DRAINAGE DISRUPTION CAUSED BY A PREVIOUSLY UNIDENTIFIED LARGE PREHISTORIC BEDROCK SLUMP ON SANTA CRUZ ISLAND, CALIFORNIA

BRUCE CARTER

Pasadena City College, 1570 East Colorado Boulevard, Pasadena, CA 91106; bacarter@pasadena.edu

Abstract—A large bedrock slump on Santa Cruz Island lies on the south side of the linear, fault-controlled central valley just west of Stanton Ranch. The slump block measures about 2,300 x 700 m and has dropped about 120–170 m. Slumping occurred approximately parallel to foliation within the Santa Cruz Island Schist. Although its age is poorly constrained, the headscarp and the upper portion of the slump block are excellently preserved although most of the toe of the slump has been removed by stream erosion. The slide blocked the original drainage along the axis of the valley producing the "hanging valley" just west of the slump and resulting in an abrupt 120-m drop of the valley floor at Cascada. This happened when a new overflow path around the slump mass about 500 m to the north placed the stream across resistant rocks of the Santa Cruz Island Volcanics. Subsequent north-side-up displacement on the north branch of the Santa Cruz Island fault has raised the elevation of the upper part of the drainage above Cascada. There has been about 1 km of left-lateral slip on the Santa Cruz Island fault since this stream displacement. The modern drainage pattern on this part of the island has resulted from a combination of fault slip and large-scale mass wasting processes.

Keywords: drainage anomalies, landslide, Santa Cruz Island fault, Santa Cruz Island Schist

INTRODUCTION

Santa Cruz Island, the largest of the California Channel Islands, is located about 42 km south of the Santa Barbara coast. The island consists of two east-west ridges separated by a central valley with the Santa Cruz Island fault running through it. The fault is a major east-west left-lateral transverse structure (Fig. 1) that forms a distinct lithologic boundary between Miocene Santa Cruz Island Volcanics and Monterey Formation on the north and pre-Jurassic plutonic and metamorphic rocks and a sequence of Tertiary clastic and volcaniclastic rocks on the south (Rand 1933, Weaver 1969, Dibblee 1982, Pinter et al. 1998). In the central and eastern part of the island, the fault includes north and south branches on opposite sides of the valley. Fault-line features suggest relatively recent displacement on the high-angle north branch of the fault (Patterson 1979, Pinter and Sorlien 1991); the south branch appears to be a lower-angle fault that has not been as recently active. Several levels of marine terraces suggest that the entire island is currently undergoing uplift (Pinter et al. 1998).

The recent faulting and uplift of the island has produced rugged terrain that includes many steep unstable slopes that are highly prone to mass-wasting processes (Brumbaugh et al. 1982, Renwick et al. 1982, Jackson 1987). Between 1904 and 1983, annual rainfall in the central valley has ranged between 16 and 142 cm (Brumbaugh 1983), and it undoubtedly was even higher during parts of the late Pleistocene and early Holocene (Chaney and Mason 1930, Johnson 1977, Junak et al. 1995). The intermittently high rainfall, coupled with the destructive effects of heavy grazing by introduced animals (sheep, cattle, and pigs), has produced considerable loss of soil on steep slopes due to small soil flows and slumps (Brumbaugh et al. 1982, Renwick et al. 1982, Brumbaugh 1983). Large landslides (1,000–100,000 m^2) are present in some of the areas of heavily eroded soils, and are particularly abundant on slopes underlain by the thin-bedded shales of the Miocene Monterey Formation on the eastern third of the island (Weaver and Nolf 1969). Near Valley Anchorage, a large (700- x 1500-m) landslide of Monterey Formation shale crosses the active north branch of

