The transtensional offshore portion of the northern San Andreas fault: Fault zone geometry, late Pleistocene to Holocene sediment deposition, shallow deformation patterns, and asymmetric basin growth

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ABSTRACT

We mapped an ~120 km offshore portion of the northern San Andreas fault (SAF) between Point Arena and Point Delgada using closely spaced seismic reflection profiles (1605 km), high-resolution multibeam bathymetry (~1600 km²), and marine magnetic data. This new data set documents SAF location and continuity, associated tectonic geomorphology, shallow stratigraphy, and deformation. Variable deformation patterns in the generally narrow (~1 km wide) fault zone are largely associated with fault trend and with transtensional and transpressional fault bends.

We divide this unique transtensional portion of the offshore SAF into six sections along and adjacent to the SAF based on fault trend, deformation styles, seismic stratigraphy, and seafloor bathymetry. In the southern region of the study area, the SAF includes a 10-km-long zone characterized by two active parallel fault strands. Slip transfer and long-term straightening of the fault trace in this zone are likely leading to transfer of a slice of the Pacific plate to the North American plate. The SAF in the northern region of the survey area passes through two sharp fault bends (~9°, right stepping, and ~8°, left stepping), resulting in both an asymmetric lazy Z–shape sedimentary basin (Noyo basin) and an uplifted rocky shoal (Tolo Bank). Seismic stratigraphic sequences and unconformities within the Noyo basin correlate with the previous 4 major Quaternary sea-level lowstands and record basin tilting of ~0.8°/100 k.y. Migration of the basin depocenter indicates a lateral slip rate on the SAF of 10–19 mm/yr for the past 350 k.y.

Data collected west of the SAF on the south flank of Cape Mendocino are inconsistent with the presence of an offshore fault strand that connects the SAF with the Mendocino Triple Junction. Instead, we suggest that the SAF previously mapped onshore at Point Delgada continues onshore northward and transitions to the King Range thrust.

INTRODUCTION

Strike-slip fault geometries and deformation patterns on plate-margin scales can be predicted from geodetic and plate circuit models. On smaller scales, small changes in fault trend and lithology can have profound effects on local deformation in strike-slip fault zones (Cunningham and Mann, 2007; Johnson and Watt, 2012), for which documentation requires high-resolution data sets and detailed observations. In the marine environment, recent studies have shown that integrating high-resolution multibeam bathymetry and high-resolution seismic reflection profiles can provide the information needed to understand recent fault deformation (Barnes and Pondard, 2010; Pondard and Barnes, 2010; Johnson and Watt, 2010; Johnson and Watt, 2012; Ryan et al., 2012). In this study we analyze 1605 km of high-resolution minisarker seismic reflection profiles, ~1600 km² of high-resolution bathymetry, and marine and/or aerial magnetic data to characterize a poorly documented, 120-km-long portion of the northern San Andreas fault (SAF) between Point Arena and Punta Gorda (south flank of Cape Mendocino), offshore northern California (Fig. 1). The seismic reflection data set includes 120 crossings of the SAF at a typical line spacing of 1 km (Fig. 2A). With a horizontal resolution of 2 m for the bathymetry and a vertical resolution of commonly ~1 m for the seismic reflection profiles, these data approach terrestrial outcrop-scale mapping with the advantage of regularly spaced and dense imaging of shallow structure and stratigraphy. The goal is to document shallow crustal deformation patterns and the tectonic geomorphology of strike-slip zones to better understand the influence of active tectonics on seismic stratigraphy, and to put this information into a context useful for assessing regional earthquake hazards. More information on data acquisition, analytical methods, vertical deformation rates, and implications for turbidite paleoseismology are in Beeson (2016) and Beeson et al. (2016).
**TECTONIC SETTING**

The SAF is a right-lateral strike-slip fault that extends for 1400 km from the Gulf of California to near Cape Mendocino, and is the main structure in the widely distributed plate boundary between the Pacific plate and the Sierra Nevada Great Valley microplate (Williams et al., 2006) (Fig. 1). The Mendocino Triple Junction (MTJ) is located at the northern termination of the SAF and has been migrating northward since ca. 28–25 Ma (Dickinson and Snyder, 1979). Estimates of cumulative right slip of basement terranes range from ~300 to 450 km along the southern and northern segments of the SAF system (the group of distributed strike-slip faults along the plate boundary), respectively (e.g., Dillon and Ehlig, 1993; James et al., 1993; Wesnousky, 2005).

The SAF system in northern California now includes three major fault zones, the SAF, the Garberville-Macama fault (GMF), and the Bartlett Springs–Lake Mountain fault (BSLMF) (Fig. 1). The GMF and BSLMF are located east of the SAF and have been described as the northward extension of the Hayward–Rodgers Creek and Calaveras–Green Valley fault zones (Castillo and Elsworth, 1993). In northern California, the SAF has an estimated...
Figure 2. (A) Map (location in Fig. 1) showing regional geography, locations of seismic profiles (blue lines), outer boundary of multibeam data (yellow line), significant faults (black lines), fault sections (offshore King Range and A–F; see text), and locations of more detailed fault maps (Figs. 6, 13, 17, and 20). PA—Point Arena; PD—Point Delgada; PG—Punta Gorda; MF—Mendocino fault; FB—Fort Bragg; CM—Cape Mendocino; KRT—King Range thrust; SAF—San Andreas fault. (B) Magnetic anomaly grid in nanoteslas (nT; 50 x 50 m) is based on data from Langenheim et al. (2013).
slip rate between 14 and 25 mm/yr (Niemi and Hall, 1992; McLaughlin et al., 1994; Prentice et al., 1999, Prentice et al., 2000; Kelson et al., 2006; Williams et al., 2006; U.S. Geological Survey and California Geological Survey, 2016). Geodetic and geologic studies have estimated GMF and BSLMF slip rates of 6.4–18 mm/yr and 6–10 mm/yr, respectively (Williams et al., 2006; Prentice et al., 2014).

Our investigation focuses on the 120-km-long northernmost portion of the SAF. Curry and Nason (1967) mapped the general location of the SAF in this offshore area on a series of widely spaced seismic reflection profiles; however, comprehensive high-resolution mapping and characterization have been lacking. The SAF in this offshore area has a distinctly more northward trend (~350°) than the predominantly onland SAF to the south between San Francisco and Point Arena (~322°), and farther south through all of California (Spotila et al., 2007). This transtensional trend (relative to plate motions and local global positioning system vectors) is unique for the SAF (Fig. 3) and notably coincides with the lower elevations of the offshore marine environment.

Near the north end of our study area, the SAF terminates and transitions into the southern end of the subduction system of the Gorda–North America plate (Fig. 1). Rapid localized uplift is occurring onland in the King Range on the south flank of Cape Mendocino, but onshore geologic mapping has not shown an unambiguous connection of this uplift with the inferred trace of the SAF at Point Delgada (McLaughlin et al., 1994).

Seismicity

On 18 April 1906, a magnitude 7.8 earthquake occurred along the SAF in northern California; the epicenter was located near San Francisco (Lawson, 1908; Lomax, 2005). This earthquake destroyed much of San Francisco causing ~$400,000,000 of damage (1906 dollars) and more than 3000 fatalities. The fault ruptured bidirectionally for ~435 km from its epicenter a few kilometers offshore San Francisco (Lomax, 2005) (Fig. 1) and extended as far north as Point Delgada and as far south as San Juan Bautista (Lawson, 1908; Prentice, 1999). Mean and maximum slip along the fault during this event have been estimated and modeled to be 4.3 and 9–11 m (Song et al., 2008).

