GEOLOGY paper

OUTLINE--GEOLOGY PAPER

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Central question--why is the Blanco Ridge a ridge?
Regional geologic setting
Previous work
1994 cruise plan
Purpose of this paper

TECTONISM
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DISCUSSION
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SUBMERSIBLE STUDIES OF TECTONISM AND SEAWATER-CRUSTAL INTERCHANGE ALONG EXTENSIONAL AND STRIKE-SLIP SEGMENTS OF THE BLANCO TRANSFORM FAULT ZONE

INTRODUCTION

Problem and Objectives

Since the late 1970s, high-tempetature hydrothermal vents, polymetallic sulfide deposits, and chemosynthetic biological communities have been discovered at numerous locations along the world-encircling midocean ridge system. The presence of chemosynthetic communities in deep-sea trenches and on their accretionary sediment prisms indicate that these boundaries are also favorable for fluid flow. Fluid circulation and water-rock interaction along the third type of plate boundary, the transform fault zone, must also occur because of the pervasive fracturing and extensional segments associated with them. Transform faults are dynamic areas; they include some of the most seismically active zones in the ocean basins (Trehu and Solomon, 1983; Fox and Gallo, 1989; Dziak et al., 1991; Wolfe et al., 1993). Deep fluid circulation beneath oceanic transform fault zones is especially interesting because these fault zones are underlain by anomalously thin ocean crust, and a greater degree of seawater-mantle interchange is likely.

We propose to continue submersible investigations of structural and magmatic features as well as fluid flow processes at a prime example of this type of plate boundary: the Blanco Transform Fault Zone off the northwest margin of the United States (Fig. 1). The study will focus on the most continuous and seismogenic strike-slip segment (Blanco Ridge) and two large extensional basins at the eastern and western ends of this strike-slip trace (Gorda and Cascadia Depressions, respectively).

Background

The Blanco Transform Fault Zone (BTFZ) is a 350-km-long right-lateral transform fault zone that connects the northern Gorda Ridge and southern Juan de Fuca Ridge (Fig. 1). Its eastern half lies within the U.S. Exclusive Economic Zone. The BTFZ is composed of a series of right-stepping extensional basins offset by strike-slip faults (Fig. 2) that are moving at a relative rate of about 6 cm/yr (Hey and Wilson, 1982). The pattern of long strike-slip segments offset by extensional basins is well-documented in continental settings (e.g., Aydin and Nur, 1982; Mann et al., 1983). This structural style has also been described in other oceanic transform fault zones (e.g., the Siquieros Fracture Zone on the East Pacific Rise; Fornari et al., 1989). The eastern BTFZ has generated four magnitude six or higher earthquakes in the past 25 years (Dziak et al., 1991; Fig. 3).

To date, the few submersible studies along oceanic transform faults have emphasized tectonic and petrologic objectives (e.g., Barany and Karson, 1989; OTTER, 1985; Tamayo Tectonic Team, 1984; Lagabrielle et al., 1992). Hydrothermal precipitates and hydrothermally altered rocks have been sampled within several fracture zones (Bonatti et al., 1976; Hoffert et al., 1978; Delaney et al., 1987; Charlou et al., 1990; Hart et al., 1990; Honnorez and Auzende, 1991) indicating that these boundaries are favorable loci for penetration and interaction with seawater.

Recent studies of continental transform zones (in particular those that have extensional offsets along them) suggest that extensive and rapid fluid flow occurs within them, especially during and immediately after earthquakes that propagate up to the estensional offsets (Sibson, 1987). The transfer of slip across the dilational jog opens linking extensional fractures, effecting a rapid increase in permeability and causing rapid inflow of fluids. In some cases, geothermal "eruptions" result from rupture arrest in the larger extensional areas (Sibson, 1987). Many oceanic fracture zones display a geometry similar to that of the major continental divergent wrench faults.

The work proposed here is a continuation of the NURP-supported PACNORWEST program on the BTFZ which started in 1994. The highly successful 1994 cruise of the Laney Chouest included four deployments of the Advanced Tethered Vehicle (ATV), two deployments of the DSV Turtle, and Sea Beam mapping at four sites along the Blanco Ridge (Fig. 4). The dives on Blanco Ridge resulted in approximately 67 hours of video, 1000 still photographs, 57 rock samples, and 10 sediment cores. Preliminary results (Koski et al., 1994; see attached abstract) indicate that the Blanco Ridge is a strongly tectonized feature exposing a mixture of rock types with both crustal and subcrustal affinities. The upper slopes are partly mantled by sedimentary breccia and loose rock debris; the lower slopes are draped with sediment. The abundant evidence of mass wasting and slumping observed on north facing slopes suggests that active faulting is concentrated on the north flank of the ridge. Although no active venting was observed along the Blanco Ridge, hydrothermally altered and veined basalt samples were obtained from the ridge flank adjacent to the Gorda Depression. Rock samples obtained from shoaler parts of the ridge to the west of Gorda Depression include gabbro and basalt with greenschist-facies mineral assemblages. In addition, a 1994 ATV survey of the East Blanco Depression, an extensional basin near the western end of the BTFZ (Fig. 2), discovered an extensive hydrothermal vent field associated with a recent pillow lava mound (Dziak et al., 1994). The vehicle dives proposed for 1995 will complement and extend the 1994 program and place greater emphasis on the extensional basins.