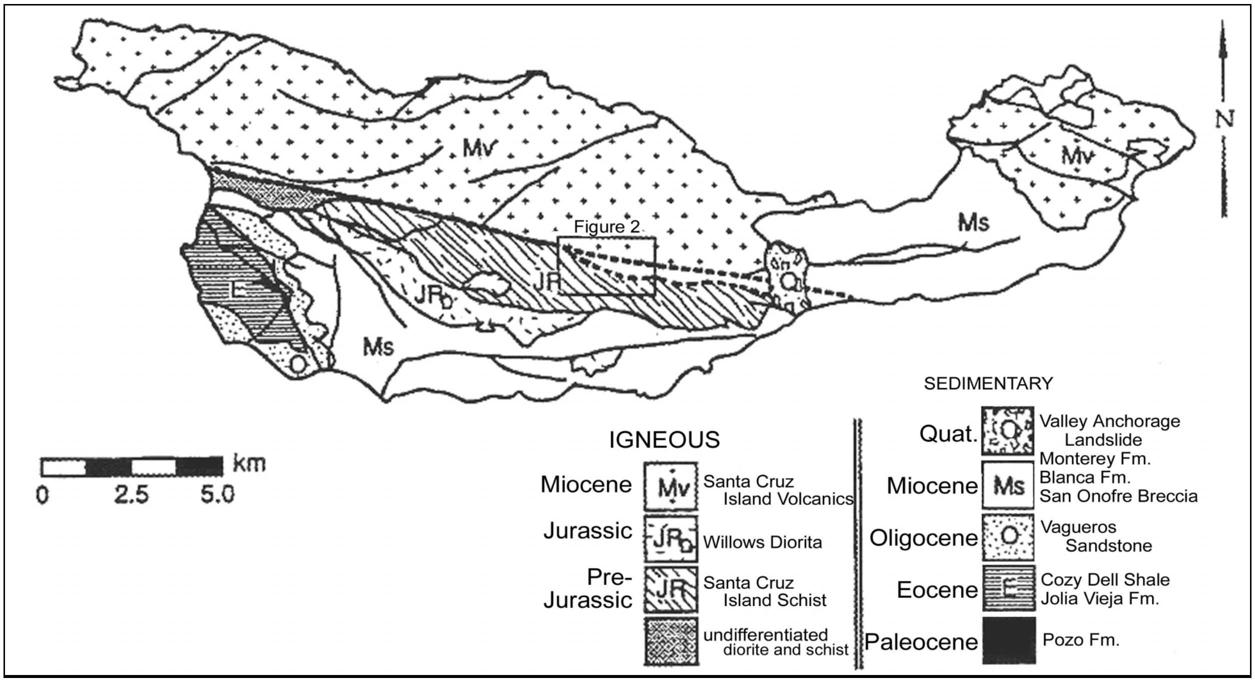

Figure 1. Generalized geologic map of Santa Cruz Island showing location of Fig. 2. Geology after Weaver (1969).

the Santa Cruz Island fault (Sorlien 1994). The north branch of the Santa Cruz Island fault displaces this landslide, which has been dated at approximately 13,000 BP (Sorlien 1994, Pinter et al. 1998).

Earthquakes have long been recognized as a major cause of landslides (Hadley 1964, Keefer 1984, Pearce and O'Loughlin 1985). The large (M 7.0–7.5) Santa Barbara earthquake of 1812 may have caused the 250- x 350-m slump in Lobo Canyon on the northeast part of Santa Rosa Island about 20 km west of Santa Cruz Island (Woolley 1994). This paper describes a large (approximately 700- x 2,300-m), previously unrecognized, bedrock slump that is associated with the Santa Cruz Island fault in the central valley about 6 km west of the landslide at Valley Anchorage.

METHODS

The unusual geomorphology of the southern side of the central valley led to the initial recognition of this feature. Subsequent examination of topographic maps and aerial photographs was followed by walking the area in order to map the orientation of slump features, to examine rock types in hand specimen and collect samples for thin-section examination, and to locate structural and topographic features related to the slump. Previous geologic maps by Weaver and Nolf (1969), Patterson (1979), and Dibblee (2001) were of great help in focusing on significant areas. This feature is deemed a bedrock slump because its upper preserved portion consists of Santa Cruz Island schist and Blanca formation rocks that have been displaced downward as a unit, while internally the rocks are relatively undisrupted.