Evidence of 1906 surface rupture at Point Delgada (Fig. 1) was documented by F.E. Matthes in June 1906 (in Lawson, 1908). These observations were called into question by Beutner et al. (1980) and McLaughlin et al. (1982), who speculated that the observations by Matthes could have resulted from landsliding and ground failure, and not from a surface rupture. Studies by Brown (1995) and Prentice et al. (1999) at Point Delgada documented the 1906 rupture as a nearly vertical, narrow fault zone that offsets young geomorphic features, confirming the initial observations of F.E. Matthes (in Lawson, 1908). The fault zone at Point Delgada is the northernmost mapped rupture associated with the 1906 SAF earthquake.

Since 1906, the northern SAF system has been nearly aseismic; there was one moment magnitude, $M_w$ 4.5 earthquake near Bolinas and a few other smaller earthquakes near Point Arena (Zoback et al., 1999, Baise et al., 2003).

There has been considerable nearby seismicity associated with the MTJ, the GMF, and the BSLMF (Castillo and Ellsworth, 1993).

The northern SAF (extending from Point Delgada to San Francisco) has been the site of repeated major strike-slip earthquakes during the late Holocene, with an inferred recurrence interval of ~250–300 yr (Prentice, 1989; Niemi and Hall, 1992; Zhang et al., 2006; Kelson et al., 2006; Goldfinger et al., 2007; Schwartz et al., 2014). Investigations using turbidite deposits inferred to be coseismically induced reveal an average recurrence interval of ~240 yr through the Holocene (Goldfinger et al., 2007).

DATA ACQUISITION

High-resolution multibeam bathymetry was collected by Fugro Pelagos (www.fugro-pelagos.com/) in the state waters portion of this area (10 m isobath to 3 nautical miles offshore, Point Arena to Cape Mendocino) in 2009 for the California Seafloor Mapping Program (http://walrus.wr.usgs.gov/mapping/csmpr/). Our subsequent data acquisition occurred on three research surveys in 2010 and one survey in 2012. In 2010, the U.S. Geological Survey (USGS) collected seismic reflection profiles crossing the SAF at 1 km spacing from Point Arena to Fort Bragg (Fig. 2A). The Active Tectonic and Seafloor Mapping Lab of Oregon State University (OSU) collected high-resolution multibeam bathymetry along the SAF outside state waters from offshore Fort Bragg to Point Delgada. Then, OSU and the USGS jointly collected seismic reflection
data crossing the SAF at 1 km spacing from offshore Fort Bragg to Point Delgada. In 2012, OSU and the USGS jointly collected additional seismic reflection and marine magnetic data west of the SAF between Point Delgada and Punta Gorda, and east of the SAF between Point Delgada and Fort Bragg. (For details of geophysical data acquisition, see Beeson et al., 2016.)

Aeromagnetic data were taken from Langenheim et al. (2013) and gridded at 50 × 50 m using the principals of minimum curvature to provide full survey area coverage (Briggs, 1974). Abrupt changes or strong gradients in the magnetic data are typically indicative of lithologic or structural boundaries.

High-resolution bathymetry collected for the California Seafloor Mapping Program (CSMP) is available through the California State University at Monterey Bay Seafloor Mapping Lab at http://seafloor.otterlabs.org/SFMLwebDATA_SURVEYMAP.htm and through the National Oceanic and Atmospheric Administration (2013).

For high-resolution single-channel seismic reflection data and marine magnetic data, see Beeson et al. (2016).

## RESULTS

### Interpretation of Seismic Data and Seismic Stratigraphic Units

Within the survey area we define four stratigraphic units, based on seismic reflection characteristics and facies (using terminology of Mitchum et al., 1977), and bathymetric data. Two older units, interpreted as (1) Mesozoic–Neogene acoustic basement, and (2) Neogene sedimentary rocks, are largely extrapolated from onshore geologic mapping and offshore geophysical exploration (Hoskins and Griffiths, 1971; Blake et al., 1978; McCulloch, 1987). On seismic reflection profiles this unit is characterized by low-to moderate-amplitude, low- to high-frequency parallel to subparallel reflections and contains numerous internal unconformities inferred to result from wave erosion during sea-level transgressions. Offshore-dipping cliniforms within unit Q are present in the nearshore parts of many seismic reflection profiles.

Uppermost Pleistocene to Holocene marine sediments (H in Fig. 4) compose the highest and youngest unit imaged in the seismic reflection data, representing deposition during the ~120–130 m sea-level rise that followed the Last Glacial Maximum (LGM; before ca. 21 ka) (Peltier, 2005; Stanford et al., 2011). This unit overlies a relatively flat to slightly inclined, commonly irregular erosional surface in shallow water, transitioning to a parallel conformable contact with underlying unit Q at water depths between 120 and 135 m. Similar to the erosional contacts within unit Q, the basal contact is interpreted as a transgressive surface of erosion. Similar post-LGM sediment facies are imaged throughout the California margin (Slater et al., 2002; Anima et al., 2002; Draut et al., 2009; Johnson and Watt, 2012; Johnson et al., 2015). The thickness of the H unit throughout the survey area ranges from 0 to 64 m (see Fig. 5; methods described in Beeson, 2016).

### Characterization of the Offshore SAF

We divide this offshore portion of the northernmost SAF into 6 sections (A–F in Fig. 2A) delineated on the basis of fault orientation, deformation patterns, seismic stratigraphy, and seafloor geomorphology. We also describe seismic reflection profiles northwest of Point Delgada in order to investigate the possible offshore continuation of the northern SAF.

#### Section A

Section A of the northern SAF extends northwest from Point Arena for ~13 km. Through this section, the fault gently bends from a trend of ~324° at the south to 331° at the north (Fig. 6). The SAF is delineated as a primary continuous fault strand bounded by an ~3.5-km-wide parallel fault zone to the west...
consisting of multiple discontinuous short (<1 km to 7 km) fault strands. We place the northern boundary of this section at a location where the width of the fault zone abruptly narrows to ~500–1000 m.

Seafloor relief along the main strand of the SAF varies from nothing (buried by sediment, Fig. 7A) to a 10-m-high, east-side-up scarp (Fig. 7B). This scarp forms the western boundary of a narrow (~200 m wide), 1-km-long section of rock outcrop that is coincident with a 7° restraining bend (Fig. 6).

Seismic reflection data reveal that the SAF in section A juxtaposes a bedrock unit (TKc) overlain by a thin layer of H to the east with a section comprising units TKc, Tu, Q, and H on the west. Post-LGM sediment (H) along this section of the SAF zone ranges from ~4 to 20 m thick (Fig. 5). East of the fault, unit H forms a lens that thins over SAF zone uplifts; west of the fault, unit H forms a westward-thinning wedge (Fig. 7).

Folding of pre-Quaternary basement rocks is imaged east of the SAF (Fig. 7). West of the SAF, there are small offsets and minor deformation of the Tu-Q contact on SAF-parallel faults, and significant warping and tilting of reflections within the Tu unit. Gentle warping and folding is imaged within Q, but there is no visible deformation within H.

This section of the SAF is coincident with a steep magnetic gradient, east (high) to west (low) (Fig. 2B). The SAF truncates a series of northwest-trending, slightly oblique, lower amplitude, short-wavelength magnetic anomalies, which Langenheim et al. (2013) interpreted as regional-scale folding of a magnetically high unit within the complexly deformed coastal belt terrane.

