Initial Observations and Preliminary Interpretations From Telepresence-Enabled Exploration of the Southern California Borderland, USA1

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INITIAL OBSERVATIONS AND PRELIMINARY INTERPRETATIONS FROM TELEPRESENCE-ENABLED EXPLORATION OF THE SOUTHERN CALIFORNIA BORDERLAND, USA

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Abstract: Much about the offshore California Continental Borderland remains unknown, despite its location off the most populated area of the west coast of North America, vital importance to US interests, and potential for seismic and tsunamigenic hazards. In 2015 and 2016, Exploration Vessel (E/V) *Nautilus* of the Ocean Exploration Trust undertook a series of seven expeditions in that region. During those cruises, we acquired 13,075 km^2 of multibeam bathymetric data, performed 58 dives with remotely operated vehicles (ROV) *Hercules* and *Argus*, totaling 500+ hours underwater (1000+ hours of video), and collected 532 geological and biological samples across this 200-km-wide, tectonically active region. Because *Nautilus* is equipped with state-of-the-art telepresence technology, numerous scientists based on shore actively participated in these expeditions in real time. Here, we describe the data acquired during these expeditions and present some very preliminary results. The digital data and physical samples are accessible to the scientific community via online request systems.

Key words: continental margin, plate tectonics, paleoshorelines, seamounts, hydrocarbon seeps, remotely operated vehicle, telepresence

BACKGROUND

The offshore Southern California Continental Borderland, a region that extends 100 to 200 km westward from the southern California coastline, displays an unusually rugged physiography for a continental margin. Instead of a shallow (<100 m), low-relief continental shelf, typical of the Gulf of Mexico and Atlantic continental margins, it consists of a series of deep (500–2000 m) basins separated by shallow ridges, some of which emerge as the Northern Channel Islands and the Southern Channel Islands (Gorsline and Teng 1989). The borderland encompasses more than 70,000 km^2 and stretches from Point Conception to San Diego and further southward into Mexican waters. The rugged seafloor relief of the southern California margin owes its origin to plate-tectonic activity associated with the evolution of the diffuse boundary between the North American and Pacific plates. Although most of the relative motion between these two tectonic plates is accommodated on land along the infamous San Andreas Fault system, it is estimated that about 20% of the motion occurs along a system of faults submerged beneath the offshore Southern California Borderland (Larson 1993). Some of the offshore faults extend through the Los Angeles and possibly San Diego metropolitan areas and thus represent a major earthquake and tsunami hazard for coastal California (e.g., Marlow et al. 2000; Ryan et al. 2009; Sorlien et al. 2013, 2015; Legg et al. 2015). Some large submarine slides, mapped from multibeam bathymetric data, raise further concerns about tsunami hazards (Lee et al. 2009, Brothers et al. 2019). Rugged bathymetric relief also impacts local coastal currents and provides variable seafloor habitats, driving a high level of biodiversity (Dailey et al. 1993).

The offshore Southern California Continental Borderland was selected by the Ocean Exploration Trust (OET) for extensive exploration because it was identified during the 2014 Workshop on Exploration of the Eastern Pacific Ocean as one of 33 high-priority target areas (Bell et al. 2015). The 2014 workshop was held by OET, in partnership with the National Oceanic and Atmospheric Administration (NOAA) Office of Ocean Exploration and Research (OER). At this workshop, 67 members of the scientific community identified and discussed targets for telepresence-enabled exploration in the eastern Pacific Ocean, ultimately selecting the southern California margin because of its potential to address fundamental questions in biology, archaeology, geology, physics, chemistry, and potential offshore hazards.

As a result, in 2015 and 2016, the Exploration Vessel (E/V) *Nautilus*, a 64 m research vessel operated by OET, undertook seven cruises in the Southern California Continental Borderland (Table 1). This region provides abundant opportunities to study a variety of topics for exploration, including deep-sea corals, plate tectonics, chemosynthetic communities, coastal upwelling, and paleolandscapes, as well as a well-established network of marine protected areas (MPAs), including the federally managed Channel Islands National Marine Sanctuary (CINMS). Exploration by *Nautilus* in this region builds upon decades of research by many other scientists and helps to broaden the fundamental knowledge of the region (e.g., Shepard and Emery 1941, Emery and Shepard 1945, Emery 1960, Gorsline et al. 1968, Crouch 1979, Vedder et al. 1981, Kennedy et al. 1987, Legg 1991, Nicholson et al. 1994, Normark et al. 2009, Legg et al. 2015).

METHODS

Seafloor Mapping

Nautilus is equipped with a hull-mounted 30 kHz EM302 multibeam echosounder and 3.5 kHz Knudsen chirp subbottom echosounder that can be operated simultaneously. A Seapath 330 with an MRU 5+ motion reference unit was used to measure instantaneous heave, attitude, and position. The Seapath was interfaced to the EM302 in real time to record and compensate for pitch, roll, and yaw. A Sippican expendable bathythermograph (XBT) system was used to acquire sound speed profiles to a depth of 760 m. For greater depths, sound speed was extrapolated from World Ocean Atlas models (WOA13).

Multibeam echosounder surveys were designed in consultation with the Southern California Seafloor Mapping Initiative to collect data in areas that had not been previously mapped or that had low-resolution maps (i.e., lead line or single-beam surveys). Footprints and basic metadata for all previously compiled bathymetry surveys are available online and include data collected by the US Geological Survey (USGS), NOAA, National Science Foundation, Monterey Bay

Table 1.—*Nautilus* undertook seven cruises in 2015 and 2016 in the Southern California Continental Borderland that included multibeam echosounder mapping and/or ROV dives.

Cruise	Dates	Cruise name	Operations
NA065	July 8–23, 2015	Seamount Mapping	seafloor mapping
NA066	July 27–August 10, 2015	California Borderland I	seafloor mapping and ROV dives
NA067	August 11–18, 2015	California Borderland II	seafloor mapping and ROV dives
NA073	June 22–July 2, 2016	Central California	seafloor mapping and ROV dives
NA074	July 3–21, 2016	Channel Islands National Marine Sanctuary	seafloor mapping and ROV dives
NA075	July 24–August 13, 2016	Southern California Borderland	seafloor mapping and ROV dives
NA078	August 29–September 12, 2016	Cascadia Margin & California Borderland	seafloor mapping and ROV dives

Aquarium Research Institute, California State University–Monterey Bay, and others (SeaSketch 2017).

Remotely Operated Vehicle Operations

After bathymetric maps were examined, interesting targets were selected for closer inspection. The *Hercules/Argus* tandem remotely operated vehicle (ROV) system is the primary robotic system aboard *Nautilus*. *Argus* is a camera-sled ROV that is connected to the vessel directly by a 4200-m-long, 1.73 cm (0.68 in.) fiber-optic cable, providing power and data transmission to both vehicles, as well as isolating *Hercules* from the ship motion. *Argus* also provides lights and a high-definition bird's-eye view of *Hercules* as it works on the seafloor. *Hercules* and *Argus* are connected with an ∼30-m-long, neutrally buoyant, fiber-optic tether. *Hercules* works close to the seafloor and is capable of picking up geological and biological samples with two manipulator arms, sampling water with up to six Niskin bottles, collecting sediment push cores up to 28 cm long, collecting up to seven slurp samples, and continuously recording oceanographic data such as salinity, temperature, and dissolved oxygen concentration. On many of the dives, *Hercules* was also equipped with a Miniature Autonomous Plume Recorder (MAPR) for measuring and logging light-backscattering, oxidation–reduction potential, temperature, and pressure.

Telepresence and Scientists Ashore

Nautilus is equipped with state-of-the-art telepresence technology. This set of tools enables shore-based scientists to actively contribute expertise to expeditions in real time, one of several advantages of telepresence capabilities (Kintisch 2013, Marlow et al. 2017). Collaboration tools include live video streaming online, a Science Chat application to facilitate communication between the science teams at sea and ashore, and a Data Dashboard for scientists ashore to view semi-real-time digital data being collected by the ROVs. During each of five cruises off southern California that included ROV dives, 11 to 19 scientists participated from shore, more than tripling the size of the science party actively engaged in each cruise.

BACKGROUND, OBJECTIVES, RESULTS, AND PRELIMINARY INTERPRETATIONS

During the *Nautilus* cruises in the southern California region, we mapped approximately 13,075 km^2 with the multibeam echosounder and conducted 58 ROV dives, during which we collected more than 1000 hours of underwater video and 532 biological and geological samples (Fig. 1; Table 2; Appendix Tables 3–11).

One of the driving tenets of the *Nautilus* exploration program is making digital and physical data resulting from expeditions accessible to the scientific community. The NOAA Ocean Exploration Digital Atlas provides basic information about *Nautilus* cruises, including cruise locations and ship tracks (http://www.ncddc.noaa.gov/website/google_maps/OE/mapsOE.htm). Once a cruise of interest is identified, scientists may request access to digital data and samples from one of OET's partner repositories. *Nautilus* data are currently archived in three locations based on data type:

- Digital data and video are archived at the University of Rhode Island (URI) Inner Space Center (ISC) and are available upon request (http://www.oceanexplorationtrust.org/data-request).
- Geological rock and core samples are archived at the URI Marine Geological Samples Laboratory (MGSL) and can be found through the National Centers for Environmental Intelligence (NCEI) Index to Marine and Lacustrine Geological Samples (IMLGS) (https://data.nodc.noaa.gov/cgi-bin/iso?id=gov.noaa.ngdc.mgg.geology:G00028). To find geological samples, search for "*Nautilus*" under "Platform Names."
- Biological samples are archived at the Harvard University Museum of Comparative Zoology (MCZ) (https://mczbase.mcz.harvard.edu/SpecimenSearch.cfm) and can be found by searching for "*Nautilus*" in the "Collector" field.