Applications, Benefits, and Importance

The proposed research is in concert with the programmatic theme of Ridge Crest Processes as well as the research categories of Global Change, Material Flux, Recruitment of Marine Organisms, and Ocean Lithosphere identified as high priority areas by NURP. We will attempt to determine the relative importance of hydrothermal venting along oceanic transform fault zones within the larger picture of chemical interchange between the ocean crust and mantle and seawater. It is important to note that the success of this project <u>does not</u> depend on finding active vents; the past history of fluid movement should be recorded in the rocks exposed along faults, both active and inactive. Furthermore, the fossil record of rock-seawater interchange will be addressed by careful transects of fault scarps and steep ridge flanks.

Because of its proximity to U.S. ports, the BTFZ can be considered as a natural laboratory for study of this important type of plate boundary in the same way that the Gorda and Juan de Fuca ridges and the Oregon margin have been for investigations of extensional and compressional plate boundaries, respectively. In 1991, a program was intitiated to monitor plate boundary seismic activity in the northeast Pacific with the cooperation of the U.S. Navy (Seem et al., 1991; Fox et al., 1994). The greatly increased accuracy and sensitivity made possible using the Navy hydrophone arrays is providing a powerful tool for monitoring seismic activity on the BTFZ (Dziak et al., 1994), and will provide an ongoing context in which to place the observations generated during this and subsequent expeditions.

METHODS

Major Tasks

This study encompasses three general areas, from east to west: the Gorda Depression, the Blanco Ridge, and the Cascadia Depression (Fig. 4).

Gorda Depression

The Gorda Depression is a deep rhombohedral basin that separates the eastern end of the Blanco Ridge on the north from a scarp that lines up with the northern termination of the Gorda Ridge (Figs. 2 and 5). Embley and Wilson (1992) concluded that the Gorda Depression is an extensional feature that offsets two strike-slip strands, one between its southern border and the northern Gorda Ridge which lies 20 km to the southeast, and the other between its northern border and southern Cascadia Depression which lies100 km to the northwest. The Gorda Depression is 4400 m deep at its center, is 11 km in its NE-SW dimension and is 18 km in its NW-SE dimension. Distinct geometrical similarities in shape are apparent between the Gorda Depression and the mature pull-apart basins along transform continental margins (Aydin and Nur, 1982; Mann et al., 1983). Sea Marc II side scan data over the Gorda Depression suggest the presence of lava flows emanating from fissures in the floor of the depression (Clague and Holmes, 1987). Hart et al. (1990) described a diverse suite of hydrothermally altered breccias and greenstones in dredges from the north wall of the Gorda Depression.

Our primary objectives for dives in the Gorda Depression are to:
(1) Examine the structure and composition of the crustal section on the south wall of the depression with ATV (dive 1, Fig. 5). The north wall of the Gorda Depression was the object of one ATV deployment and one Turtle deployment in 1994. Samples collected include basalt and volcanic breccia with varying degrees of alteration. The south wall should be an interesting contrast to the north wall since its history suggests less time spent in the transform regime. Samples from the south wall will provide additional information about the history of fluid flow through the oceanic crust.
(2) Investigate with DSV Turtle the intersection of the strike-slip segment (Blanco Ridge) with the Gorda Depression (dive 2, Fig. 5) to look for structural indicators of recent movement and evidence of venting and recent mineralization.
(3) Examine the floor of the depression for recent lava flows and active venting with ATV (dive 3, Fig. 5). Chemical analysis of volcanic rock samples will determine the nature of the mantle source feeding the flows and allow us to compare these to the chemistry of rocks from the Gorda and Juan de Fuca ridges and from elsewhere on the BTFZ. Analysis of samples from similar extensional basins within the Siqueiros Transform Fault Zone (Fornari et al, 1989) showed a wide diversity in chemistry, and those workers concluded that the small basins within the transform tapped deep melt anomalies within the mantle. Samples from the Gorda Depression will allow us to test this hypothesis in a transform setting with a differential motion about half that of the Siqueiros.

Blanco Ridge

The Blanco Ridge trends at about 108° and is composed of a series of lozenge-shaped highs with as much as 800 m of relief. Teleseismic epicenters plot 20 km or more north of the Blanco Ridge (Fig. 3), but taking into account the displacement error resulting from the crustal velocity model used in the calculations (Northrup, 1970), the actual location of the earthquakes are almost surely on the Blanco Ridge (Dziak et al., 1991). Also, the largest earthquakes within the entire BTFZ have occurred along this segment of the BTFZ (Fig. 3), probably because this is the longest structurally uninterrupted segment (Dziak et al., 1991). Independent evidence for seismic activity along the Blanco Ridge is the presence of an extensive secondary channel system draining northward from the ridge into Cascadia Channel. One of the contributing factors in the erosion of these channels is probably earthquake-triggered slumping and turbidity currents off the sediment bench on the north side of the Blanco Ridge.

The Blanco Ridge is an example of one of the more enigmatic morphotectonic elements of fracture zones, the transform-parallel or transverse ridge. Proposed origins of such ridges within the transform domain include serpentinite intrusion (Bonatti, 1976), volcanism resulting from a component of extension (Thompson and Melson, 1972), and uplift caused by a component of compression (Bonatti, 1976). Observations and recovery of highly brecciated rocks during ALVIN dives along the Clipperton tranform fault suggest that some of these features are sites of long-term shear (Barany and Karson, 1989; Clipperton Tectonic Team, 1986). The preliminary results from our program in 1994 suggest that shearing is a dominant process in Blanco Ridge formation, but the mechanism for vertical mixing of lithologies is uncertain.

