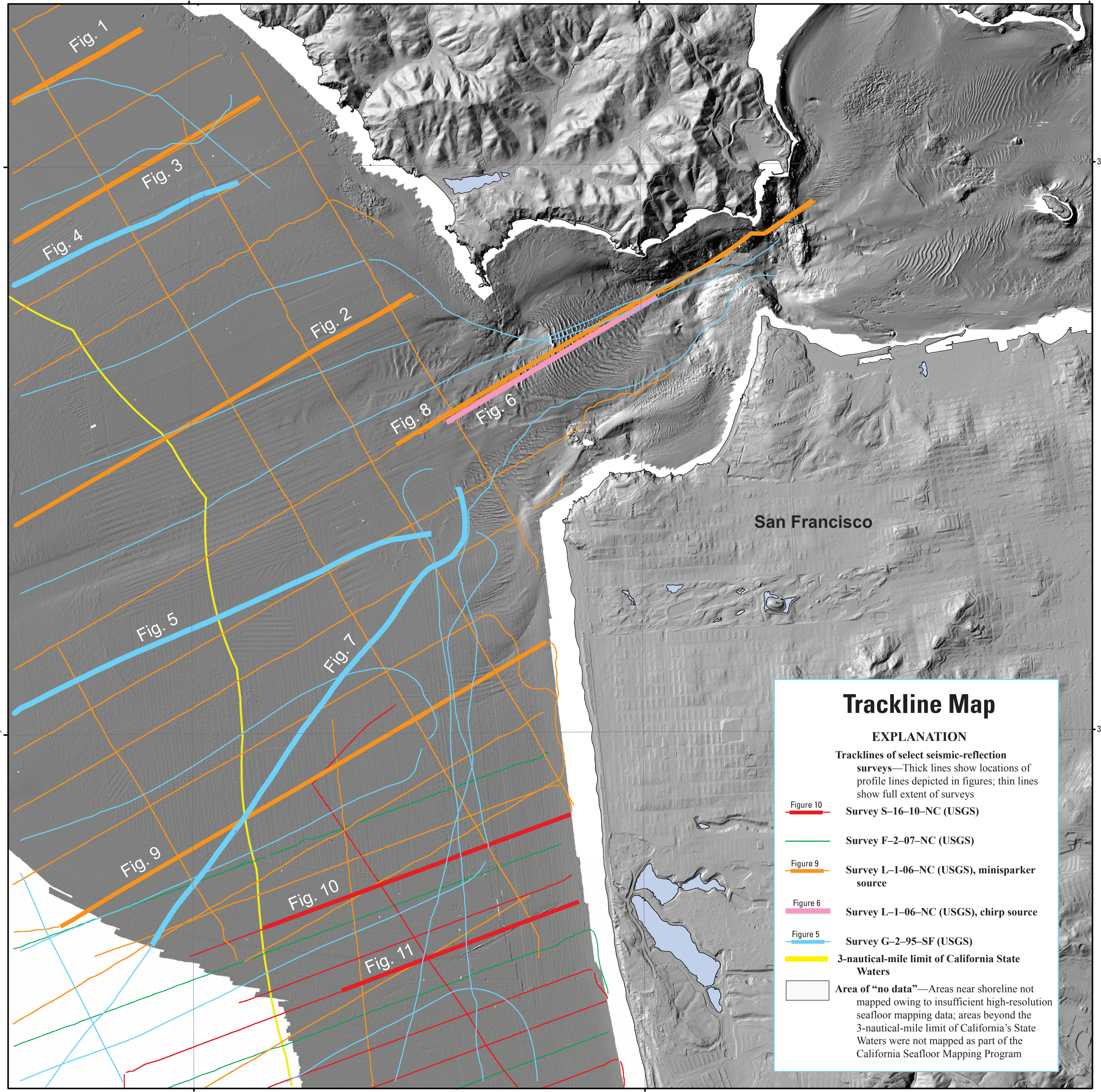
U.S. Department of the Interior
U.S. Geological Survey

Open-File Report 2015–1068
Sheet 8 of 10
Pamphlet accompanies map



Trackline Map

EXPLANATION

Tracklines of select seismic-reflection surveys—Thick lines show locations of profile lines depicted in figures; thin lines show full extent of surveys

- Figure 10 — **Survey S–16–10–NC (USGS)**
- **Survey F–2–07–NC (USGS)**
- Figure 9 — **Survey L–1–06–NC (USGS), minisparker source**
- Figure 6 — **Survey L–1–06–NC (USGS), chirp source**
- Figure 5 — **Survey G–2–95–SF (USGS)**
- **3-nautical-mile limit of California State Waters**
- **Area of "no data"**—Areas near shoreline not mapped owing to insufficient high-resolution seafloor mapping data; areas beyond the 3-nautical-mile limit of California's State Waters were not mapped as part of the California Seafloor Mapping Program

Onshore elevation data collected by Earth Eye in 2010 for San Francisco State University and the U.S. Geological Survey. 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

14°
TRUE NORTH
MAGNETIC NORTH
APPROXIMATE MEAN DECLINATION, 2015

SCALE 1:50 000
2 1 0 2 MILES
7000 3500 0 7000 FEET
1 0.5 0 1 KILOMETER
BATHYMETRIC CONTOUR INTERVAL 10 METERS
ONE MILE = 0.869 NAUTICAL MILES

CALIF.
MAP LOCATION

GIS database and digital cartography by Eleyne L. Phillips and Florence L. Wong
Manuscript approved for publication April 7, 2015

