Chapter 4
Neotectonics of Santa Cruz Island, California

JACOB A. SELANDER AND ALISHA N. CLARK
DEPARTMENT OF GEOLOGY
UNIVERSITY OF CALIFORNIA, DAVIS, CA 95616
**JASELANDER@UCDAVIS.EDU*

Abstract

Active tectonics in the Northern Channel Islands typifies the styles of modern deformation taking place in the Western Transverse Ranges. North-south shortening and east-west extension of the Transverse Ranges is a result of transpression south of the Big Bend of the San Andreas Fault. North-south shortening is accommodated via slip along the Channel Islands Thrust, and westward-directed extension through slip along en echelon sinistral faults bisecting the islands. In this paper, the tectonics of the Northern Channel Islands is discussed, focusing on Santa Cruz Island. Structures, styles, and rates of modern deformation are presented and discussed in the context of growth of positive relief on Santa Cruz Island.

Introduction

The Pacific-North American boundary in southern California is one of the most exhaustively studied tectonic margins on the planet. Over the past ~40 Ma, this margin has been re-organized from northeast directed subduction to a complex and diffuse transform boundary (see Chapter 2). Although dextral slip along the San Andreas Fault accounts for the majority of the ~50 mm/yr motion between North America and the Pacific Plate, geodetic and geologic data show that strain is distributed over a broad region, extending from the western Transverse Ranges through the eastern Great Basin (e.g. Atwater, 1989; Bennett et al., 1999; Meade and Hager, 2005; McCaffrey, 2005; Wesnousky et al., 2005; Oskin et al., 2007) (Figure 4.1a). This distributed strain is well displayed throughout the western Transverse Ranges (TR) and the Big Bend of the San Andreas Fault (SAF), where an ~30° change in strike of the SAF creates a broad zone of transpression (Figure 4.1a). The TR themselves are accommodating north-south shortening via suites of reverse faults and folds, and westward-directed extension through left-slip transform faults in contrast with the overall dextral transpressional regime on southern California (e.g. Pinter et al., 1998).

The Northern Channel Islands represent the south westernmost expression of the Transverse Ranges (Atwater, 1998), and display styles of deformation typical of the TR (Pinter et al., 1998). Active sinistral strike-slip faults bisect many of the islands, and low-angle north- and south-vergent thrust faults accommodate north-south shortening and uplift of the islands (Davis et al., 1989; Shaw and Suppe, 1994; Pinter et al., 1998) (Figure 4.1b). These islands present a unique opportunity to study active tectonics; as preserved marine terraces, either subaereal or subaqueous (Pinter et al., 2003; Scott and Pinter, 2003; Chaytor et al., 2008), provide dateable markers from which to measure vertical deformation (Dickinson, 2001; Perg et al., 2001; Chaytor et al., 2008). By examining the modern-day deformation kinematics of the Northern Channel Islands, we can gain additional insights in to the kinematics of and how strain is distributed throughout the Transverse Ranges and the overall Pacific-North American boundary.