Ibach (1981) has suggested that the north side of the ridge between about 127°30'W and 128°05'W longitude consists of uplifted sediments, possibly turbidites. This bench is outlined approximately by the 2500-2600 m contours, implying an uplift of approximately 500 m. North-south seismic reflection profiles across the ridge (Ibach, 1981; Embley, 1985; EEZ SCAN, 1986) do show what appears to be a layered sequence of sediments beneath the north flank of the ridge. Our north-south ATV survey in 1994 at approximately 127°47'W longitude (Fig. 6) also shows that sedimentary units on the north flank of the ridge are in fault contact with crystalline rocks that form the ridge crest.

Our <u>principal objectives</u> for the dives on the Blanco Ridge are to:
(1) Determine the structural style and composition of the Blanco Ridge by obtaining samples from the steepest scarps along the middle section using ATV (dives 4 and 6; Fig. 6).
(2) Investigate the contact between sediment and basement rock along the northern flank of the ridge with ATV (dive 4).
(3) Investigate the nature of large tectonic blocks or slivers that form the shoalest parts of the ridge crest with ATV (dive 4) and with Turtle (dive 5; Fig. 6).
(4) Examine evidence for fluid circulation along this predominantly slike-slip segment of the BTFZ (all three dives).

<u>Cascadia Depression</u>

The Cascadia Depression is 20 km in its NE-SW dimension and, in its deepest area (approximately 3500 m), is about 8 km in the NW-SE dimension (Fig. 7). The Depression is bounded on either side by a series of inward-facing back-tilted blocks which are covered with a thick sequence of turbidites (Griggs and Kulm, 1973). The normal faults are oriented within 10° to 15° of orthogonal relative to the strike of the Blanco Ridge and the BTFZ. These blocks extend out as far as about 50 km on either side of the Cascadia Depression and those on the southeastern side appear to be of consistently higher relief than those to the northwest (Embley et al., 1987; deCharon, 1988). At least 500 m of turbidites are ponded in Cascadia Depression and the bathymetry also confirms the conclusion of Griggs and Kulm (1973) that Cascadia Depression currently forms an endpoint for Cascadia Channel sediments, whereas prior to 6,600 yrs B.P. the channel bypassed the BTFZ. The downdrop in the thalweg was interpreted by Griggs and Kulm as having a tectonic origin, with a rate of downdropping estimated to be 1.8 cm/yr over the past 6,600 years.

Seismic reflection records indicate that the turbidites within the Cascadia Depression have undergone recent deformation (Embley et al., 1987; deCharon, 1988). There is a small (up to 60 m relief) ridge in the center of the basin flanked by a symmetric series of 5 to 10 m relief, inward-facing back-tilted blocks which mirror the larger-scale structures surrounding the depression (Fig. 7). Seismic reflection profiles (Embley et al., 1987) reveal acoustically opaque zones within the basin fill which may be sills similar to those described from the Guaymas Basin (Einsele, 1985). Their intrusion could account for the domed area in the center of the depression. On the basis of the morphologic relationships and seismic reflection data, Embley et al. (1987) concluded that Cascadia Depression has behaved as a small spreading center.

At present, the evidence for fluid discharge within Cascadia Depression is circumstantial. High methane values measured over the depression (Embley et al., 1987) could be a product of hydrothermal exhalation. Alternatively, the signal could result from outgassing of methane that was generated within the clastic sediment. However, the persuasive evidence for rapid tectonic deformation plus the methane anomaly argues strongly for some type of hydrothermal venting. The most likely venting site probably lies along the eastern boundary fault or along the axial ridge in the center of the basin. A single Alvin dive in 1984 failed to find evidence for venting along the central ridge.

Our primary objective for two ATV deployments in Cascadia Depression is to look for evidence of hydrothermal venting in the area of the axial high not examined during the 1984 ALVIN dive (dive 7; Fig. 7) as well as along the eastern boundary fault and its intersection with the transform fault in the southeast corner of the basin (dive 8; Fig. 7).

Laboratory Methods

The sampling of volcanic, sedimentary, and intrusive rocks, hydrothermal deposits (veins, crusts, mounds, etc.), sediment, and biology is an important element of the dive program. It is important to note that the BTFZ provides opportunities for systematic sampling of oceanic lithosphere in three dimensions. Shipboard handling of samples includes descriptions and subsampling, mineral identifications with a binocular microscope, rock sawing, and preservation of organisms. Following the cruise, polished thin sections of altered rock and hydrothermal samples will be analyzed by petrographic microscope, scanning electron microscopy, and electron microprobe. Selected samples of hydrothermal material will be analyzed for oxygen and sulfur isotope ratios. The petrology and geochemistry of volcanic rocks and glasses will be determined by standard techniques including microscopy, microprobe, X-ray fluorescence, induction-coupled plasma-atomic emission spectrometry, and neutron activitation analysis. Sediment samples will be analyzed for mineralogy, organic carbon, and evidence for hydrocarbons. These analyses will be performed in laboratories of the U.S. Geological Survey. Other data from dives, navigation, and Sea Beam surveys will be processed at NOAA's Newport facility.

Sites and System Descriptions

The proposed dive sites are described above and shown in Figures 5-7. The maximum water depths for each dive are: dive 1 (4430 m), dive 2 (3000 m), dive 3 (4430 m), dive 4 (2800 m), dive 5 (2400 m), dive 6 (3200 m), dive 7 (3400 m), and dive 8 (3500 m).

The Advanced Tethered Vehicle is required for longer deployments at water depths greater than 3000 m. At shallower depths and for more site-specific deployments, the DSV Turtle will be used. It is important that each vehicle have high-quality external 35 mm and video camera capability. Rock and core sampling capabilities are also required. A temperature probe is requested for the ATV. A data logging system capable of logging time, X and Y coordinates, altitude, water depth, and gyro heading is highly desirable. A CTD will be provided by the PIs. We would like to use a long baseline navigation system for the dives in Gorda and Cascadia depressions.

