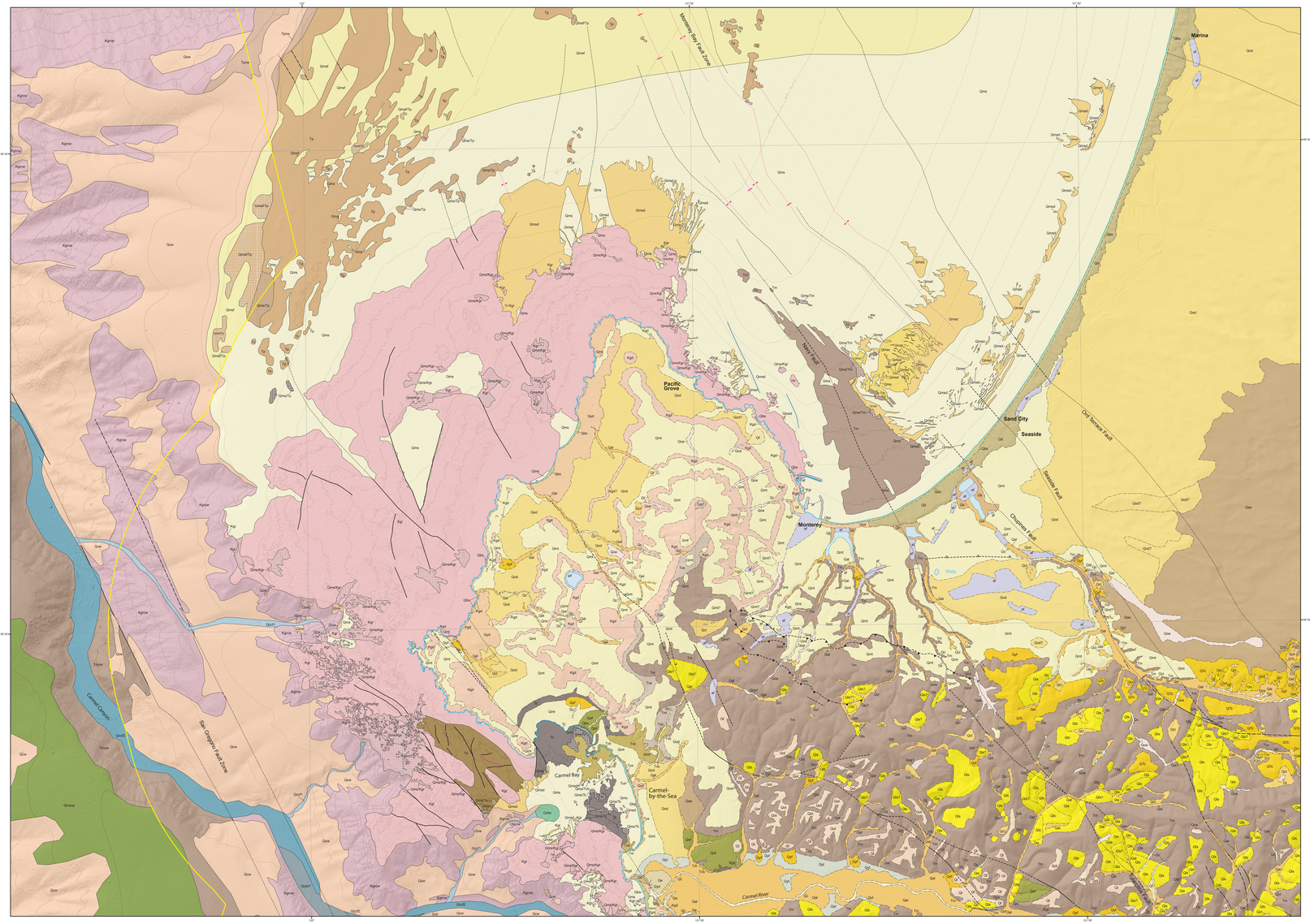
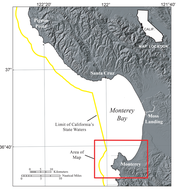
U.S. Department of the Interior
U.S. Geological Survey

Open-File Report 2016–1110
Sheet 10 of 10
Pamphlet accompanies map





Onshore elevation data from National Oceanic and Atmospheric Administration (NOAA) Office for Coastal Management's Digital Coast (available at http://www.csc.noaa.gov/digitalcoast/data/coastallidar/). Offshore shaded-relief bathymetry from multibeam data (available at http://ned.usgs.gov/). Offshore shaded-relief bathymetry from map sheet 2, this report. California's State Waters limit from NOAA Office of Coast Survey.