RESULTS

The slump lies on the south side of the central valley approximately 2 km west of Stanton Ranch (Fig. 2). It extends about 2,300 m along the southern margin of the central valley and is about 700 m at its widest point. The scar of this slump has a distinctly rectilinear plan (Fig. 3) and portions of the original slip plane appear to be preserved south of the western part of the slump. The main part of the block has a single slip plane which strikes approximately N 55^{o}W and dips about 38^o northeast; the eastern end of the block consists of two slip planes about 300 m apart that strike about N 60^{o}E and dip westward; the western end of the block has a single slip plane which strikes

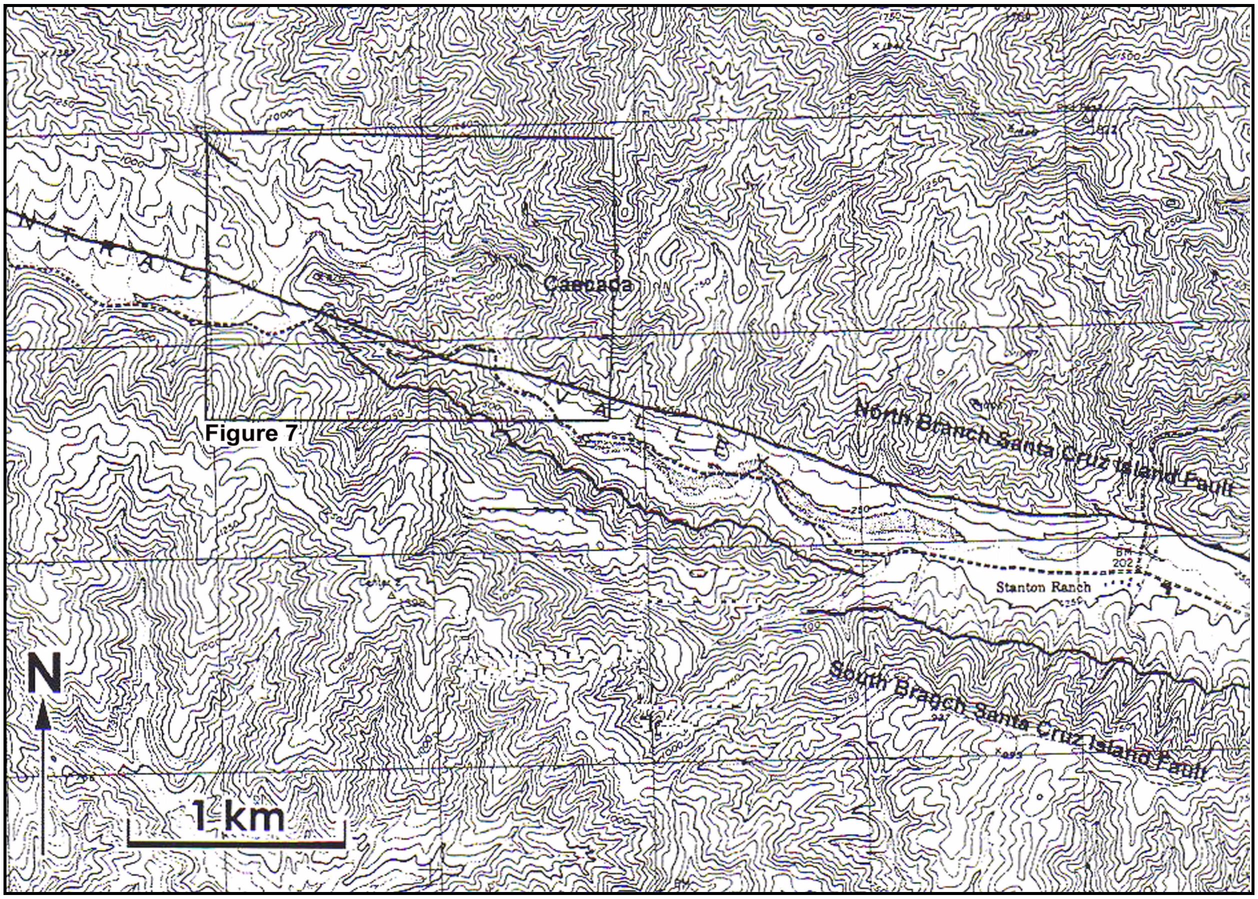

Figure 2. Topographic map of bedrock slump and area, including traces of the north and south branches of the Santa Cruz Island fault (modified from Patterson 1979) and location of Fig. 7. Contour interval of 50 ft (16 m).

approximately north-south and dips eastward. The central and western parts of the block have dropped approximately 100–120 m vertically and the eastern part has dropped up to 170 m from the top of the headscarp. Elsewhere in the area, for about 2 km west and 3 km east of the slump, the crest of the ridge on the south side of the central valley is quite linear and lies consistently about 750 m south of the southern margin of the valley floor (Fig. 4). The crest of the slump block along most of its length is also linear, and is consistently about 350 m closer to the valley axis, whereas the top of the headscarp now lies 150–700 m south of the likely position of the pre-slump crest of the ridge (Fig. 4). Looking southward at topographic profiles along the axis of the central valley and the ridgelines to the south gives an excellent perspective of the extent of this slump (Figs. 4 and 5).