Alternative Approach

Sampling and camera work from a surface vessel would not be of sufficient precision to accomplish the tasks on the steep slopes in the study areas.

Dive Schedule

We propose that the dive series be conducted during August or early September which is the most favorable weather window in the region. The dives would begin in the Gorda Depression and proceed successively to the Blanco Ridge and Cascadia Depression sites. ATV and DSV Turtle deployments would alternate at the Gorda Depression and the Blanco Ridge sites. The average ATV deployment is projected to be 30 hours; the average DSV Turtle deployment is 12 hours. We would conduct Sea Beam surveys to map dive sites and to expand previous surveys. The total ship time requested is 10 complete 24 hour days with the cruise beginning and ending in Newport, Oregon.

Constraints and Risks

Several dive sites have water depths greater than the 3050 m limitation of DSV Turtle. There are no expected environmental impacts related to this research.

DISCUSSION

Justification

This project represents the first systematic approach to examine the structural style and fluid circulation and venting along an oceanic transform fault. The proposed work in 1995 is a continuation of the successful PACNORWEST program conducted along the BTFZ in 1994. We plan to further test Sibson's (1987) model which predicts the movement of fluids and control of mineralization in dilational jogs of seismically active fault systems. We will also examine the evidence for large-scale venting in the two rhombohedral basins (Gorda and Cascadia) that lie within the eastern part of the BTFZ. An active hydrothermal vent field was discovered in the East Blanco Depression during the PACNORWEST program in 1994. The objectives of the project are consistent with

NURP's goals regarding chemical and heat fluxes into the world ocean and tectonics and evolution of the oceanic lithosphere as well as programmatic efforts within both the USGS and NOAA to study hydrothermal processes at major tectonic boundaries within the U.S. EEZ. Although the oceanic transform fault zone is a major type of plate boundary, its role in seawater-crust-mantle interchange is still poorly understood.

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PROJECT MANAGEMENT

Project Co-chiefs

Koski, Embley, and Ross will share administrative responsibilities. Koski will serve as the principal point of contact.

Participating Scientists

Dr. Randolph Koski -- hydrothermal deposits and rock alteration
Dr. Robert Embley -- transform fault geology and tectonics
Ms. Stephanie Ross -- seafloor mapping and physical volcanology
Mr. Robert Dziak -- seismicity and seafloor mapping
Dr. Robert Bohannon -- structure and tectonics
Ms. Alice Davis -- basalt petrology and petrochemistry
Dr. Tracy Vallier -- petrologic investigations and tectonic analogs
Ms. Jane Reid -- navigation and igneous petrology
Ms. Ledabeth Gray -- geochronology
Dr. Monty A. Hampton -- sedimentary processes
Dr. James R. Hein -- geochemistry of sediments

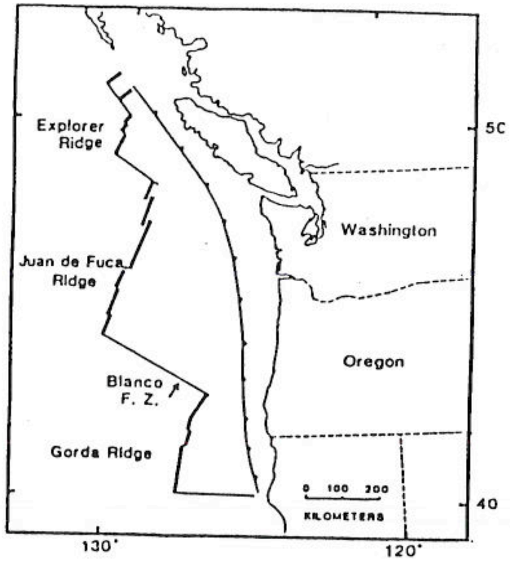
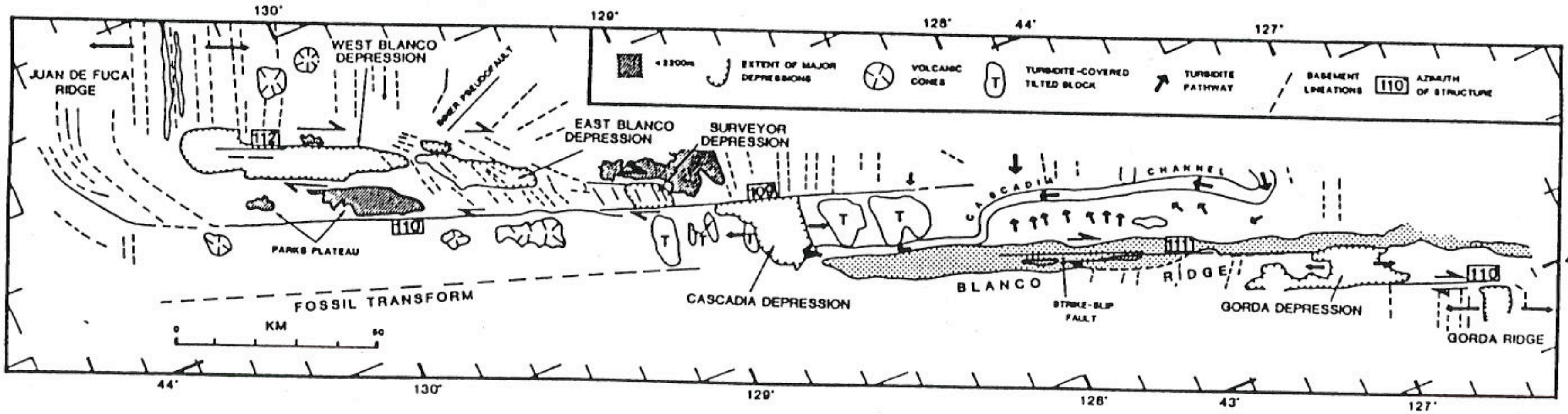


Fig. 1. Location map of Blanco Fracture Zone (referred to in text as Blanco Transform Fault Zone).