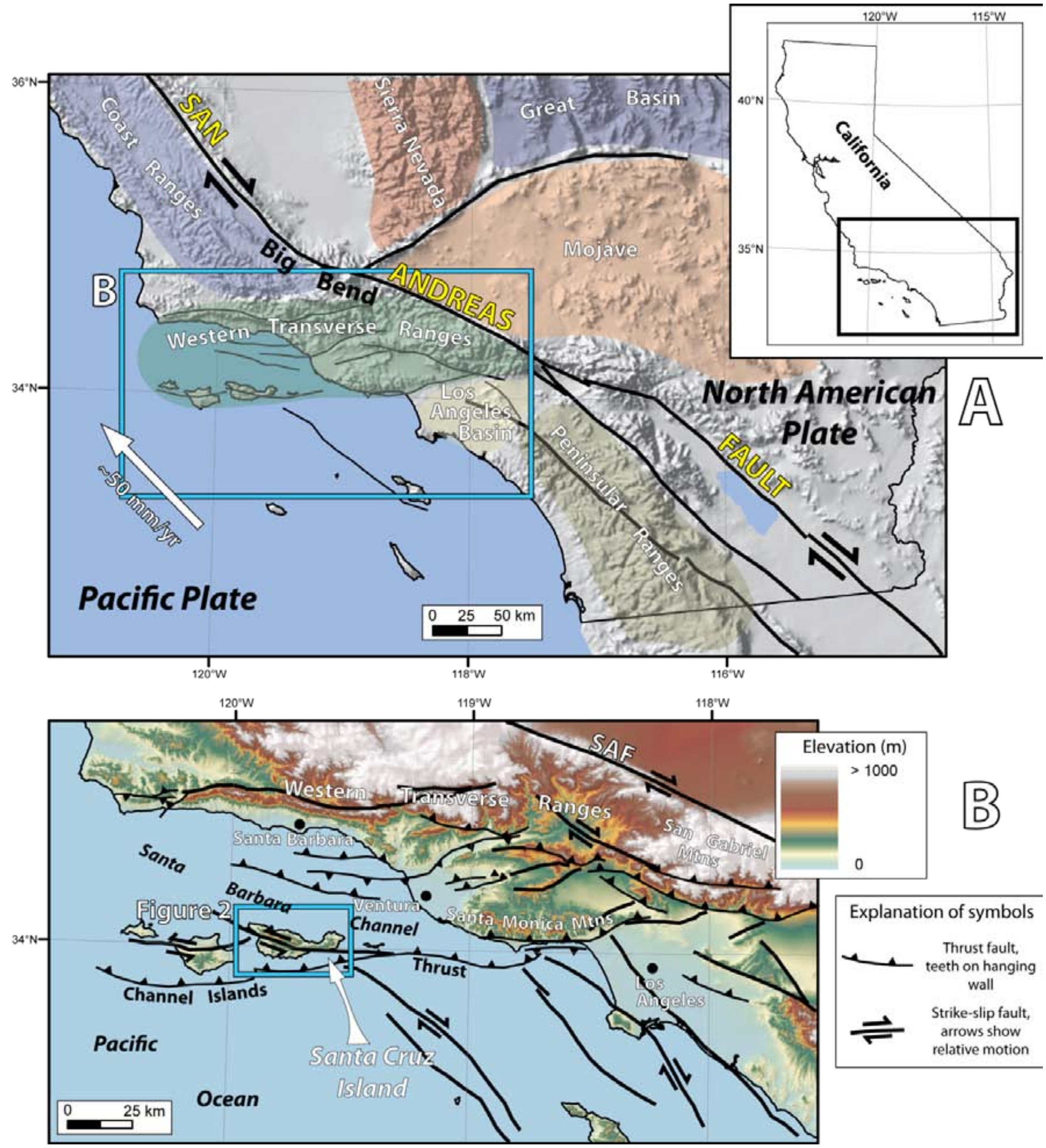

Figure 4.1. **[A]** Location map of Southern California with major faults, tectonic provinces, and relative motion of the Pacific Plate with respect to a stable North America. **[B]** Fault map of the western Transverse Ranges and Northern Channel Islands. Maps and geology simplified from Atwater (1998) and Chaytor et al. (2008).