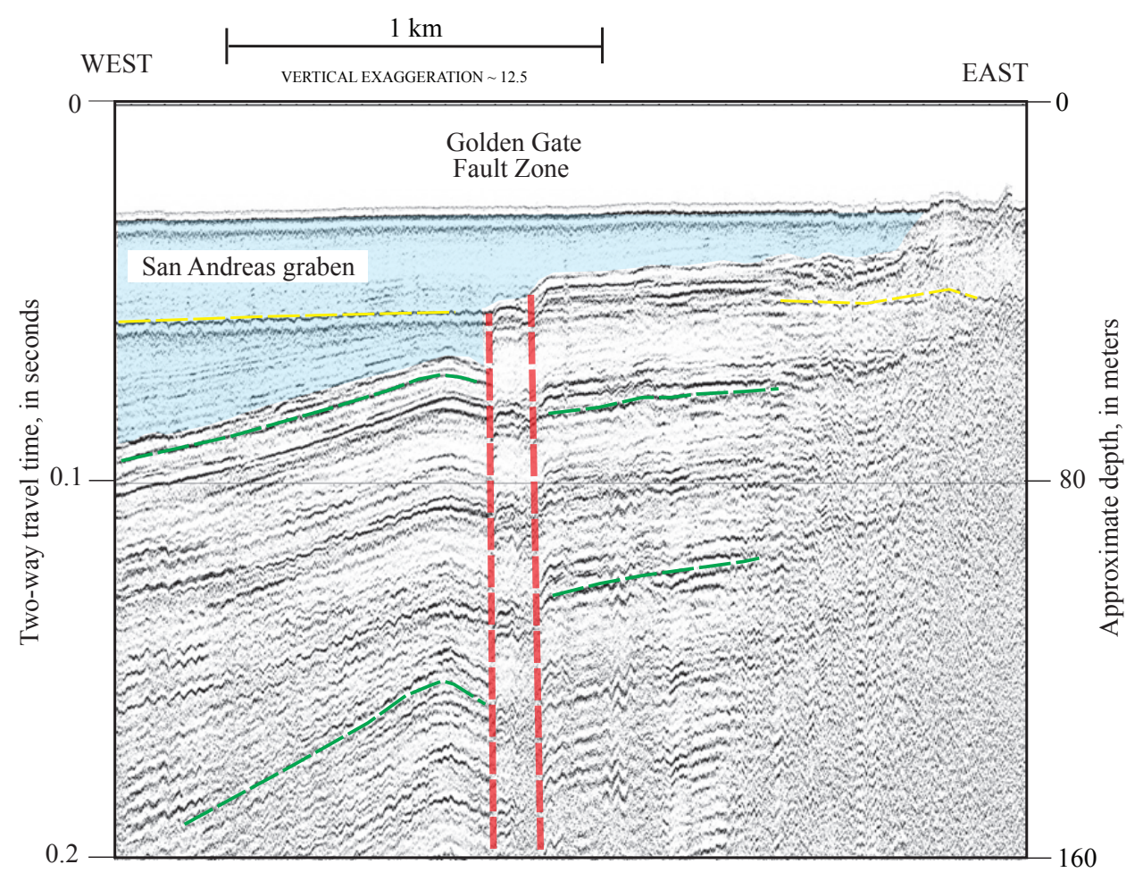


Figure 1 (left). USGS high-resolution minisparker seismic-reflection profile GG–008 (collected in 2006 on survey L–1–06–NC), which crosses shelf northwest of San Francisco; see trackline map for location. Dashed red lines show Golden Gate Fault, eastern margin of San Andreas graben (Cooper, 1973; Bruns and others, 2002; Ryan and others, 2008). Blue shading shows inferred uppermost Pleistocene and Holocene strata, deposited since last sea-level lowstand about 21,000 years ago. Dashed green lines highlight continuous reflections that reveal structure (not distinctive stratigraphic markers). Dashed yellow line is seafloor multiple (echo of seafloor reflector).

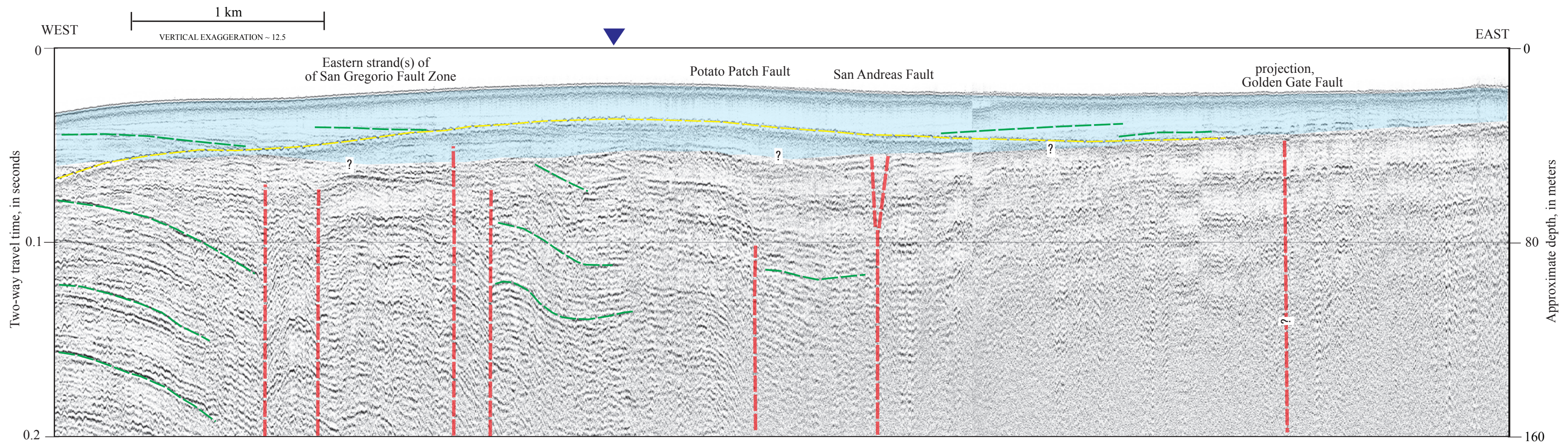
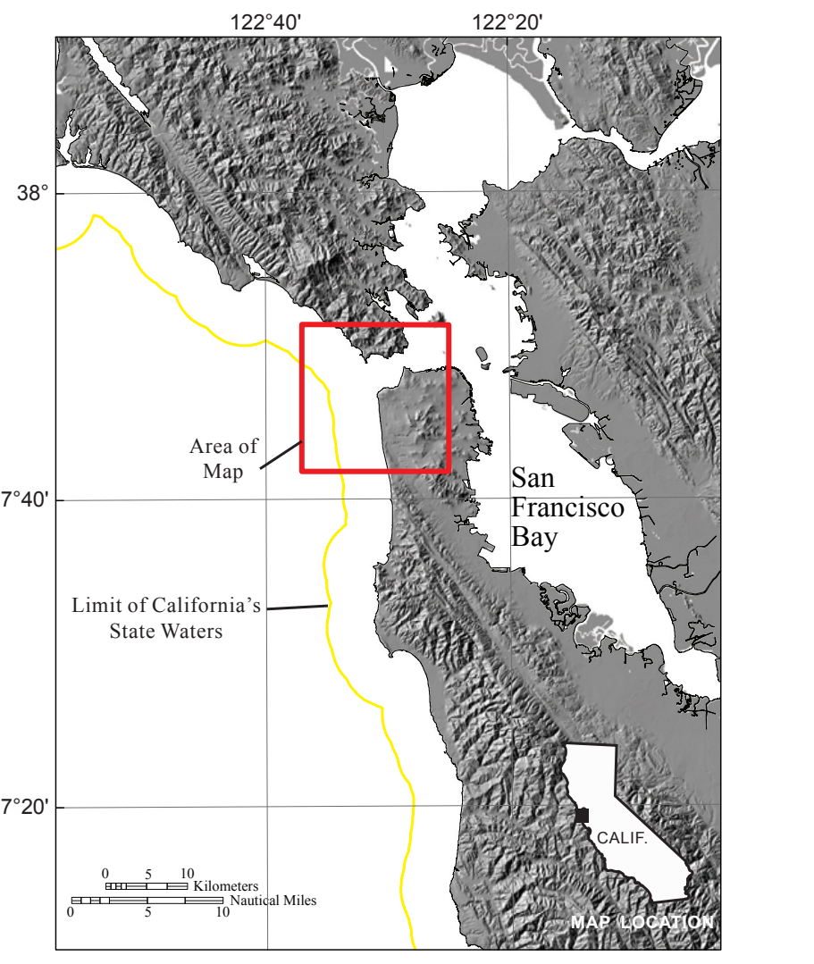


Figure 2. USGS high-resolution minisparker seismic-reflection profile GG–02B (collected in 2006 on survey L–1–06–NC), which crosses shelf northwest of San Francisco; see trackline map for location. Dashed red lines show faults and projections of faults within broad San Andreas Fault Zone, including San Andreas Fault, Golden Gate Fault, Potato Patch Fault, and eastern strand of San Gregorio Fault (Bruns and others, 2002; Ryan and others, 2008). Relatively poor profile quality, revealed by relative absense or lack of continuous shallow reflections and abrupt changes in reflection amplitudes, is typical of high-resolution seismic profiles crossing San Francisco Bay ebb-tidal delta and probably results from combination of complex deformation associated with active faulting, presence of homogeneous sandy sediment (reworked by strong waves) in shallow subsurface, and interstitial gas responsible for "acoustic masking" (for example, Fader, 1997). Result is that stratigraphic interpretations are more questionable, including base and thickness of inferred uppermost Pleistocene and Holocene strata (blue shading). Dashed green lines highlight continuous reflections that reveal structure (not distinctive stratigraphic markers). 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).