Universal Transverse Mercator projection, Zone 10N

NOT INTENDED FOR NAVIGATIONAL USE

NOTE: APPROXIMATE MEAN DECLINATION, 2016

SCALE 1:24 000

1 0 1 2 3 4 MILE
1000 0 1000 2000 3000 4000 5000 6000 7000 FEET
500 0 500 1000 1500 2000 KILOMETER

BATHYMETRIC CONTOUR INTERVALS 10 METERS, 50 METERS, and 200 METERS

ONE MILE = 0.869 NAUTICAL MILES

MAP LOCATION

Offshore geology mapped by Stephen R. Hartwell and Samuel Y. Johnson, 2015. Onshore geology compiled by Clifton W. Davenport from Clark and others (1997) and Wagner and others (2002). Bathymetric contours by Peter Dartnell, 2015

GIS database and digital cartography by Peter Dartnell and Stephen R. Hartwell

Manuscript approved for publication June 27, 2016

Offshore and Onshore Geology and Geomorphology, Offshore of Monterey Map Area, California

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2016

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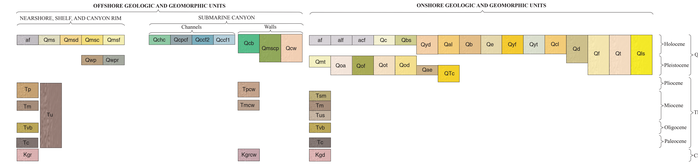
CORRELATION OF MAP UNITS

[See Description of Map Units (chapter 8, in pamphlet) for precise unit ages]



LIST OF MAP UNITS

[See Description of Map Units (chapter 8, in pamphlet) for complete map-unit descriptions]

OFFSHORE GEOLOGIC AND GEOMORPHIC UNITS

[Note that composite units (gray- and white-stippled areas) are designated on map by composite label indicating both overlying sediment cover and lower (older) unit, separated by slash (for example, Qmsc/Tp indicates that thin sheet of Qmsc overlies Tp)]

NEARSHORE, SHELF, AND CANYON RIM

- **af** — **Artificial fill (late Holocene)**—Rock, sand, and mud, placed and (or) dredged, associated with Monterey Harbor
- **Qms** — **Marine nearshore and shelf deposits (late Holocene)**—Mostly sand; ripple marks common
- **Qmsd** — **Marine shelf scour depressions (late Holocene)**—Inferred to be coarse sand and gravel, in low-relief scours
- **Qmsc** — **Coarse-grained marine nearshore and shelf deposits (late Holocene)**—Coarse sand to gravel; mainly found about 2 km offshore of Point Pinos
- **Qmsf** — **Fine-grained marine shelf deposits (late Holocene)**—Mostly mud, very fine sand, and silt; commonly bioturbated
- **Qwp** — **Submerged wave-cut platform, about 80 to 90 m deep (late Pleistocene)**—Inferred to be sand and gravel; may be draped with fine-grained sediment; smooth, offshore-dipping surface
- **Qwpz** — **Submerged wave-cut platform riser, base about 80 to 90 m deep (late Pleistocene)**—Inferred to be sand and gravel; may be draped with fine-grained sediment; smooth, offshore-dipping surface
- **Tp** — **Purisima Formation (Pliocene and late Miocene)**—Thick-bedded siltstone; contains thick interbeds of fine-grained sandstone and mudstone
- **Tm** — **Monterey Formation (Miocene)**—Porcellaneous shale, chert, and mudstone; calcareous claystone; and small amounts of siltstone and sandstone
- **Tvb** — **Volcanic rocks (Oligocene)**—Basaltic andesite flows and flow breccias
- **Tv** — **Sedimentary and (or) volcanic rocks, undivided (Oligocene to Paleocene)**—May consist of the Oligocene volcanic rocks (Tvb) or rocks of the Carmelo Formation (Tc)
- **Tc** — **Carmelo Formation (Paleocene)**—Thin- to thick-bedded and graded arkosic sandstone that contains interbedded siltstone and pebble and cobble conglomerate
- **Kgr** — **Granitic rocks of Monterey (Cretaceous)**—Mainly porphyritic granodiorite (Ross, 1976)