The following sections include our initial observations and interpretations of data from many of the dive sites that were visited during these cruises.

Santa Barbara Basin

Santa Barbara Basin Floor and Slope: *Study area*—The sediment record from Santa Barbara Basin (SBB) is a uniquely high-quality paleoclimate archive (e.g., Hendy and Kennett 1999, 2000) that has "submillennial synchrony" with the climate records from Greenland (GISP2), meaning that SBB sediments record both regional oceanographic change and global-scale change in climate (Behl and Kennett 1996, Hendy et al. 2002). Seafloor biodiversity records from SBB have demonstrated that past events of climate warming have been accompanied by large oscillations of the oxygen minimum zone (OMZ) vertical structure (Moffitt et al. 2015).

Objectives—The objectives of dives H1462, H1463 (2015), H1525, H1527, and H1530 (2016) were to investigate the OMZ, collecting surficial sediments and characterizing the observed habitats and ecosystems along vertical transects. The resulting data are contributing to a long-term time-series investigation of the OMZ in SBB.

Results—On the northern slope of SBB (Fig. 2A; Appendix Table 3), we collected seven push cores on dive H1462 and six push cores on dive H1527 at various depths across the OMZ. On dive H1530, we characterized the geochemical, microbiological, and macro- and megafaunal diversity of the sediments and overlying water column. On the southern slope (Fig. 2B), we conducted a video survey of an area explored by ROV *Doc Ricketts* in 2014. Whereas that ROV observed only microbial mats at this site, ROV *Hercules* found gastropods and some fish, but little evidence of a seep community during dive H1463. On dive H1525, we collected six push cores at 20 m intervals across the OMZ. There was special interest taken in observing *Alia permodesta*, the indicator species for very low oxygen concentrations (<0.15 ml/L^2), as well as conducting water-column transects upon ascent.

Data collected during dive H1462 along the northern slope document that the OMZ extends from 450 m water depth, near the SBB sill depth (475 m), down to the basin floor; they also reveal major changes in the distribution of biota that are tied largely to changes in dissolved oxygen concentration (Myhre et al. 2018). Analysis of the samples collected during the other four dives will help to refine the observed changes in benthic communities, nitrogen cycling, and vertical hydrographic structure across the California Current OMZ. As the northern and southern transects are associated with different local conditions (e.g., seafloor geology, ocean currents, nutrient density), the baseline data collected during these dives can help to identify local effects and the potential future evolution of the benthic communities across the OMZ boundary.

Southern Shelf of SBB: *Study area*—During the Last Glacial Maximum (∼18,000 years ago), the Northern Channel Islands formed a 100-km-long contiguous island called Santarosae Island (Orr 1968), and the southern shelf of SBB corresponded to one continuous subaerially exposed area. Recently acquired multibeam backscatter imagery suggests that the shelf comprises many areas of hard bottom, probably eroded during lowstand. These rocky areas are expected to provide favorable habitat for cold-water corals.

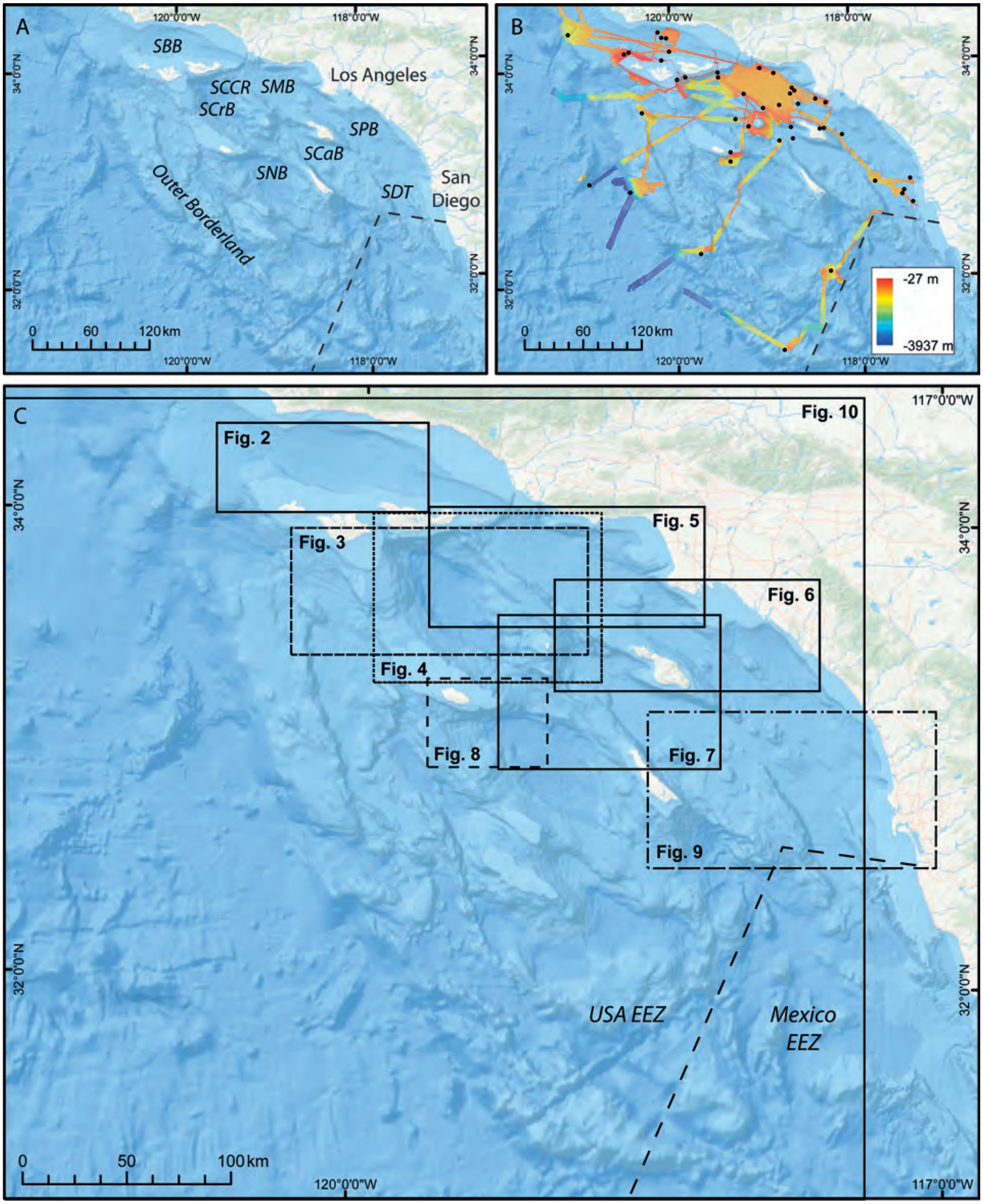

FIG. 1.—In 2015 and 2016, *Nautilus* undertook seven cruises that mapped 13,075 km^2 of seafloor and completed 58 ROV dives in the southern California Borderland, south of Point Conception and north of the border with Mexico. **A)** The area of study includes Santa Barbara Basin (SBB); Santa Cruz–Catalina Ridge (SCCR); Santa Monica Basin (SMB); Santa Cruz Basin (SCrB); San Pedro Basin (SPB); San Nicolas Basin (SNB); Santa Catalina Basin (SCaB); San Diego Trough (SDT); and the Outer Borderland. **B)** Multibeam coverage (colored swaths) and ROV dive locations (black dots). **C)** Boxes indicate locations of Figures 2–10.

TABLE 2.—Remotely operated vehicle dives in the Southern California Borderland, listed by region: Santa Barbara Basin (SBB), Santa Cruz Basin (SCrB), Santa Cruz–Catalina Ridge (SCCR), Santa Monica Basin (SMB), San Pedro Basin (SPB), Santa Catalina Basin (SCaB), San Nicolas Basin (SNB), San Diego Trough (SDT), and Outer Borderland (OB).