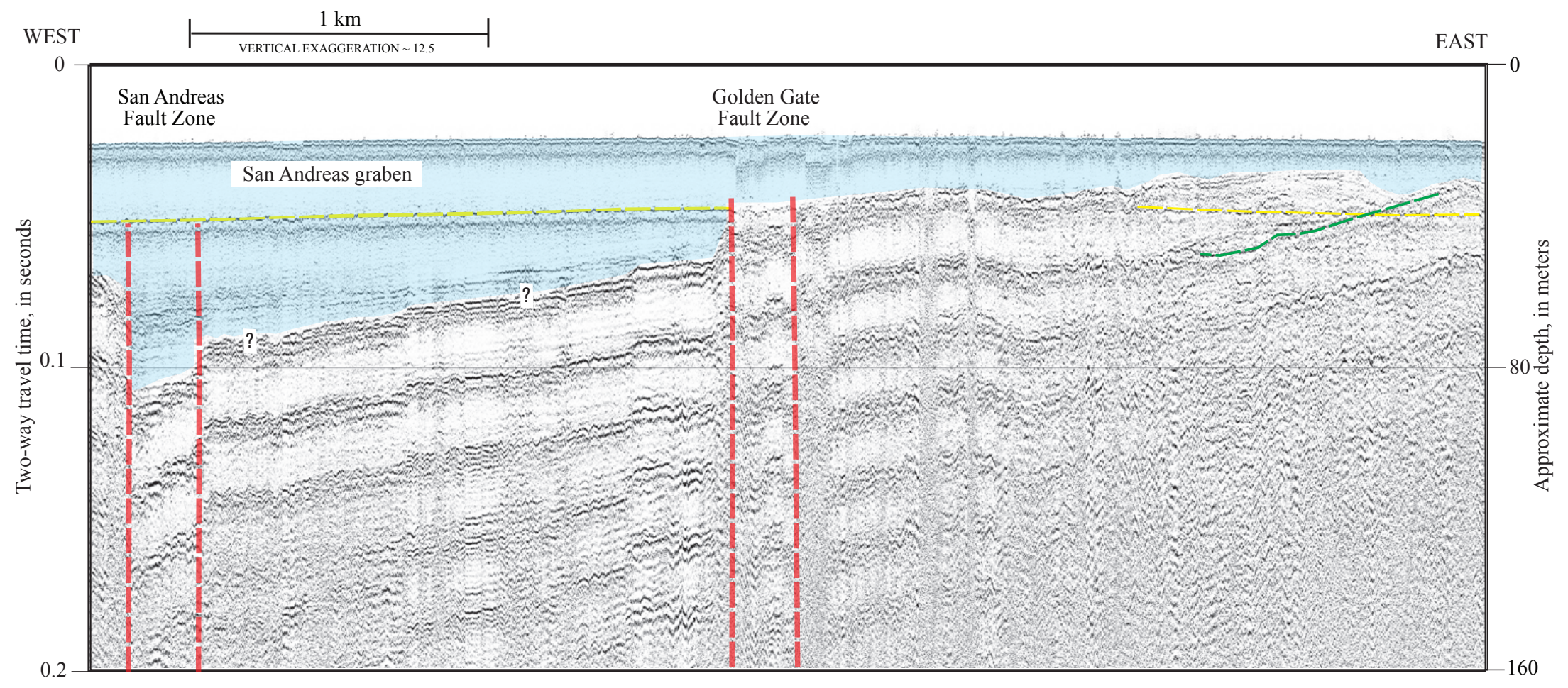


Figure 3 (left). USGS high-resolution minisparker seismic-reflection profile GG–004 (collected in 2006 on survey L–1–06–NC), which crosses shelf northwest of San Francisco; see trackline map for location. Dashed red lines show San Andreas Fault and Golden Gate Fault, within and on eastern margin of San Andreas graben (Cooper, 1973; Bruns and others, 2002; Ryan and others, 2008). Blue shading shows inferred uppermost Pleistocene and Holocene strata, deposited since last sea-level lowstand about 21,000 years ago. Dashed green lines highlight continuous reflections that reveal structure (not distinctive stratigraphic markers). Dashed yellow line is seafloor multiple (echo of seafloor reflector).