SUBMARINE CANYON

Channels

- **Qchc** — **Submarine-canyon-head channel deposits (late Holocene)**—Primarily sand; mapped at uppermost part of northeast-trending head of Carmel Canyon in Carmel Bay
- **Qcpsf** — **Proximal active submarine-canyon axial-channel fill (late Holocene)**—Primarily sand; found in upper Carmel Canyon; characterized by crescent-shaped bedforms
- **Qcof2** — **Active submarine-canyon axial-channel fill (late Holocene)**—Sand and gravel; locally forms crescent-shaped bedforms; minor bedrock outcrops and landslide deposits; mapped in main Carmel Canyon channel
- **Qcof1** — **Active tributary-submarine-canyon axial-channel fill (late Holocene)**—Sand and gravel; minor bedrock outcrops and landslide deposits; in eye-limiting tributaries on north and east flanks of Carmel Canyon

Walls

- **Qcfs** — **Submarine-canyon inner bench deposits (Holocene and)**—Mud and sand; areas of lower gradient adjacent to axial channel that accumulate dominantly fine-grained sediments
- **Qmscp** — **Submarine-canyon platform deposits (Holocene and Pleistocene)**—Mud and minimal sand; relatively smooth areas of lower gradient on crests of bathymetric divide between Carmel Canyon and canyon to west
- **Qcw** — **Submarine-canyon-wall deposits (Holocene and Pleistocene)**—Inferred to be draped by marine and hemipelagic sediments; may contain bedrock outcrops and landslide deposits too small to show at map scale
- **Tpcw** — **Purisima Formation (Pliocene and late Miocene)**—Marine sandstone, siltstone, and mudstone; found within submarine-canyon walls
- **Tmcw** — **Monterey Formation (Miocene)**—Porcellaneous shale, chert, and mudstone; calcareous claystone; and small amounts of siltstone and sandstone; found within submarine-canyon walls
- **Kgrcw** — **Granodiorite (Cretaceous)**—Found within submarine canyon walls

ONSHORE GEOLOGIC AND GEOMORPHIC UNITS

[Units compiled from Clark and others (1997) and Wagner and others (2002); unit ages, which are from these sources, reflect local stratigraphic relations. In addition, some Quaternary units modified by C.W. Davenport on basis of analysis of 2009 lidar imagery]

