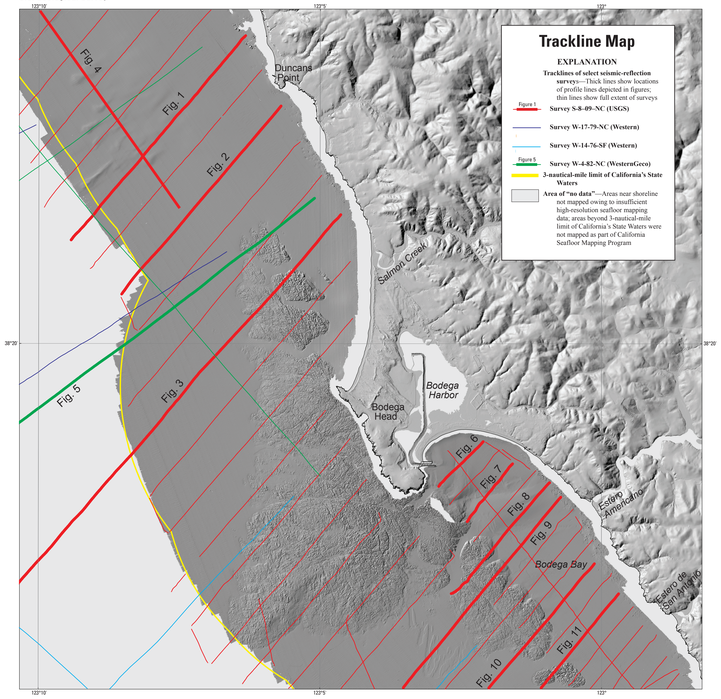
U.S. Department of the Interior
U.S. Geological Survey

Open-File Report 2015–1140
Sheet 8 of 10
Pamphlet accompanies map



Onshore elevation data from California Coastal Conservancy (available at http://www.csc.noaa.gov/digitalcoast/data/coastallidar/) and from U.S. Geological Survey's National Elevation Dataset (available at http://ned.usgs.gov/). Offshore shaded-relief bathymetry from map on sheet 2, this report.
California State Waters limit from NOAA Office of Coast Survey
Universal Transverse Mercator projection, Zone 10N

NOT INTENDED FOR NAVIGATIONAL USE

SCALE 1:50 000
2 0 2 MILES
7000 3500 0 7000 FEET
1 0 1 KILOMETER
ONE MILE = 0.869 NAUTICAL MILES

APPROXIMATE MEAN DECLINATION, 2015

GIS database and digital cartography by Peter Dartnell and Stephen R. Hartwell
Manuscript approved for publication July 21, 2015

MAP LOCATION

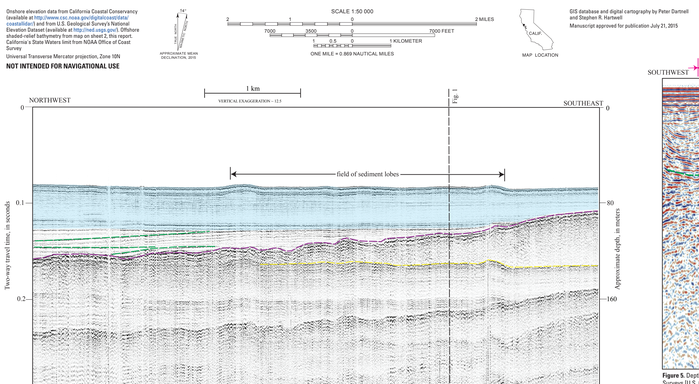


Figure 4. USGS high-resolution minisparker seismic-reflection profile PR–147C (collected in 2009 on cruise S–8–09–NC), which crosses shelf west of Duncans Point; see trackline map for location. Profile crosses field of sediment lobes on shelf (see sheets 1, 2, 4, 18), and gently dipping strata beneath continental shelf sediments. Blue shading shows inferred uppermost Pleistocene and Holocene strata, deposited since last sea-level lowstand about 21,000 years ago. Dashed purple line shows erosional unconformity above bedrock. Dashed green lines show flat to gently dipping reflections in inferred Pleistocene strata. Dashed yellow line is seafloor multiple (echo of seafloor reflector).