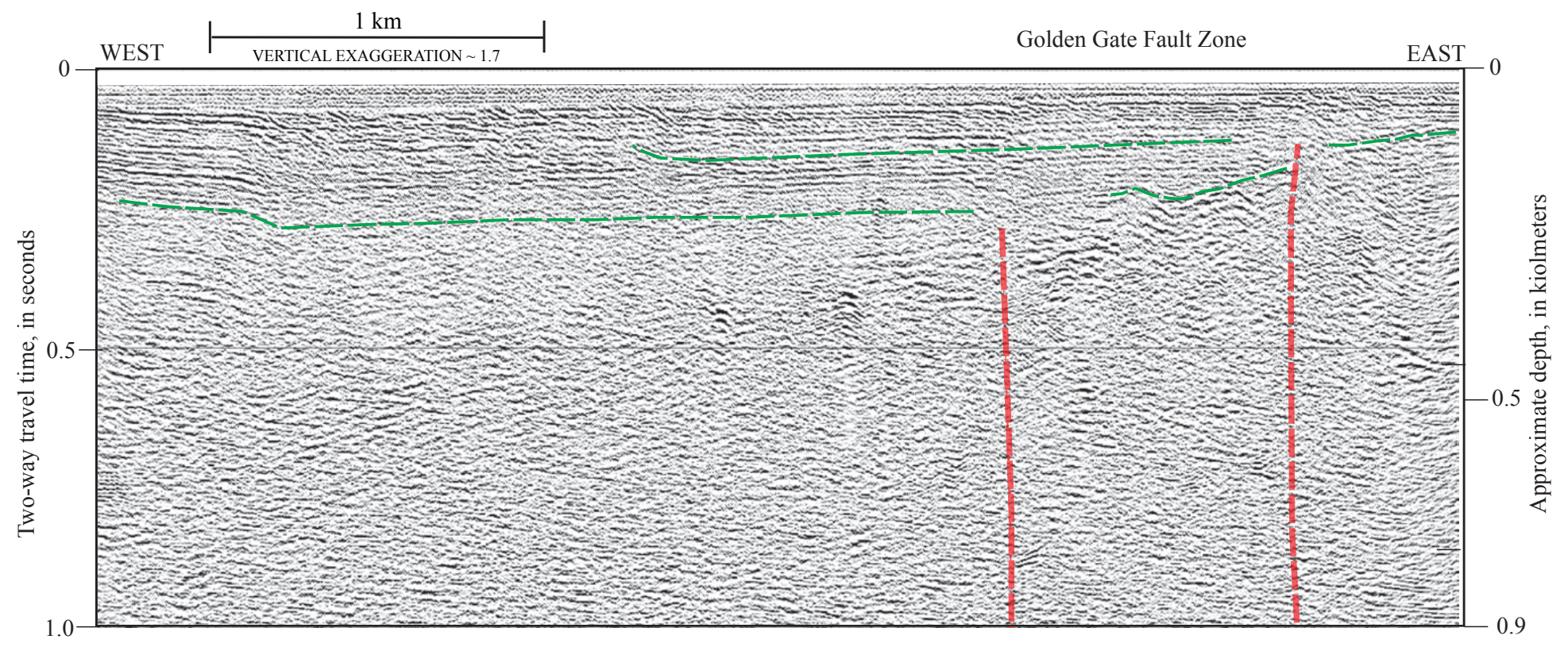


Figure 4. USGS multichannel airgun seismic-reflection profile SF–123 (collected by USGS in 1995 on survey G–2–95–SF), which crosses shelf northwest of San Francisco; see trackline map for location. Dashed red lines show faults within Golden Gate Fault Zone, east of San Andreas Fault, but part of broader San Andreas Fault Zone (modified from Bruns and others, 2002; their fig. 19). Dashed green lines highlight some continuous reflections that reveal structure (not distinctive stratigraphic markers). Contrast in vertical exaggeration (1.7 versus 12.5) between this profile and high-resolution profiles shown in figures 1, 2, 3, 8, 9, 10, 11 highlights gently dipping character of shallow strata in shallow subsurface (0 to about 200 m).

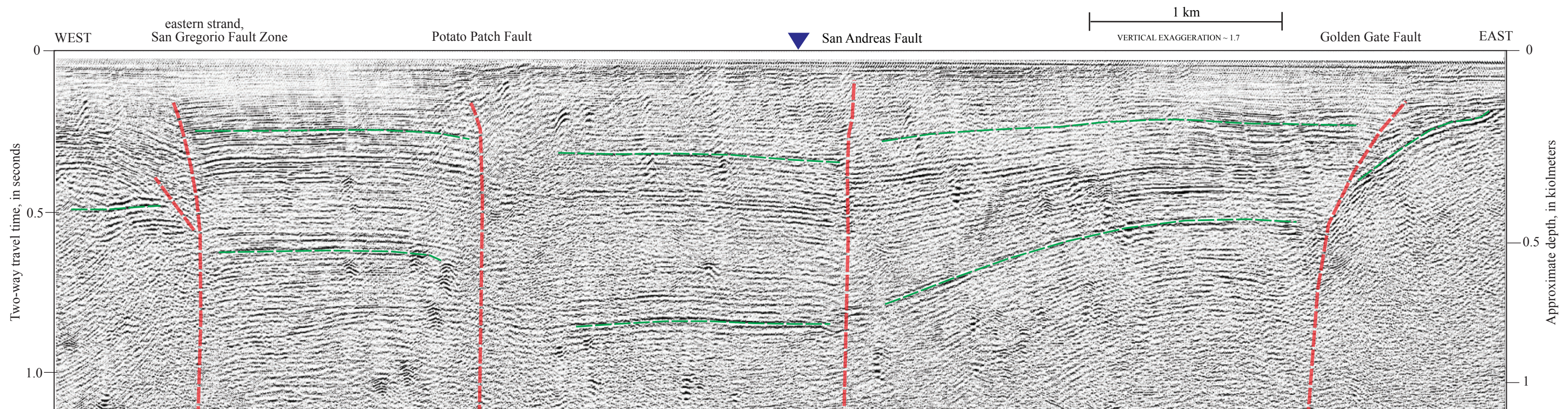


Figure 5 (left). USGS multichannel airgun seismic-reflection profile SF–123 (collected by USGS in 1995 on survey G–2–95–SF), which crosses shelf west of San Francisco; see trackline map for location. Dashed red lines show faults within broad San Andreas Fault Zone, including San Andreas Fault, Golden Gate Fault, Potato Patch Fault, and eastern strand of San Gregorio Fault (modified from Bruns and others, 2002, their fig. 17; Ryan and others, 2008, their fig. 3). Dashed green lines highlight continuous reflections that reveal structure (not distinctive stratigraphic markers). Contrast in vertical exaggeration (1.7 versus 12.5) between this profile and high-resolution profiles shown in figures 1, 2, 3, 8, 9, 10, 11 highlights gently dipping character of shallow strata in relatively shallow subsurface (about 500 to 1,000 m). Purple triangle shows location of California's State Waters limit (yellow line on trackline map).

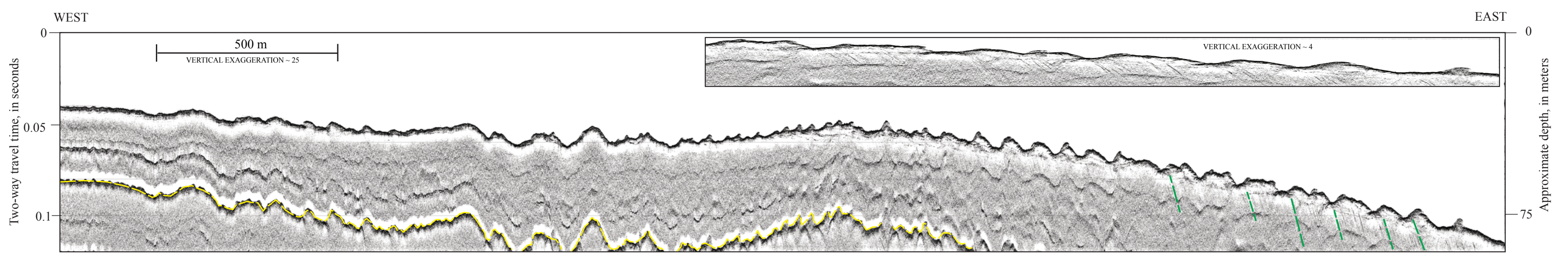


Figure 6 (right). USGS high-resolution chirp seismic-reflection profile GG–05A (collected in 2006 on survey L–1–06–NC), which crosses shelf and large sand-wave field at inlet of Golden Gate channel north of San Francisco; see trackline map for location (see sheets 1, 2, 3, 4; note partial overlap with figure 8). Barnard and others (2006a) report that entire sand-wave field covers approximately 4 km² in water depths ranging from 30 m to 106 m, and that individual sand waves have average wavelength of 82 m and average height of 6 m. Large bedform field results from strong tidal currents (typically exceeding 2.5 m/sec), forced by an enormous tidal prism of 2 billion m³ (Hanes and Barnard, 2007). Vertically exaggerated (25x) profile highlights significant variability in sand-wave wavelength, height, and symmetry, as well as common superposition of smaller and larger sand waves. Profile generally does not reveal internal sand-wave structure, largely due to uniform grain size and associated lack of acoustic impedance contrasts. East-dipping internal crossbeds (shown by green dashed lines) are, however, imaged within several sand waves on eastern part of profile and shown in less vertically exaggerated insert. Dashed yellow line is seafloor multiple (echo of seafloor reflector).

