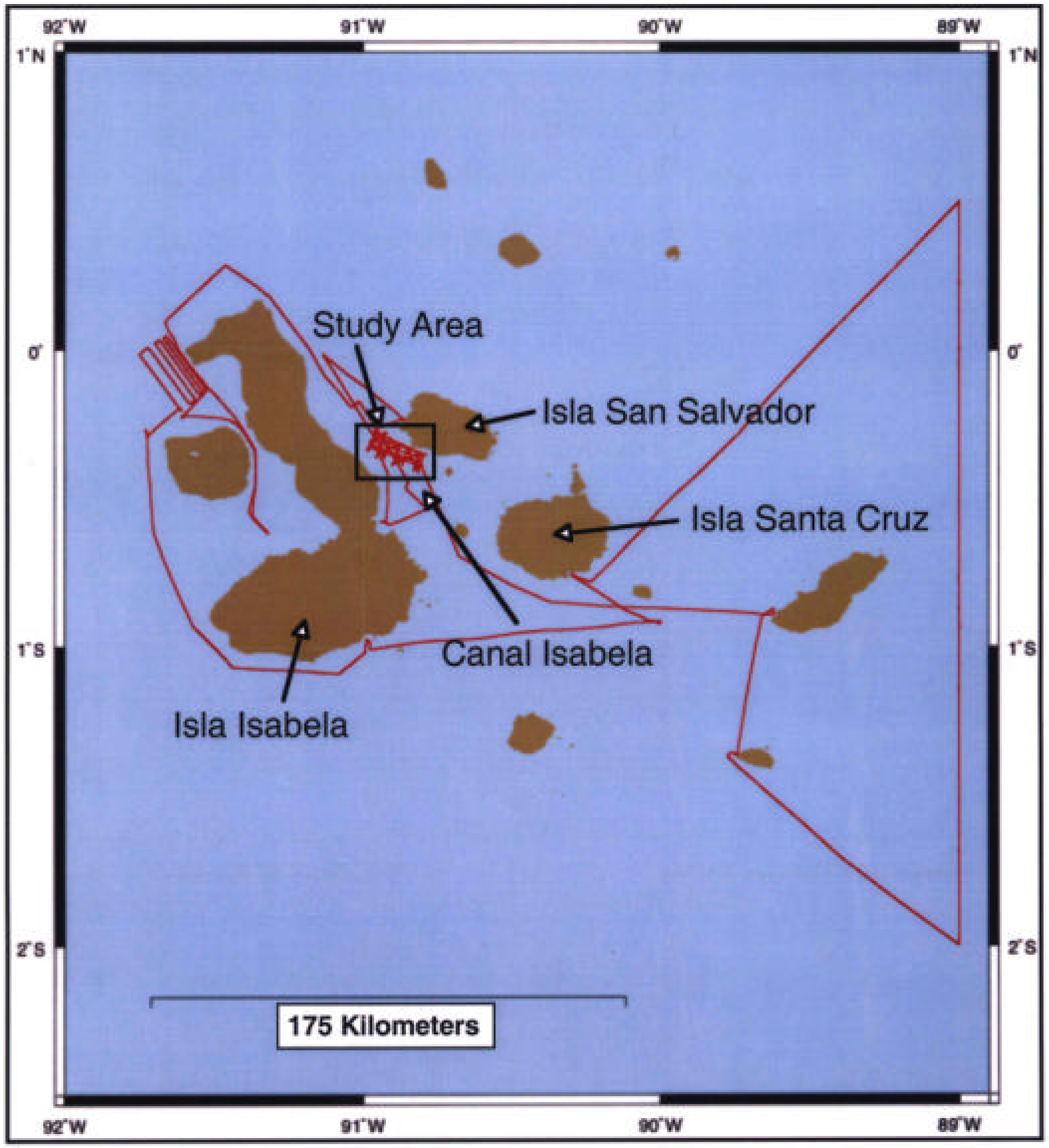

Figure 2-Allison Cougan