Section B

The trend of this ~18-km-long SAF section gently changes from 336° (southern 4 km) to 333° (middle 4.5 km) to 340° (northern 9 km) (Fig. 6). We place the northern boundary of this section at a location where the fault zone abruptly changes from a single fault strand to two main strands (section C). The SAF is
Figure 5. Post–Last Glacial Maximum (LGM) isopach map and lower parts of coastal drainages (blue, with larger drainages labeled). San Andreas fault is in red. H—latest Pleistocene to Holocene deposits.

Figure 6. (A) Southern part of study area between Point Arena and Fort Bragg. Red lines show faults mapped with offshore seismic reflection data. Black letters indicate San Andreas fault sections (A–C). Shaded relief shows onshore-offshore relief; gray-white boundary is that of available multibeam bathymetry. Pale green areas show seafloor outcrops of Mesozoic and Neogene bedrock. White arrows indicate locations of fault bend locations. Yellow lines show locations of seismic reflection profiles in Figures 4, 7, 8, and 10. Orange boxes show locations of high-resolution bathymetry displayed in Figures 9 and 11. Black lines indicate 20 m contour intervals.

Figure 7. (B) Northern part of study area between Point Arena and Tolo Bank. Red lines show faults mapped with offshore seismic reflection data. Black letters indicate San Andreas fault sections (A–C). Red lines show locations of seismic reflection profiles in Figures 4, 7, 8, and 10. Orange boxes show locations of high-resolution bathymetry displayed in Figures 9 and 11. Black lines indicate 20 m contour intervals.

Figure 8. (C) Midsection of study area between Point Arena and Tolo Bank. Red lines show faults mapped with offshore seismic reflection data. Black letters indicate San Andreas fault sections (A–C). Shaded relief shows onshore-offshore relief; gray-white boundary is that of available multibeam bathymetry. Pale green areas show seafloor outcrops of Mesozoic and Neogene bedrock. White arrows indicate locations of fault bend locations. Yellow lines show locations of seismic reflection profiles in Figures 4, 7, 8, and 10. Orange boxes show locations of high-resolution bathymetry displayed in Figures 9 and 11. Black lines indicate 20 m contour intervals.

Figure 9. Post–Last Glacial Maximum (LGM) isopach map and lower parts of coastal drainages (blue, with larger drainages labeled). San Andreas fault is in red. H—latest Pleistocene to Holocene deposits.

Figure 10. (A) Southern part of study area between Point Arena and Fort Bragg. Red lines show faults mapped with offshore seismic reflection data. Black letters indicate San Andreas fault sections (A–C). Shaded relief shows onshore-offshore relief; gray-white boundary is that of available multibeam bathymetry. Pale green areas show seafloor outcrops of Mesozoic and Neogene bedrock. White arrows indicate locations of fault bend locations. Yellow lines show locations of seismic reflection profiles in Figures 4, 7, 8, and 10. Orange boxes show locations of high-resolution bathymetry displayed in Figures 9 and 11. Black lines indicate 20 m contour intervals.
Figure 7. U.S. Geological Survey offshore seismic reflection profiles (locations shown in Fig. 6). TWT—two-way traveltime. SAF—San Andreas fault. Q—Quaternary deposits; H—latest Pleistocene to Holocene deposits; Tu—inferred Neogene bedrock; TKc—inferred Cretaceous to Paleogene–Neogene Coastal Range terrane; M—seafloor multiple (see Fig. 4). (A) MS-16. (B) MS-18. (C) MS-20.
Figure 8. U.S. Geological Survey seismic reflection profiles (locations shown in Fig. 6). TWT—two-way traveltime. SAF—San Andreas fault; Q—Quaternary deposits; H—latest Pleistocene to Holocene deposits; TKc—inferred Cretaceous to Paleogene–Neogene Coastal Range terrane; M—seafloor multiple (see Fig. 4). (A) MS-36. (B) MS-41. (C) MS-45. The gas charged areas labeled in C are relatively common on seismic profiles and are subsequently labeled only on select profiles where the presence of gas influences interpretations.
consistently east-side-up through section B (Fig. 8), and the southern 3° transpressional bend notably coincides with the southern end of an east-side-up scarp (as high as 10 m) and a 3-km-long bedrock uplift (inferred TKc) east of the main SAF strand (Figs. 6 and 9).

East of the SAF, H deposits (10–20 m thick) thin to the west and overlie both TKc bedrock and erosional troughs enclosing chaotic reflections that we interpret as paleochannel deposits (Figs. 5 and 8A–8C). These paleochannels are inferred to have formed during late Pleistocene sea-level lowstands, when this section of the shelf was emergent and traversed by coastal drainages. The shelf paleochannels must have connected with the erosional gaps in the present nearshore wave-cut platform (Fig. 6), which also would have hosted coastal drainages during lowstands. To the west, the shelf paleochannel fills correlate with Q deposits.

The Q unit west of the SAF includes a number of erosional unconformities likely associated with Pleistocene sea-level fluctuations. Several of the faults imaged west of the SAF offset and warp unit Q strata. Many profiles contain isolated high-amplitude reflections (bright spots) within Q (Figs. 8B, 8C), indicating local gas charging (Fader, 1997).

The SAF in section B is parallel to a moderate- to high-amplitude magnetic anomaly to the west in the southern part of the section that transitions to a broader, lower amplitude magnetic anomaly in the north part of the section (Fig. 2B). Low-amplitude anomalies east of the SAF continue to trend northwest, similar to those in section A (Langenheim et al., 2013).

Section C

The narrow SAF zone of section B transitions to a broader zone (as wide as 750 m) characterized by two main fault strands in 16-km-long section C (Fig. 6). The western strand in section B gently bends from a trend of 343° (southern 10 km) to 347° (northern 6 km). The eastern strand extends roughly parallel to the main strand for ~10 km (Fig. 6). Bathymetry data reveal the local presence of steep sharp fault scarps on both the western and eastern strands of the SAF in section C (Fig. 11). Because this area has undergone recurring sea-level transgressions and regressions at these water depths (100–115 m), which would likely erode old fault scarps, we interpret these steep sharp fault scarps as indicative of post-LGM slip occurring on both SAF strands. In the southern part of section C, the area between the two fault strands contains small isolated bathymetric depressions (Fig. 11, depressions 1–3). The depressions are bounded by low-relief uplifts, imaged as reflection-free zones on seismic profiles (Figs. 10A, 10B). In the northern part of section C, bathymetric data show four isolated bedrock uplifts with ribbed surface relief, suggesting differential erosion of layered sedimentary rocks, most likely unit Tu (Fig. 11, uplifts 1–4). Three of the uplifts have more than 35 m of relief above adjacent seafloor and are bound between the eastern and western SAF strands. (The origins of these intrafault zone uplifts and depressions are considered in ANALYSIS AND DISCUSSION herein.)

East of the SAF, seismic profiles reveal westward-thinning (0–20 m) post-LGM deposits (H) above chaotic reflections that are faint, deformed, and discordant (Figs. 8 and 10). A prograding wedge of H sediments (as thick as 20 m) with cliniform geometries is imaged adjacent to Caspar Creek (Figs. 6 and 10D). As in section B, we interpret the faint, discontinuous reflections of underlying unit Q as mainly fills of fluvial paleochannels cut during late Pleistocene sea-level lowstands. The contact between bedrock TKc units and Q is an irregular west-dipping surface, likely reflecting fluvial erosion during repeated Quaternary lowstands (Fig. 10A).