The upper part of the slump occurred in pre-Jurassic rocks of the Santa Cruz Island Schist (Weaver and Nolf 1969). This is a fine-grained quartz-albite-chlorite schist produced by greenschist-grade metamorphism of mostly volcanic and sedimentary rocks (Dibblee 1982). The schist is greenish gray but typically weathers to a dark rusty brown color, and displays a strong foliation due to the abundance of chlorite. Although the orientation of the foliation is variable, it mostly strikes about east-west in the slump area and has a steep northward dip (Weaver and Nolf 1969). It is evident that the upper part of the slump broke off sub-parallel to foliation in the schist. The common deep weathering of the schist results in very clay-rich material that undoubtedly facilitated the sliding. No actual slip-plane surfaces were found despite careful examination of outcrops around the periphery of the slump. However, schist on or close to the slip planes is notably more brecciated and pervasively sheared than it is elsewhere, except immediately adjacent to the south branch of the Santa Cruz Island fault, where shearing is also prominent.

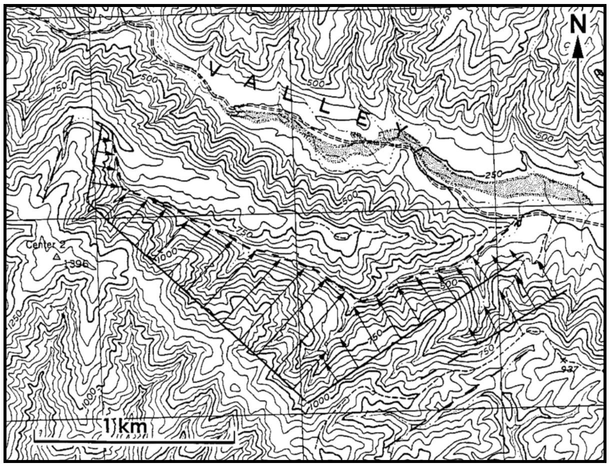

Figure 3. Topographic map showing slip planes of slump on Santa Cruz Island. Solid lines with perpendicular arrows represent approximate slip planes. Shorter dashed lines represent the upper boundary of the slump block. Longer dashed lines represent probable fractures along which little or no downslope movement occurred. Contour interval 50 ft (16 m).

The lower part of the slump must have slipped along a much lower angle surface that was mainly within rocks of the Blanca formation below the south branch of the Santa Cruz Island fault. The central valley below the slump is wide (mostly 150–300 m) and is now filled with coarse alluvium derived mainly from the Santa Cruz Island Volcanics and the Blanca Formation. Most of the rubble of Blanca Formation and Santa Cruz Island Schist that might have originally been present at the toe of the slump has now been removed by stream erosion.