Region	Cruise	Dive	Dive site	SOD date (year-month-day)	SOD time (UTC)	SOD lat (°N)	SOD lon (°W)	EOD date (year-month-day)	EOD time (UTC)	EOD lat (°N)	EOD lon (°W)
SBB	NA067	H1462	Santa Barbara Basin, North	2015-08-16	15:15:43	34.3482	−120.1233	2015-08-17	07:06:01	34.3615	−120.1147
SBB	NA073	H1527	Santa Barbara Basin, North	2016-06-26	07:12:26	34.3521	−120.1210	2016-06-26	15:37:26	34.3867	−120.1436
SBB	NA073	H1530	Santa Barbara Basin, North	2016-06-30	14:29:03	34.3002	−120.0807	2016-07-01	07:16:29	34.3017	−120.0708
SBB	NA067	H1463	Santa Barbara Basin, South	2015-08-17	11:00:04	34.1589	−120.0005	2015-08-17	15:15:40	34.1518	−119.9990
SBB	NA073	H1525	Santa Barbara Basin, South	2016-06-23	19:58:05	34.1722	−120.0061	2016-06-24	14:06:35	34.1731	−120.0072
SBB	NA073	H1526	Goleta Landslide Complex	2016-06-25	02:05:03	34.2943	−120.0294	2016-06-26	03:10:55	34.3596	−119.8925
SBB	NA074	H1535	Wilson Rock	2016-07-14	20:17:14	34.1684	−120.4524	2016-07-15	01:59:53	34.1577	−120.4356
SBB	NA074	H1536	Richardson Rock	2016-07-15	04:03:37	34.1541	−120.5026	2016-07-15	07:14:57	34.1412	−120.5077
SBB	NA074	H1538	Carrington Point	2016-07-16	14:20:15	34.0909	−120.0896	2016-07-16	18:43:13	34.0874	−120.1059
SCrB	NA074	H1540	South Santa Rosa	2016-07-19	15:43:19	33.9063	−119.9186	2016-07-20	05:14:42	33.9010	−119.9257
SCrB	NA074	H1533	Santa Cruz Canyon	2016-07-12	16:31:20	33.9244	−119.8259	2016-07-13	03:43:33	33.9471	−119.8436
SCrB	NA074	H1532	Santa Barbara Island Knoll	2016-07-09	21:52:13	33.4578	−119.1468	2016-07-10	03:56:04	33.4792	−119.1464
SCrB	NA075	H1557	SE Santa Cruz Basin	2016-08-08	22:56:09	33.5258	−119.2872	2016-08-09	15:13:21	33.5140	−119.2454
SCCR	NA074	H1534	Footprint Reef	2016-07-14	01:04:36	33.9608	−119.4717	2016-07-14	07:07:54	33.9620	−119.4825
SCCR	NA074	H1541	Piggy Bank	2016-07-20	15:55:10	33.9173	−119.4676	2016-07-20	20:56:16	33.9169	−119.4642
SCCR	NA075	H1544	Pilgrim Banks	2016-07-26	07:18:50	33.7634	−119.1787	2016-07-26	18:09:39	33.7524	−119.2021
SCCR	NA075	H1545	Pilgrim Banks	2016-07-26	21:28:46	33.7538	−119.2002	2016-07-27	00:15:29	33.7663	−119.1821
SCCR	NA075	H1543	Hillside Valley	2016-07-25	15:32:43	33.6190	−118.9770	2016-07-26	04:13:19	33.6504	−119.0073
SMB	NA066	H1454	Point Dume	2015-08-06	23:05:09	33.9415	−118.8446	2015-08-07	15:29:01	33.9428	−118.8459
SMB	NA066	H1456	Point Dume	2015-08-09	03:14:14	33.9385	−118.8547	2015-08-09	23:25:04	33.9434	−118.8447
SMB	NA067	H1457	Point Dume	2015-08-12	15:36:04	33.9384	−118.8536	2015-08-13	03:32:29	33.9441	−118.8482
SMB	NA073	H1528	Point Dume	2016-06-27	00:03:12	33.9408	−118.8482	2016-06-27	18:59:17	33.9332	−118.8402
SMB	NA066	H1451	Redondo Canyon	2015-08-04	03:45:33	33.7989	−118.6500	2015-08-04	07:10:55	33.8016	−118.6523
SMB	NA066	H1455	Redondo Knoll	2015-08-08	03:04:54	33.6459	−118.5904	2015-08-08	19:05:01	33.6597	−118.5750
SMB	NA067	H1461	Redondo Knoll	2015-08-15	23:17:33	33.7450	−118.6737	2015-08-16	06:47:50	33.7465	−118.6793
SMB	NA075	H1542	Redondo Knoll	2016-07-24	21:02:28	33.7709	−118.6241	2016-07-25	06:55:56	33.6725	−118.6063
SMB	NA075	H1548	Santa Monica Basin	2016-07-29	07:16:48	33.6424	−118.8010	2016-07-29	18:30:04	33.6408	−118.8097
SMB	NA078	H1570	Sycamore Knoll	2016-09-07	17:37:23	33.9867	−119.0025	2016-09-07	22:09:53	33.9831	−119.0017
SMB	NA078	H1571	Sycamore Knoll	2016-09-08	21:36:15	33.9895	−119.0094	2016-09-09	04:45:10	33.9911	−119.0172
SPB	NA066	H1452	Palos Verdes	2015-08-04	15:16:26	33.6844	−118.4038	2015-08-05	19:09:29	33.6850	−118.3707
SPB	NA073	H1531	Palos Verdes	2016-07-01	17:08:10	33.6919	−118.3926	2016-07-01	22:10:04	33.6986	−118.3708
SPB	NA066	H1453	San Pedro Sea Valley	2015-08-06	03:07:18	33.6503	−118.2874	2015-08-06	15:10:13	33.6618	−118.2790
SPB	NA067	H1458	Long Point Fault	2015-08-13	15:10:10	33.4139	−118.3265	2015-08-13	17:23:43	33.4121	−118.3235
SPB	NA067	H1459	Long Point Fault	2015-08-14	01:49:36	33.4124	−118.3271	2015-08-14	14:34:28	33.4001	−118.3322
SPB	NA075	H1556	Long Point	2016-08-08	02:59:13	33.4089	−118.3608	2016-08-08	15:10:56	33.4040	−118.3619
SPB	NA066	H1450	USGS Wipeout	2015-08-03	01:08:12	33.3492	−118.1228	2015-08-03	07:19:01	33.3571	−118.1274
SCaB	NA075	H1554	Kimki Ridge	2016-08-06	01:36:12	33.3129	−118.8106	2016-08-06	15:22:41	33.2894	−118.7564
SCaB	NA075	H1555	Catalina Canyon	2016-08-06	19:08:18	33.3275	−118.6614	2016-08-07	07:01:51	33.3592	−118.6515
SCaB	NA067	H1460	Catalina Escarpment	2015-08-14	19:07:42	33.4352	−118.6807	2015-08-15	15:07:59	33.4730	−118.6397
SNB	NA075	H1546	San Nicolas Escarpment	2016-07-27	20:01:11	33.1379	−119.3589	2016-07-28	11:03:37	33.1968	−119.3745
SNB	NA075	H1547	San Nicolas Shelf	2016-07-28	16:44:34	33.2211	−119.3586	2016-07-29	01:53:14	33.2206	−119.3598

TABLE 2.—*Continued.*

Region	Cruise	Dive	Dive site	SOD date (year-month-day)	SOD time (UTC)	SOD lat (°N)	SOD lon (°W)	EOD date (year-month-day)	EOD time (UTC)	EOD lat (°N)	EOD lon (°W)
SDT	NA066	H1444	Del Mar Seep	2015-07-27	23:11:23	32.9041	−117.7810	2015-07-28	16:08:13	32.9114	−117.7739
SDT	NA066	H1445	Del Mar Seep	2015-07-28	19:39:13	32.9039	−117.7827	2015-07-29	03:40:49	32.9032	−117.7848
SDT	NA066	H1449	La Jolla Canyon	2015-08-02	07:18:57	32.9154	−117.4010	2015-08-02	18:08:07	32.9130	−117.3329
SDT	NA066	H1448	OMZ Transect	2015-08-01	11:03:14	32.8127	−117.4709	2015-08-02	03:08:33	32.8158	−117.4036
SDT	NA066	H1447	Rosebud Whalefall	2015-07-31	23:17:18	32.7765	−117.4887	2015-08-01	07:22:33	32.7789	−117.4844
SDT	NA066	H1446	Fish Bands	2015-07-29	15:15:50	32.6980	−117.3784	2015-07-29	18:47:48	32.6947	−117.3824
OB	NA074	H1537	Arguello Canyon	2016-07-15	16:15:44	34.3499	−121.1237	2016-07-16	05:40:48	34.3417	−121.1269
OB	NA074	H1539	Arguello Canyon	2016-07-17	15:42:19	34.3382	−121.1172	2016-07-18	17:17:18	34.3650	−121.1074
OB	NA078	R1047	Arguello Canyon	2016-09-10	15:58:08	33.8397	−121.3174	2016-09-10	23:12:07	33.8394	−121.3170
OB	NA075	H1558	Trask Knoll	2016-08-10	03:41:30	33.6062	−120.3168	2016-08-10	19:21:11	33.6104	−120.2613
OB	NA073	H1529	San Juan Seamount	2016-06-28	07:16:59	32.9507	−120.9153	2016-06-29	18:24:22	32.9970	−121.0298
OB	NA075	H1559	Patton Escarpment	2016-08-11	19:29:01	32.8737	−120.4664	2016-08-12	22:53:46	32.8904	−120.3949
OB	NA075	H1553	Northeast Bank	2016-08-04	14:56:28	32.2899	−119.7123	2016-08-05	15:32:20	32.3346	−119.6393
OB	NA075	H1551	Sixtymile Bank	2016-08-01	23:08:06	32.0902	−118.3060	2016-08-02	19:11:29	32.0814	−118.2588
OB	NA075	H1552	Southwest Bank	2016-08-03	07:01:03	31.3770	−118.8449	2016-08-03	19:23:12	31.4009	−118.8300

SOD = start of dive; EOD = end of dive; UTC = Coordinated Universal Time.

Objectives—Three hard-bottom areas were investigated for seafloor habitat and geological outcrops. On Richardson Rock (H1536), we planned to conduct an exploratory dive in a newly mapped area of CINMS to ground truth the seafloor habitat, focusing on corals and rock samples. After collecting new mapping data around Wilson Rock (H1535), we planned to investigate the seafloor morphology, geological character, and habitat along the transect path. Off Carrington Point (H1538), we planned a shallow dive along a reef to collect live coral samples for thermal tolerance experiments while conducting transects of coral habitat.