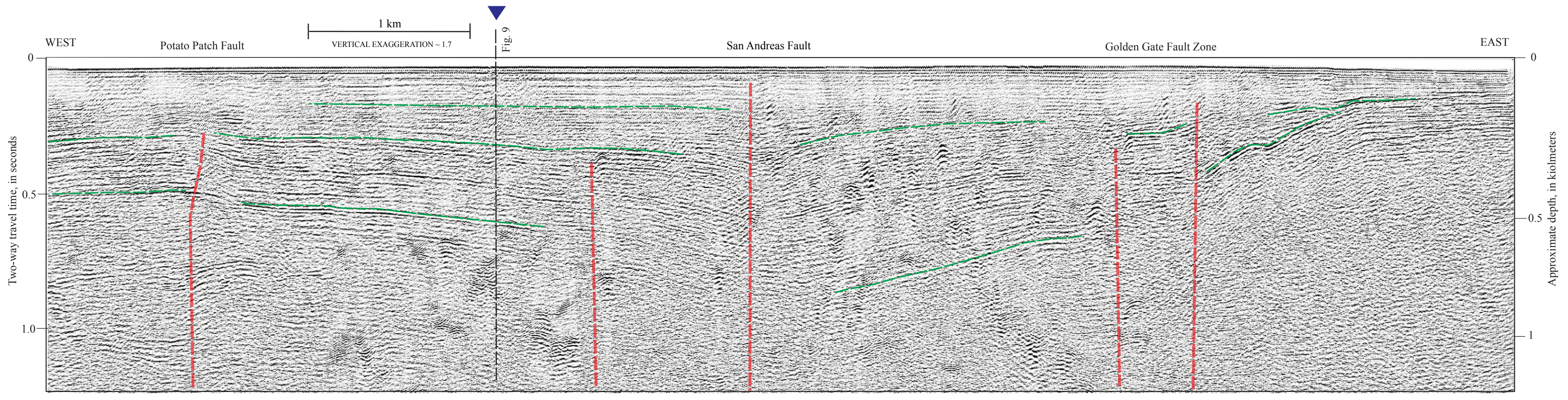


Figure 7. USGS multichannel airgun seismic-reflection profile SF–123 (collected in 1995 on survey G–2–95–SF), which crosses shelf west of San Francisco; see trackline map for location. Dashed red lines show faults within broad San Andreas Fault Zone, including San Andreas Fault, Golden Gate Fault Zone, and Potato Patch Fault (modified from Bruns and others, 2002, their fig. 23). Dashed green lines highlight continuous reflections that reveal structure (not distinctive stratigraphic markers). Contrast in vertical exaggeration (1.7 versus 12.5) between this profile and high-resolution profiles shown in figures 1, 2, 3, 8, 9, 10, 11 highlights gently dipping character of shallow strata in relatively shallow subsurface (about 500 to 1,000 m). Purple triangle shows location of California's State Waters limit (yellow line on trackline map).

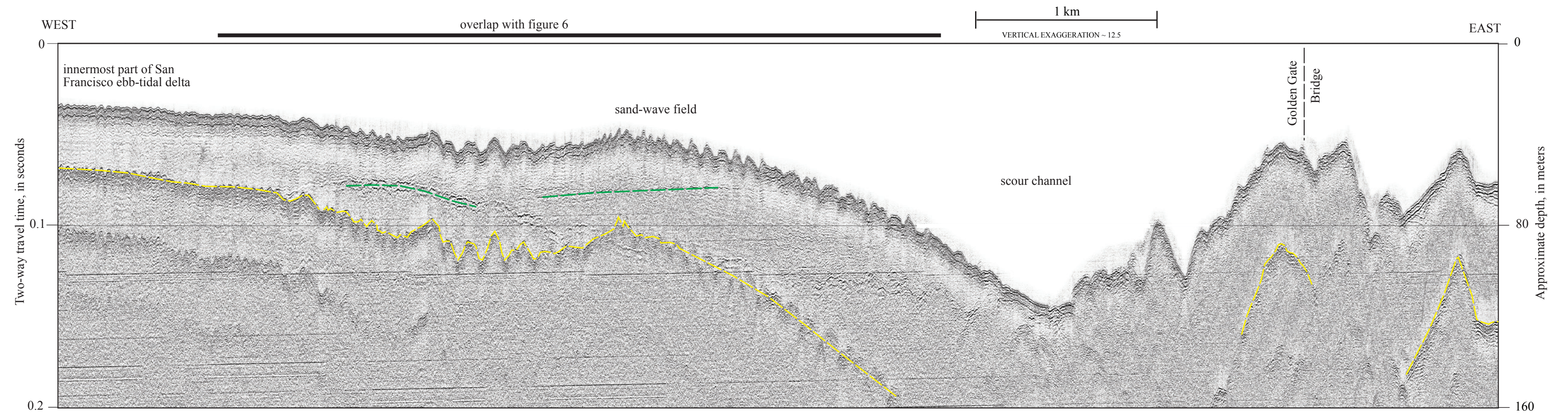


Figure 8. USGS high-resolution minisparker seismic-reflection profile GG–001 (collected in 2006 on survey L–1–06–NC), extending from beneath Golden Gate Bridge, through large scour channel and sand-wave field at mouth of San Francisco Bay, to innermost part of San Francisco ebb-tidal delta; see trackline map for location (see sheets 1, 2, 3, 4; Barnard and others, 2006a). Scour channel and large sand-wave field result from strong tidal currents (typically exceeding 2.5 m/sec), forced by enormous tidal prism of 2 billion m³ (Hanes and Barnard, 2007). Absence of internal reflections in eastern part of seismic profile consistent with presence of shallow, structurally complex bedrock (see sheet 10). General lack and (or) low amplitude of reflections (dashed green lines) in western part of profile may result from interstitial gas ("acoustic masking;" Fader, 1997) or lack of acoustic impedance contrasts due to uniform sediment grain size. Dashed yellow line is seafloor multiple (echo of seafloor reflector).