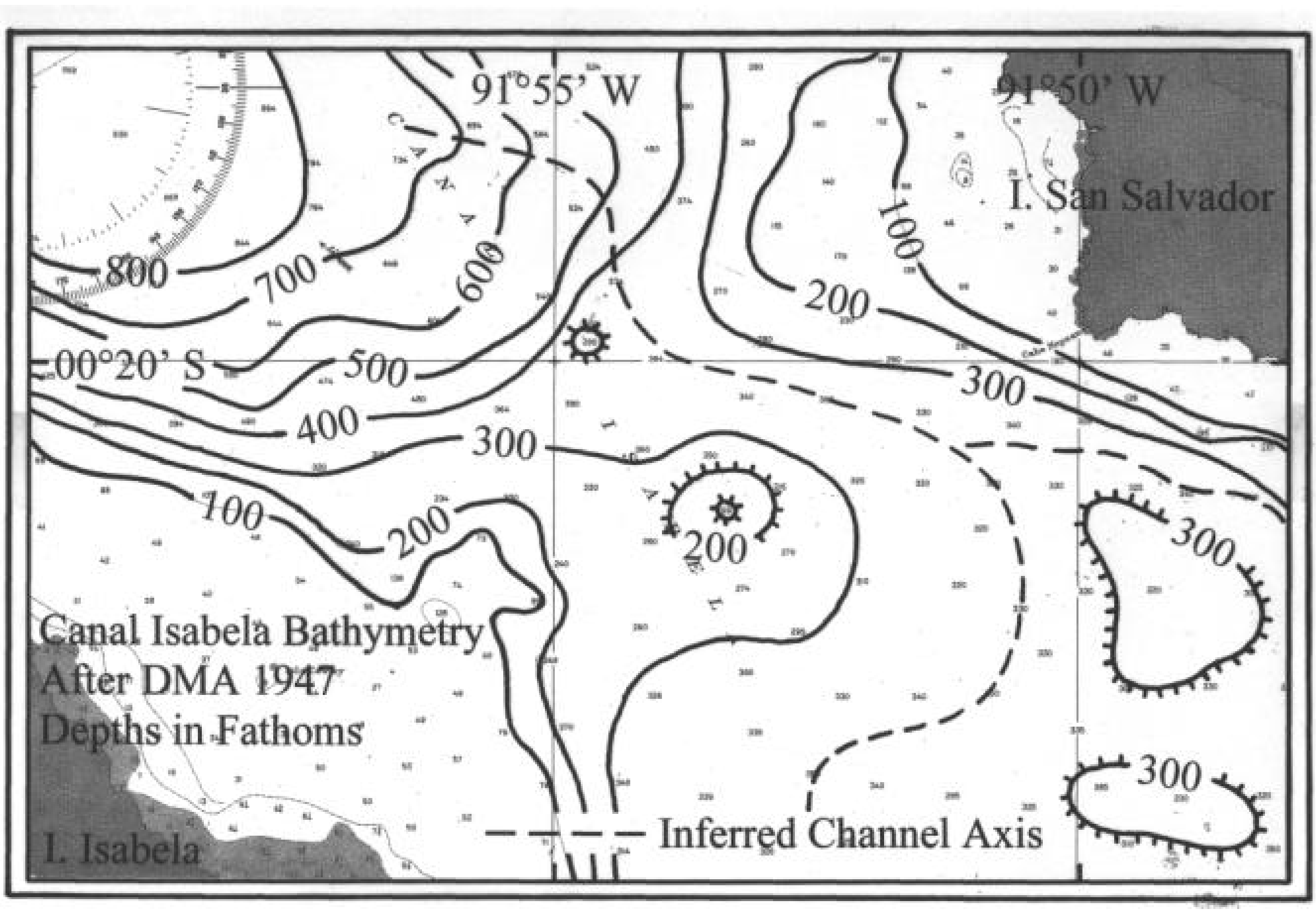

Figure 3-from Staly 2002