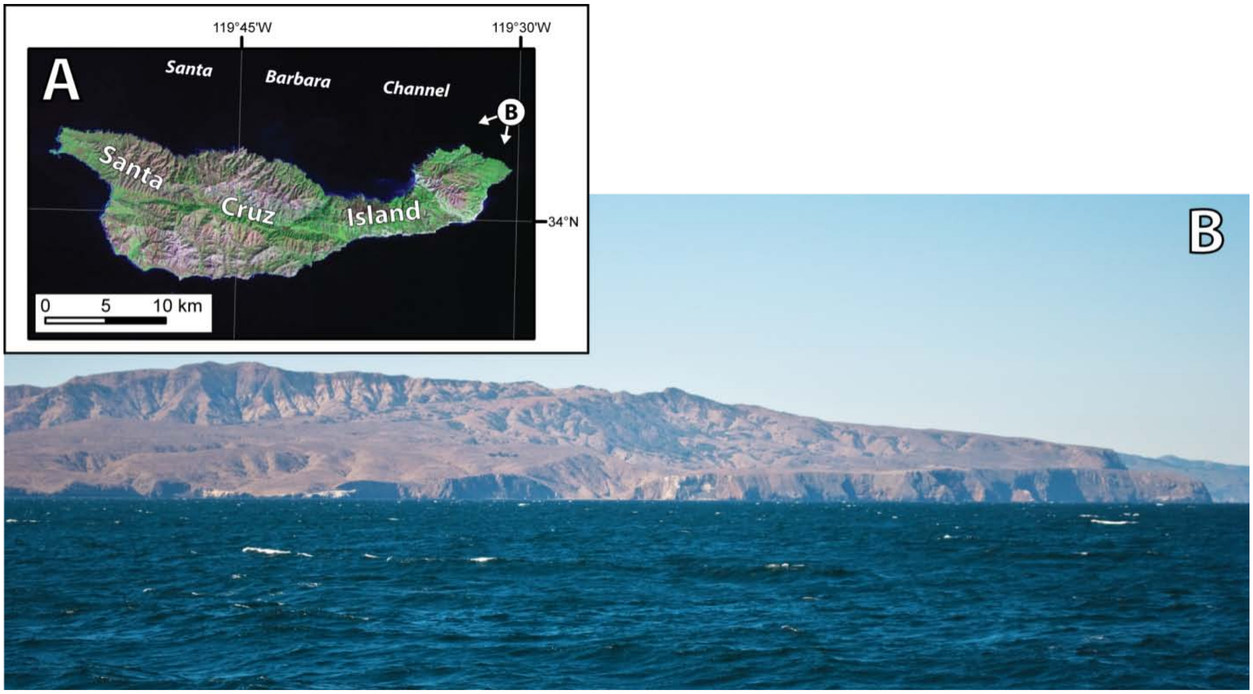

Figure 4.2. **[A]** Satellite image of Santa Cruz Island (MrSid; https://zulu.ssc.nasa.gov/mrsid/). **[B]** Photo of the eastern end of Santa Cruz Island, taken from point (B).

Within the context of the western Transverse Ranges, this paper discusses the active tectonics of the Northern Channel Islands, with emphasis placed on Santa Cruz Island (Figure 4.2). Here, suites of preserved, deformed marine terraces (Scott and Pinter, 2003; Pinter et al., 2003; Chaytor et al., 2008), and exposure of active sinistral faulting (Pinter and Sorlien, 1991; Pinter et al., 1998) can be combined with studies of blind thrusts underlying the Santa Barbara Channel (Shaw and Suppe, 1994; Seeber and Sorlien, 2000) to describe the generation of positive relief on Santa Cruz Island.

Geologic history and setting

The Transverse Ranges have a complex tectonic history, ranging from ~30 Ma to the present (see Chapter 2 for a detailed description). Following the subduction of the East Pacific Rise at ~27 Ma, the Mendocino Triple Junction migrated northwards and the Pacific- North American margin evolved to accommodate transtension between the two plates (Atwater, 1998). This resulted in the extension and clockwise rotation of the Transverse Range block and Borderland region from ~19- 5 Ma (Crouch and Suppe, 1993; Atwater, 1998). At ~5- 6 Ma, transtension became localized within the Gulf of California (Atwater, 1998; Oskin and Stock, 2003), and the region surrounding the Transverse Range block reconfigured to become transpressional with the development of the Big Bend of the SAF (Luyendyk, 1991; Atwater, 1998).

At present, the Transverse Ranges are pinned against the Big Bend of the SAF resulting in the accommodation of north-south shortening and westward-directed extension throughout the TR (Atwater, 1998) (Figure 4.3). Left-lateral transform faults have formed in the southern Transverse

Ranges to allow for east-west extrusion, and normal faults from Miocene extension have been re-activated as thrust faults to accommodate north-south shortening (Atwater, 1998). At the southwest extent of the Transverse Ranges, a blind thrust fault system underlying the Santa Barbara Channel and sets of left-lateral faults have been responsible for the uplift and deformation of the Northern Channel Islands (Yeats, 1983; Atwater, 1998; Sorlien et al., 1998) (Figure 4.3).