West of the fault zone, the Q stratigraphic section is thicker, extending below the level of our seismic reflection profiles. Multiple unconformities within the Quaternary unit bound sequences attributed to Quaternary sea-level cycles. The magnetic gradient along the SAF in section C is similar to that of section B, characterized by higher values to the west, lower values to the east, and a steep gradient along the western strand of the SAF (Fig. 2B). The steep mag-
Figure 10. U.S. Geological Survey seismic reflection profiles (locations shown in Fig. 6). TWT—two-way traveltime. SAF—San Andreas fault; Q—Quaternary deposits; H—latest Pleistocene to Holocene deposits; Tu—inferred Neogene bedrock; TKc—inferred Cretaceous to Paleogene–Neogene Coastal Range terrane; M—seafloor multiple (see Fig. 4). (A) MS-60. (B) MS-63. (C) MS-65. (D) MS-68.
etic gradient that consistently tracks the western SAF imaged from seismic data bulges east at the northern end of the paired fault zone. Magnetic anomalies between the SAF system and the coastline are generally characterized by low values with little discernable fabric.

Section D

Section D of the SAF extends northwest for 17 km and is distinguished from section C to the south by the disappearance of the eastern SAF strand of section C and the elongated rocky uplift that occurs between the 2 section C strands (Fig. 12). The southern ≈4 km of section D strikes 344°, is associated with an east-side-up scarp (≈4 m high), and includes a 4-km-long parallel fault ~300 m to the west (Fig. 12). The SAF bends to the right (from 345° to 350°) and the resulting transtension has produced an elongate (1000 × 200 m) sag depression that is 35 m below the surrounding seafloor (Fig. 12). To the north, section D of the SAF bends back to the left and trends 345° for 4 km, at which point it intersects and extends through the head of the Noyo submarine canyon for ~4.5 km (Fig. 12). Farther north of Noyo Canyon, the SAF in the northernmost 3.7 km of section D exits Noyo Canyon and bends 9° to the right (new trend of 356°).

Faulting east of the main trace of the SAF includes (1) an ~175-km-long zone of northwest-trending (334°) discontinuous faults that obliquely converge on the SAF in southern section E, and (2) farther east, a series of more north-trending, steeply east-dipping structures (Figs. 12 and 13) interpreted as normal or oblique-slip faults that accommodate the extensional component of the transtensional fault system, similar to structures described by Parke et al. (1999) and Cunningham and Mann (2007). These faults show as much as 25 m of east-side-down vertical separation on the TKc-Q contact (Fig 13B).

East of the SAF, TKc bedrock is overlain by thin (0–20 m) H deposits near the shoreline and Q deposits farther offshore (Fig. 13). The upper TKc contact dips west and the overlying Q unit thickens to the west and includes multiple unconformities (Fig. 13A, B, C), providing a potential record of late Pleistocene sea-level changes. These Q sediments make up the southernmost part of an elongate sedimentary basin that lies east of most of section D, section E, and a small part of section F to the north. The Q stratigraphic section is notably incised by a significant, west-dipping (>8°) erosional unconformity interpreted as the eastern margin of a large emergent river valley connected with the Noyo submarine canyon (Fig. 13). This paleovalley is filled with aggrading marine sediments that are not well imaged on seismic profiles, possibly because of depositional geometries or gas charging. West of the SAF, thin (0–10 m) H deposits overlie westward-thickening Q deposits.

The head of the Noyo submarine canyon coincides with and is elongate along section D of the SAF (Fig. 14). This is inferred to result from SAF offset and/or fault parallel elongation of the Pleistocene Noyo River valley during sea-level lowstands. Paleo-river flow was deflected northward along the fault zone, a pattern similar to capture of terrestrial river systems elsewhere along the SAF (Wallace, 1968). The channel thalweg is inferred to be offset ~14 km from the submarine canyon head and the paleochannel connection with Noyo River. The numerous landslide headwall scarps imaged along the margins of the canyon head likely formed by ground failure during large SAF earthquakes (Fig. 14).

The SAF zone shows a consistent sense of east-side-up vertical motion throughout section D (Fig. 13). This sense of motion is counter to the imaging of basin sediments to the east that thicken west toward the fault zone, suggesting a longer-term history of east-side-down motion.

Magnetic anomalies in this section don’t reveal the trace of the SAF as clearly as in sections A, B, and the southern part of C (Fig. 2B). The section is
characterized by low magnetic anomalies throughout, with a slight gradient imaged east of the main trace of the SAF. Magnetic anomalies east of section D of the SAF continue to trend northwest.

Section E

Section E extends for 33.5 km from the northern flank of Noyo Canyon to the southern margin of the Tolo Bank (Fig. 12). The SAF zone in this section comprises one continuous, east-side-down, primary fault and several shorter, discontinuous, subparallel faults west of the main strand. From south to north, the strike of the fault changes from 356° (9.3 km) to 351° (7.1 km) to 353° (1.4 km) to 348° (3.3 km) to 353° (11 km). The overall trend of this section (~352°) is distinctly more northward than section D (~352°) to the south and section F (~341°) to the north. In section E and part of section D, the SAF is located as much as 14 km from the shoreline, significantly farther than the SAF location (3–7 km offshore) in sections A through C.

The SAF in section E and the northern part of section D form the western margin of an ~11-km-wide x ~37-km-long sedimentary basin referred to herein as the Noyo basin (Fig. 12). The basin is markedly asymmetric; the Q basin fill generally thickens by a factor of 10 or more from east (near the shoreline) to west (Fig. 15). This basin is cut by several north-northwest–trending, east-side-down, vertical faults, a sense of motion opposite to the asymmetric subsidence. These intrabasinal faults range in length from 1 to 17 km (Fig. 12) and clearly deform bedrock and Q units but do not obviously extend upward into the post-LGM (H) unit (Fig. 15).

We interpret the Noyo basin as a so-called lazy Z–shaped transtensional basin based on (1) the coincidence with the significant (~9°) releasing bend at Noyo Canyon and the restraining bend at the north end of section E (~8°), (2) the elongate, fault-bound basin shape, and (3) the asymmetry of basin fill. Lazy Z basins are common in strike-slip settings and have been documented and described in numerous fault zones (e.g., Mann, 2007, Table 2 therein). (For more extensive discussion of this basin and its depositional and tectonic history, see ANALYSIS AND DISCUSSION herein.)

Within the Noyo basin, seismic profiles image as much as 40 m of H deposits above the westward-thickening Q strata and underlying TkC bedrock (Figs. 15 and 16). The thickest H deposits are present near the coast, adjacent to Flat Rock Creek, Usal Creek, and Cottaneva Creek (Figs. 5 and 12). Seaward bulging of bathymetric contours adjacent to Flat Rock and Cottaneva Creek coincides with channels cut in the nearshore bedrock platform, suggesting that thicker H deposits represent prograding delta-mouth bars (Fig. 12).