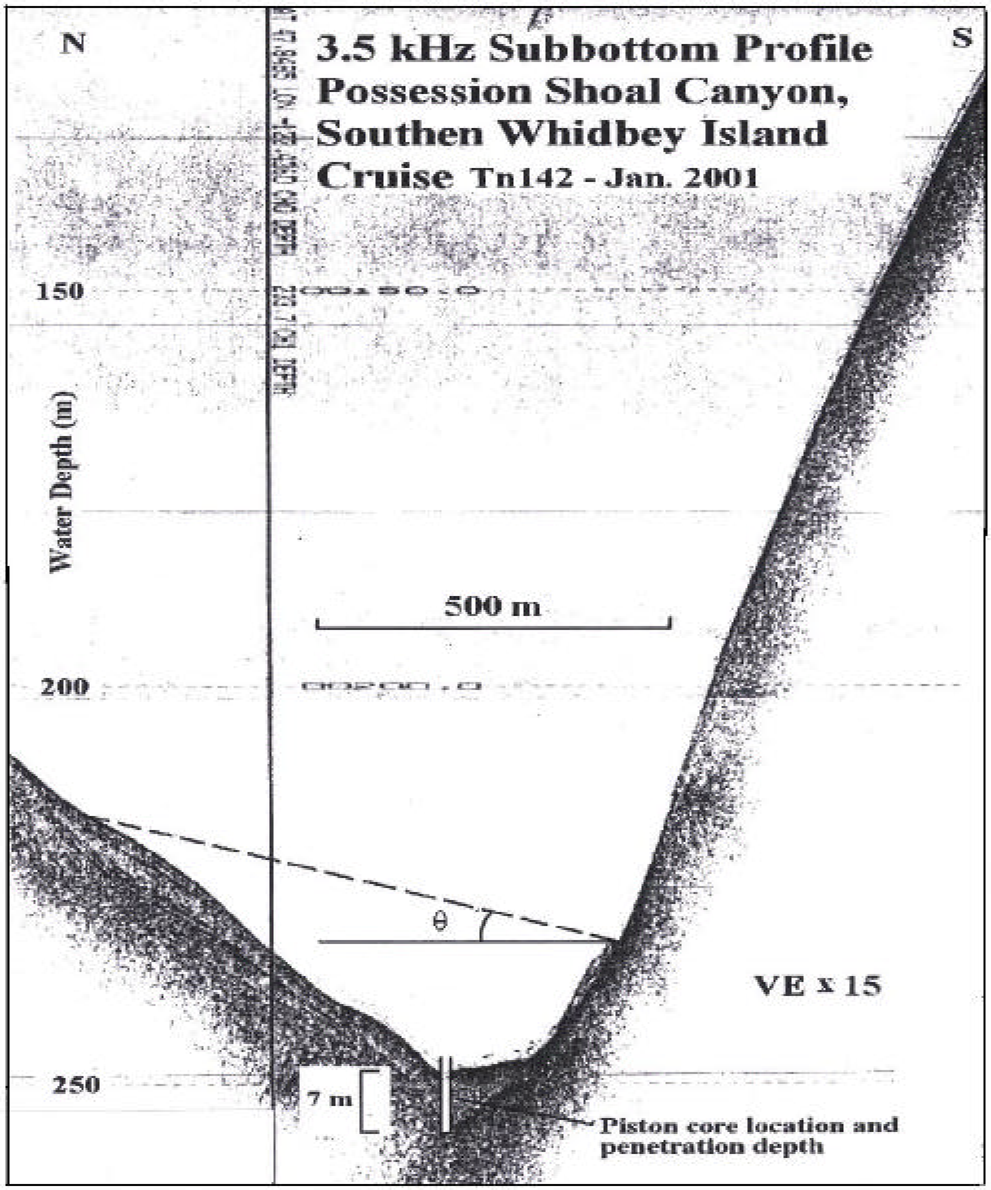

Figure 4- Allison Cougan

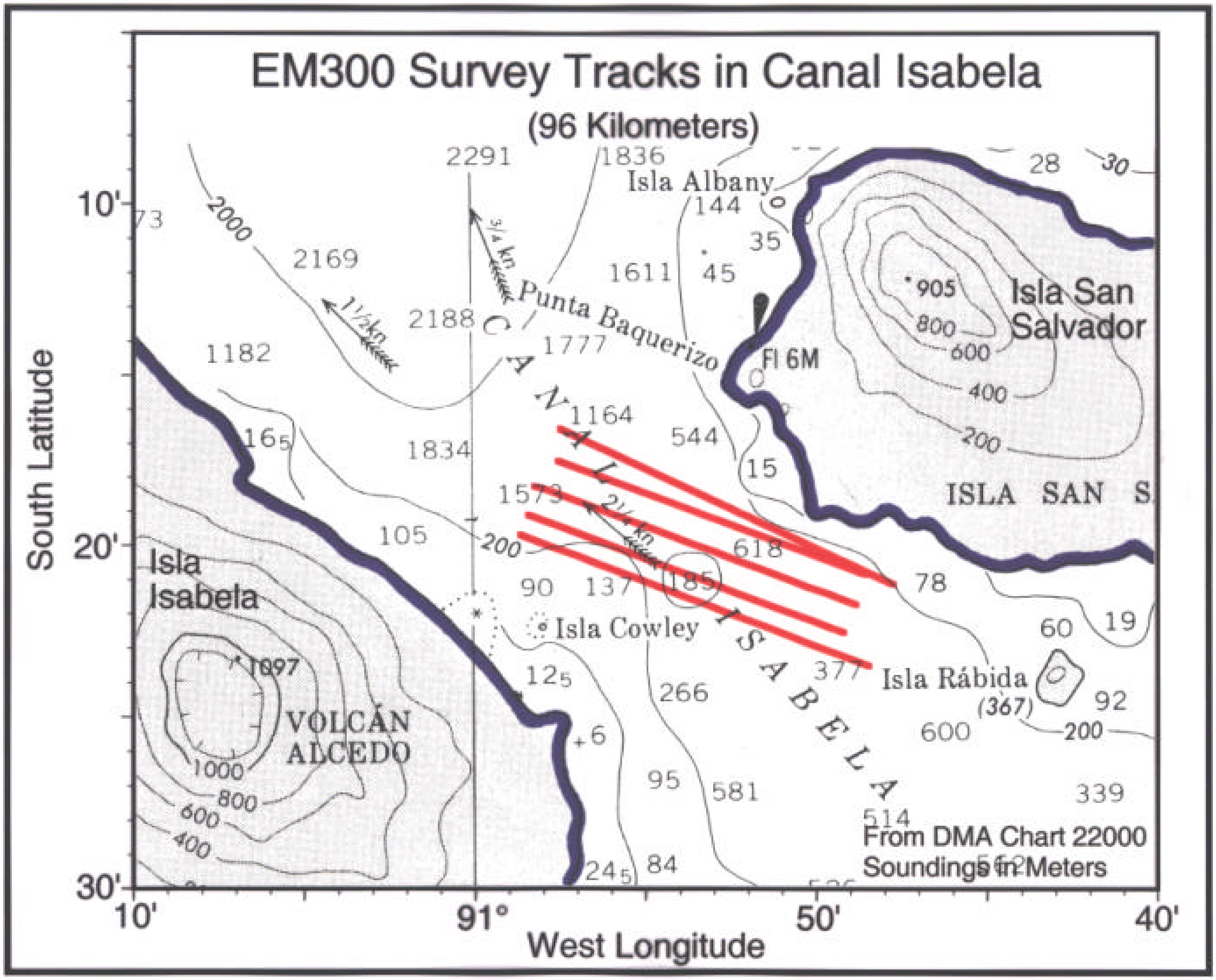