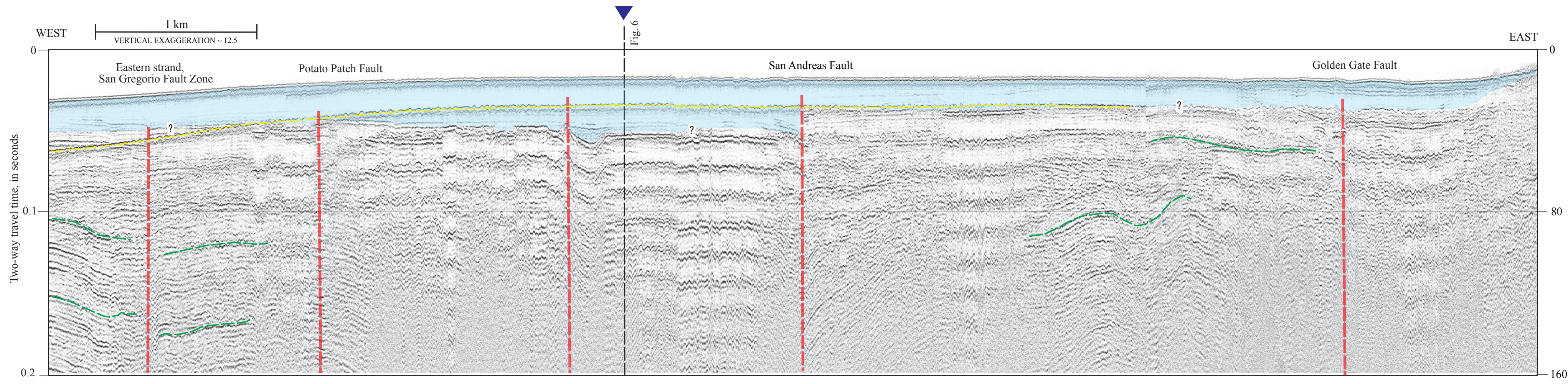


Figure 9. USGS high-resolution minisparker seismic-reflection profile GG–013 (collected in 2006 on survey L–1–06–NC), which crosses shelf west of San Francisco; see trackline map for location. Dashed red lines show faults within broad San Andreas Fault Zone, including San Andreas Fault, Golden Gate Fault, Potato Patch Fault, and eastern strand of San Gregorio Fault (Bruns and others, 2002; Ryan and others, 2008). Relatively poor quality of profile, revealed by relative absense or lack of continuous shallow reflections and abrupt changes in reflection amplitudes, is typical of high-resolution seismic profiles crossing San Francisco Bay ebb-tidal delta and probably reflects combination of complex deformation associated with active faulting, presence of homogeneous sandy sediment (reworked by strong waves) in shallow subsurface, and interstitial gas in sediment column that is responsible for "acoustic masking" (Fader, 1997). Blue shading shows inferred uppermost Pleistocene and Holocene strata, deposited since last sea-level lowstand about 21,000 years ago. Dashed green lines highlight continuous reflections that reveal structure (not distinctive stratigraphic markers). 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).

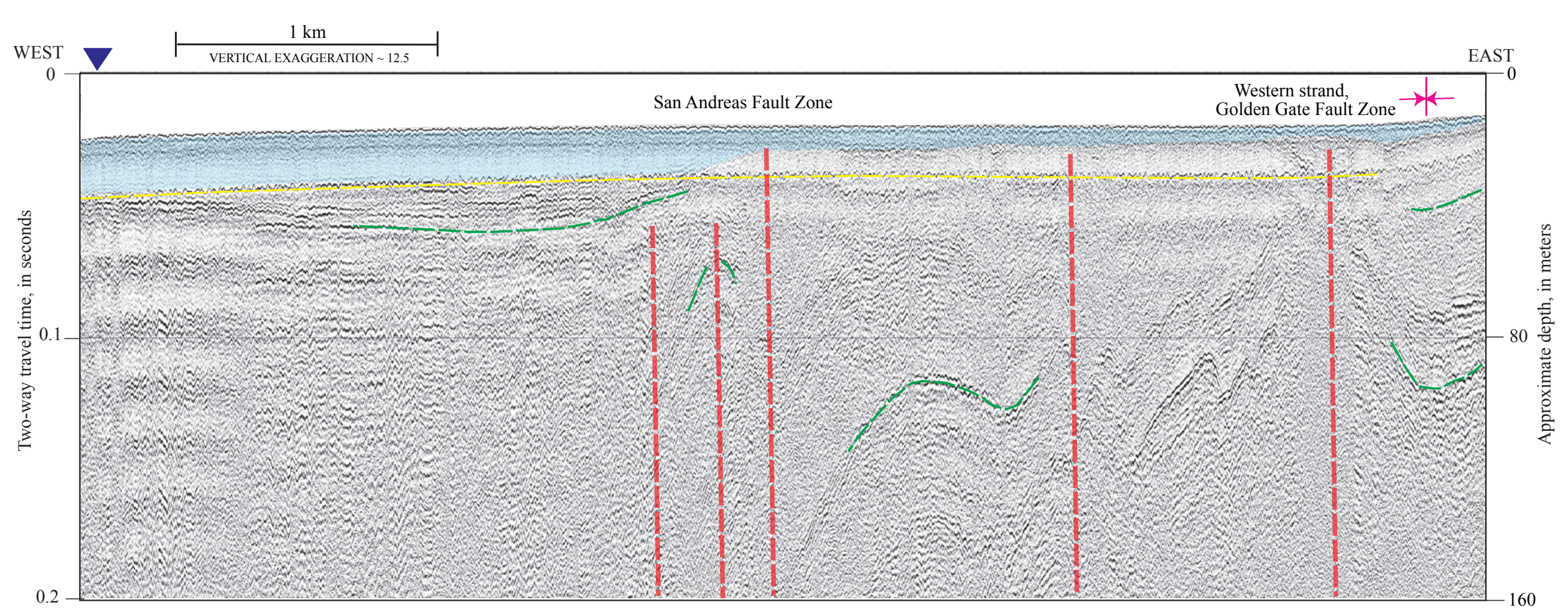


Figure 10. USGS high-resolution minisparker seismic-reflection profile PS–19 (collected in 2010 onsurvey S–16–10–NC), which crosses shelf west of San Francisco; see trackline map for location. Dashed red lines show faults within San Andreas Fault Zone, including Golden Gate Fault (Bruns and others, 2002; Ryan and others, 2008), juxtaposing less deformed, relatively flat strata west of zone and more deformed and uplifted strata within and east of zone. Pink symbol shows syncline axis. Blue shading shows inferred uppermost Pleistocene and Holocene strata, deposited since last sea-level lowstand about 21,000 years ago. Dashed green lines highlight continuous reflections that reveal structure (not distinctive stratigraphic markers). 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).