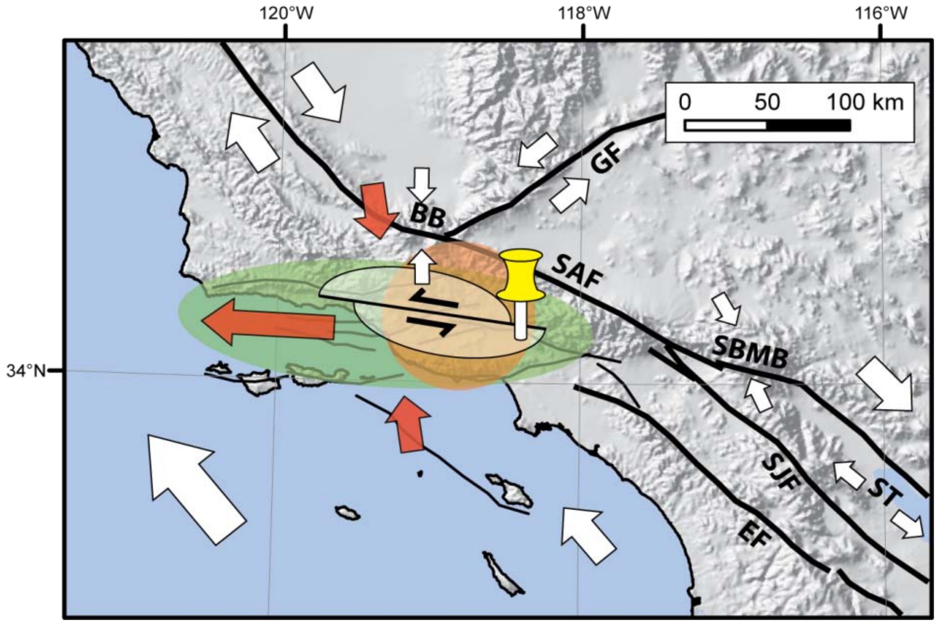

Figure 4.3. Schematic fault and deformation map of the Western Transverse Ranges. White arrows indicate relative motions on opposite sides of major faults; green ellipse is the approximate extent of the Western Transverse Ranges; red arrows show approximate north-south compression and westward directed extension of the TR; orange and white strain ellipses show the pre- and syn-deformation kinematics of the Western TR (respectively) with the eastern end "pinned" against the Big Bend of the SAF. Abbreviations: SAF- San Andreas Fault; BB- Big Bend of the SAF; GF- Garlock Fault; SBMB- San Bernadino Mountains Bend; ST- Salton Trough; SJF- San Jacinto Fault; EF- Elsinore Fault.

Active deformation on Santa Cruz Island

The recent tectonic evolution of Santa Cruz Island (SCI) can best be described as fault-related uplift and isostatic response. Anticlinal growth of SCI is taking place on a shorter wavelength than isostatic subsidence from topographic loading, resulting in net growth of the island (e.g. Pinter et al., 2003). Although this description seems simplistic, the actual mechanisms by which uplift is accomplished and the techniques to measure this uplift are not. In this section, the use of marine terraces and paleoshorelines in conjunction with studies of active faulting on SCI (Figure 4.4) is discussed to describe the late Quaternary growth of the island.

Marine terraces and paleoshorelines

The formation and preservation of marine terraces can provide strain markers from which to measure vertical deformation in relation to eustatic sea level (Muhs et al., 1990; Anderson et al., 1999; Perg et al., 2001; Pinter et al., 2003). Marine terraces generated as planar wave-cut platforms are raised above sea level, through eustatic changes which may be augmented by tectonic uplift (Anderson et al., 1999; see Chapter 5) (Figure 4.5). Ages of these terraces can be found using U-series analysis of carbonates (corals) developed on the bench (e.g. Muhs et al., 1990; Muhs et al., 1994; Pinter et al., 1998), or through exposure-age dating techniques (e.g. Perg et al., 2001). With a known eustatic sea level curve and age of the terrace, overall surface uplift rates can be calculated.