Figure 5-Allison Cougan

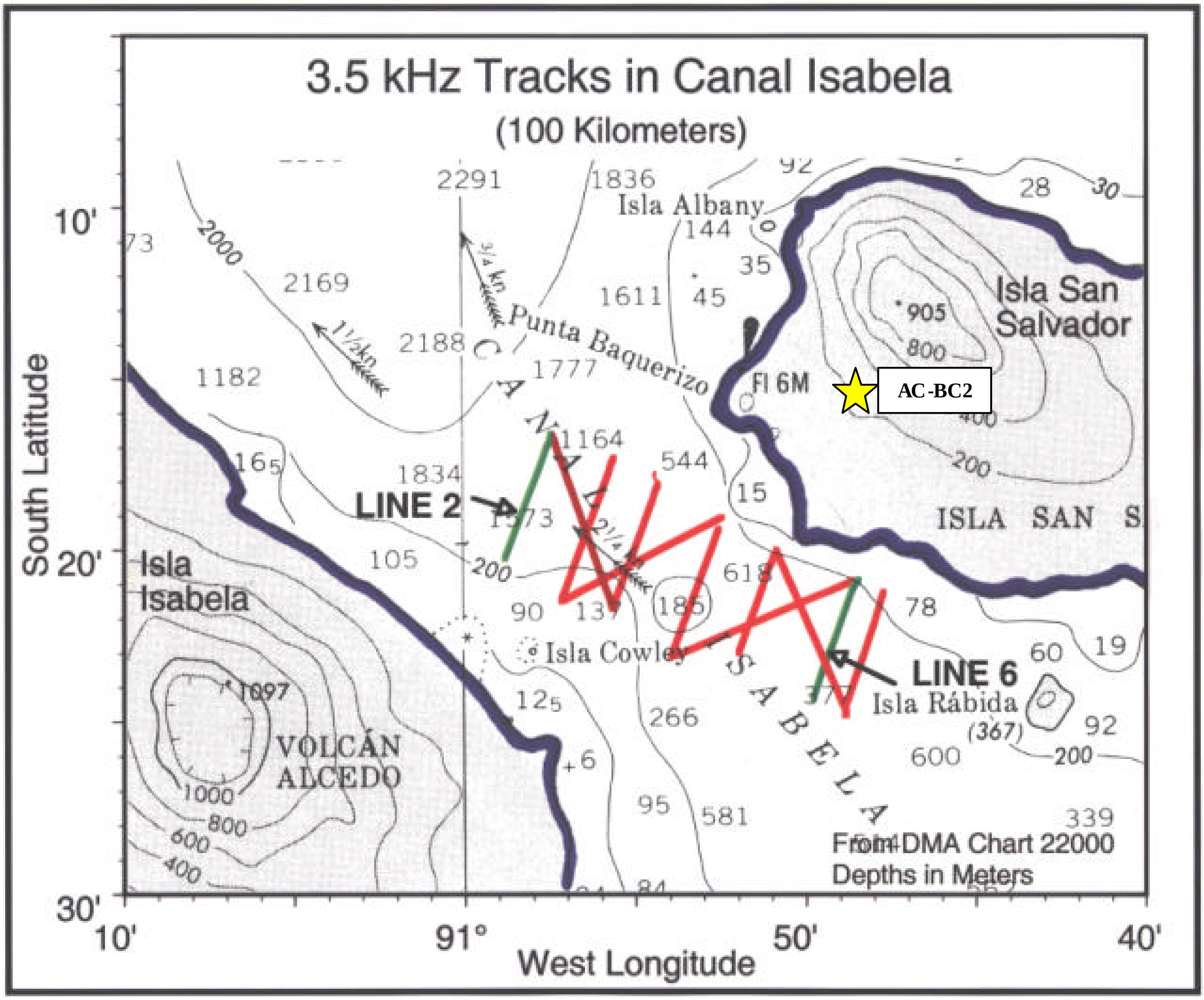