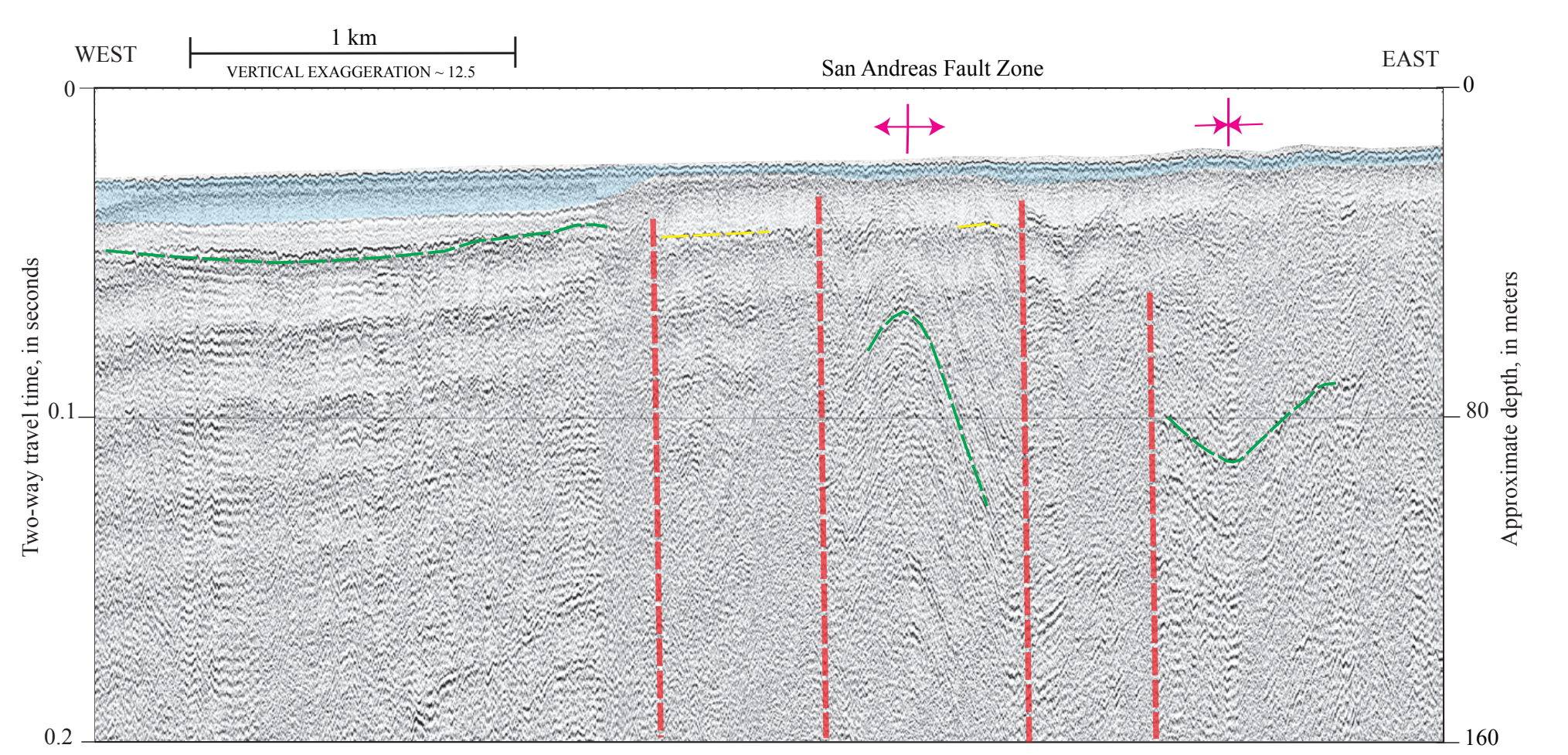


Figure 11. USGS high-resolution minisparker profile PS–17 (collected in 2010 on survey S–16–10–NC), which crosses shelf west of San Francisco; see trackline map for location. Dashed red lines show faults within San Andreas Fault Zone, juxtaposing less deformed, relatively flat strata west of zone and more deformed and uplifted strata within and east of zone (Bruns and others, 2002; Ryan and others, 2008). Magenta symbols show fold axes (diverging arrows, anticline; converging arrows, syncline). Blue shading shows inferred uppermost Pleistocene and Holocene strata, deposited since last sea-level lowstand about 21,000 years ago. Dashed green lines highlight continuous reflections that reveal structure (not distinctive stratigraphic markers). Dashed yellow line is seafloor multiple (echo of seafloor reflector).

DISCUSSION

This map sheet shows seismic-reflection profiles from four different surveys of the Offshore of San Francisco map area, providing imagery of the subsurface geology. The dominant submerged physical features in this map area are San Francisco Bay, the narrow Golden Gate channel that connects San Francisco Bay and the Pacific Ocean, and the large, associated, ebb-tidal delta offshore of the channel. The seismic-reflection profiles provide the database for interpreting sub-bottom stratigraphy, sediment thickness, and geologic structure (see sheets 9 and 10 of this report).

The Offshore of San Francisco map area, which straddles the right-lateral transform boundary between the North American and Pacific plates, is cut by several active northwest-striking faults that cumulatively form a distributed shear zone, including the San Andreas Fault, the eastern strand of the San Gregorio Fault, the Golden Gate Fault, and the Potato Patch Fault (Zoback and others, 1999; Bruns and others, 2002; Parsons and others, 2005; Ryan and others, 2008). These faults are identified on seismic-reflection data and mapped on the basis of abrupt truncation or warping of reflections and (or) juxtaposition of reflection panels with different seismic parameters such as reflection amplitude, frequency, geometry, continuity, and vertical sequence. The San Andreas Fault (figs. 2, 3, 5, 7, 9, 10, 11), which is the dominant plate-boundary structure, extends northward from the onshore into the offshore at Mussel Rock, about 3 km south of the map area, and southward into the offshore from Bolinas Lagoon, about 6 km north of the map area. This section of the San Andreas Fault has an estimated slip rate of 17 to 24 mm/yr (U.S. Geological Survey and California Geological Survey, 2010), and the devastating great 1906 California earthquake (M7.8) is thought to have nucleated on the San Andreas Fault in this map area (sheet 9, Map E; Bolt, 1968; Lomax, 2005).

The San Gregorio Fault, another major strike-slip fault system within the distributed transform plate boundary, extends predominantly offshore for about 400 km from Point Conception in the south (where it is known as the Hosgri Fault) to Bolinas and Point Reyes in the north (Dickinson and others, 2005). Cumulative lateral slip on the San Gregorio Fault is estimated to be about 4 to 10 mm/yr (U.S. Geological Survey and California Geological Survey, 2010) near San Francisco, divided between an eastern strand that is converging with the San Andreas Fault in the map area (figs. 2, 5, and 9; see also sheet 10), and a western strand located west of the map area (Bruns and others, 2002; Ryan and others, 2008). The Potato Patch Fault (figs. 2, 5, 7, 9) strikes obliquely between the San Andreas Fault and the eastern strand of the San Gregorio Fault between Pacifica and Bolinas, and the Golden Gate Fault (figs. 1, 2, 3, 4, 5, 7, 9, 10) parallels and lies east of the San Andreas Fault between San Francisco and Bolinas (Map E, sheet 9).

Zoback and others (1999) noted a northward change in the strike (from 325° to 330°) of both the San Andreas and San Gregorio Faults offshore of San Francisco, resulting in a change from local contractional to extensional deformation. The inferred extensional setting is consistent with subsidence of the San Francisco ebb-tidal delta and with development of the San Andreas graben (figs. 1, 3; Cooper, 1973; Bruns and others, 2002; Ryan and others, 2008). This graben (about 7 km long and 2.5 km wide) is bounded on the east by the Golden Gate Fault and its basin floor dips gently westward toward the continuous San Andreas Fault, along which it has its maximum depth. The abrupt northern basin margin (Map D, sheet 9) could have formed either as an extensional normal fault, or as a northwest "restraining bend" as the Golden Gate Fault converges northward with the San Andreas Fault. The southern basin margin appears gradational offshore of San Francisco within a sea-level lowstand paleovalley.

Several high-resolution seismic profiles show an upper unit (blue shading in profiles; figs. 1, 2, 3, 9, 10, 11) that is inferred to have been deposited in about the last about 21,000 years during the latest Pleistocene and Holocene post–Last Glacial Maximum sea-level rise. These deposits typically are characterized either by "acoustic transparency" or by parallel, low-amplitude, low- to high-frequency, continuous to moderately continuous, diffuse reflections (terminology from Mitchum and others, 1977); this seismic "facies" is attributable to the inferred uniform grain size caused by wave winnowing, which results in the general lack of acoustic-impedance contrasts needed to yield seismic reflections. The section is typically 15- to 35-m thick beneath the ebb-tidal delta and thins southward onto the northern end of a bedrock platform (Maps B and D, sheet 9). Maximum subsidence is occurring in the San Andreas graben where the uppermost Pleistocene and Holocene section is as much as 57 m thick. It is emphasized that the base of this unit is an interpretation locally hindered by data of marginal quality and by "acoustic masking" associated with interstitial gas (Fader, 1997; Ryan and others, 2008).

Strong tidal currents through the Golden Gate strait, typically exceeding 2.5 m/sec, are associated with an enormous tidal prism of about 2 billion m³ (Barnard and others, 2006). Acceleration of these currents through the constricted channel has led to scouring of a bedrock channel (see sheets 9, 10) that has a maximum depth of 113 m. Large fields of sand waves have formed both east and west of this channel as flow expands and current decelerates (see sheets 1, 2, 3, 4). Seismic-reflection profiles that image the scour channel and sand-wave field (figs. 6, 8) reveal the surface morphology of these large bedforms (note vertical exaggeration) and internal east-dipping crossbeds in the eastern part of the field.