Fig. 2. Morphotectonic map of Blanco Transform Fault Zone based on Sea Beam and GLORIA data. From Embley and Wilson (1992).



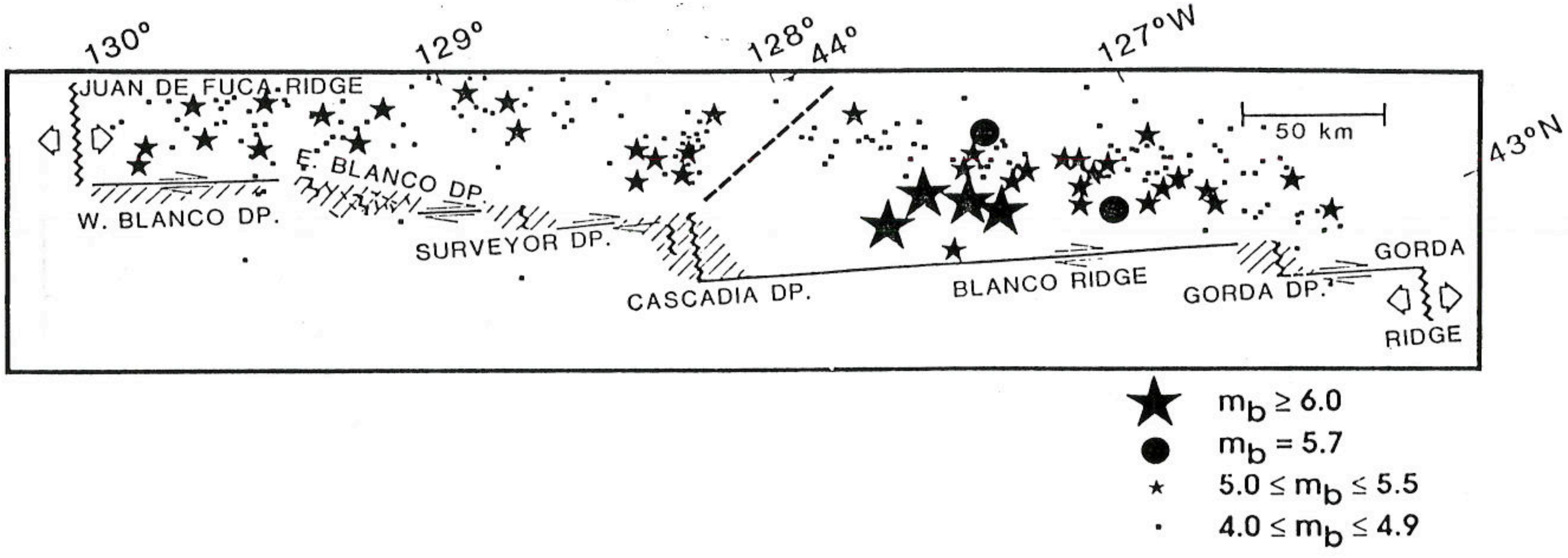


Fig. 3. Earthquake epicenters superimposed on a schematic diagram of the Blanco Transform Fault Zone. Epicenters are of all earthquakes with magnitude (m_b) greater than or equal to 4.0 located near the region from July 1963 to July 1988. Thick wavy lines represent the centers of extensional basins except for the West Blanco Depression, which is the trough of a strike-slip section. The abbreviation DP indicates a depression. From Dziak et al. (1991).