The south branch of the Santa Cruz Island fault is located along the northern edge of the slump block and along the northern edge of the ridge that runs eastward to the ocean (Fig. 1). Exposures of this fault are difficult to locate precisely, particularly on the northern edge of the slump block, due to extensive weathering, deep soil, and thick brush covering the steep slopes of highly brecciated and pervasively sheared rocks adjacent

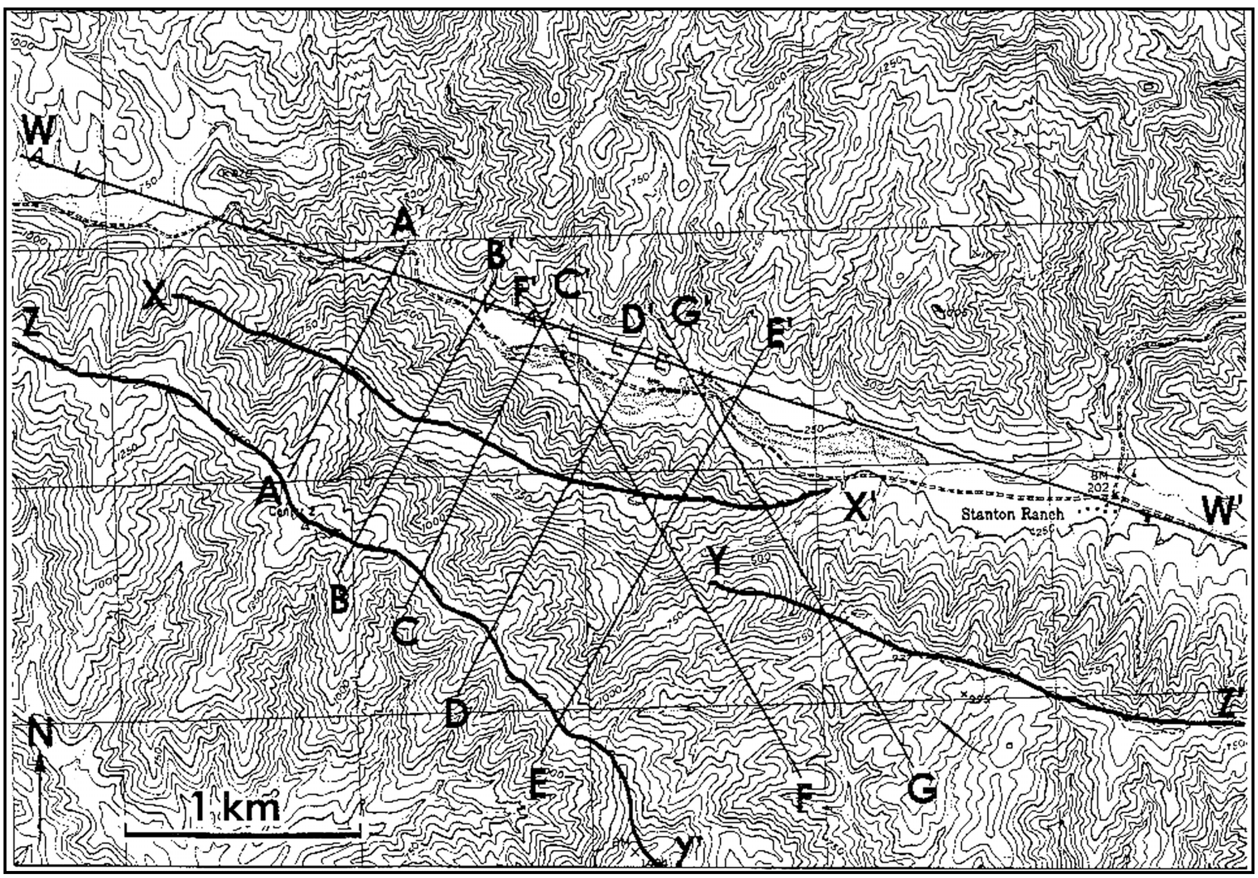

Figure 4. Index map to topographic cross sections of the slump (A–A’ to G–G’) and topographic profiles of the axis of the central valley (W–W’) and ridgelines to the south (X–X’ to Z–Z’) on Santa Cruz Island. Contour interval 50 ft (16 m).