Results and preliminary interpretation—The dives at Wilson Rock (H1535), Richardson Rock (H1536), and Carrington Point (H1538) spanned depths ranging from approximately 50 to 120 m (Fig. 2C–E). Near Wilson Rock, the seafloor was characterized by alternating sedimented and rocky areas, as well as at least two rocky outcrops, from which four samples were collected (Fig. 2D; Appendix Table 3). Sedimentary rock ledges, large boulders, and a large sandstone outcrop were found at Richardson Rock (Fig. 2C; Appendix Table 3). Microbial mats were also noted, which could represent seep activity or colonized kelp/eelgrass falls. At Carrington Point, large rock outcrops were observed with an abundance of diverse corals including *Acanthogorgia*, *Eugorgia*, *Paragorgia*, *Acanthogorgia*, and *Lophelia*, many of which were sampled (Fig. 2E; Appendix Table 3).

Goleta Landslide Complex: *Study area*—The Goleta landslide complex is located on the northern slope of the SBB, off Coal Oil Point near the town of Goleta, California (Fig. 2). The complex is 14.6 km long by 10.5 km wide, lies at water depths from 90 to 574 m, and is a compound submarine landslide composed of slump blocks and mud flows that may be cut by active faults (Greene et al. 2006). Previous research on the complex included seismic reflection profiling, vibracoring, and ROV dives conducted by MBARI (Greene et al. 2006) and the USGS, work that enabled slide stratigraphy to be dated by correlation to Ocean Drilling Program (ODP) Site 893, located just south of and off the slide complex (Fisher et al. 2005).

Objectives—The objective of dive H1526 was to explore three lobes of the Goleta landslide complex, conducting a visual survey and water sample collection.

Results and preliminary interpretation—The observational dive began on the toe of the western lobe, where linear methane seeps and microbial mats were observed at a depth of 552 m, and moved upslope to a depth of 533 m (Fig. 2F). We then proceeded east and south toward the central lobe; cracks and black sediment in linear east–west features were observed, which could be a possible sign of faulting, continued lateral spreading, or further incipient failure of the slide. The vehicles were towed in the midwater to an E–W-trending fissure, located on the eastern side of the complex about halfway up the eastern lobe, and began two short transects, one along the fissure or gully, and another upslope from 414 to 150 m along the eastern edge of the Eastern Section of the complex. The transect to the headwall scarp of the Eastern Section where we hoped to find potential hanging-wall fault strands was relatively featureless, with a heavily sedimented seafloor and an abundance of fauna, including echinoderms, fishes, cephalopods, gastropods, and siphonophores. Four suction samples were collected during the transect, and four water samples were collected at 100 m intervals from 500 to 200 m (Appendix Table 3).

Santa Cruz Basin

Northwest Santa Cruz Basin: *Study area*—Santa Cruz Canyon descends into Santa Cruz Basin between Santa Cruz and Santa Rosa

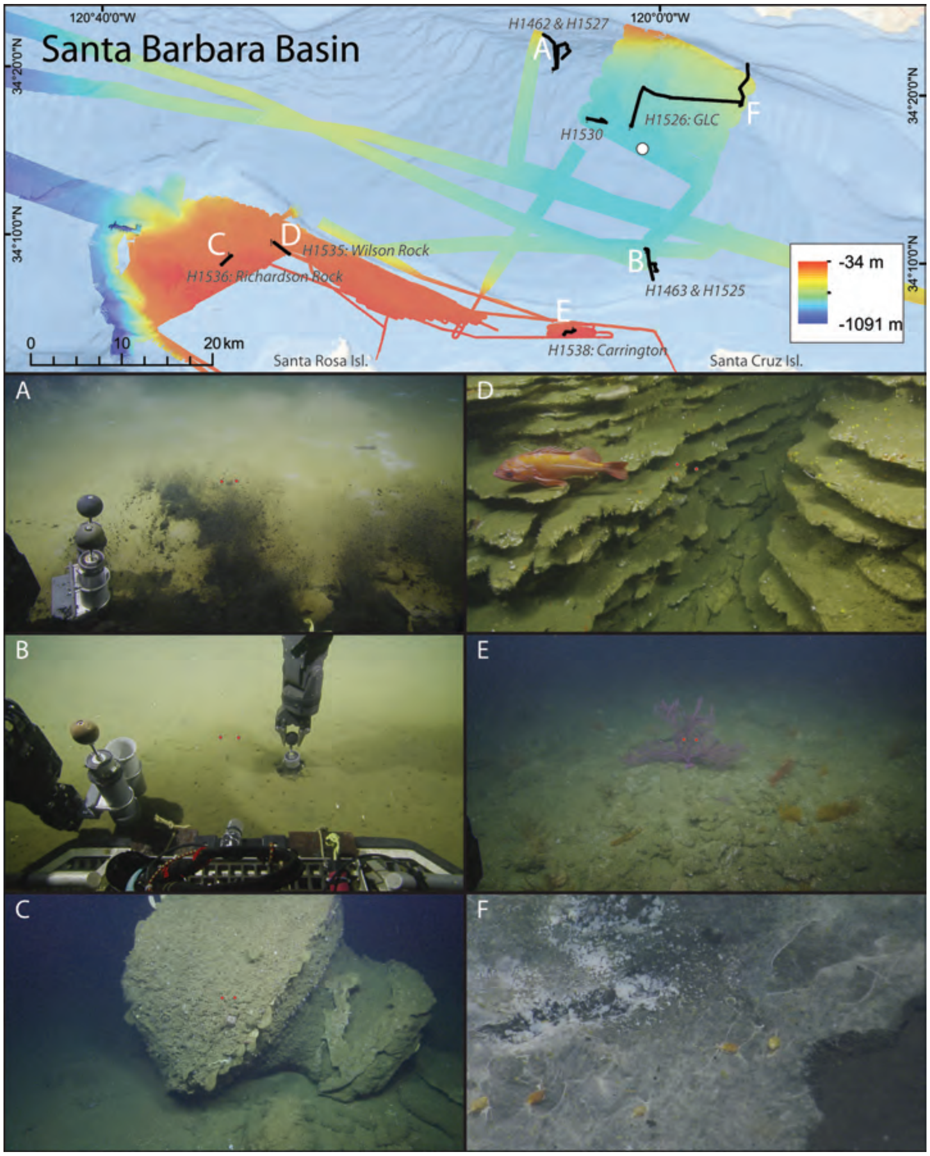

FIG. 2.—Santa Barbara Basin. Top: Newly acquired multibeam bathymetric data (colored swaths) and *Hercules* dive tracks (black lines). White dot indicates the approximate location of Ocean Drilling Program (ODP) Site 893. Select still frames from *Hercules*: **A)** In the north Santa Barbara Basin, *Hercules* stirred up black anoxic sediment below a thin surficial layer of hemipelagic mud during an oxygen minimum zone (OMZ) transect. **B)** *Hercules* collected several sediment push cores during transects through OMZs on both the north and south slopes of the basin. **C)** Large circular sedimentary concretion on Richardson Rock may be evidence of ancient seepage. **D)** A layered sedimentary rock formation on Wilson Rock is colonized by crinoids, sponges, and other invertebrates, as well as an abundance of rockfish. **E)** Purple gorgonian coral at Carrington Point, one of many corals observed at this site. **F)** Slurp samples collected from microbial mats on the Western Section of the Goleta landslide complex (GLC), including this one at 550 m that was home to several *Alia permodesta* gastropods (sample NA073-010). For scale, red scaling dots are 10 cm apart (A–E); the field of view for F is ~0.5 m.

Islands (Fig. 3), incising the marine terraces surrounding these Northern Channel Islands (Chaytor et al. 2008). Detrital material transported in Santa Cruz Canyon is a primary sediment source for Santa Cruz Basin (Nardin et al. 1979). Santa Cruz Canyon is also a conduit for both upwelling and downwelling currents that impact biological productivity (Blanchette et al. 2006). An unnamed knoll south of Santa Cruz Island with a minimum depth below sea level of 87 m was an island during the Last Glacial Maximum, when relative sea level is thought to have been 95 m (Muhs et al. 2014) to 140 m (Lambeck et al. 2014) lower than today, depending on the locations and data used in modeling. New, unpublished seismic reflection data collected from the east side of Santa Rosa Island (Southern California Underwater Mapping Cruise, Stanford University, May 29–June 2, 2016) indicated that folded strata crop out on the shelf. Furthermore, these same data imaged upward-folded sediments surrounding a prominent zone of nonstratified, possibly volcanic, material.