The older underlying Q unit includes as many as 6 erosional surfaces that can be correlated across the basin and are inferred to coincide with Pleistocene sea-level fluctuations over the past 350–500 k.y. (numbered horizons on the profiles in Figs. 15 and 16). Correlating these erosional surfaces across profiles reveals a thinning of the Q unit from north to south, best indicated by changes in thickness between numbered horizons in Figures 15D and 15A. Basin downwarding adjacent to the main SAF strand is most obvious in Figures 16A–16C.
Figure 13. Combined U.S. Geological Survey and Active Tectonic and Seafloor Mapping Lab of Oregon State University seismic reflection profiles. SAF—San Andreas fault; Q—Quaternary deposits; H—latest Pleistocene to Holocene deposits; TKc—inferred Cretaceous to Paleogene–Neogene Coastal Range terrane; M—seafloor multiple (see Fig. 4). Normal faults may also have strike-slip component. (A) MS-83. (B) MS-92 and NSAF-148. (C) MS-94 and NSAF-149 (locations shown in Fig. 12).
Two vertically alternating types of stratigraphic unit are imaged within the Q unit (Fig. 15): (1) seaward-thickening units consisting of continuous, parallel, low- to moderate-amplitude, low- to moderate-frequency reflections that prograde and offlap to the west; and (2) units that thin to the west and internally consist of parallel, continuous, low- to moderate-amplitude, moderate- to high-frequency reflections. On seismic profiles, these latter units are similar to the post-LGM H unit. When paired, these two units form stratigraphic sequences, discussed in more detail in the following (see ANALYSIS AND DISCUSSION).

In the northern part of section E, the main SAF traverses the western Noyo basin and is between 500 and 2000 m east of the western basin margin (Figs. 16A–16C). The zone between the western basin margin and the main SAF to the east consists of warped and faulted Q sediments overlying an older, more deformed unit.

West of the SAF zone, seismic reflection data primarily image west-dipping Q sediments inferred to represent a westward-prograding shelf (Figs. 15 and 16). These inferred Q deposits are typically overlain by very thin (~0–2 m) post-LGM (unit H) deposits.

Aerial magnetic data reveal regionally low magnetic anomalies across the fault for the southern half of section E with little resolvable coincidence with the location of the SAF. There is a slight magnetic gradient of low (east) to high (west) magnetic intensity over the SAF in the northern part of section E. East of the fault zone, the northwest-trending anomalies characteristic of the region east of the SAF are not present (Fig. 2B).

Section F

Section F of the SAF is 16.5 km long and extends from the north end of section E to the SAF landfall at Point Delgada (Fig. 17A). The southernmost end of section F coincides with an ~8° left (transpressional) bend (from 353° to 345°) in the SAF, and forms the eastern margin of a bedrock uplift, the Tolo Bank, which covers an area of 74 km² and is imaged in the high-resolution bathymetry as a highly jointed and fractured rocky outcrop. McLaughlin et al. (1982) assigned outcrops in the intertidal zone at Point Delgada to the Point Delgada subterrane of the King Range terrane, and we infer that the Tolo Bank is the offshore continuation of these rocks.

The western edge of the Tolo Bank is a west-dipping erosional unconformity (Figs. 18C and 19).

The main SAF in section F forms a continuous strand in a zone as wide as 600 m that includes several subparallel faults that are mostly to the west of the main strand (Fig. 17A). The main strand is located ~4 km to the west of the onland Whale Gulch fault (Beutner et al., 1980; McLaughlin et al., 1994) (Fig. 17A), described as the contact between the King Range terrane on the west and the Coastal Belt terrane (TKc) to the east, and the easternmost fault in the local SAF system. None of the seismic profiles collected for this study revealed a shallow offshore extension of the Whale Gulch fault.

Figure 14. Bathymetric map of Noyo Canyon. The trace of the San Andreas fault is in red (location shown in Fig. 12). Black arrows indicate sidewall failures imaged along the canyon walls. EQ—earthquake.
Figure 15. Active Tectonic and Seafloor Mapping Lab of Oregon State University–U.S. Geological Survey combined seismic reflection profiles (locations shown in Fig. 12). SAF—San Andreas fault; Q—Quaternary deposits; H—latest Pleistocene to Holocene deposits; TKc—inferred Cretaceous to Paleogene–Neogene Coastal Range terrane; M—seafloor multiple (see Fig. 4); green lines show angular unconformities (some numbered and discussed in text); (A) NSAF-09 and NSAF-158. (B) NSAF-17 and NSAF-180. (C) NSAF-47 and NSAF-178. (D) NSAF-51 and NSAF-175.
Figure 16. Active Tectonic and Seafloor Mapping Lab of Oregon State University–U.S. Geological Survey seismic reflection profiles (locations shown in Fig. 12). SAF—San Andreas fault; Q—Quaternary deposits; H—latest Pleistocene to Holocene deposits; M—seafloor multiple (see Fig. 4); green lines show angular unconformities (some numbered and discussed in text); (A) NSAF-65. (B) NSAF-63. (C) NSAF-59.
The thickness of the uppermost Pleistocene to Holocene unit (H) in this section ranges from 0 to 40 m (Fig. 5). East of the SAF, H sediment thickens eastward, although reflections are locally obscured by gas (Figs. 18A, 18B). West of the SAF, the rocky Tolo Bank is largely sediment free; the west flank of the bank, however, is onlapped by a thick (as much as 40 m), west-prograding sediment wedge (Figs. 5, 18, and 19) of Q and H deposits locally incised by inferred lowstand paleochannels (Figs. 18A, 19B, and 19C).

Aerial and marine magnetic data in section F reveal a steep magnetic gradient coincident with the SAF, characterized by juxtaposition of low-amplitude magnetic anomalies to the east and high-amplitude, short-wavelength anomalies to the west (Figs. 2B and 17F). Marine magnetic data collected along this section of the fault similarly revealed a steep magnetic gradient from high (west) to low (east) across the SAF.

**Offshore King Range**

Geophysical data were also acquired for 40 km along the coast northwest of the SAF between Point Delgada and Punta Gorda to investigate potential faulting and deformation that could be associated with the northernmost SAF and the transition from the San Andreas transform margin to the Cascadia convergent margin (Fig. 1).

The two major bathymetric features west of the SAF in this region are the heads of Delgada and Spanish submarine canyons (Fig. 20A). Within state waters (shoreline to 3 nautical miles offshore), these submarine canyons have widths ranging to 1800 m and are as deep as 400 m. Canyon heads are close to shore, <250 m for Delgada Canyon, and ~3000 m for Spanish Canyon.
Figure 18. Active Tectonic and Seafloor Mapping Lab of Oregon State University–U.S. Geological Survey seismic reflection profiles (locations shown in Fig. 17A). SAF—San Andreas fault; Q—Quaternary deposits; H—latest Pleistocene to Holocene deposits; TKk—TKk-inferred Cretaceous to Paleogene–Neogene King Range terrane; M—seafloor multiple (see Fig. 4). (A) NSAF-57. (B) NSAF-40 and NSAF-40A. (C) NSAF-190 and NSAF-37.
Figure 19. Active Tectonic and Seafloor Mapping Lab of Oregon State University–U.S. Geological Survey seismic reflection profiles (locations shown in Fig. 17A). SAF—San Andreas fault; Q—Quaternary deposits; H—latest Pleistocene to Holocene deposits; TKk—TKk-inferred Cretaceous to Paleogene–Neogene King Range terrane; M—seafloor multiple (see Fig. 4). (A) NSAF-182 and NSAF-25. (B) NSAF-181 and NSAF-24. (C) NSAF-20A.
Figure 20. (A) Offshore King Range section of our survey extending between Point Delgada (PD) and Punta Gorda (PG). Red lines show faults mapped with seismic reflection profiles within the King Range section. Shaded relief shows onshore-offshore relief; gray-white boundary shows the limit of available multibeam bathymetry. Pale green areas are underlain by seafloor outcrops of Mesozoic and Cenozoic bedrock. Yellow lines show locations of seismic reflection profiles in Figures 21–23. Black lines indicate 20 m contour intervals. (B) Filtered marine magnetic anomaly grid (250 m) based on data collected during 2012 seismic cruise.
Between Point Delgada and Delgada Canyon, seismic reflection profiles reveal thick (as much as 45 m), unfaulted, post-LGM (H) sediments (Figs. 21A, 21B). The high-resolution seismic reflection profiles we collected lack the depth penetration needed to image deep structures, but the younger H strata are clearly not offset by faults. Most of the sediment imaged in these profiles must be sourced from Telegraph and Horse Mountain Creeks (Fig. 20A). Delgada Canyon is likely restricting sediment transport from sources farther to the northwest, and Point Delgada and the Tolo Bank act as barriers for sediment transport from the south.