Figure 6-Allison Cougan

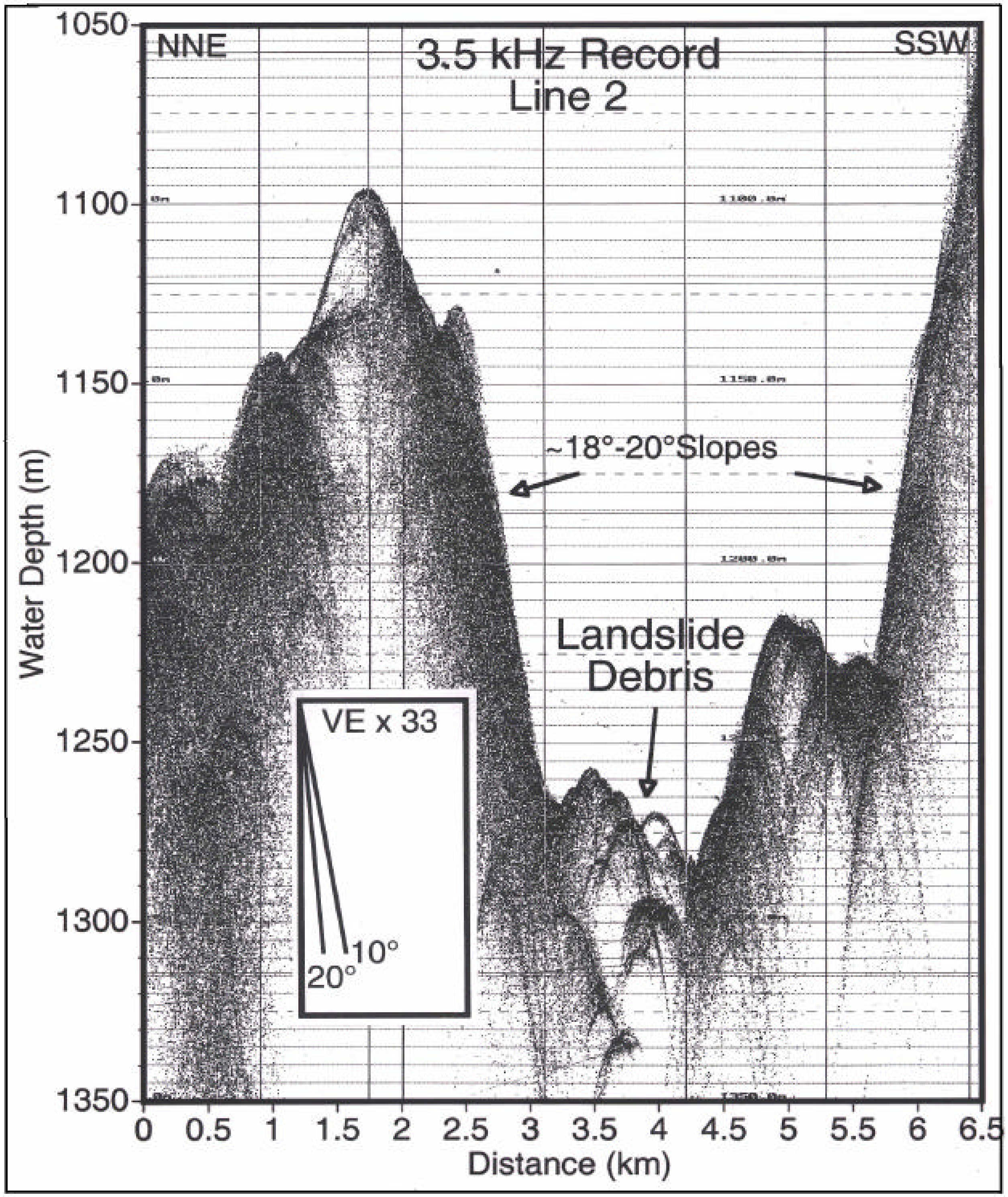