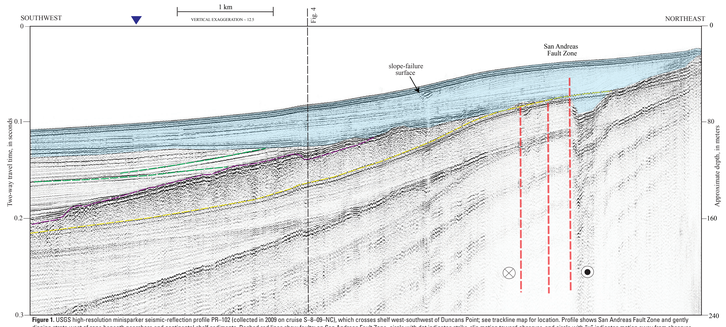


Figure 1. USGS high-resolution minisparker seismic-reflection profile PR–102 (collected in 2009 on cruise S–8–09–NC), which crosses shelf west-southwest of Duncans Point; see trackline map for location. Profile shows San Andreas Fault Zone and gently dipping strata west of zone beneath nearshore and continental shelf sediments. Dashed red lines show faults; on San Andreas Fault Zone, circle with dot indicates strike-slip motion toward observer, and circle with "x" indicates motion away from observer. Blue shading shows inferred uppermost Pleistocene and Holocene strata, deposited since last sea-level lowstand about 21,000 years ago. Dashed purple line shows erosional unconformity above reflection-free bedrock (probably the granitic rocks of Bodega Head). Dashed green lines highlight continuous reflections that illustrate gentle dip and low-angle bedding of strata. Dashed yellow line is seafloor multiple (echo of seafloor reflector). Purple triangle shows location of California's State Waters limit (yellow line on trackline map).

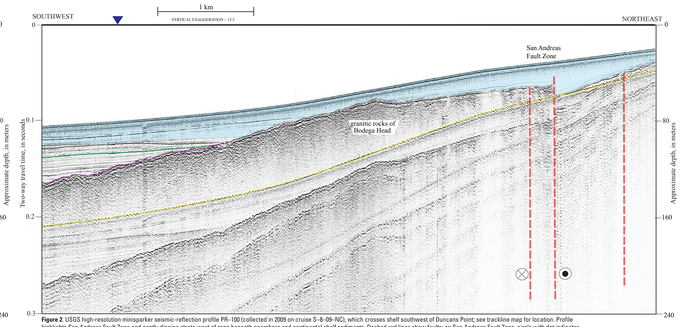


Figure 2. USGS high-resolution minisparker seismic-reflection profile PR–100 (collected in 2009 on cruise S–8–09–NC), which crosses shelf southwest of Duncans Point; see trackline map for location. Profile highlights San Andreas Fault Zone and gently dipping strata west of zone beneath nearshore and continental shelf sediments. Dashed red lines show faults; on San Andreas Fault Zone, circle with dot indicates strike-slip motion toward observer, and circle with "x" indicates motion away from observer. Blue shading shows inferred uppermost Pleistocene and Holocene strata, deposited since last sea-level lowstand about 21,000 years ago. Dashed purple line shows erosional unconformity above reflection-free bedrock (probably the granitic rocks of Bodega Head). Dashed green lines highlight continuous reflections that illustrate gentle dip and low-angle bedding of strata. Dashed yellow line is seafloor multiple (echo of seafloor reflector). Purple triangle shows location of California's State Waters limit (yellow line on trackline map).