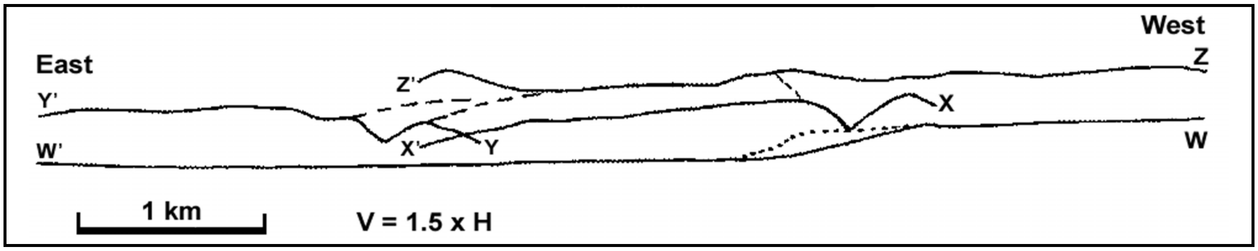

Figure 5. Topographic profiles of the central valley and ridgelines to the south (looking south) on Santa Cruz Island. Dotted line represents elevation of the stream drainage through Cascada projected to the axis of the central valley. Dashed lines represent tops of ridges connecting the major ridgelines (inferred to represent the top of the headscarp along the sides of the slump).

to the fault. Previous maps have shown this fault running continuously from the ridge above Stanton Ranch westward across the slump block (Weaver and Nolf 1969, Patterson 1979, Dibblee 2001). Careful mapping of lithologies, shear zones and slope morphology suggests that the fault trace on the slump block is displaced about 200 m northward on the east end of the block (Fig. 2). The fault trace could not be located west of the projected western end of the block. This fault, which shows little evidence of Quaternary displacement, appears to dip moderately southward in this area. The one dip measurement of 35^{o} just east of the slump (Weaver and Nolf 1969) could not be verified, but in several places both the map pattern and shear zones in rocks immediately adjacent to the fault suggest a southward dip of less than 45^{o}. Since the slump block must have slid northward along a low angle surface that may have been sub-parallel to the fault plane and about 350 m of its northern edge was subsequently removed by erosion, the fault trace now shows less separation than the total movement of the slump block.

DISCUSSION

Earthquake-Triggered Slumping

Several factors must have contributed to initiation of movement on this slump. The Santa Cruz Island Schist rocks are clearly prone to mass-wasting processes. They are distinctly foliated parallel to the slope, rich in chlorite, and typically deeply weathered and rich in clay minerals. The likely long-term location of the stream bed along the base of the slope has localized erosion there to produce an especially steep slope along this part of the valley. Although annual rainfall in the central valley is moderate, on occasion, large amounts of rain can fall over short periods of time (Brumbaugh 1983). The slump is located along the margin of a major rift valley less than 500 m south of a large, active, left-lateral fault capable of producing M 7.2–7.5 earthquakes, the most recent of which probably occurred about five thousand years ago (Pinter et al. 1998). Although it is impossible to be certain, it seems likely that seismic shaking,