Thick (40–60 m) deposits of latest Pleistocene to Holocene (H) sediments are also imaged farther northwest, between Delgada Canyon and Spanish Canyon (Fig. 22). These thick deposits occur offshore of the mouths of steep coastal drainages in the King Range and include prograding cliniforms. The Q unit below the post-LGM erosional surface thickens from north to south along these profiles and includes several low-angle unconformities similar to those described in the Noyo basin on the east flank of the SAF in section E. Both Q and H sediments overlie a prominent unconformity above west-dipping bedrock. There is a significant (~50 m high) basement step imaged in Figures 22B and 22C that is onlapped by Quaternary (Q) deposits. It is significant that the Q and H deposits imaged in seismic profiles between Delgada Canyon and Spanish Canyon are not cut by faults.

Northwest of Spanish Canyon, seismic profiles image a west-northwest–trending fault zone (Figs. 23A, 23B) considered to be the Mattole Canyon fault. On seismic profiles, this fault aligns with a local ~5-m-high (northeast side down) scarp and warps and offsets shallow reflections (Fig. 23B).

**SAF Zone Summary**

The SAF zone is imaged from Point Arena to Point Delgada as a continuous, narrow (<1 km wide) fault zone. Sections A–D show the SAF undergoing a gentle releasing bend from Point Arena to Noyo Canyon, changing strike from 332° to 344° (a change of 12°) over ~65 km. Section C notably shows the SAF splitting into two active strands with uplift and deformation occurring between and adjacent to the two fault strands indicated by young fault scarps. At Noyo Canyon, the strike of the SAF abruptly bends 9° to the north, then trends between 352° and 356° for the ~32 km of section E. This transtensional bend and more northern trend coincides with the presence of an asymmetric lazy Z sedimentary basin (Noyo basin) east of the SAF. North of section E, the SAF passes through an ~9° transpressional left bend, which coincides with the seafloor bedrock uplift of the Tolo Bank. The SAF extends onshore at Point Delgada into the King Range. We did not find evidence for a strand of the SAF on the south flank of Cape Mendocino. The offshore Mattole Canyon fault zone intersects the coast ~30 km northwest of Point Delgada, and probably represents an important link between the SAF and the Mendocino transform fault (see following).

**ANALYSIS AND DISCUSSION**

**Role of SAF in Post-LGM Sediment Distribution and Thickness**

Sediment distribution and depositional patterns are generally controlled by a combination of eustatic sea-level change, tectonic forces, climatic forces on erosion, and sediment supply (Orange, 1999). During the present and previous sea-level highstands, sediment typically is trapped in nearshore and shelf environments, although progradation into deeper water can occur when rates of sediment supply are high. Sediment supply to the study area is provided by ~50 coastal watersheds traversing forested terrain (Fig. 5).
In section A, the thickest post-LGM (H) sediment deposits are in nearshore bars. Deposits as much as 15 m thick are also present west of the SAF, reflecting the proximity of the SAF to onland sediment sources and the general lack of relief in the fault zone. Sea-level rise provides accommodation space and the SAF is an insignificant control on sediment distribution and thickness.

In sections B and C, the thickest H deposits are similarly trapped in nearshore bars and there is little sediment west of the SAF, probably because of slightly greater distance from sediment sources and because uplift across the SAF may be blocking sediment from reaching deeper water (Fig. 5). In section D, the thickest H deposits are also present in nearshore bars and there is little sediment west of the SAF (Fig. 5). With progressive post-LGM sea-level rise and associated shelf widening, Noyo Canyon was progressively cut off from terrestrial sediment supply.

The thickest H sediment in section E is also present in nearshore bars adjacent to coastal watersheds (Usal Creek and Jackass Creek); these bars increase in thickness and width from south to north along the coast and in the north are bounded by the SAF. It is significant that the rapidly subsiding Noyo basin includes only a thin H interval.

The SAF has greatly influenced sediment deposition in section F through the transpressive uplift of the Tolo Bank. This uplift restricts longshore sediment transport to the southeast, resulting in a substantial sediment wedge on the western flank of the Tolo Bank (Fig. 19).

West of the Tolo Bank on the south flank of Cape Mendocino, mean sediment thickness is ~25 m (within state waters, excluding the Tolo Bank and submarine canyons) compared to a mean sediment thickness of 10 m between Point Arena and Point Delgada. We attribute this thickness contrast to increases in sediment supply associated with much higher coastal uplift rates along the adjacent coast. Uplift rates in the King Range are >4 mm/yr, whereas rates near Fort Bragg are <1 mm/yr (Merritts and Vincent, 1989; Merritts and Bull, 1989; Snyder et al., 2000). The higher rates in the King Range result from transpression as the Pacific plate edge interacts with the North American and Gorda plates (Mendocino Triple Junction) along the SAF and King Range thrust (Dickinson and Snyder, 1979).

In summary, the thickest post-LGM sediment is found in prograding nearshore bars and the most important controls on post-LGM sediment distribution and thickness are sea-level rise (to create accommodation space) and sediment supply. Sediment supply is significantly greater in areas of higher coastal uplift rates. Transtensional subsidence along the SAF is not a significant control on post-LGM sedimentation.

**Regional Vertical Deformation and SAF Trend**

The trend of the SAF offshore in northern California ranges between 324° and 354°, which is transtensionally oblique to Pacific–North American plate motions (DeMets and Dixon, 1999; Spotila et al., 2007). This transtensional...
obliquity coincides with lower (offshore) topography. It is notable that the SAF is farthest from shore and in deepest water in section E where the fault has its most northward trend (Fig. 2). The relief and low elevation of this transtensional regime seems contrary to the observation of coastal uplift along the coast between Point Arena and Point Delgada indicated by emergent marine terraces (Merritts and Bull, 1989). This discrepancy suggests that the regional trend of the SAF has the most influence on near-field topography and that this influence attenuates with distance from the fault so that along the coast it is overwhelmed by the different processes that are driving coastal uplift. Dickinson and Snyder (1979) and Furlong and Schwartz (2004) suggested that passage of the MTJ left a slab window in its wake through which mantle upwelling is occurring; such upwelling could account for the regional onshore uplift east of the SAF.

**Paired Fault Bends, Slip Transfer, and Fault Straightening**

While the overall trend of the SAF is transtensional, our high-resolution mapping indicates that the SAF is similar to other strike-slip fault zones in that small-scale transpressional and transtensional bends are associated with near-fault bedrock uplifts and seafloor depressions (Mann, 2007; Johnson and Watt, 2012). One important example of this near-fault deformation occurs within the paired fault bend of section C (Figs. 10 and 11). The SAF splits at the south end of section C into 2 strands ~700–1000 m apart. Each fault strand is partly defined by a sharp, steep fault scarp that is inferred to be recently active because it offsets and thus postdates the post-LGM transgressive surface of erosion. There is a releasing (right) bend at the southern end of this 10-km-long zone and a restraining (left) bend at the northern end. We postu-
late that this section of the SAF is evolving from this paired fault bend to a more continuous, straighter, orientation via slip transfer from the eastern SAF strand (unfavorable orientation) to the western strand (straighter and more favorable).