- **af** — **Artificial fill (late Holocene)**—Heterogeneous mixture of artificially deposited material; ranges from well-compacted sand and silt to poorly compacted sediment high in organic content
- **alf** — **Artificial fill, jetties, and levees (late Holocene)**—Jetties, entrance to Monterey Harbor, and levees around lakes
- **acf** — **Artificial fill in stream channels (late Holocene)**—Material placed in historically active stream channels
- **Qc** — **Active stream-channel deposits (late Holocene)**—Active stream channels that contain unconsolidated sand, silt and gravel deposits
- **Qbs** — **Beach and dune deposits (late Holocene)**—Fine to very-coarse sand; forms active beaches along coast; may form veneer over bedrock platforms
- **Qyd** — **Dune-sand deposits (Holocene)**—Very well-sorted, fine to medium sand; forms active dunes along coast
- **Qal** — **Alluvial deposits, undivided (Holocene)**—Alluvium deposited adjacent to active stream channels; including flood plain deposits of Wagner and others (2002)
- **Qb** — **Basin deposits (Holocene)**—Unconsolidated, fine-grained sediment; deposited in low-energy environments that include estuaries, lagoons, marsh-filled sloughs, and lakes
- **Qe** — **Estuarine deposits (Holocene)**—Unconsolidated silt and clay and interbedded, organic-rich layers; deposited in low-energy environments near mouth of Carmel River
- **Qyf** — **Alluvial fan deposits (Holocene)**—Unconsolidated, heterogeneous layers of sand, silt, and gravel; relatively undissected; deposited by streams emanating from canyons onto alluvial plains
- **Qyt** — **Stream-terrace deposits (Holocene)**—Sand, gravel, silt, and minor clay; overlies relatively flat platforms that are elevated slightly above, and are adjacent to, alluvial deposits or stream channels
- **Qct** — **Colluvium (Holocene)**—Loose to firm, unsorted sand, silt, clay, gravel, rock debris, and organic material, in varying proportions
- **Qd** — **Dune-sand deposits (Holocene and Pleistocene)**—Very well-sorted, fine to medium sand; forms stabilized dunes of uncertain age near coast
- **Qf** — **Alluvial fan deposits (Holocene and Pleistocene)**—Mapped either where elder age is indicated by greater degree of dissection, or at areas higher, than that of adjacent Holocene alluvial fans
- **Qt** — **Stream-terrace deposits (Holocene and Pleistocene)**—Sand, gravel, silt, and minor clay of uncertain age, on relatively flat, elevated surface above stream channels
- **Qls** — **Landslide deposits (Holocene and Pleistocene)**—Weathered and disintegrated rocks and soil; physically weathered, queried where uncertain. Internal contacts differentiate individual landslide bodies
- **Qmt** — **Marine-terrace deposits, undivided (Pleistocene)**—Semiconsolidated sand and local gravel deposits, on uplifted marine-abrasion platforms along coast; queried where uncertain
- **Qoa** — **Older alluvium (Pleistocene)**—Moderately to deeply dissected alluvial deposits; commonly mapped on gently sloping to moderately steep surfaces at regional plane adjacent to present alluvial surface; queried where uncertain
- **Qof** — **Alluvial fan deposits (Pleistocene)**—Unconsolidated to moderately consolidated deposits of semiconsolidated, moderately to poorly sorted, fluvial silty clay, silt, sand, and gravel; deposited adjacent to mountains
- **Qcd** — **Stream-terrace deposits (Pleistocene)**—Sand, gravel, silt, and minor clay; underlies relatively flat surfaces elevated well above stream channels
- **Qod** — **Older dune-sand deposits (Pleistocene)**—Very well-sorted, fine to medium sand; forms extensive coastal dune fields; queried where uncertain
- **Qaw** — **Aromas Sand, eolian lithofacies (early Pleistocene)**—Moderately well-sorted, wind-blown sand
- **QTc** — **Continental deposits, undivided (Pleistocene and Pliocene?)**—Semiconsolidated, fine-grained, oxidized sand and silt; may represent highly weathered eolian sediment
- **Tsm** — **Santa Margarita Sandstone (late Miocene)**—Marine and brackish-marine, yellowish-gray to white, friable, fine- to medium-grained arkosic sandstone; queried where uncertain
- **Tm** — **Monterey Formation (Miocene)**—Pale-orange to white, porcellaneous shale that has chert; mudstone, calcareous claystone, and small amounts of siltstone and sandstone near base
- **Tsb** — **Unnamed sandstone (early Miocene)**—Light-yellowish-orange, poorly to well sorted arkosic sandstone that has conglomerate near base; queried where uncertain
- **Tvb** — **Volcanic rocks (Oligocene)**—Thin flows and flow breccias of basaltic andesite
- **Tc** — **Carmelo Formation (Paleocene)**—Thin- to thick-bedded, graded arkosic sandstone interbedded with pebble and cobble conglomerate
- **Kgd** — **Granodiorite of Monterey (Cretaceous)**—Porphyritic, gray, medium-grained granodiorite that contains orthoclase phenocrysts of various sizes (Ross, 1976); queried where uncertain