Figure 7-Allison Cougan

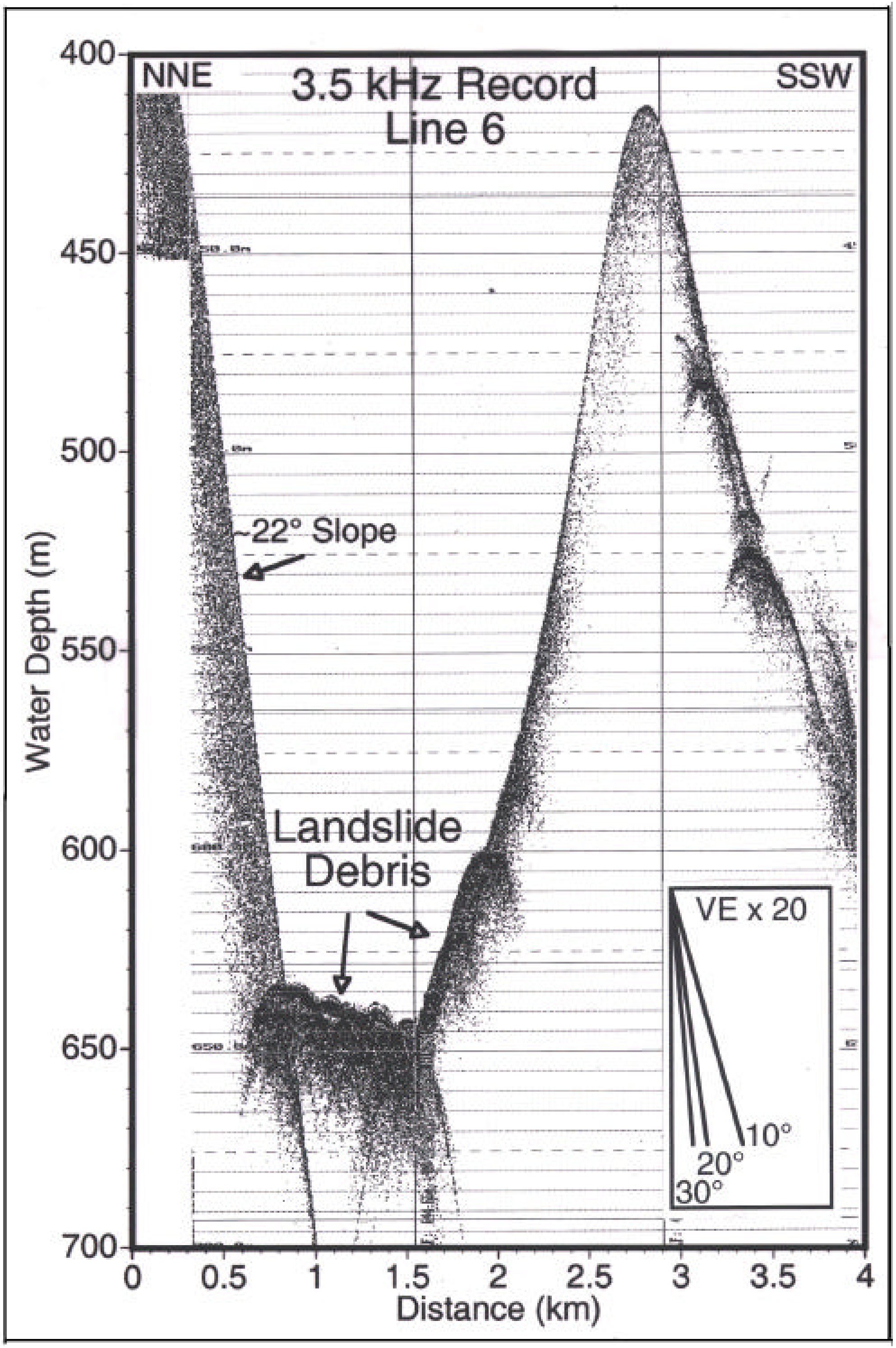