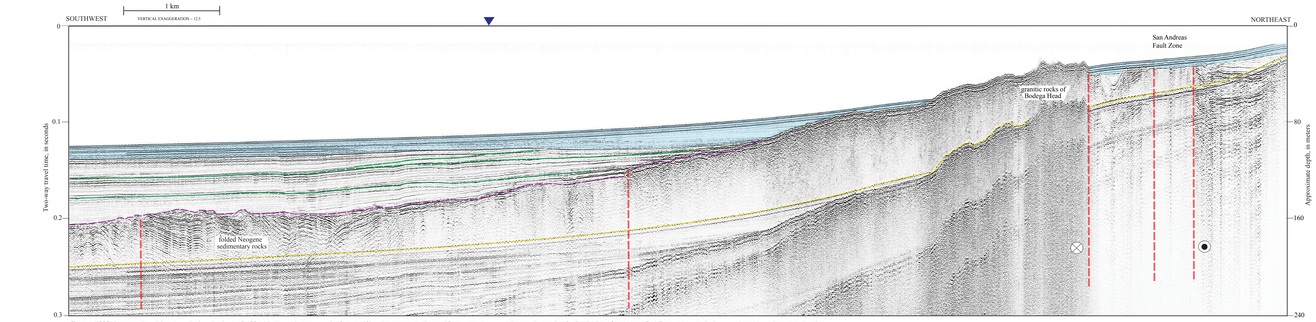


Figure 3. USGS high-resolution minisparker seismic-reflection profile PR–95 (collected in 2009 on cruise S–8–09–NC), which crosses shelf west of Bodega Head; see trackline map for location. Profile highlights San Andreas Fault Zone and gently dipping strata beneath continental shelf sediment. Dashed red lines show faults; on San Andreas Fault Zone, circle with dot indicates strike-slip motion toward observer, and circle with "x" indicates motion away from observer. Blue shading shows inferred uppermost Pleistocene and Holocene strata, deposited since last sea-level lowstand about 21,000 years ago. Dashed purple line shows erosional unconformity above reflection-free bedrock (the granitic rocks of Bodega Head) on west flank of San Andreas Fault (see sheet 10) and also above folded Neogene sedimentary rocks farther offshore in southwestern part (to left) of profile. Dashed green lines show continuous, flat to gently dipping reflections in inferred Pleistocene strata. Dashed yellow line is seafloor multiple (echo of seafloor reflector). Purple triangle shows location of California's State Waters limit (yellow line on trackline map).

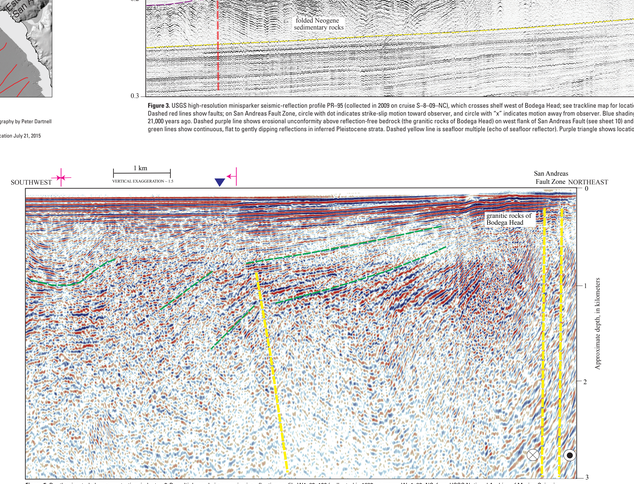


Figure 5. Depth-migrated, deep-penetration, industry, 2-D, multichannel air-gun seismic-reflection profile W4–82–120 (collected in 1982 on survey W–4–82–NC, from USGS National Archive of Marine Seismic Surveys [U.S. Geological Survey, 2009]), which crosses shelf west-northwest of Bodega Head; see trackline map for location. Note that vertical scale and exaggeration are significantly different than that of high-resolution seismic-reflection profiles (figs. 1, 2, 3, 4, 6, 7, 8, 9, 10, 11). Dashed yellow lines show faults (including San Andreas Fault Zone at northeast end [to right] of profile); on San Andreas Fault Zone, circle with dot indicates strike-slip motion toward observer, and circle with "x" indicates motion away from observer. Magenta symbols show syncline axis (converging arrows) and sharp flexure (single arrow shows direction of increasing dip). Dashed green lines highlight reflections that show deeper structure beneath continental shelf, revealing increasingly steeper dips in proximity to San Andreas Fault. Shallow high-amplitude reflections at northeast end of profile are reverberations of seafloor reflections generated by the (massive) granitic rocks of Bodega Head (see sheet 10). Purple triangle shows location of California's State Waters limit (yellow line on trackline map).