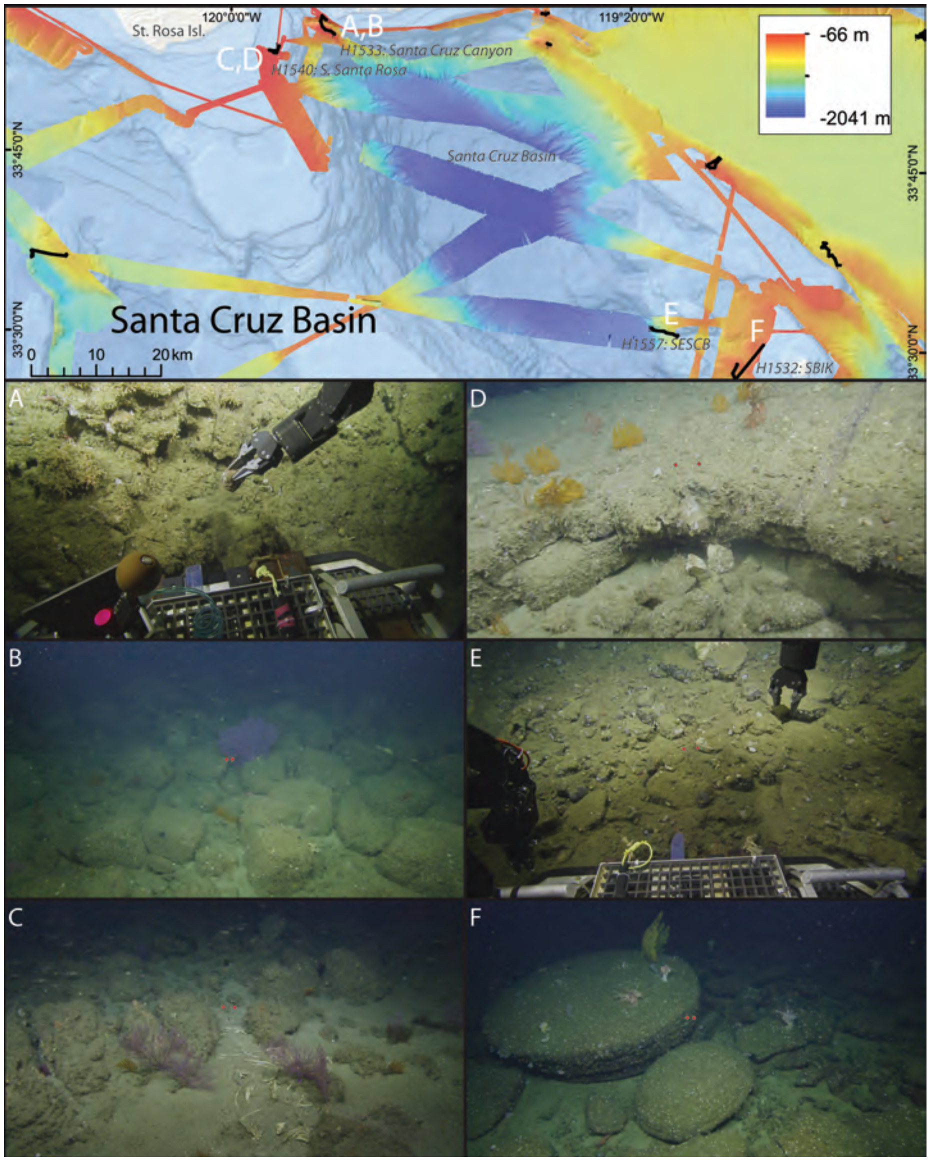

FIG. 3.—Santa Cruz Basin. Top: Newly acquired multibeam bathymetric data (colored swaths) and *Hercules* dive tracks (black lines). Select still frames from *Hercules*: **A)** *Hercules* collects a small sediment-covered cobble from a steep slope in Santa Cruz Canyon (sample NA074-009). **B)** Sediment-covered boulders encrusted by corals at the summit of the unnamed knoll in Santa Cruz Canyon. **C)** Unidentified bones, possibly from a marine mammal, were found amongst carbonate rocks colonized with purple corals south of Santa Rosa Island (SRI). **D)** A carbonate shelf on the South Santa Rosa dive from which *Hercules* collected a sample (sample NA074-106). **E)** *Hercules* collecting a sample in the southeast Santa Cruz Basin (SESCB) from a talus pile on a steep slope that may be in close proximity to the fault zone (sample NA075-125). **F)** Large circular rocks (concretions?) found on the southwest slope of Santa Barbara Island Knoll (SBIK) that could be evidence of ancient carbonate chimneys. For scale, the claw at the end of the manipulator arm is 18 cm long (A); red scaling dots are 10 cm apart (B–F).

Objectives—On dive H1533, we planned to explore Santa Cruz Canyon and a nearby unnamed knoll to: (1) collect samples of exposed Holocene to latest Pleistocene marine terraces at slide features; (2) inspect canyons and ancient deltas for evidence of Pleistocene human activity; and (3) assess benthic habitat for *Lophelia pertusa*. Southeast of Santa Rosa Island (H1540), we dove on a low-relief area to: (1) collect potentially volcanic rocks; (2) image the seafloor habitat, especially cold-water coral populations; and (3) investigate the seafloor morphology and geological character of the shelf habitat.

Results and preliminary interpretation—Southwest of Santa Cruz Island, *Hercules* ascended the unnamed knoll and sampled features indicative of the shoreface, intertidal zone, and beach formed during the Last Glacial Maximum (H1533), as well as the likely subaerial land surface (Fig. 3A, B; Appendix Table 4). Approaching the 100 m contour, the seafloor was characterized by sand to silt with interspersed patches of angular pieces of broken carbonate rock, including rounded cobbles, potentially rounded by wave action. At a depth of 100 m, we observed erosional patterns indicative of the intertidal zone that had exposed bedrock with angular to rounded edges and many undercut notches. Depressions now filled with a thin veneer of soft sediment cover were likely tide pools during the Last Glacial Maximum. At 97 m, we observed a prominent ledge with an undercut notch up to 0.3 m deep. The seafloor between 97 and 95 m was covered primarily in coarse sand with no bedrock outcrops. An apparent, paleoshoreline was observed at 95 m depth, where sandy deposits abruptly transitioned to exposed bedrock with angular to subangular edges. Owing to the relative lack of sediment cover on the exposed basement, it is likely that this area was subaerial until ~19.5 ka and the onset of postglacial sea-level rise (Lambeck et al. 2014); alternatively, it may have been swept clear of sediment by currents. This is the type of feature that, if exposed, would have been an attractive environment for fishing during the early stages of human occupation of North America.

Southeast of Santa Rosa Island (H1540; Appendix Table 4), we conducted seven visual seafloor transects that were primarily focused on coral and habitat observation, but they also included a photomosaic survey and the collection of several water, biological, and geological samples, including a carbonate rock (Fig. 3D). We also observed the bones of an unidentified animal, likely a marine mammal (Fig. 3C). We encountered many outcrops of folded sedimentary formations, features that were clearly imaged by an existing seismic profile (see "Study Area" subsection above); however, we did not find any evidence of volcanic outcrop, as was suggested by that same seismic profile.

Southeast Santa Cruz Basin: *Study area*—The East Santa Cruz Basin Fault is commonly assumed to mark the transition between the Inner California Continental Borderland, a region that has been tectonically extended and exhumed during the Miocene (20–5 Ma), and the Outer California Continental Borderland, a region that preserves the accretionary prism and forearc that developed during the very long period (Mesozoic to mid-Cenozoic) of subduction of the Farallon plate beneath North America (Crouch 1979). Recent work (De Hoogh et al. 2019) suggests that this fault system is an oblique reverse fault that may be "blind" (i.e., not cropping out at the seafloor) along most of its length.

Objectives—The purpose of dive H1557 was to follow a canyon upslope that deeply incises the east flank of Santa Cruz Basin, with the goal of locating the East Santa Cruz Basin Fault where it might be exposed in the eroded canyon wall. To the northwest of Santa Barbara Island Knoll (H1532), our goal was to ground truth newly mapped seafloor, specifically to examine a small seamount to investigate its geological character and benthic habitat and collect rock samples and pieces of living coral.

Results and preliminary interpretation—Dive H1557 followed a canyon up the eastern flank of the 1900-m-deep Santa Cruz Basin (Fig. 3E). The dive focused on the north wall of the canyon rather than the canyon floor, a strategy that allowed for locating and sampling unsedimented rocky outcrops (Appendix Table 4). The East Santa Cruz Basin Fault is interpreted to occur at around 1200 m depth, as expressed by steeply dipping and pervasively fractured strata (sample NA075-125). During the dive on the knoll west of Santa Barbara Island (H1532), we discovered large circular sedimentary concretions that could be evidence of ancient seeps (Fig. 3F). In total, 15 geological and two biological (coral) samples were collected in this region (Appendix Table 4).

Santa Cruz–Catalina Ridge

The Santa Cruz–Catalina Ridge is an ~1000-m-high NW-trending ridge, which, as its name suggests, extends between Santa Cruz Island and Catalina Island (Fig. 4). It owes its origin to the Santa Cruz–Catalina Ridge Fault Zone, a transpressional fault zone marking the oblique convergence between the Inner Borderland and the Northern Channel Islands (Legg et al. 2015). A M_w 6.0 dextral strike-slip earthquake that occurred in 1981 along the ridge documents that this fault zone is active (Corbett 1984, Legg et al. 2015).

Northwestern Banks: *Study area*—Footprint Reef, Piggy Bank, and Pilgrim Banks occur along the Santa Cruz–Catalina Ridge. All three are interpreted to be "pressure ridges," which are push-up features that develop along faults where displacement involves a small component of compression in addition to strike-slip motion. Pilgrim Banks is a subsided feature characterized by sharp pinnacles of igneous rock surrounded by a large marine terrace platform (Normark et al. 2004, Chaytor et al. 2008, Francis et al. 2019). Four clear bathymetric terraces surround Pilgrim Banks, extending to the north and south around most of the larger Kidney Bank. Several dives were planned along the Santa Cruz–Catalina Ridge to explore the fault trace for evidence of recent activity, as well as across shallow banks thought to have been exposed above sea level during the Last Glacial Maximum.

Objectives—Dives to Footprint Reef (H1534) and Piggy Bank (H1541) were intended to collect photomosaic data of coral habitat and live coral samples. On Pilgrim Bank (dives H1544 and H1545), we planned to follow a canyon up the eastern slope of Pilgrim Bank, collect geological samples, document pinnacle structures, look for evidence of submerged marine terraces, and collect 360° video of the pinnacles atop the banks.