Figure 8-Allison Cougan

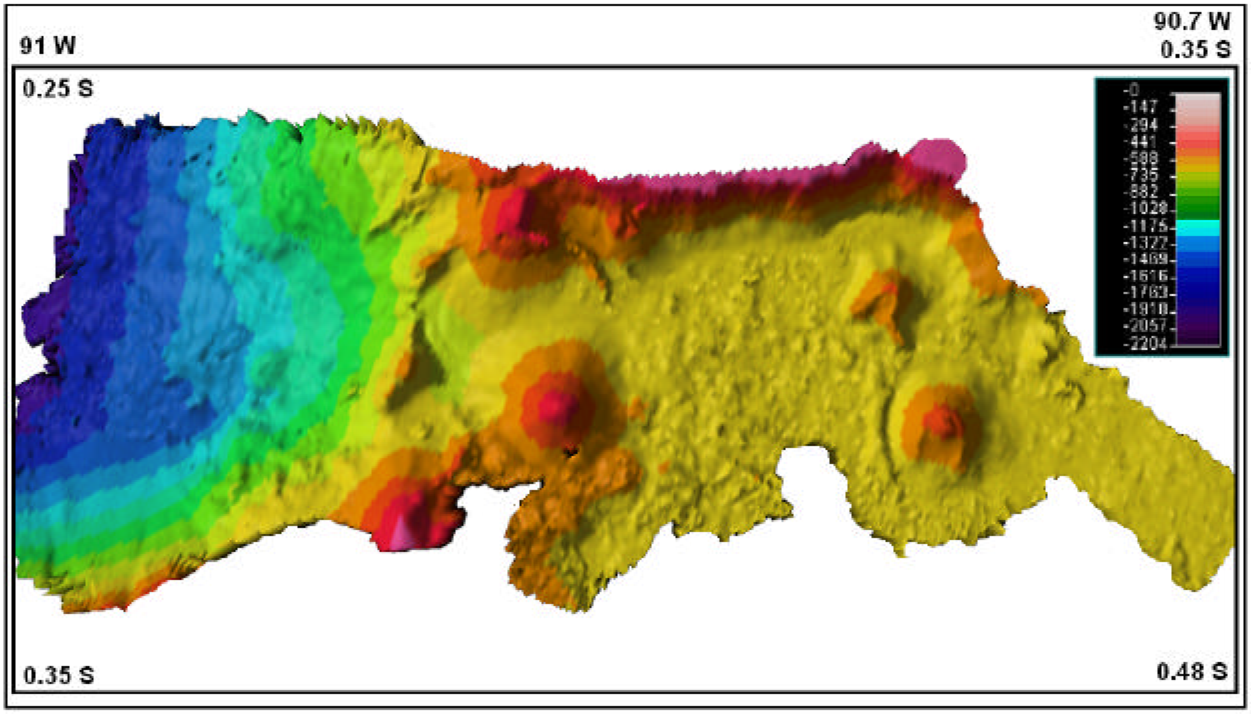

Figure 9-Allison Cougan