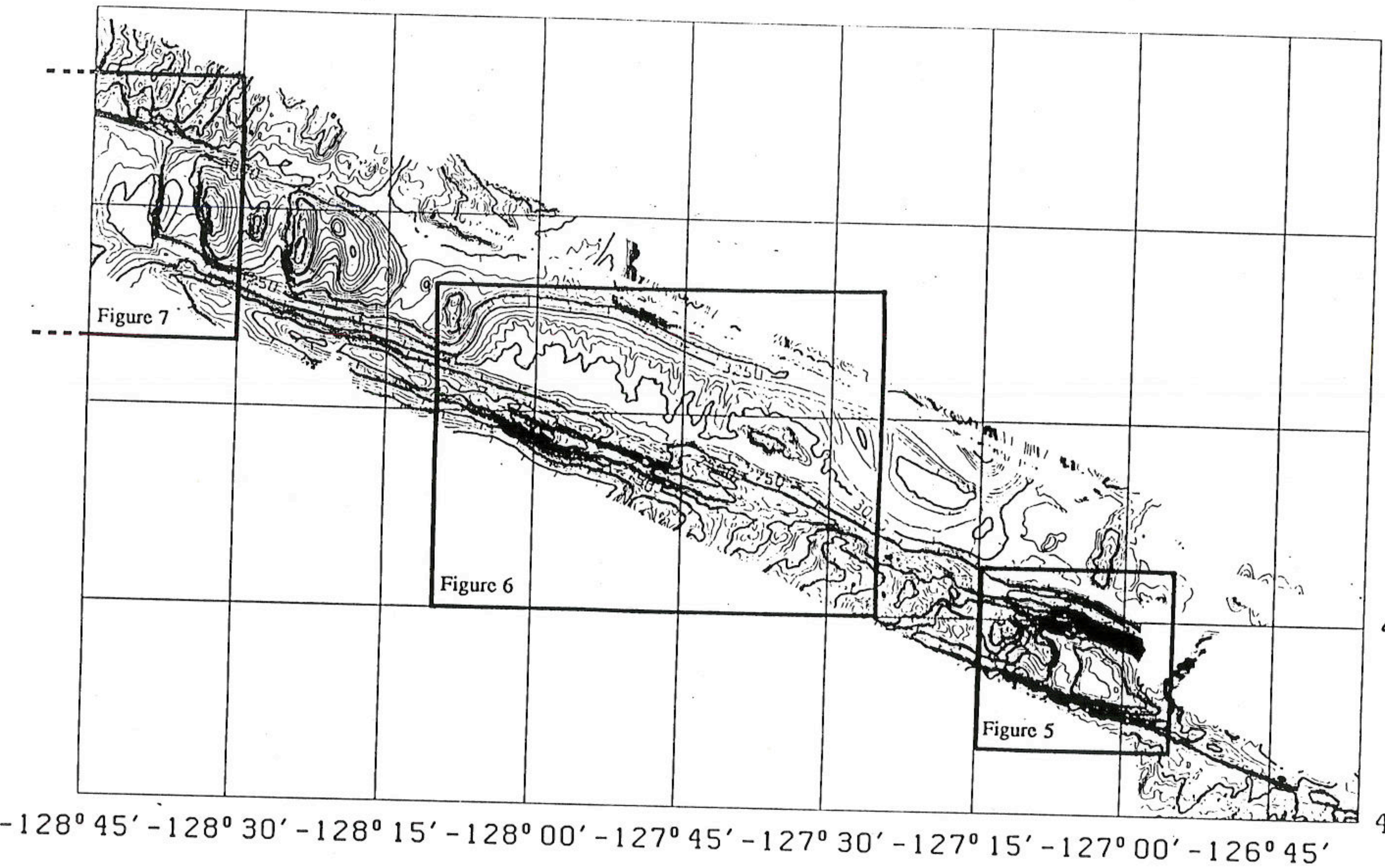


Fig. 4. Sea Beam bathymetry of Blanco Ridge. Boxes delineate areas shown in figures 5-7; figure 7 extends further to the west than this figure. Contour interval is 50m.