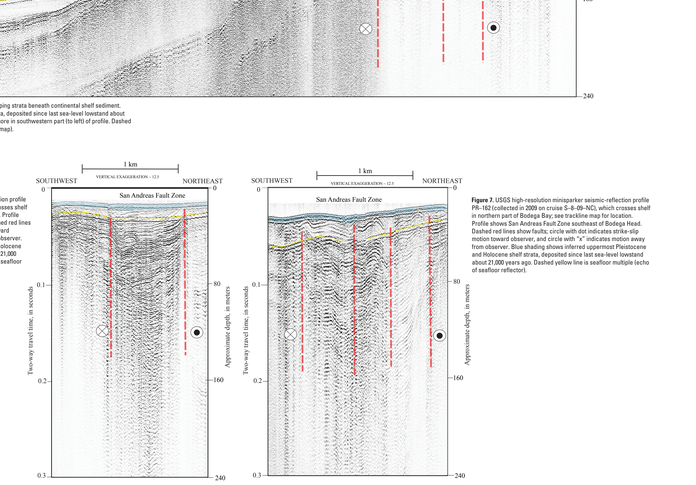


Figure 6. USGS high-resolution minisparker seismic-reflection profile PR–160 (collected in 2009 on cruise S–8–09–NC), which crosses shelf at north end of Bodega Bay; see trackline map for location. Profile shows San Andreas Fault Zone east of Bodega Head. Dashed red lines show faults; circle with dot indicates strike-slip motion toward observer, and circle with "x" indicates motion away from observer. Blue shading shows inferred uppermost Pleistocene and Holocene shelf strata, deposited since last sea-level lowstand about 21,000 years ago. Dashed yellow line is seafloor multiple (echo of seafloor reflector).

Figure 7. USGS high-resolution minisparker seismic-reflection profile PR–162 (collected in 2009 on cruise S–8–09–NC), which crosses shelf in northern part of Bodega Bay; see trackline map for location. Profile shows San Andreas Fault Zone southeast of Bodega Head. Dashed red lines show faults; circle with dot indicates strike-slip motion toward observer, and circle with "x" indicates motion away from observer. Blue shading shows inferred uppermost Pleistocene and Holocene shelf strata, deposited since last sea-level lowstand about 21,000 years ago. Dashed yellow line is seafloor multiple (echo of seafloor reflector).

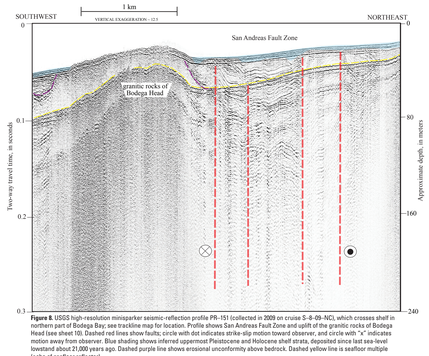


Figure 8. USGS high-resolution minisparker seismic-reflection profile PR–151 (collected in 2009 on cruise S–8–09–NC), which crosses shelf in northern part of Bodega Bay; see trackline map for location. Profile shows San Andreas Fault Zone and uplift of the granitic rocks of Bodega Head (see sheet 10). Dashed red lines show faults; circle with dot indicates strike-slip motion toward observer, and circle with "x" indicates motion away from observer. Blue shading shows inferred uppermost Pleistocene and Holocene shelf strata, deposited since last sea-level lowstand about 21,000 years ago. Dashed purple line shows erosional unconformity above bedrock. Dashed yellow line is seafloor multiple (echo of seafloor reflector).

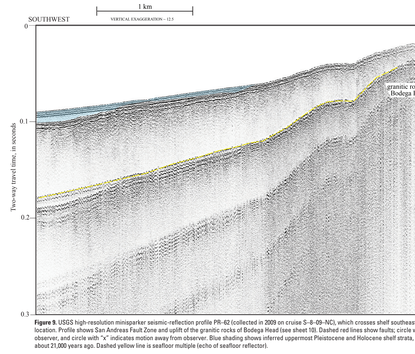


Figure 9. USGS high-resolution minisparker seismic-reflection profile PR–82 (collected in 2009 on cruise S–8–09–NC), which crosses shelf southeast of Bodega Head; see trackline map for location. Profile shows San Andreas Fault Zone and uplift of the granitic rocks of Bodega Head (see sheet 10). Dashed red lines show faults; circle with dot indicates strike-slip motion toward observer, and circle with "x" indicates motion away from observer. Blue shading shows inferred uppermost Pleistocene and Holocene shelf strata, deposited since last sea-level lowstand about 21,000 years ago. Dashed yellow line is seafloor multiple (echo of seafloor reflector).