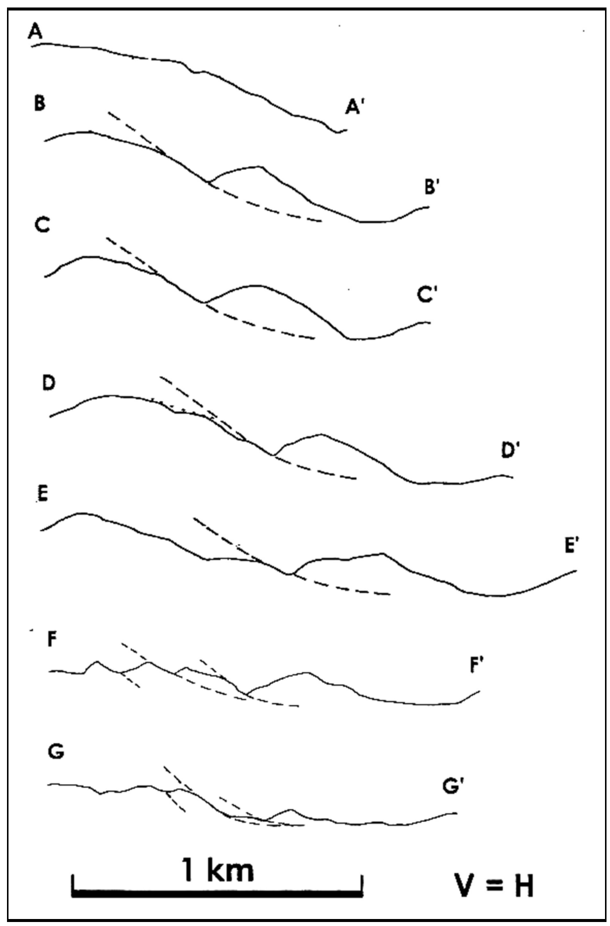

Figure 6. Topographic cross sections of the slump on Santa Cruz Island. Dashed line represents inferred location of slip plane(s).

probably from an earthquake along the north branch of the Santa Cruz Island fault, triggered this slump. On nearby Santa Rosa Island, a smaller slump with evidence of more recent slip has been attributed to shaking from the 1812 Santa Barbara earthquake (Woolley 1994).

Cascada Origin

One of the puzzling features of the drainages on Santa Cruz Island is Cascada, where the southeast-flowing stream swings north out of the axis of the central valley and has a much steeper gradient, loosing about 100 m in about 1/2 km in a narrow canyon cut into resistant rocks of the Santa Cruz Island Volcanics (Fig. 7). This pattern is anomalous compared to the central valley both above (west of) and below (east of) Cascada, where the stream cuts into either alluvium or volcaniclastic rocks of the Blanca Formation and has developed relatively wide valleys and is well graded. A profile along the valley axis parallel to the north branch of the Santa Cruz Island fault shows that the Cascada drop results in a “hanging valley” which loses about 120 m elevation over a distance of only 1 km (2 km along a longitudinal profile following the stream) compared to an average of about 15 m/km both above and below Cascada (Fig. 5). Bremner (1932) described this pattern as resulting from “stream capture,” but did not explain how the stream on the north, cutting through very resistant volcanic rock, could have captured the upper part of the central valley

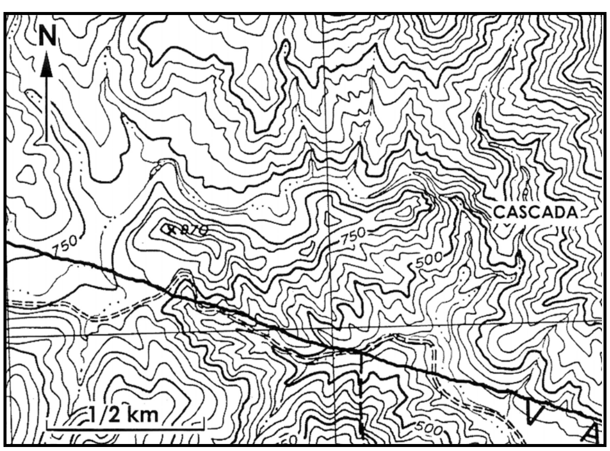

Figure 7. Topographic map of the Cascada area showing the trace of the north branch of the Santa Cruz Island fault (solid line) and inferred western limit of the slump (dashed line). Contour interval 50 ft (16 m).

drainage located in the much more easily eroded crushed rocks along the Santa Cruz Island fault zone.