EXPLANATION OF MAP SYMBOLS

- **Contact**—Solid where location is certain, long-dashed where location is approximate, short-dashed where location is inferred
- **Fault**—Solid where location is certain, long-dashed where location is approximate, short-dashed where location is inferred, dotted where location is concealed, queried where uncertain
- **Thrust fault**—Solid where location is certain, dashed where location is approximate or inferred, dotted where location is concealed, queried where uncertain. Sawteeth on upper plate
- **Folds**—Solid where location is certain, dotted where location is concealed
- **Anticline**
- **Syncline**
- **Former shoreline or marine limit**
- **Approximate modern shoreline**—From National Oceanic and Atmospheric Administration's Shoreline Data Explorer (National Geodetic Survey, 2015)
- **Limit of California's State Waters**

DISCUSSION

Marine geology and geomorphology were mapped in the Offshore of Monterey map area from approximate Mean High Water (MHW) across the continental shelf, as well as in Carmel Canyon to a water depth of about 1,600 m. This map area includes much of southern Monterey Bay, as well as open coastal waters west of the Monterey peninsula to beyond the limit of California's State Waters (note that the California's State Waters limit, which generally is 3 nautical miles [5.6 km] from shore, extends farther offshore between Santa Cruz and Monterey, so that it encompasses all of Monterey Bay). The shoreline, which is from the National Oceanic and Atmospheric Administration's (NOAA's) Shoreline Data Explorer, is based on their analysis of lidar data (National Geodetic Survey, 2015). Offshore geologic units were delineated on the basis of integrated analyses of adjacent onshore geology with multibeam bathymetry and backscatter imagery (sheets 1, 2, 3), seafloor-sediment and rock samples (Wong and Eittreim, 2002; Reid and others, 2006), digital camera and video imagery (sheet 6), and high-resolution seismic-reflection profiles (sheet 8). Aerial photographs taken in multiple years were used to map the nearshore area (0 to 10 m water depth) and to link the offshore and onshore geology.

The onshore geology was compiled from Clark and others (1997) and Wagner and others (2002); unit ages, which are from these sources, reflect local stratigraphic relations. In addition, some Quaternary units were modified by C.W. Davenport on the basis of analysis of 2009 lidar imagery.

The offshore part of the map area contains two geomorphic features, (1) the continental shelf, and (2) Carmel Canyon and its tributaries (part of the "Monterey Canyon system" of Greene and others [2002]). Most of the relatively flat continental shelf in the Offshore of Monterey map area consists of either exposed bedrock or bedrock overlain by a thin (less than 5 m) cover of sediment. The thickest sediment in the map area (about 16 m) is found in a broad depression about 2 km north of the northernmost tip of the Monterey peninsula, at water depths of about 75 to 85 m (see Map B on sheet 9). Inner shelf to midshelf and nearshore deposits are mostly sand (Qmsc); coarse sand and gravel (Qmsc) is present in the midshelf area about 2 km offshore of Seaside. Unit Qmsf, which lies offshore of unit Qmsc in the midshelf to outer shelf area (water depths of 65 to 150 m), primarily consists of mud and muddy sand, and it commonly is extensively bioturbated.

Unit Qmsd typically is mapped as erosional lags in scour depressions that are bounded by relatively sharp or, less commonly, gradational contacts. Scour depressions are common along this stretch of the California coast (see, for example, Cacchione and others, 1984; Hallenbeck and others, 2012; Davis and others, 2013), where offshore sandy sediment can be relatively thin (sand, thus, is unable to fill the depression) owing to low sediment supply from rivers and also to significant erosion and offshore transport of sediment during large northwest winter swells. Such features have been referred to as "rippled scour depressions" (see, for example, Cacchione and others, 1984) or "sorted bedforms" (see, for example, Goff and others, 2005; Trembanis and Hume, 2011). Although the general areas in which both unit Qmsd scour depressions and surrounding Qmsa sand sheets are found are not likely to change substantially, the boundaries of the unit(s) likely are ephemeral, changing seasonally and during significant storm events.