Results and preliminary interpretation—On Footprint Reef, we observed an abundance of biologically encrusted outcrops and slabs (Fig. 4A). Terrace-like features were not observed on this dive, suggesting that Footprint Reef did not reach shallow enough depths to be eroded by waves or currents, even during sea-level lowstands. On Piggy Banks, two high-resolution photomosaics were completed on a large lophelia coral reef area (Fig. 4D), and a temperature logger was recovered. Dive H1544 ascended the submarine canyon near Pilgrim Banks and sampled sedimentary units (Appendix Table 5) with the aim of sampling fossils from the subsided marine terrace sequence that could precisely constrain the age of Pilgrim Banks' marine terraces (Fig. 4C). On the ascent up the succession of terraces, abundant evidence of wave erosion was observed, including abandoned sandy beaches covered with rounded rocks and shell hash. On the pinnacles near the shoal part of Pilgrim Banks, we collected stunning 360° video (Fig. 4D).

Hillside Valley: *Study area*—South of Pilgrim Banks, the Santa Cruz–Catalina Ridge Fault Zone is expressed along the northeast flank of the Santa Cruz–Catalina Ridge as a 3- to 5-km-wide, 30- to 40-km-long valley, referred to as "Hillside Valley." The fault zone was host to the 1981 Santa Barbara Island (M_w 6.0) earthquake (Corbett 1984). That earthquake was a dextral-slip event on a vertical fault zone along the Hillside Valley, near the junction of the Santa Cruz–Catalina Ridge Fault and the San Clemente Fault (Hauksson et al. 2012, Legg et al. 2015). Stanford University conducted a detailed seismic reflection survey along the Santa Cruz–Catalina Ridge fault during spring of 2016 to help identify dive targets within the valley and along its flanks (Castillo and Klemperer 2016), and these seismic profiles were used to plan dive H1543.

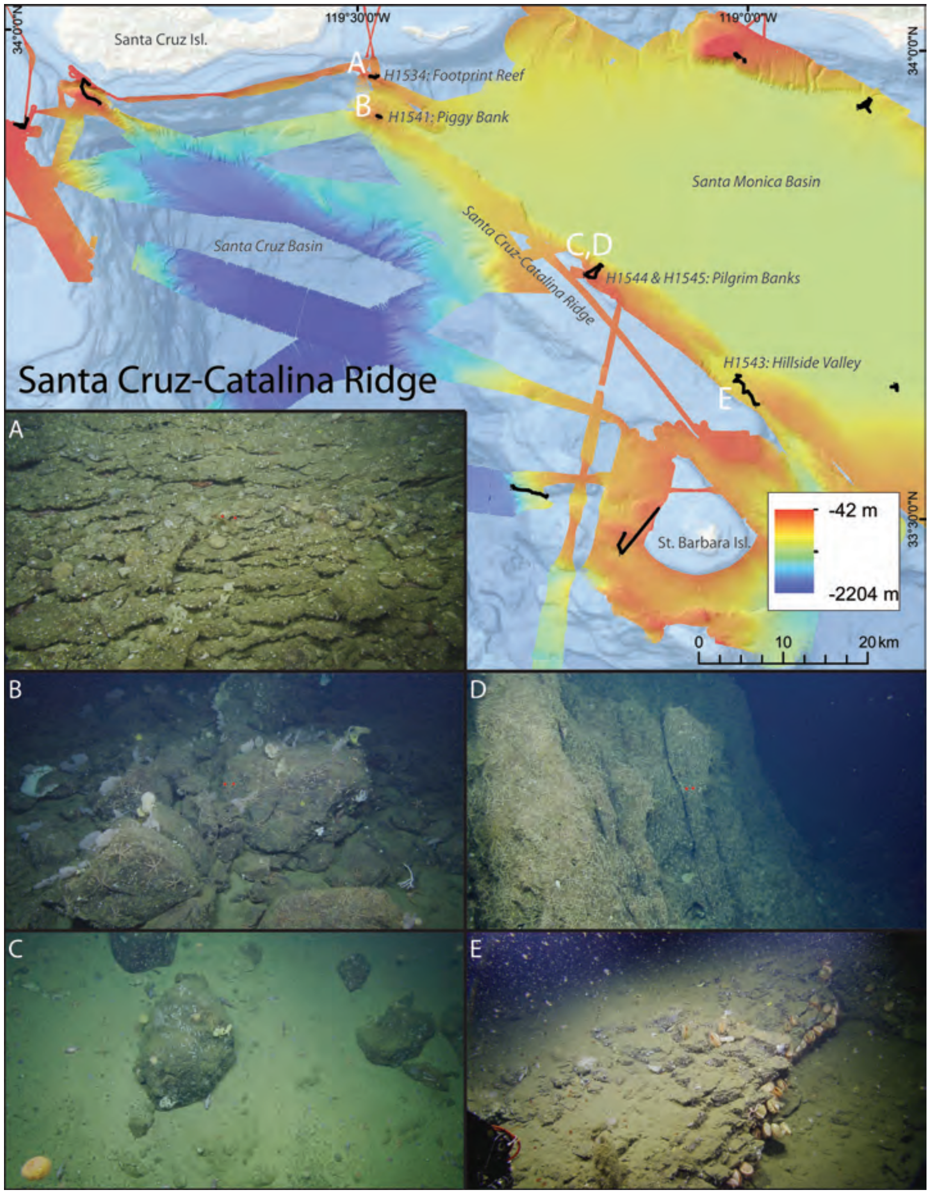

FIG. 4.—Santa Cruz–Catalina Ridge. Top: Newly acquired multibeam bathymetric data (colored swaths) and *Hercules* dive tracks (black lines). **A)** Possible conglomerate outcrops associated with surficial cobble deposits on Footprint Reef that could indicate a formerly subaerial paleoshoreline. **B)** Piggy Bank, characterized by a soft, sedimented seafloor with scattered cobble to boulder gravel and rocky outcrops (shown here) covered with brittle stars, corals, and sponges. **C)** Sandstone and carbonate from terraced ledges were sampled when lithified rock was not present, as expected at a depth of ~300 to 350 m around Pilgrim Banks (samples NA075-020, NA075-021, NA075-022). **D)** Steep rock pinnacles blanketed with brittle stars and crinoids were found on top of Pilgrim Banks, at ~120–140 m. **E)** Black rocky outcrops in the Hillside Valley were moderately sedimented and colonized by numerous invertebrates, including bivalves, sponges, and echinoderms. For scale, red scaling dots are 10 cm apart (A, B, D); panoramic frames are approximately 8–10 m across (C, E).

Objective—During dive H1543 within the Hillside Valley, we planned to conduct two transects at Santa Cruz–Catalina Ridge following the Santa Cruz–Catalina Ridge Fault Zone. The goal was to explore for evidence of seafloor rupture at the site of the 1981 strike-slip earthquake, and to explore for active seeps that may be associated with the recent faulting.

Results and preliminary interpretation—During the two transects, we did not find direct evidence for a recent seafloor rupture. However, in places, the fault trace was well expressed as a ridge up to 30 m high covered with angular blocks of bedrock, subsequently inferred by Legg et al. (2016) to have been brecciated and squeezed upward during large earthquake ruptures along the fault. In a sense, these ridges may represent the long-term expression of "mole tracks," a feature common to large strike-slip earthquake ruptures onshore. These features may be better preserved over multiple earthquake cycles in the deep marine environment, where erosion and anthropogenic impacts are subdued and sedimentation is slow. We recovered nine grab and two suction samples of sedimentary rocks exposed near the fault (Fig. 4E), as well as one push core within sediments adjacent to the fault (Appendix Table 5). Microbial mats observed in lineaments parallel to the faults in the Hillside Valley are likely indicative of increased pore-fluid pressure along the Santa Cruz–Catalina Ridge Fault Zone (Legg et al. 2016).

Santa Monica Basin

Point Dume: *Study area*—In 2013, chemosynthetic clams were found in a sediment grab sample off Point Dume, California, by the Southern California Coastal Water Research Project (Fig. 5). *Nautilus* returned in 2015 and found water-column anomalies typically indicative of gas discharge in the same location using multibeam sonar.

Objectives—The primary goal of dives H1454, H1456, H1457, and H1528 was to investigate the seep communities detected by the Southern California Coastal Water Research Project and determine their extent and activity. The suite of tools deployed with the ROVs included the acquisition of video transects, photomosaics, near-bottom echosounder profiles, temperature measurements, and the collection of biological samples, push cores, and water samples.

Results and preliminary interpretation—The Point Dume seep area was shown to extend over 1.4 km NE–SW along the SE side of a deep-sea channel and is possibly fault controlled. Two ROV dives followed the extent of the seeps by tracing a low sediment ridge that had microbial mats and, in some places, small chimneys (Fig. 5A, B). Seep faunas, including clams, polychaetes, galatheid crabs, and anemones, were abundant (Levin et al. 2016). The extensive field of white, yellow, and orange microbial mats extended for approximately 1 km in a shallow sublinear north–south-trending depression. Given the similarity of the mats' texture and coloration to better-characterized methane seeps (Mills et al. 2004, Omoregie et al. 2008), as well as the region's abundant hydrocarbon reservoirs, the system is likely a hydrocarbon-associated seep site supporting anaerobic methanotrophic, sulfate-reducing, and sulfide-oxidizing microbial communities. Despite the abundant microbial mats, no advective fluid flow or bubble ebullition was observed, unlike observations made in 2015; such temporal variation, as reported at other seep sites, can result from tidal loading or subsurface hydrologic heterogeneity (Boles et al. 2001, Tryon et al. 2002). Interspersed among the microbial mats, abundant submeter, vertical chimney-like structures were observed (see images in Levin et al. 2016). Such carbonate "reefs" have not previously been reported at marine methane seeps, although similar structures occur in the anoxic, methane-rich Black Sea (Michaelis et al. 2002). When sampled with *Hercules*' robotic arm, a thin outer crust fell away to reveal an internal structure of black, likely sulfidic, sediment. Samples were collected for mineralogical, biological, and chemical analysis (Appendix Table 6). Initial experiments suggest the microbes within the structures contain methane-oxidizing potential and dense microbial communities of anaerobic methanotroph–sulfate-reducing microbial consortia. These unusual reefs represent a high-priority target for follow-up expeditions to enact a detailed program of sampling and experimentation.