Our model for the evolution of this section of the SAF is illustrated in Figure 24, showing a series of slip transfers and progressive development of the western strand as the fault straightens. This reorganization occurs along a set of transfer structures (thrust faults and normal faults) between the two master fault strands. The transpressional left bend to the north is migrating south, while the transtensional right fault bend to the south is migrating north. When the SAF assumes its new straighter orientation, a slice of the Pacific plate will have been transferred to the North American plate. We lack age data necessary to document the duration of this process; therefore, Figure 24 is not a palinospastic reconstruction but rather a conceptual hypothesis for how a step-over in a fault zone can reorganize and evolve into a straighter fault zone.

Given its map pattern (Figs. 6 and 11), the zone between the two subparallel fault strands can be considered a complex flower structure, a feature characterized by an array of upward-diverging fault splays within a strike-slip zone (Harding, 1985; Biddle and Christie-Blick, 1985). This zone, however, notably differs from both positive and negative flower structures by enclosing both uplifts and depressions.

**Noyo Basin**

Sedimentary basins forming along strike-slip systems commonly form in releasing step-overs between subparallel fault strands or along transtensional bends (Mann, 2007). The Noyo basin is asymmetric (deeper to west along the SAF) and is bounded by the ~9° extensional (right) bend and compressional (left) bend at the ends of SAF section E, a geometry similar to lazy Z sedimen-

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**Figure 24.** Model for straightening of the San Andreas fault (SAF) across a paired fault bend with a series of releasing and restraining step-overs. These fault step-overs lead to a straighter and more favorable orientation of the SAF while also creating areas of uplift and subsidence (see text for discussion). Maps move in time steps from right (time unknown but inferred to be early or mid-Pleistocene) to present (t4).
tary basins described in other strike-slip zones (e.g., Mann, 2007). Such lazy Z basins occur along releasing fault bends and are asymmetric, bounded on one margin by a steep strike-slip fault and by a tilted basement ramp (no bounding strike-slip fault) on the opposing basin margin.

Multichannel seismic reflection profile WNC82–178 (Triezenberg et al., 2016) shows the larger scale geometry and structure of the Noyo basin (Fig. 25C), and reveals that the marked asymmetry of the basin continues at depth. Both deep and shallow high-resolution profiles reveal a series of overlapping, SAF-parallel, normal (possibly oblique slip) faults that cut through the basin (Figs. 13, 15, 16, and 25D). We speculate that these SAF-parallel faults could be caused by gravitational collapse forming fault tilt blocks as the crust extends into the void space created by the SAF transtensional geometry (Fig. 25E).

Horizon mapping in the shallow high-resolution profiles indicates that the greatest amount of recent subsidence is occurring at the north end of section E, near the fault bend that separates sections E and F (Fig. 5). This characteristic, coupled with the asymmetry, makes the Noyo basin comparable to other well-described and modeled transform basins on the North Anatolian fault and elsewhere (Crowell and Link, 1982; Seeber et al., 2006, 2010; Sorichetta et al., 2010; Johnson and Watt, 2012). For the development of the Noyo basin, we infer that the north and south SAF bends that constrain the basin length are attached to the Pacific plate and North American plate, respectively. Crust in the North American footwall plate subsidizes as it moves laterally past the northern bend, and this area is the largest basin depocenter. With continuing SAF lateral slip, the distance between the two fault bends grows and the basin lengthens, while the most rapid subsidence continues to be adjacent to the northern fault bend (Fig. 25A).

Figure 25. (A) Plan view look of the Noyo basin formation in time stamps (t0, t1, t2, t3). An initial bend fixed to the Pacific plate causes a bend to form and migrate south on the North American (NA) plate, illustrating the void created by this geometry over time. (B) Present-day geometry of the San Andreas fault (SAF) system and faulting associated with the Noyo basin. (C) Uninterpreted, deeper, industry multichannel seismic reflection profile NSAF-175 (U.S. Geological Survey, 2016; location in B) overlain by NSAF-175 (Fig. 15D). V.E.—vertical exaggeration. (D) Interpreted multichannel seismic reflection profile WNC82–178. (E) Cross-sectional view of the basin with interpretations for orientation and sense of vertical motion on faults within the Noyo basin.
Seismic Stratigraphy

Seismic stratigraphy is a powerful tool in analyzing and interpreting seismic reflection profiles and basin history. This is especially true in shelf and marginal marine settings, where depositional environments commonly modulate in response to sea-level fluctuations and sediment supply (Vail et al., 1977; Mitchum et al., 1977). Here we apply seismic stratigraphic concepts to develop a conceptual model for the depositional and tectonic history of the Noyo basin.

Quaternary glaciations and deglaciations have forced repetitive fluctuations in global sea level; the sea-level curve over the past 450 k.y. is notably asymmetric, characterized by long, slow regressions followed by rapid transgressions (Wright, 2000; Waelbroeck et al., 2002; Peltier, 2005; Stanford et al., 2011). Figure 26 illustrates our interpretation of basin evolution, in which depositional geometries and rates are controlled by sea-level fluctuations and asymmetric subsidence. First, during the initial falling sea level of our model, we show onlapping, west-prograding, nearshore sediments deposited over an inclined bedrock surface (Fig. 26A). Next, as sea-level rises and the shoreline moves eastward, an inclined ravinement surface (i.e., transgressive surface of erosion) caused by wave erosion truncates the underlying regressive deposits (Fig. 26B), completing deposition during one full sea-level cycle.

Noyo basin fill is dominated by the two depositional geometries described here. Regressive and lowstand deposits (R) are the largest volumetric unit within the basin, in large part due to the significantly greater time occupied by regressions (Fig. 27C). The R units thicken seaward (where subsidence rates are highest) and internally consist of continuous parallel reflections.

The second depositional geometry represents sediments deposited during transgressions and highstands (grouped into HST), analogous to the post-LGM H unit mapped on seismic reflection profiles (e.g., Fig. 7). These HST seismic stratigraphic units also thin to the west, and are notably thinner than R units because the transgressions and highstands occur over significantly less time than the late Quaternary regressions.

Because sea-level fluctuations over the past ~450 k.y. have been relatively cyclic (Fig. 27C) and the Noyo basin is actively subsiding, the sea-level controlled pattern of deposition and modification of primary depositional surfaces should be repetitive. Seismic units designated R1, R2, R3, and R4 are therefore inferred to correlate with the four most significant recent sea-level regressions and lowstands (Fig. 27). The similarity between these units indicates similar rates and magnitudes of sea-level fall, consistent with the sea-level curve in Figure 27C. This correlation results in relatively high maximum sediment accumulation rates of ~1 mm/yr in the deepest parts of the Noyo basin.

Alternatively, the sequences in the Noyo basin seismic profiles could represent the high-frequency sea-level changes that occurred between marine isotope stages (MIS) 2 and 5e (Fig. 27C). The regression following the Stage 5e highstand (~120 k.y. ago) was punctuated by three (MIS 5c, 5a, and 3) minor (~20–35 m) transgressions (Fig. 27C). We think it highly unlikely that such minor fluctuations could result in the development of >100-m-thick sequences and note that this would result in extremely high (and probably unrealistic)
sediment accumulation rates of ~3 mm/yr in the deeper parts of the basin. It is also important to note that the depths at which R units pinch out to HST units are roughly the same for R1–R4 (Fig. 27B). This suggests that the sea level was roughly the same for each maximum sea-level fall when the deposition of each R unit ceased.