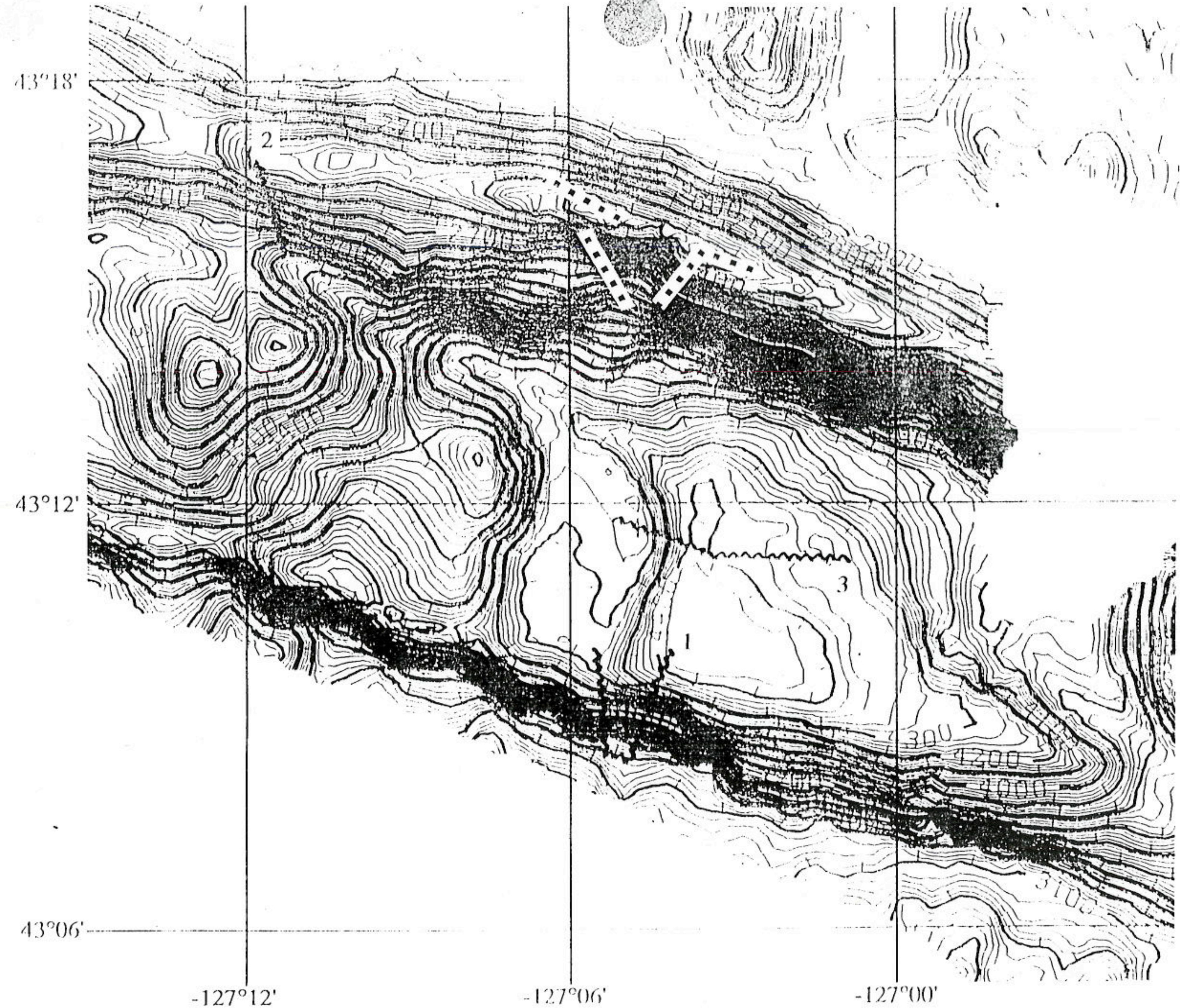


Fig. 5. Sea Beam bathymetry of Gorda Depression (location shown on figure 4). Proposed dive locations shown as zigzag lines; 1994 dive locations shown as dotted lines. Contour interval is 20m.

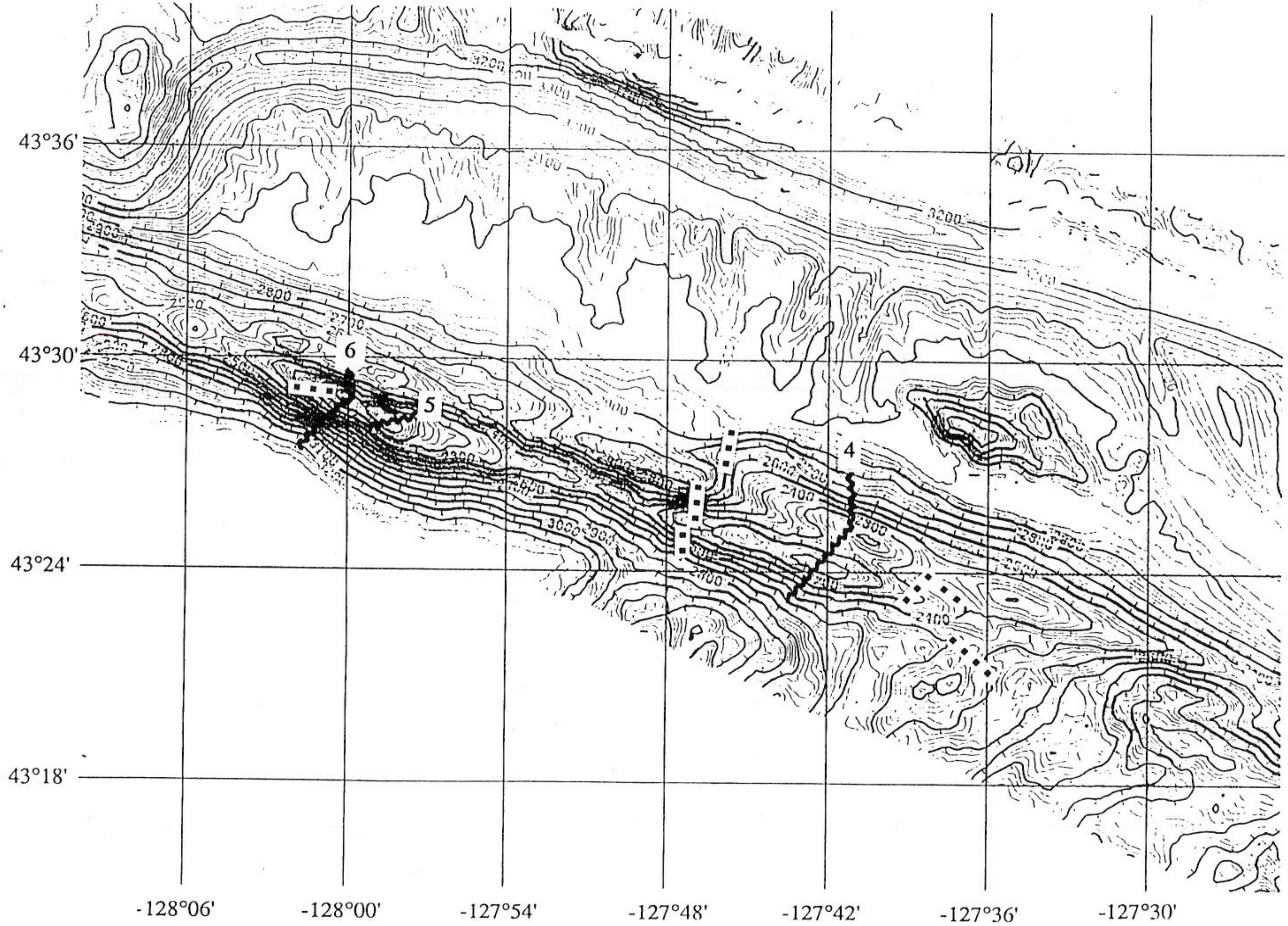


Fig. 6. Sea Beam bathymetry of central Blanco Ridge (location shown on figure 4). Proposed dive tracks shown as zigzag lines; 1994 dive t[illegible] shown as dotted lines. Contour interval is 20m.