Data for the seismic-reflection profiles shown in figures 1, 2, 3, 6, 8, and 9 were collected in 2006 on U.S. Geological Survey (USGS) cruise L–1–06–NC. Data for the seismic-reflection profiles shown in figures 10 and 11 were collected in 2010 on USGS cruise S–16–10–NC. Both cruises used the SIG minisparker system, and the L–1–06–NC survey also collected some profiles using the EdgeTech 512 chirp system. The SIG minisparker system used a 500-J high-voltage electrical discharge fired 1 to 4 times per second, which, at normal survey speed 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 Triton Subbottom Logger (SBL) software that merges seismic-reflection data with differential GPS-navigation data. The EdgeTech 512 chirp subbottom-profiling system consists of a source transducer and an array of receiving hydrophones housed in a 500-lb fish towed at a depth of several meters below the sea surface. The swept-frequency chirp source signal was 500 to 4,500 Hz and 50 ms in length, and it was recorded by hydrophones located on the bottom of the fish. After the survey, a short-window (20 ms) automatic gain control algorithm was applied to both the chirp and minisparker data, and a 160- to 1,200-Hz bandpass filter was applied to the minisparker data.

Figures 4, 5, and 7 show multichannel seismic-reflection profiles collected in 1995 on USGS cruise G–2–95–SF (Childs and others, 2000; Bruns and others, 2002). Two 0.65-L air guns fired at 12.5-m intervals provided the seismic source, and data were digitally recorded on a 24-channel, 150-m-long streamer merged with GPS navigation data. Data-processing steps included deconvolution, automatic gain control, filtering at 50 to 160 Hz, stacking, and migration.

REFERENCES CITED

Barnard, P.L., Hanes, D.M., Kvitek, R.G., and Iampietro, P.J., 2006a, Sand waves at the mouth of San Francisco Bay, California: U.S. Geological Survey Scientific Investigations Map 2944, 5 sheets, available at http://pubs.usgs.gov/sim/2006/2944/.

Barnard, P.L., Hanes, D.M., Rubin, D.M., and Kvitek, R.G., 2006b, Giant sand waves at the mouth of San Francisco Bay: EOS, v. 87, p. 285–289.

Bolt, B.A., 1968, The focus of the 1906 California earthquake: Bulletin of the Seismological Society of America, v. 58, p. 457–471.

Bruns, T.R., Cooper, A.K., Carlson, P.R., and McCulloch, D.S., 2002, Structure of the submerged San Andreas and San Gregorio Fault zones in the Gulf of the Farallones off San Francisco, California, from high-resolution seismic-reflection data, *in* Parsons, T., ed., Crustal structure of the coastal and marine San Francisco Bay region, California: U.S. Geological Survey Professional Paper 1658, p. 77–117, available at http://pubs.usgs.gov/pp/1658/.

Childs, J.R., Hart, P., Bruns, T.R., Marlow, M.S., and Sliter, R., 2000, High-resolution marine seismic reflection data from the San Francisco Bay area: U.S. Geological Survey Open-File Report 00–494, available at http://pubs.usgs.gov/of/2000/0494/.

Cooper, A.K., 1973, Structure of the continental shelf west of San Francisco, California: U.S. Geological Survey Open-File Report 73–48, 65 p., available at http://pubs.er.usgs.gov/publication/ofr7348.

Dickinson, W.R., Ducea, M., Rosenberg, L.I., Greene, H.G., Graham, S.A., Clark, J.C., Weber, G.E., Kidder, S., Ernst, W.G., and Brabb, E.E., 2005, Net dextral slip, Neogene San Gregorio–Hosgri fault zone, coastal California—Geologic evidence and tectonic implications: Geological Society of America Special Paper 391, 43 p.

Fader, G.B.J., 1997, The effects of shallow gas on seismic reflection profiles, *in* Davies, T.A., Bell, T., Cooper, A.K., Josenhans, H., Polyak, L., Solheim, A., Stoker, M.S., and Stravers, J.A., eds., Glaciated continental margins, an atlas of acoustic images: London, Chapman and Hall, p. 29–30.

Hanes, D.M., and Barnard, P.L., 2007, Morphological evolution in the San Francisco Bight: Journal of Coastal Research, Special Issue 50, p. 469–473.

Lomax, A., 2005, A reanalysis of the hypocentral location and related observations for the Great 1906 California earthquake: Bulletin of the Seismological Society of America, v. 95, p. 861–877, doi:10.1785/0120040141.

Mitchum, R.M., Jr., Vail, P.R., and Sangree, J.B., 1977, Seismic stratigraphy and global changes of sea level, part 6—Stratigraphic interpretation of seismic reflection patterns in depositional sequences, *in* Payton, C.E., ed., Seismic stratigraphy—Applications to hydrocarbon exploration: Tulsa, Okla., American Association of Petroleum Geologists, p. 117–133.

Parsons, T., Bruns, T.R., and Sliter, R., 2005, Structure and mechanics of the San Andreas-San Gregorio fault junction, San Francisco, California: Geochemistry, Geophysics, Geosystems, v. 6, 7 p., doi:10.1029/2004GC000838.

Ryan, H.F., Parsons, T., and Sliter, R.W., 2008, Vertical tectonic deformation associated with the San Andreas fault zone offshore of San Francisco, California: Tectonophysics, v. 427, p. 209–223, doi:10.1016/j.tecto.2008.06.011.

U.S. Geological Survey and California Geological Survey, 2010, Quaternary fault and fold database of the United States: U.S. Geological Survey database, accessed April 5, 2014, at http://earthquake.usgs.gov/hazards/qfaults/.

Zoback, M.L., Jachens, R.C., and Olson, J.A., 1999, Abrupt along-strike change in tectonic style: San Andreas fault zone, San Francisco Peninsula: Journal of Geophysical Research, v. 104 (B5), p. 10,719–10,742.

Seismic-Reflection Profiles, Offshore of San Francisco Map Area, California

by

Samuel Y. Johnson, Ray W. Sliter, Terry R. Bruns, Stephanie L. Ross, and John L. Chin

2015

ISSN 2331-1258 (online)
http://dx.doi.org/10.3133/ofr20151068

For sale by U.S. Geological Survey, Information Services, Box 25286, Federal Center, Denver, CO 80225, 1–888–ASK–USGS

Digital files available at http://dx.doi.org/10.3133/ofr20151068 or http://pubs.usgs.gov/of/2015/1068/

Suggested Citation: Johnson, S.Y., Sliter, R.W., Bruns, T.R., Ross, S.L., and Chin, J.L., 2015, Seismic-reflection profiles, Offshore of San Francisco map area, California, *sheet 8 in* Cochrane, G.R., Johnson, S.Y., Dartnell, P., Greene, H.G., Erdey, M.D., Golden, N.E., Hartwell, S.R., Endris, C.A., Manson, M.W., Sliter, R.W., Kvitek, R.G., Watt, J.T., Ross, S.L., and Bruns, T.R. (G.R. Cochrane and S.A. Cochran, eds.), California State Waters Map Series—Offshore of San Francisco, California: U.S. Geological Survey Open-File Report 2015–1068, pamphlet 39 p., 10 sheets, scale 1:24,000, http://dx.doi.org/10.3133/ofr20151068.