Sea level has risen about 125 to 130 m over about the last 21,000 years (see, for example, Stanford and others, 2011), leading to broadening of the continental shelf, progressive eastward migration of the shoreline, and associated transgressive erosion and deposition. Sea level rise was apparently not steady, leading to development of a submerged shoreline along the flank of Carmel Canyon (water depths of 80 to 90 m) during a relative sea-level stillstand. Associated with this shoreline is a broad, sandy bench (Qcpsf) at the canyon head.

Bedrock outcrops on the shelf include the Cretaceous granitic rocks of Monterey (Kgr), the Paleocene Carmelo Formation (Tc; Bowen, 1965), the Oligocene volcanic rocks (Tvb), consisting of basaltic andesite, the Miocene Monterey Formation (Tm), and the upper Miocene and Pliocene Purisima Formation (Tp) (Clinton and others, 2002; Wagner and others, 2002). In areas where rocks of the Carmelo Formation and the Oligocene volcanic rocks cannot be confidently divided, unit Tv is mapped. Unit Kgr notably is characterized by high backscatter (sheet 3) and rough, massive, and fractured seafloor texture. In contrast, the less indurated Neogene sedimentary rocks (most notably units Tm and Tp) form lower relief outcrops that commonly have "ribbed" morphology, which reflects the differential hardness (and, hence, erodibility) of sedimentary layers. Several of these bedrock units are in places overlain by a thin (less than 1 m?) veneer of sediment, recognized on the basis of high backscatter, flat relief, continuity with moderate- to high-relief outcrops, and (in some cases) high-resolution seismic-reflection profiles; these areas, which are mapped as composite units (for example, Qmsc/Kgr, Qmsc/Tp) are interpreted as ephemeral sediment lenses that may or may not be continuously present, depending on storms, seasonal and (or) annual patterns of sediment movement, or longer term sediment supply.

The shelf northeast and north of the Monterey peninsula in the map area is cut by the diffuse zone of northwest-striking, steeply dipping to vertical faults of the Monterey Bay Fault Zone. This fault zone, originally mapped by Greene (1977, 1990), extends about 43 km across-coast Monterey Bay (see Map E on sheet 9). Fault strands within the Monterey Bay Fault Zone are mapped with high-resolution seismic-reflection profiles (see sheet 8). Seismic-reflection profiles in the map area that traverse this diffuse zone cross as many as five faults over a width of about 4 to 5 km (see, for example, figs. 3, 5 on sheet 8). The Monterey Bay Fault Zone lacks a continuous "master fault" along which deformation is concentrated. Fault strands are as long as about 20 km (on the basis of mapping outside the map area), but most strands are only about 2 to 7 km long. Faults in this diffuse zone cut through Neogene bedrock, and they locally appear to have minimally disrupted the overlying inferred Quaternary sediments. The presence of warped-reflections along some fault strands suggests that both vertical and strike-slip offset may have occurred. To the south-southeast, the Monterey Bay Fault Zone connects with the Navy, Chupines, Seaside, and Ord Terrace faults onland (Clark and others, 1997; Wagner and others, 2002).

Carmel Canyon, a relatively straight, northwest-trending arm of the Monterey Canyon system that cuts through the northwestern part of the Offshore of Monterey map area, has three heads (Greene and others, 2002). At the south edge of the map area, the canyon is about 3 km wide and has relief of about 300 m. Near the edge of the map area, the three heads coalesce into a single main canyon axis that is about 3 km beyond the southern extent of the map. Steep, sandy canyon-head channel deposits (Qchc) are mapped at the head of the northeast-trending arm of Carmel Canyon, in Carmel Bay.

Active Carmel Canyon channel fill is mapped as three distinct units: unit Qcpsf, which is mapped in upper Carmel Canyon, is characterized by sandy, crescentic bedforms; unit Qcof1, which is mapped in eye-limiting tributaries on the north and east flanks of Carmel Canyon, consists of gravel and minor bedrock outcrops and landslide deposits; unit Qcof2, which is mapped in primary Carmel Canyon channels, consists of sand and gravel that locally forms crescentic bedforms, and it also includes small bedrock outcrops and landslide deposits. Sand and mud deposited on a bench immediately adjacent to the axial channel of Carmel Canyon is mapped as unit Qcfs; although only present only in a small part of the map area, it is more widespread in Monterey Canyon (Maier and others, 2016) to the north, and it also is more extensive in the parts of Carmel Canyon that are south of the map area.