Redondo Knoll: *Study area*—Redondo Knoll is a transpressional pop-up structure approximately 14 km across that rises 350 m above surrounding seafloor (Fig. 5C, D). Located between Palos Verdes and Catalina Island and separating the Santa Monica and San Pedro Basins, it is a feature that was largely unexplored prior to the 2015 *Nautilus* expedition. Two large gas hydrate seep mounds located ~5 km NNW of the knoll described by Hein et al. (2006) and Paull et al. (2008) suggested that cold seeps may also occur on the knoll.

Objectives—The goal of dive H1455 was to examine the SE edge of Redondo Knoll along the steep slope and transect to the top. Water-column anomalies observed in the multibeam and 3.5 kHz echosounder data to the NW of Redondo Knoll led to dive H1461, during which our goal was to locate a new, deep seep site and, once found, to photomosaic the area and collect representative samples. On the north flank of Redondo Knoll during dive H1542, our goal was to search for seafloor evidence of the San Pedro Basin Fault and collect geological samples.

Results and preliminary interpretation—The 2015 dives H1451, H1455, and H1461 located small methane seeps along the northern flank, and a very large seep in the basin northwest of the knoll. The seeps proved to be devoid of biota except for microbial mats, as would be expected due to the seeps' location in the anoxic Santa Monica Basin (Levin et al. 2016) (Fig. 5C). The northeast flank of Redondo Knoll (dive H1542) was heavily sedimented, but one rock sample was collected at the summit (sample NA075-004); that sample appears to be a metamorphosed breccia and awaits further characterization. In total, three push cores, seven grab samples, six suction samples, and five water samples were collected in the vicinity of Redondo Knoll (Appendix Table 6).

Santa Monica Basin Seep: *Study area*—While transiting west from Redondo Knoll to Pilgrim Banks across the southern portion of Santa Monica Basin, an acoustic anomaly was detected in the multibeam echosounder water-column data. This kind of acoustic anomaly, a flare-shaped reflection initiating at the seafloor, is commonly interpreted as produced by clusters of small gas bubbles rising through the water (e.g., Schneider von Deimling et al. 2007). A follow-up multibeam survey carried out on a tight grid pattern confirmed the presence of a water-column anomaly at a depth of 897 m in the southeastern region of Santa Monica Basin. The acoustic anomaly, north of the Santa Catalina Island uplift, did not appear to be associated with surface fault deformation, although seismic reflection profiles show complex deformation related to collision between Catalina and Redondo Knoll in that area. On an industry seismic reflection profile (deep penetration), the seep also is associated with a velocity–amplitude anomaly that is characteristic of gas accumulation in sediments (Normark et al. 2004). It may also be associated with methane hydrate deposits found further north in Santa Monica Basin (Hein et al. 2006).

Objective—The purpose of dive H1548 in the southern Santa Monica Basin was to explore the water-column anomaly and look for evidence of seeps and associated vent fauna. The primary objectives were to locate the source of the bubbles, determine the extent of the presumed seep, and collect representative geological and biological samples of the site.

Results and preliminary interpretations—One bubbling seep was located (Fig. 5E), and diffuse seeps extending for 150 to 200 m from north to south were observed during dive H1548; the east–west extent of the seep field was not determined owing to time constraints. The temperature anomaly of the bubbling seep was recorded to 0.35° C above ambient. The northern portion of the seep field is relatively flat, and white, gray, orange, and yellow microbial mats were observed and sampled (Fig. 5E; Appendix Table 6). The southern region of the field had significantly more relief; it is hummocky with mounds on the order of 1 to 2 m high (Fig. 5F). There was a low abundance of fauna on the seeps, possibly because of low oxygen concentrations in the basin. Subsequent multibeam mapping of the Santa Monica Basin on

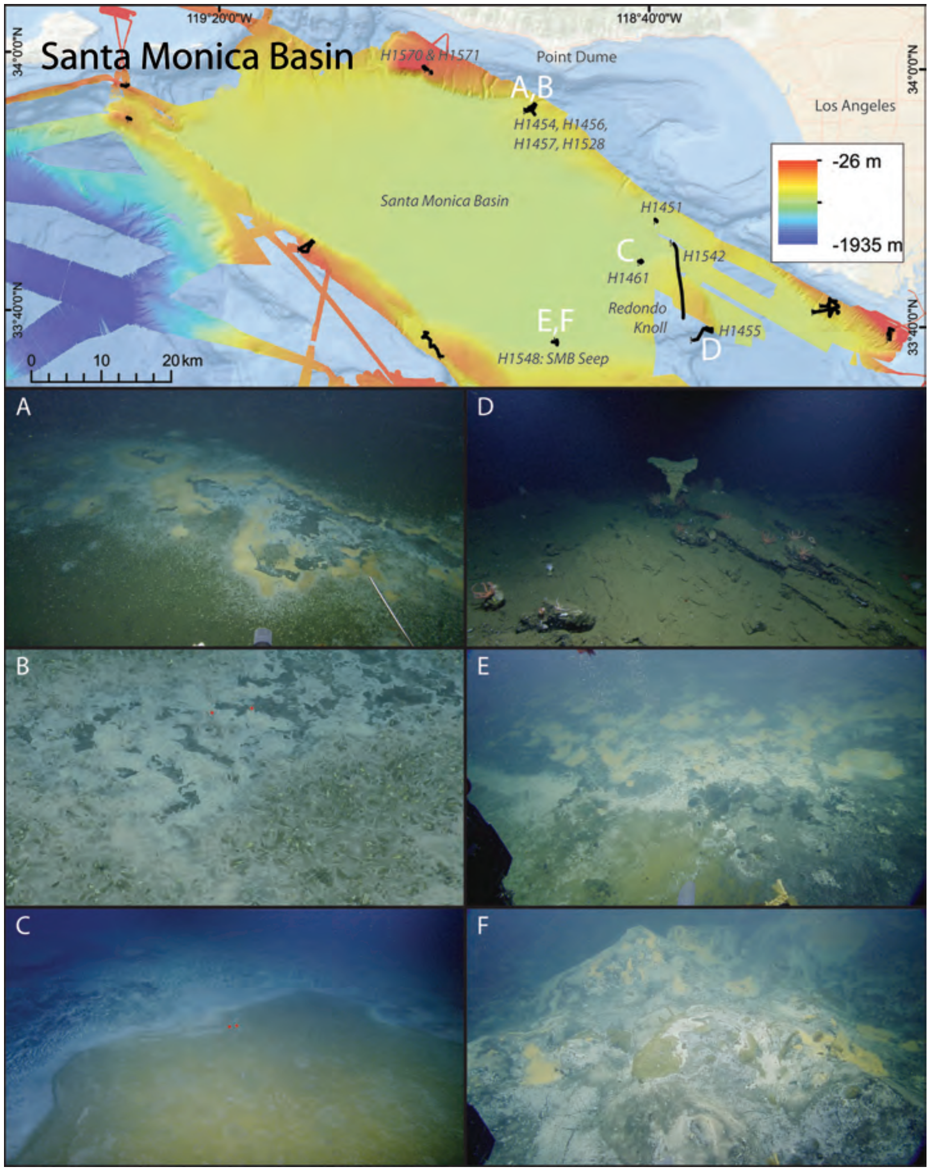

FIG. 5.—Santa Monica Basin. Top: Newly acquired multibeam bathymetric data (colored swaths) and *Hercules* dive tracks (black lines). Select still frames from *Hercules*: **A, B)** A new seep site discovered in 2015 south of Point Dume with faunas including microbial mats, clams, polychaetes, galatheid crabs, and anemones. **C)** On the northern slope of Redondo Knoll, a new seep discovered in 2015. **D)** Carbonate crusts colonized by sessile organisms such as corals and sponges that characterize the southern scarps of Redondo Knoll. **E)** Bubbling seeps found in the northern region of the Santa Monica Basin Seep field. **F)** Large, ~2-m-high hummocky mounds covered in white, gray, and yellow microbes found in the southern region of the Santa Monica Basin Seep field. For scale, panoramic frames are approximately 8–10 m across (A, D, E, F); red scaling dots are 10 cm apart (B, C).

cruise NA078 revealed seeps ringing the southwestern side of the basin. Based on these findings, continued exploration of this area could reveal additional natural hydrocarbon seeps and their associated ecosystems.