The “hanging valley” was produced when the slump deposited a mass of rubble at its toe, which blocked the main valley floor and displaced the valley’s low point 500–600 m northward, at a time when the land surface on the northern side of the fault was somewhat lower relative to the valley than it is at present. Although the upper part of the slump was a large intact block that moved northward only about 350 m, the toe of the slump would have consisted of rubble that produced subsidiary slides that extended farther across the valley. Overflow of the landslide dam established a new stream course across the resistant volcanic rocks. Subsequent to establishment of this new stream course the upper part of the valley has been unable to erode downward very much because of the current relatively high base level in the resistant volcanic rocks at Cascada.

Below Cascada, the eastward-draining central valley lies south of the north branch of the Santa Cruz Island fault, but above Cascada, the valley is either within or north of the fault zone (Figs. 2 and 7). Because the resistant volcanic rock forms a temporary base level north of the fault, the higher elevation of the upper part of the valley is probably primarily due to the north-side-up displacement on the Santa Cruz Island fault relative to the lower part of the valley on the south side of the fault. This suggests that there has been a minimum of about 120 m north-side-up displacement on the Santa Cruz Island fault since the slump first displaced the drainage at Cascada.

The western end of the slump is now about 1 km east of where the drainage was originally forced northward to form Cascada. Therefore there must have been about 1 km left-lateral offset along the north branch of the Santa Cruz Island fault since the slump diverted the stream to form Cascada. The small steep tributary eroded into crushed rocks along the trace of the northern branch of the Santa Cruz Island fault south of Cascada can be expected to capture the upper portion of the central valley drainage in the future (Fig. 7). The present canyon between this capture point and Cascada will then be abandoned completely except for several small tributaries draining the ridge to the north of the central valley.

Age

Although no good evidence of the absolute age of the slump has been recognized, a few generalizations can be made. The slump cuts the south branch of the Santa Cruz Island fault, but there is little indication that this branch of the fault has undergone displacement during Quaternary time (Patterson 1979, Pinter et al. 1998). There is no recognizable deposit of landslide rubble present in the central valley at the toe of the slump, suggesting that the small intermittent stream in the valley has now removed nearly all of the landslide rubble. The stream channel has eroded the base of the slump, which is one of the steepest slopes of its size anywhere in the central valley. This process has eroded back the toe of the slump by about 250 m.

Several geomorphic features suggest a relatively young age of the slump. The slip plane is excellently preserved in the central part of the slump. The ridge top of the slump block is also remarkably well-preserved and, when compared to the top of the ridge both east and west of the slump, it gives a clear indication of the magnitude of total lateral as well as vertical slip.

Since the slump diverted the drainage, movement on the north branch of the Santa Cruz Island fault has produced at least 120 m of north-side-up and 1 km of left-lateral displacement. These numbers compare with best estimates of current displacement rates of 0.1–0.2 mm/yr north-side-up and 0.8 mm/yr left-lateral movement (Pinter et al. 1998). If these rates are typical of long-term rates, this suggests that the slump originally diverted the drainage as early as about 1.2 my BP and as recently as 0.6 my BP.

CONCLUSIONS

Major fault zones in many areas have produced numerous striking tectonic landforms, some of which demonstrate the sense and magnitude of slip on the faults. Features along the Santa Cruz Island fault such as deflected drainages, offset streams, shutter ridges and back-facing scarps have been extensively described previously. This study documents larger-scale geomorphic features including slumps and drainage anomalies which are also related to the presence of a major fault zone but which have not been previously described, probably because their scale is much larger. When studying a major fault zone such as the Santa Cruz Island fault, it may be important to look at the larger-scale geomorphology, which can sometimes give additional insights on the interplay of tectonics and the tectonic landforms developed along the fault zone.

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