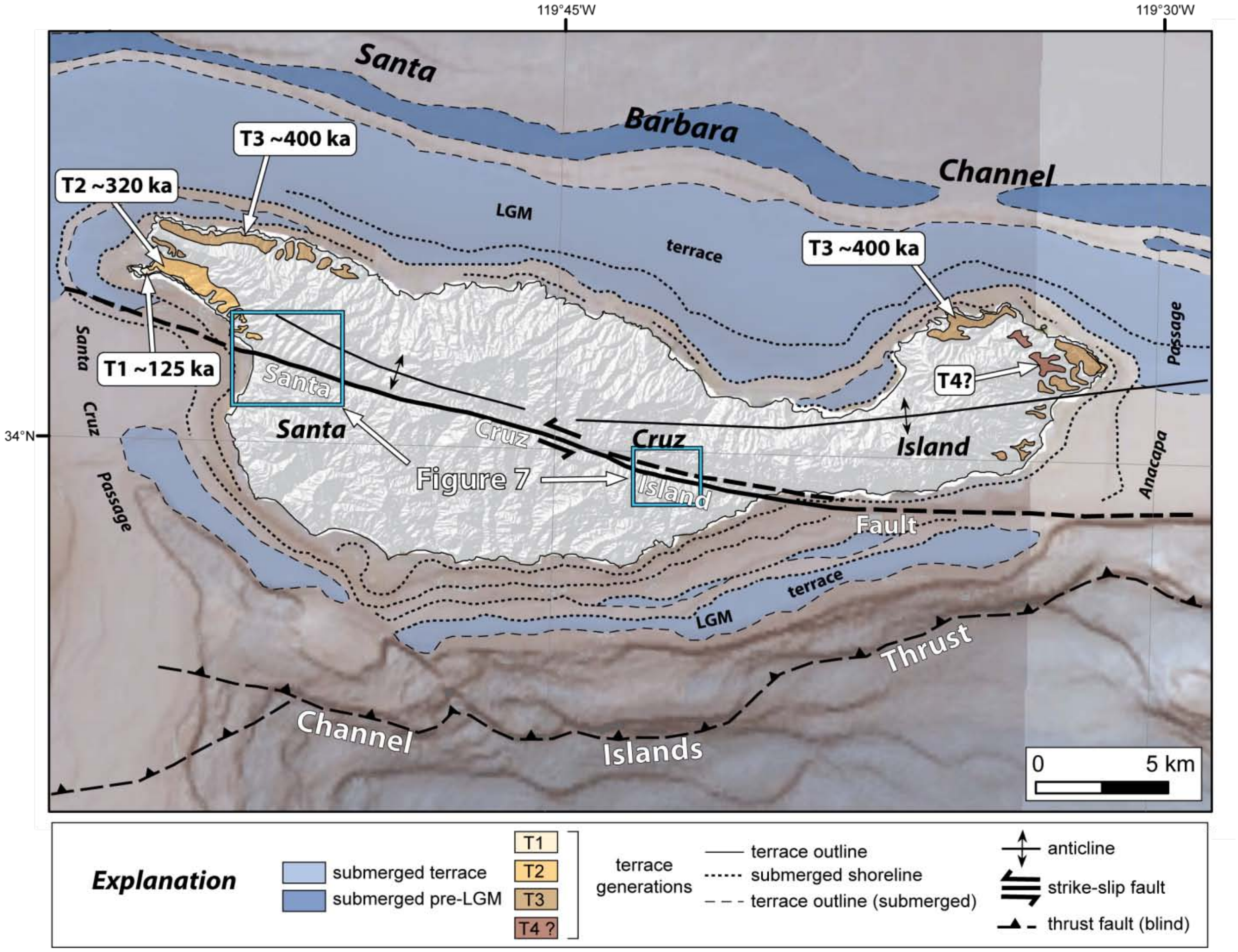

Figure 4.4. Quaternary geologic and structural map of Santa Cruz Island, showing the extent of preserved marine terraces, both subareal and subaqueous. Terraces on the island are labeled with approximate age; T4? represents a higher, semi-planar geomorphic surface not previously identified. Anticlinal trace is approximated from terrace uplift data. Modified after Pinter et al. (1998), Pinter et al. (2003), Scott and Pinter (2003), Chaytor et al. (2008).