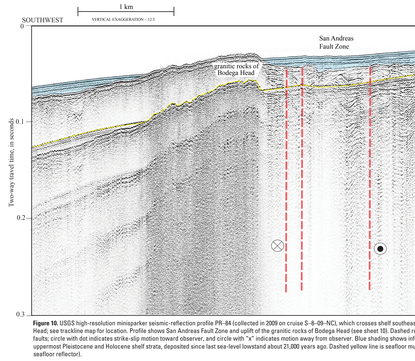


Figure 10. USGS high-resolution minisparker seismic-reflection profile PR–84 (collected in 2009 on cruise S–8–09–NC), which crosses shelf southeast of Bodega Head; see trackline map for location. Profile shows San Andreas Fault Zone and uplift of the granitic rocks of Bodega Head (see sheet 10). Dashed red lines show faults; circle with dot indicates strike-slip motion toward observer, and circle with "x" indicates motion away from observer. Blue shading shows inferred uppermost Pleistocene and Holocene shelf strata, deposited since last sea-level lowstand about 21,000 years ago. Dashed yellow line is seafloor multiple (echo of seafloor reflector).

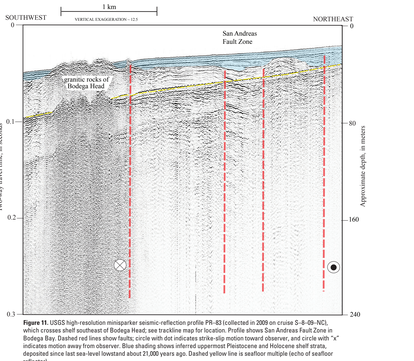
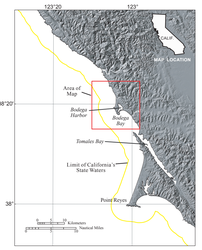


Figure 11. USGS high-resolution minisparker seismic-reflection profile PR–83 (collected in 2009 on cruise S–8–09–NC), which crosses shelf southeast of Bodega Head; see trackline map for location. Profile shows San Andreas Fault Zone in Bodega Bay. Dashed red lines show faults; circle with dot indicates strike-slip motion toward observer, and circle with "x" indicates motion away from observer. Blue shading shows inferred uppermost Pleistocene and Holocene shelf strata, deposited since last sea-level lowstand about 21,000 years ago. Dashed yellow line is seafloor multiple (echo of seafloor reflector).



DISCUSSION

This map sheet shows seismic-reflection profiles from surveys of the Offshore of Bodega Head map area, providing imagery of the subsurface geology. The seismic-reflection profiles provide the data for interpreting subbottom stratigraphy, sediment thickness, and geologic structure (see sheets 9, 10 of this report).

The Offshore of Bodega Head map area is cut by the northwest-striking San Andreas Fault (see sheet 10), the right-lateral transform boundary between the North American and Pacific plates. From southeast to northwest, this fault runs through Bodega Bay and Bodega Harbor, crosses the Bodega Head isthmus at the mouth of Salmon Creek, and extends offshore for about 20 km before passing onland just south of Fort Ross, about 10 km north of the map area.

Uplift of granitic bedrock on the southwest side of the San Andreas Fault has created an extensive, rugged and rocky seafloor, centered offshore of Bodega Head, that extends northwestward for about 15 km, from the west flank of Bodega Bay to the shelf offshore of the mouth of Salmon Creek. To the south and north, this rocky seafloor reaches water depths of about 40 and 50 m, respectively, where it is onlapped by young sediment; offshore of Bodega Head, the rocky seafloor reaches water depths of 80 m. Both the rocky seafloor and the smooth, sediment-covered parts of the shelf dip offshore about 0.7° to 0.8°.