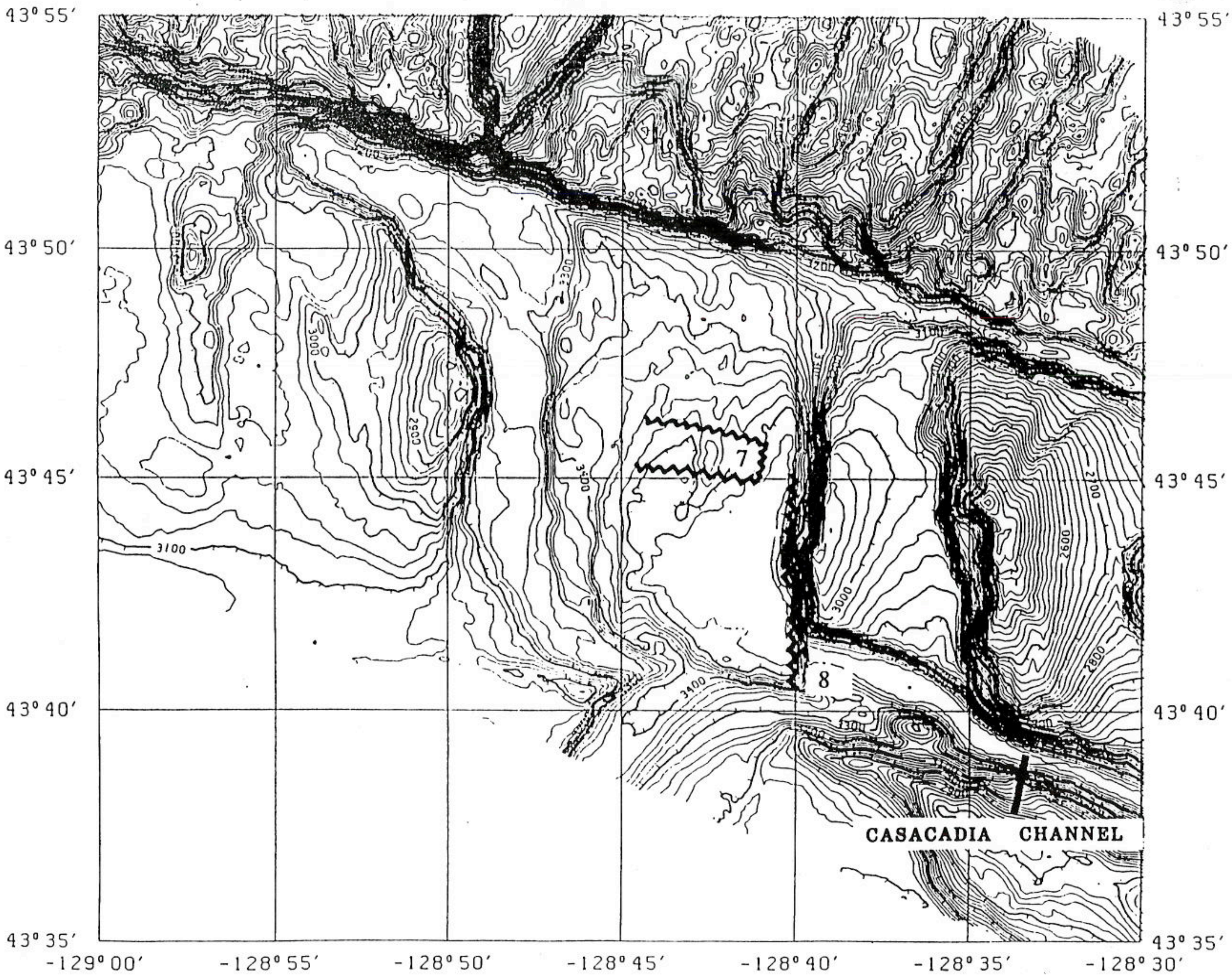


Fig. 7. Sea Beam bathymetry of Gorda Depression with proposed dive locations.

Tectonism and Lithologic Variation Along the Blanco Ridge, Eastern Blanco Fracture Zone, NE Pacific: Preliminary Results from the PACNORWEST III Cruise, 1994

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The 200-km-long Blanco Ridge is a right-lateral transform fault segment of the Blanco Fracture Zone that extends at 290° from the northern termination of Gorda Ridge (43°16'N, 127°06'W) to Cascadia Basin (43°40' N, 128°40' W). Detailed bathymetric data for Blanco Ridge reveal a narrow linear ridge morphology with a series of steepsided lenticular-shaped highs; in places, a subsidiary ridge is parallel to and north of the main ridge axis. Teleseismic data indicate the largest earthquakes recorded within the Blanco Fracture Zone occurred along the Blanco Ridge. In August and September, 1994, a NURP-sponsored cruise conducted jointly by the USGS and NOAA, and using the U.S. Navy's deep-diving *DSV Turtle* and Advanced Tethered Vehicle (ATV), investigated the structure and composition of the Blanco Ridge at four sites at depths between 3400 and 1900 m.

In general, the upper slopes and crest of the ridge are sediment free and covered by a thin mantle of loose rock debris. The relatively greater degree of recent mass wasting on north-facing slopes, as shown by rock avalanches, slumps, and landslides, indicates that the locus of active faulting lies along the north flank of the main ridge. Rock and core samples recovered from north-south traverses across the ridge include basalt, metabasalt, diabase, gabbro, serpentinite and greenstone breccias, sedimentary breccias with volcanic and mudstone clasts, graywacke, and mudstone. The mixture of rock types, including breccias and gabbro with tectonized fabrics, as well as the morphology of the ridge, the scarcity of large outcrops, and the scree-covered surfaces, support a strike-slip tectonic origin for the ridge. Additional sampling suggests the subsidiary parallel ridge lying north of the main ridge axis is underlain by sediment. A section of at least 300 m of gabbro and basalt was sampled from the shoalest portion of the main ridge (1900 m, 44°28'N; 128°00'W). This part of the ridge is oriented obliquely (315°) to the regional strike of the Blanco Ridge suggesting that it may be a sliver of relatively undeformed oceanic crust which has been uplifted and tectonically eroded within the transform regime.