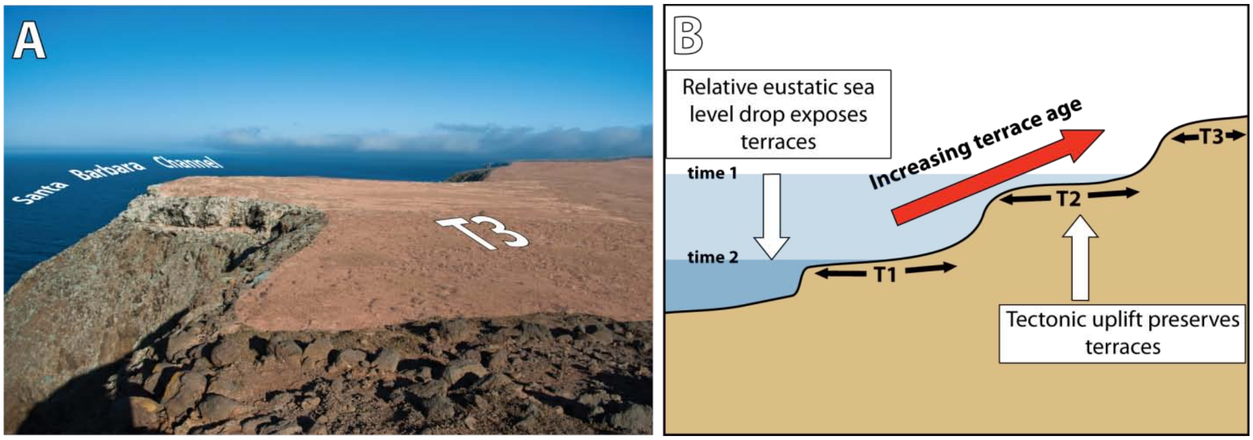

Figure 4.5. **[A]** Annotated photo of marine terrace T3 (after Pinter et al. (2003), Scott and Pinter (2003)) on the eastern end of Santa Cruz Island. **[B]** Schematic cross-section through multiple generations of marine terraces showing mechanisms for relative uplift and preservation of terraces.

As many as five generations of marine terraces and paleoshorelines have been identified on and in the shallow water (<100 m depth) surrounding Santa Cruz Island (Pinter et al., 1998; Pinter et al., 2003; Scott and Pinter, 2003; Chaytor et al., 2008) with ages ranging from ~125 – 400 ka for marine terraces (Pinter et al., 1998) and ~11.5 – 27 ka for submerged paleoshorelines (Chaytor et al., 2008) (Figure 4.4). Topographically higher terraces are chronologically older than lower preserved surfaces (Pinter et al., 1998; Scott and Pinter, 2003), indicating that Santa Cruz Island has been experiencing net topographic uplift for at least the past ~400 ka. Differential amounts of uplift across equivalent surfaces shows broad anticlinal warping of the island with vertical uplift rates between 0.7 and 1.5 mm/yr (Pinter et al., 2003; Chaytor et al., 2008).