**Basin Tilting**

We interpret the seismic units designated R1, R2, R3, and R4 in Figure 26 as deposits of the previous four major sea-level regressions (Fig. 27B), and we use this chronologic framework to estimate the asymmetric subsidence or tilt rate of the basin (Fig. 27D). We infer each R unit to have been deposited during the ~100 k.y. regression between maximum highstands. By measuring the angles of the various R unconformities and assigning each of them the age of the corresponding maximum sea-level fall and/or onset of transgression, we estimate a tilt rate of ~0.6°/100 k.y. for this section of the basin (Fig. 27D). For comparison, similarly determined tilt rates based on turbidites in the Karamursel Basin on the North Anatolian fault are 0.3°/100 k.y. (Sorichetta et al., 2010).

**Lateral Fault Slip Rates Estimated Using Basin Geometry and Age Control**

The basin geometry and sequence stratigraphy for the Noyo basin outlined here provide a framework for estimating rates of SAF lateral slip. We infer that the northern bend is fixed to the Pacific plate, suggesting that a particular location on
the North American plate subsides rapidly as it passes by the fixed bend, then subsidence slows as that location is translated away from the bend (Fig. 25).

Using seismic data interpretations and correlations of unconformity surfaces, we constructed isosurface maps of each R surface and the LGM surface (Fig. 28; methods described in Beeson, 2016). Depth points taken from generated grids were plotted along profile A-A’ (Fig. 28) and show the southward migration of the deepest part of the Noyo basin moving away from the site of the most rapid subsidence adjacent to the northern fault bend. We can then use the migrating depocenter locations and the age constraints on sequences outlined here to estimate a lateral slip rate. Uncertainties in the slip rate derive from a window interpretation of the broad troughs that characterize each depocenter.

Based on R location and depth of R4, the slip rate needed to explain the lateral separation of depocenters and stratigraphic geometry imaged in Figure 28, A-A’ is 10.2–19.1 mm/yr or 3.6–6.7 km in ~350 k.y. (Fig. 29). Assigning a window interpretation to the broad troughs outlining depocenter location ensures capturing the offset range. The median slip rate, ~15 mm/yr, is our preferred slip rate for this section of the SAF.

This range of slip rates is consistent with both decadal-scale geodesy and thousand-year time scales from geomorphic evidence near Point Delgada (Prentice et al., 1999; Williams et al., 2006). Geodetic modeling suggests a regional rate of 17 mm/yr on the SAF in northern California (Williams et al., 2006). Offset streams from Point Delgada suggest minimum late Holocene...
rates of 14 mm/yr (Prentice et al., 1999). While both geodetic and Holocene rates represent shorter time ranges, and thus may not represent a longer Quaternary SAF slip rate, our results suggest that longer term and Holocene rates may be similar.

We interpret the two fault bends that bound the sedimentary basin to be fixed to their respective fault blocks, a relationship that allows the distance between the bends to be used for estimating the age of the basin. Given a median slip rate of ~15 mm/yr and the 37 km distance between fault bends, the estimated basin age is ~2.4 m.y.

**Plate Boundary Tectonics**

Our data and mapping show that the shallow SAF intersects the shoreline at Point Delgada (consistent with Brown, 1995; Prentice et al., 1999). On land, we think it is most likely that the SAF merges with the King Range thrust and associated faults so that the King Range is part of the Pacific plate, consistent with tomographic data and interpretations in Henstock and Levander (2003) and Evangelidis (2004) (Fig. 30). A branch of the King Range thrust (McLaughlin et al., 1994) appears to merge westward with the offshore Mattole Can-
yon fault (Figs. 20 and 23), which merges farther west and offshore with the Mendocino transform fault.

The above SAF interpretation differs from some previous work (e.g., Curray and Nason, 1967; McLaughlin et al., 1994) that suggested that the SAF bends westward into the offshore only a few kilometers northwest of Point Delgada (instead of extending north into the King Range) and extends for ~40 km throughout the offshore area of the south flank of Cape Mendocino. We found no evidence of this postulated offshore SAF extension in our shallow geophysical data set. It is conceivable that such an offshore fault could be located in the narrow (~400 m wide) offshore zone between our data and the shoreline; however, this would require a sinuous, narrow fault zone and trace that we consider unlikely for the plate boundary SAF. There is significant relief on the top of Mesozoic basement rocks across this narrow coastal reach, between onland outcrops and the offshore subsurface imaged on seismic reflection profiles (Figs. 21 and 22). The basement step imaged in Figures 22B and 22C could be related to an inactive or basement fault. Therefore, it seems possible that an older SAF is present in this area below the level of our shallow data. If present, this older and deeper SAF does not correspond with either a magnetic (Fig. 2B) or tomographic anomaly (Henstock and Levander, 2003).

CONCLUSIONS

High-resolution seismic reflection and multibeam bathymetry data illuminate the 120-km-long offshore portion of the SAF between Point Arena and Point Delgada, revealing structural style, fault continuity, fault trend and bends, multiple parallel fault strands, transtensional basin development, and transpressional uplifts. Observations and interpretations lead to the following conclusions.

1. This portion of the SAF can be divided into six discrete sections based on fault trend, fault geometry, deformation patterns, and shallow stratigraphy.
The SAF has a continuous main strand that generally bounds or occurs within a narrow (width <1 km) fault zone. 2. The southern offshore region of the SAF (sections A–C, strike of ~340°) includes a 10-km-long paired fault bend characterized by 2 active parallel fault strands. Zones of uplift and subsidence occur between these paired faults with fresh fault scarps imaged on both strands. Long-term straightening of the fault trace in this zone is likely leading to transfer of a slice of the Pacific plate to the North American plate. 3. The northern offshore region of the SAF (sections D–F) includes significant transtensional and transpressional fault bends. This region includes (1) the Noyo basin, a rapidly subsiding, asymmetric, 37 km x 11 km lazy Z basin, formed on the east flank of a SAF transtensional east of the SAF; and (2) the Tolo Bank, a 74 km² transpressional uplift. This uplift significantly restricts coastal sediment transport. 4. Seismic stratigraphic analysis of translating growth strata in the Noyo basin suggests that SAF lateral slip rates are between 10.2 and 19.1 mm/yr, and basin tilt rates are ~0.6°/100 k.y. 5. Sea-level rise creates nearshore accommodation space and is the most important control on post-LGM sediment thickness and distribution. The SAF regime in this region is, for the most part, too transtensional to generate rapid coastal uplift and associated high sediment supply. The SAF is also too far offshore for coastal processes to transport significant post-LGM sediment to intrafautz zone basins. 6. Regional coastal uplift between Point Arena and Point Delgada, represented by onland marine terraces, is contrary to the overall transtensional regime of the offshore SAF. Other processes (not directly associated with the SAF) must be responsible for this uplift. 7. The Quaternary active trace of the SAF extends from offshore to onshore at Point Delgada as reported by Brown (1995) and Prentice et al. (1999), and may extend to the King Range thrust, which in turn extends offshore and merges with Mattole Canyon fault. This transition results in high uplift rates in the King Range and increased sediment supply. We consider the possibility of a direct offshore connection between the modern SAF and the Mendocino transform fault as unlikely.

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REFERENCES CITED