Carmel Canyon walls that are relatively smooth generally are covered by muddy Quaternary sediments (Qcw), which commonly are draped over bedrock outcrops and landslide deposits. Quaternary sediments are absent on most of the Purisima Formation and Monterey Formation canyon walls in the southwestern corner of the map area (Tpcw, Tmcw), underlying bedrock units exposed at greater depths in the canyon walls (Greene, 1977; Greene and others, 1991; Wong and Eittreim, 2002) include the Miocene Monterey Formation (Tmcw) and the Cretaceous granitic rocks of Monterey (Kgrcw). The relatively smooth, flat area in the southwest corner of the map area forms a bathymetric divide between Carmel Canyon to the east and Point Lobos canyon (an informally named submarine canyon west of the map area; see fig. 1–1 in pamphlet) to the west, and it is inferred to be covered by mud and minimal sand (Qmscp).

Carmel Canyon roughly aligns with, and is structurally controlled by, the San Gregorio Fault Zone (Greene and others, 1991), an important structure in the distributed transform boundary between the North American and Pacific plates (see, for example, Dickinson and others, 2005). This fault zone is part of a regional fault system that is present predominantly in the offshore for about 400 km, from Point Conception in the south (where it is known as the Hosgri Fault; Johnson and Watt, 2012) to Bolinas and Point Reyes in the north (Hoose and others, 2002; Ryan and others, 2008). The San Gregorio Fault Zone in the map area is part of a 90-km-long offshore segment that extends northward from Point Sur (about 25 km south of the map area), across-outer Monterey Bay to Point Año Nuevo (about 50 km north of the map area) (see sheet 9; see also, Weber and Lajoie, 1980; Brabb and others, 1998; Wagner and others, 2002). High-resolution seismic-reflection profiles (see sheet 8) show that the fault zone in the map area is characterized largely owing to its significant depth and steep canyon walls. Accordingly, we have mapped the 1,800- to 1,200-m-wide fault zone largely on the basis of the presence of prominent, linearly geomorphic lineaments (see sheets 1, 2), as well as the geomorphic and lithologic contrasts across the fault. Following Greene and others (2002), we map the relatively straight-sloping drainage channels and slumps that lightly dissect the east wall of Carmel Canyon, which is underlain by the Cretaceous granitic rocks of Monterey (Kgrcw). In contrast, the steep cliffs along the west wall of the canyon are underlain by a mix of the Miocene Monterey Formation (here, mapped as Tmcw) and, west of the map area, Cretaceous sedimentary rocks (Greene, 1977; Greene and others, 1991; Eittreim and others, 2002; Wong and Eittreim, 2002).

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Suggested Citation: Hartwell, S.R., Johnson, S.Y., Davenport, C.W., and Watt, J.T., 2016, Offshore and onshore geology and geomorphology, Offshore of Monterey map area, California: U.S. Geological Survey Open-File Report 2016–1110, sheet 10 of 10, 2 sheets, scale 1:24,000. Hartwell, S.R., Johnson, S.Y., Davenport, C.W., Dartnell, P., Kvitek, R.G., Endris, R.G., Erdey, M.D., Watt, J.T., Bretz, C.K., Ritchie, A.C., Kelley, K.S., Kluesner, J.W., Silva, R.M., and Edwards, B.D., 2016, Offshore and onshore geology and geomorphology, Offshore of Monterey map area, California: U.S. Geological Survey Open-File Report 2016–1110, sheet 10 of 10, 2 sheets, scale 1:24,000. http://dx.doi.org/10.3133/ofr20161110.

ISSN 2331-1258 (online)
http://dx.doi.org/10.3133/ofr20161110