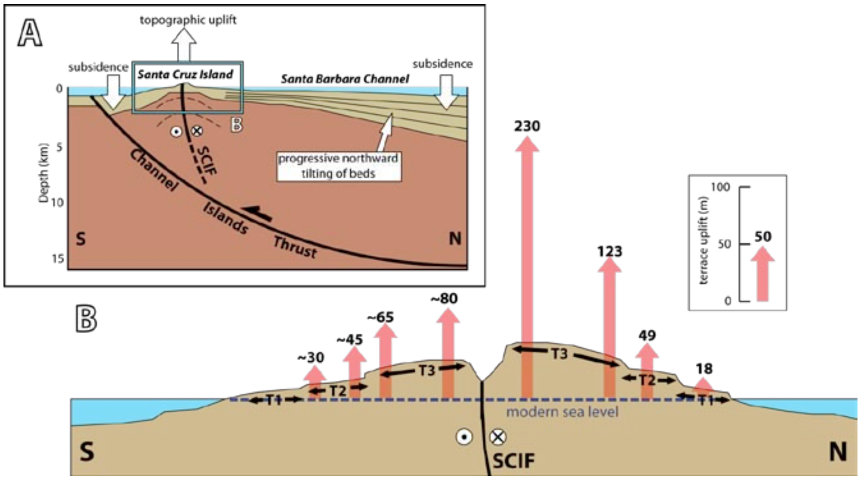

Figure 4.6: **[A]** Schematic north-south structural cross-section through the Santa Barbara Channel and SCI (after Shaw and Suppe (1994), Seeber & Sorlien (2000), Pinter et al. (2003)) showing uplift of island subsidence of surrounding bathymetry. SCIF- Santa Cruz Island Fault **[B]** Schematic section through SCI, showing relative terrace positions and amounts of uplift relative to eustatic sea level (after Pinter et al., 2003)). Note the uplift asymmetry on north and south sides of the SCIF.

Active structures

The net surface uplift of Santa Cruz Island has developed through motion along blind thrust faults that underlie the Santa Barbara Channel, and sinistral- oblique motion along the Santa Cruz Island fault. SCI is located in the hanging wall of the Channel Islands Thrust, a south-vergent fault that roots into a mid-crustal detachment (Shaw and Suppe, 1994; Seeber and Sorlien, 2000) (Figure 4.6). The Channel Islands Thrust, similar to many other faults in the Transverse Ranges, is interpreted as a Miocene extensional fault which has been re-activated to accommodate shortening in the current stress field (Seeber and Sorlien, 2000; Tsutsumi et al., 2001). Slip rates estimated along the Channel Islands Thrust (1.3 mm/yr; Shaw and Suppe, 1994) closely match vertical uplift rates of SCI (~1.5 mm/yr; Chaytor et al., 2008). This slip on the CIT is a significant component of the geologically and geodetically determined 6 mm/yr north-south shortening across the Santa Barbara Channel (Namson and Davis, 1988; Larson and Webb, 1992).