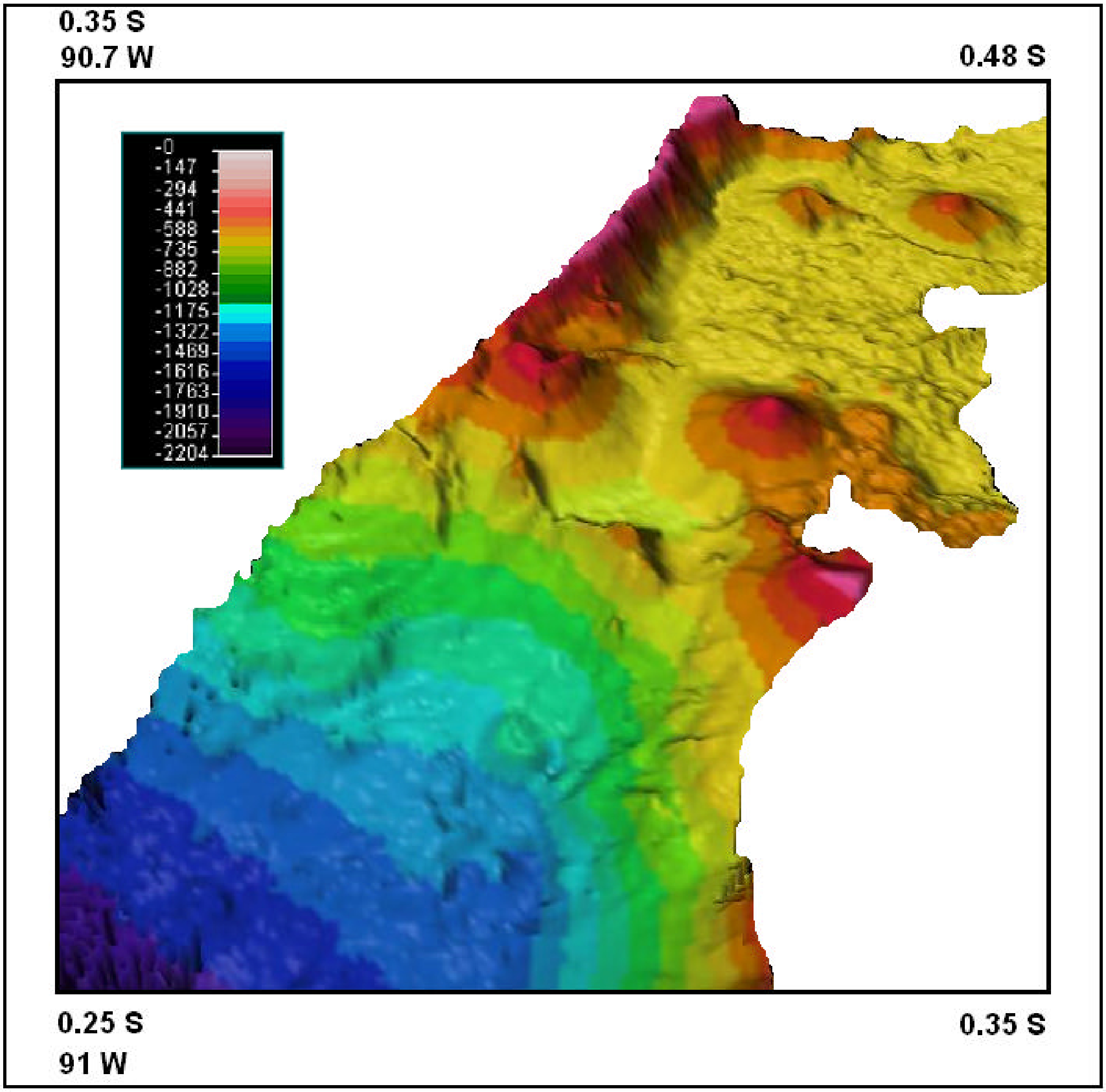

Figure 10-Allison Cougan