Surficial and shallow sediments were deposited in the last about 21,000 years during the sea-level rise that followed the last major lowstand associated with the Last Glacial Maximum (LGM) (Lambeck and Chappell, 2001; Peltier and Fairbanks, 2006). Sea level was about 125 m lower during the LGM, at which time the Offshore of Bodega Head map area was emergent and the shoreline was about 20 km west of its present-day location. The post-LGM sea-level rise was rapid (about 9 to 11 m per thousand years) until about 7,000 years ago, when it slowed considerably to about 1 m per thousand years (Peltier and Fairbanks, 2006; Stanford and others, 2011). Sea-level rise led to a broadening of the continental shelf, the progressive eastward migration of the shoreline and wave-cut platform, and the associated transgressive erosion and deposition.

The sediments deposited during the post-LGM sea-level rise (the rapid transgression and highstand) are shaded blue in the high-resolution seismic-reflection profiles (figs. 1, 2, 3, 4, 6, 7, 8, 9, 10, 11), and their thickness is shown on sheet 9 (Maps B, D). The contact between underlying units and the post-LGM sediment is an abrupt transgressive surface of erosion, commonly marked by minor channeling and an upward change to lower amplitude, more diffuse reflections. These relatively low-amplitude reflections typically have low- to high-frequency, parallel to divergent geometries, and they are continuous to moderately continuous (terminology from Mitchum and others, 1977). The relatively low amplitude can be caused by extensive winnowing from wave energy and currents, resulting in uniform sediment grain size. These conditions tend to minimize the acoustic-impedance contrasts needed to produce seismic reflections that have higher amplitudes.

Sediment supply to the shelf north and west of Bodega Head is predominantly from coastal watersheds, which include the Russian River (4.5 km north of the map area) and Salmon Creek. Sediment supply to Bodega Bay and the shelf in the southern part of the map area is from small coastal watersheds and estuaries such as Estero Americano and Estero de San Antonio, and it also most likely is from sediment flux out of the mouth of Tomales Bay, 2 km south of the map area.

The smooth shelf in the northern part of the map area, in water depths of between 40 and 70 m, notably includes an about 3.5-km-wide field of elongate, shore-normal sediment lobes (fig. 4; see also, sheets 1, 2). Individual lobes within the field, which are as much as 1,000 m long and 150 m wide (see sheet 10), have as much as 4 m of relief above the surrounding smooth seafloor. Seismic-reflection profile PR–147C (fig. 4), which crosses the field of lobes, shows their minor seafloor relief (with vertical exaggeration = 12.5:1) but not their internal structure. Profile PR–102 (fig. 1), which extends southwestward across the shelf through the southeast end of the sediment lobe field, reveals a shallow zone of disturbance at the upper end of the sediment-lobe field that is interpreted as a slope-failure surface. This sediment-lobe field lies just 1 km west of the San Andreas Fault, and we infer that strong ground motions generated by large earthquakes on this fault have triggered such slope failures, mobilizing small flows of sediment that move down the gently sloping shelf and are deposited as lobes.

Strata that underlie the post-LGM transgressive surface of erosion and overlie bedrock (see for example, figs. 1 through 4) are represented by low- to high-amplitude, high-frequency, parallel to subparallel, continuous reflections. Reflections are flat to very gently folded and typically have dips of 0° to 2° (note that dips may appear steeper on the profiles because of the 12.5:1 vertical exaggeration). These strata are inferred to be Pleistocene in age (marine isotope stage 3 and older; Waelbroeck and others, 2002) because they underlie post-LGM strata; in addition, their horizons can be traced continuously, along with other U.S. Geological Survey (USGS) data (from cruise S–8–09–NC), to the Quaternary section penetrated by nearby Shell Oil Company offshore well P–053–1 (Heck and others, 1990), which lies 12 km southwest of the map area. Similar to the overlying post-LGM deposits, these inferred Pleistocene strata predominantly represent wave-reworked shelf sediments.