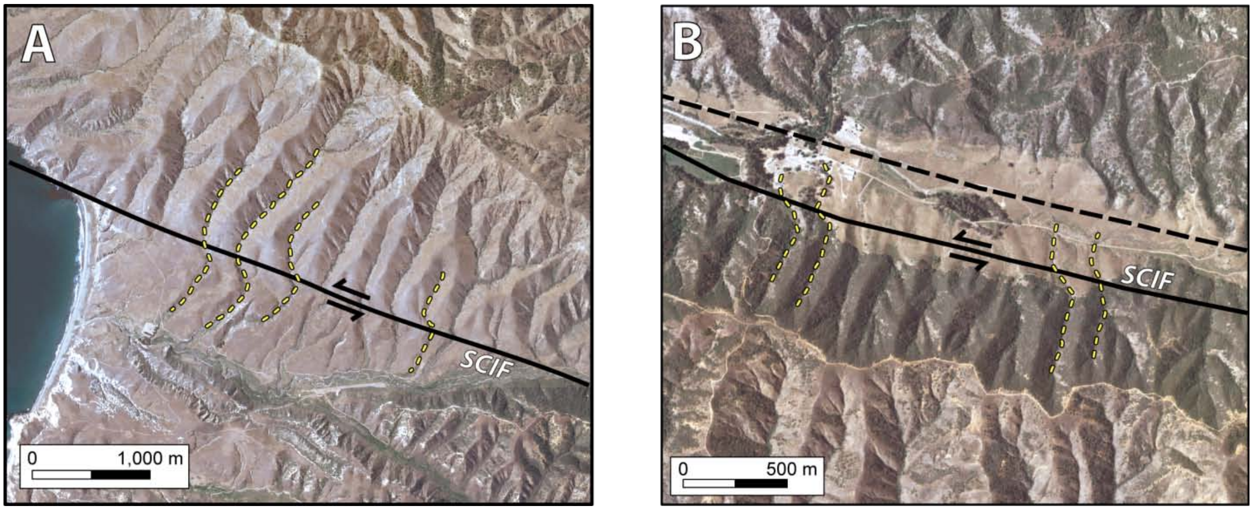

Figure 4.7. NAIP imagery of sinistrally offset channels on the eastern (after Pinter et al., 1998) and western exposures of the SCIF.

Bisecting Santa Cruz Island is the Santa Cruz Island Fault, and east-west striking left-slipping transform fault (Figure 4.4). The Santa Cruz Island Fault is part of a network of left-lateral faults that denote a boundary between the east-west striking structures of the western Transverse Ranges to the north and northwest-southeast trending structures to the south (Pinter et al., 1998). Late Quaternary activity is expressed along the Santa Cruz Island Fault as sinistrally offset stream channels (Pinter and Sorlien, 1991; Pinter et al., 1998) (Figure 4.7) along the fault trace. Slip on the fault calculated from trenching studies and measurements of offset channels in dated terrace deposits at its western exposure on SCI shows a horizontal slip rate of 0.8-1.1 mm/yr with a vertical, north-side-up component of 0.1-0.2 mm/yr (Pinter et al., 1998). Using these Quaternary slip rates in conjunction with measured slip per event suggests that the Santa Cruz Island Fault is capable of producing earthquakes of magnitude Mw 7.2-7.5 with a recurrence interval of 2.7- 5 ka (Pinter et al., 1998).

Uplift of Santa Cruz Island

The Northern Channel Islands represent the exposure of a broad east-west trending anticline developed in the hanging wall of the Channel Islands Thrust. Although two competing models for the geometry of the CIT exist (Shaw and Suppe, 1994; Seeber and Sorlien, 2000), both require the development of a fault-bend-fold (e.g. Suppe, 1983) as a result of the CIT shallowing at depth. This folding is best expressed through the differential uplift of marine terraces present on Santa Cruz Island (Pinter et al., 2003) (Figure 4.6). Additionally, sedimentary deposits shed from Santa Cruz Island northward into the Santa Barbara Channel have dips that increase with age, showing progressive northward-tilting of the Channel Islands anticline backlimb (Seeber and Sorlien, 2000; Chaytor et al., 2008) (Figure 4.6). Local thickening of the crust as a result of folding and growth of SCI has caused local isostatic subsidence, although subsidence rates are lower than uplift rates and spread out over a larger area, creating net topographic uplift of the island (Pinter et al. 2003). Topographic uplift is estimated to be ~0.51 km since ~400 ka (the age of the oldest marine terrace (Pinter et al., 1998)) at rates of 0.7 – 1.5 mm/yr (Pinter et al., 2003; Chaytor et al., 2008).

Conclusion

Through use of uplifted marine terraces and geometric studies of blind thrust faults underlying the Santa Barbara Channel, the growth of topography on Santa Cruz Island during the Quaternary can be described as a hanging-wall anticline above the Channel Islands Thrust. Slip on the CIT of ~1.3 mm/yr (Shaw and Suppe, 1994) is a significant portion of the 6 mm/yr north-south shortening accommodated across the Santa Barbara Channel (Namson and Davis, 1988; Larson and Webb, 1992). Since the CIT roots into a sub-horizontal detachment at depth (Shaw and Suppe, 1994; Seeber and Sorlien, 2000), horizontal shortening very closely matches measured uplift rates of ~1.5 mm/yr on Santa Cruz Island (Chaytor et al., 2008). Active oblique-sinistral faulting along the Santa Cruz Island Fault at 0.8-1.1 mm/yr (Pinter and Sorlien, 1991; Pinter et al., 1998) is consistent with westward-directed extension of the Transverse Ranges in response to transpression south of the Big Bend of the San Andreas Fault.

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