The San Andreas Fault juxtaposes rocks of the Jurassic and Cretaceous Franciscan Complex to the northeast with Cretaceous granitic rocks to the southwest. The granitic rocks are well exposed onland at Bodega Head (Blake and others, 2002), and the Franciscan Complex rocks are exposed on the east flank of Bodega Bay. Both basement units are reflection free on the seismic-reflection profiles. Nearby outcrops onshore (Clark and Brabb, 1997), as well as wells offshore, beyond the limit of California's State Waters (Heck and others, 1990), reveal that the granitic rocks are overlain to the west and north by folded Neogene sedimentary rocks, which are imaged as a zone of folded, high-frequency seismic reflections at the southwest end of profile PR–95 (fig. 3).

In the offshore part of the map area, the San Andreas Fault and other faults are identified on seismic-reflection profiles on the basis of the abrupt truncation or warping of reflections and (or) the juxtaposition of reflection panels that have differing seismic parameters, such as reflection presence, amplitude, frequency, geometry, continuity, and vertical sequence. Our mapping north of Bodega Head (figs. 1, 2, 3, 5) reveals a 500- to 1,100-m-wide zone characterized by two or three primary fault strands (see sheet 10). An elongate, narrow, asymmetric, intra-fault zone, post-LGM sedimentary basin is imaged on the two northernmost profiles (figs. 1, 2).

Mapping of the San Andreas Fault Zone to the south in Bodega Bay (sheet 10) reveals a more complex zone characterized by multiple fault strands. Bathymetric data (sheets 1, 2) and seismic-reflection profiles (figs. 8 through 11) show that Bodega Bay is flanked by rough seafloor, which consists of reflection-free rocks of the Franciscan Complex on the northeast and Cretaceous granitic rocks on the southwest. The smooth seafloor in the center of Bodega Bay is underlain by thin, post-LGM sediments, as well as an underlying unit of inferred Pleistocene age that is characterized by faulted and folded seismic reflections that reveal numerous channels and angular unconformities. The presence of this sedimentary unit between fault-bounded uplifts of much older rocks suggests that Bodega Bay originated as a pull-apart sedimentary basin (see, for example, Mann, 2007), and it probably formed by an eastward transfer of slip within the San Andreas Fault Zone. If so, the pervasive internal folding and faulting of the young basin fill suggests that basin subsidence has ended and the basin fill is now being deformed. The size of this intra–fault zone basin (about 9 × 2 km) is notably similar to that of the San Andreas graben (Cooper, 1973; Johnson and others, 2015), present within the San Andreas Fault Zone between Bolinas and San Francisco, about 55 km to the south. The San Andreas graben is at an earlier stage of development; subsidence is ongoing, and the basin fill is undeformed.

Except for the profile shown in figure 5, all profiles displayed on this map sheet were collected in 2009 on USGS cruise S–8–09–NC. The single-channel seismic-reflection data were acquired using the SIG 2Mille minisparker, which used a 500-J high-voltage electrical discharge fired 1 to 4 times per second, which, at normal survey speeds of 4 to 4.5 nautical miles per hour, gives a data trace every 0.5 to 2.0 meters. The data were digitally recorded in standard SEG-Y 32-bit floating-point format, using PC-based Triton Subbottom Logger (SBL) software that merges seismic-reflection data with differential GPS-navigation data. After the survey, a short-window (20 ms) automatic gain control algorithm was applied to the data, along with a 160- to 1,200-Hz bandpass filter and a heave correction that uses an automatic seafloor-detection window (averaged over 30 m of lateral distance covered). These data can resolve geologic features just a few meters thick, down to subbottom depths of about 400 m.

Figure 5 shows a deep-penetration, migrated, multichannel seismic-reflection profile collected in 1982 by WesternGeco on cruise W–4–82–NC. This profile and other similar data were collected in many areas offshore of California in the 1970s and 1980s when these areas were considered a frontier for oil and gas exploration. Much of these data have been publicly released and are now archived at the USGS National Archive of Marine Seismic Surveys (U.S. Geological Survey, 2009). These data were acquired using a large-volume air-gun source that has a frequency range of 3 to 40 Hz and recorded with a multichannel hydrophone streamer about 2 km long. Shot spacing was about 30 m. These data can resolve geologic features that are 20 to 30 m thick, down to subbottom depths of about 4 km.

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Seismic-Reflection Profiles, Offshore of Bodega Head Map Area, California

by
Samuel Y. Johnson, Ray W. Sliter, Stephen R. Hartwell, and John L. Chin

2015

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