San Pedro Basin

Palos Verdes: *Study area*—Just offshore south Los Angeles, the Palos Verdes margin consists of a narrow (<3.5 km), shallow shelf and a steeply sloping seafloor (9–18°), descending to the San Pedro Basin, where the maximum water depth exceeds 900 m (Fig. 6). Previous subbottom profiling and sidescan sonar investigations of this margin revealed strong reflectors characteristic of acoustic scattering by gas bubbles impounded beneath an impermeable sediment layer ("gas-charged sediments"), as well as a series of small mounds (<1 m high) on the seafloor, features that have been interpreted as evidence of shallow hydrothermal venting (e.g., Kleinschmidt and Tschauder 1985, Hampton et al. 2002). The 2015 *Nautilus* dives H1452 and H1453 in this area were in response to sonar surveys conducted earlier in the cruise that confirmed that gases were trapped there beneath the

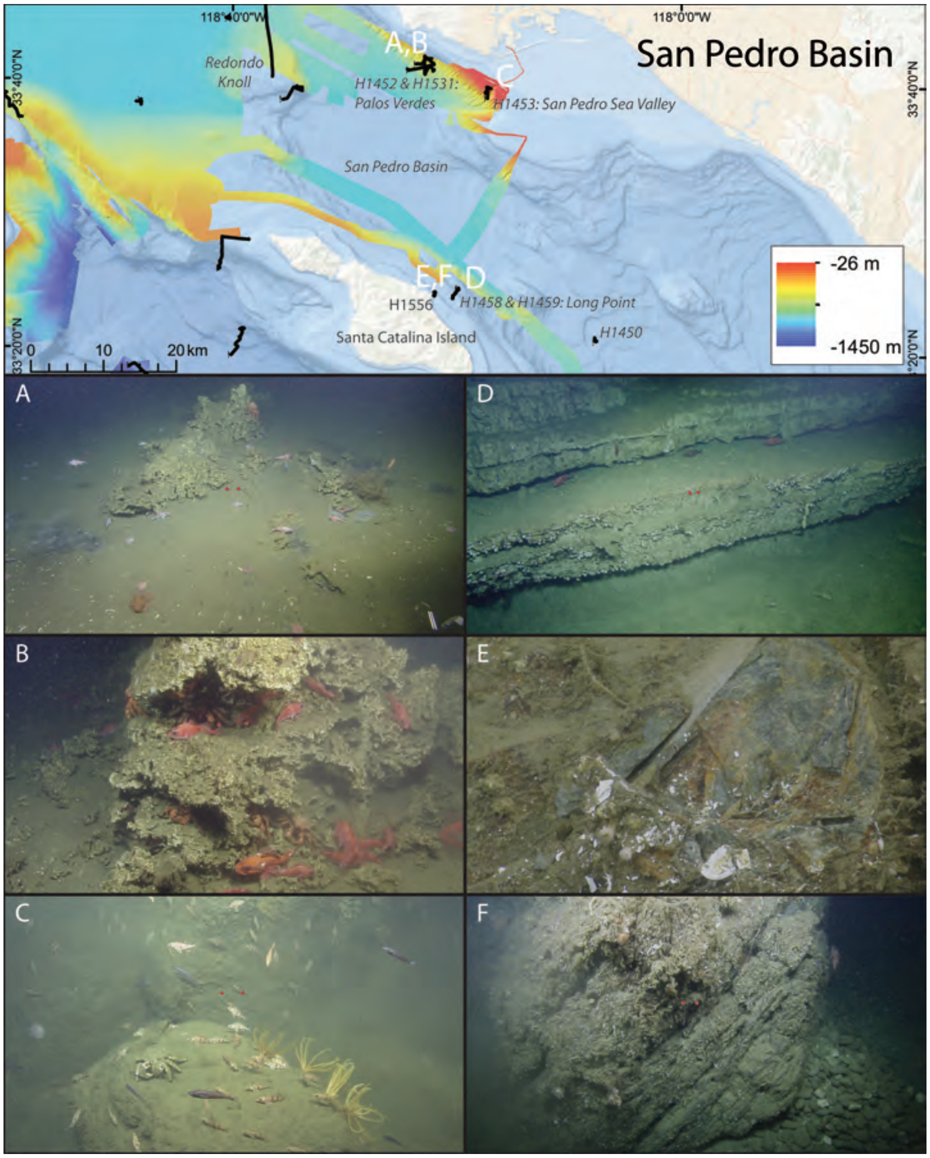

FIG. 6.—San Pedro Basin. Top: Newly acquired multibeam bathymetric data (colored swaths) and *Hercules* dive tracks (black lines). Select still frames from *Hercules*: **A, B)** Rockfish and other faunas are present on a carbonate outcrop with diffuse cold seeps found at Palos Verdes. **C)** large boulders found in San Pedro Sea Valley were lightly sedimented and colonized by crinoids, crabs, and fishes. **D)** *Hercules* transects up Long Point Fault revealed these layered outcrops at the mouth of the canyon in 300–320 m of water. **E)** Several samples were collected in this canyon, including schist (Catalina?) with some serpentine and quartz veins found within a large outcrop at 124 m. **F)** Large outcrop at 124 m (shown in E); this outcrop is representative of those observed and sampled in this region (sample NA075-109). For scale, panoramic frames are approximately 8–10 m across (A); red scaling dots are 10 cm apart (B, C, D, F); the field of view for zoomed-in frames is 0.5–1 m across (E).

seafloor. We traversed the region in 2016 in search of further signs of gas venting or hydrothermal activity (H1531).

Objectives—The goal of dive H1452 was to investigate potential seep sites found in a multibeam survey earlier in the cruise. Starting from the deepest site, we planned to move upslope to higher potential seep locations, conducting visual surveys at every seep site to document gas plumes, temperature anomalies, microbial mats, and carbonate crusts. To the southeast, a transect upslope in the San Pedro Sea Valley canyon to the south of Palos Verdes was planned to look for and sample hydrothermal vents (H1453).

Results and preliminary interpretation—The initial dive (H1452) transected water depths from 780 to 200 m and throughout observed irregular, porous carbonate mounds 1 to 4 m in height, which exhibited varying levels of bubbling, presumably methane and hydrogen sulfide (Fig. 6A, B). Faunas common to such methane seeps were present here, including clams and microbial mats. These mounds are likely surficial expressions of subsurface fluid flow, as predicted by earlier sonar surveys, although no evidence of fluid flow was observed. In 2016, samples of methane-derived carbonate crust were collected as well as a sample of a carbonate chimney (H1531; Appendix Table 7). *Hercules* dive H1453 explored the head of a canyon, the San Pedro Sea Valley, that deeply incises the San Pedro shelf; during this dive, one grab sample and two water samples were collected (Fig. 6C; Appendix Table 7).

Long Point Fault: *Study area*—The SE–NW-striking Long Point Fault runs onshore Santa Catalina Island between Two Harbors and Long Point and continues to the NW offshore for ∼10 km, hugging the NE coastline of the island (Fig. 6). It is a right-lateral transpressional fault that is responsible for the sublinear morphology of the northeast coastline of Catalina, although its slip history is poorly constrained (Castillo et al. 2015). Steep topography generated by motion along this fault system has led to the formation of submarine canyons that we hypothesized would allow *Hercules* to access several marine terraces that have been offset by the Long Point Fault.

Objectives—Dives H1458 and H1459 were intended to investigate the tsunamigenic potential of the Long Point Fault and look for submerged marine terraces. We planned to transect up the sloped foot of a canyon that cuts into the Catalina margin. The purpose of dive H1556 was to explore a submarine canyon off Long Point on the east coast of Catalina Island, looking for marine terraces from the last two glacial cycles. We planned to conduct dense sampling at ∼5 m depth intervals between 140 and 85 m depth.

Results and preliminary interpretation—Samples collected from the upper marine terraces on dives H1458 and H1459 correspond to the Last Glacial Maximum paleoshoreline and may help with the accurate positioning of this paleoshoreline around Catalina Island, as well as characterizing the extent of viable land on that Channel Island for human occupation during the Pleistocene (Fig. 6D–F; Appendix Table 7). Fossils collected in sediment samples in the vicinity of the fault may be useful to constrain the slip rate on this fault system and for correlation to the three-dimensional (3D) stratigraphy derived from the 2016 seismic survey conducted by Stanford University (Castillo and Klemperer 2016).

Santa Catalina Basin

Kimki Ridge: *Study area*—Kimki Ridge is a NW–SE transpressional ridge bracketed by two strands of the San Clemente Fault in the western Catalina Basin. It has long been suspected to have fluid seeps along its crest (Ford and Normark 1980; Fig. 7). Indeed, multichannel seismic reflection data collected by the USGS in 2014 suggested the possibility of fluid seeps or vents on this ridge, and subsequent multibeam bathymetric data collected during a cooperative University of Washington/USGS cruise in 2016 showed subtle seafloor buildups and anomalously high backscatter areas in three places along Kimki Ridge that were considered likely fluid vents. Fluid seeps are thought to have important links to active faulting, and part of the transect was planned to cross the two strands of the San Clemente Fault for evidence of recent offset.

Objectives—The goal of H1554 was to conduct three transects across Kimki Ridge, each starting at the base of the ridge, where the Kimki Fault is presumably breaking the surface, and ascending to the top, where the cold seeps are thought to be located. These dives were to confirm the presence, activity level, and character of the seeps and any associated biological communities. In addition, beds of glass sponges known to occur on the floor of Catalina Basin were to be sampled if encountered.

Results and preliminary interpretation—The two fault strands that bound Kimki Ridge to the east and west turned out to be heavily sedimented, and we did not reach the bottom of the narrow, steep-sided trough that marks the major fault trace on the east side, so direct evidence for recent fault offset was not observed. Two of the three potential seeps were explored, however. These showed abundant evidence of fluid seepage, including characteristic microbial mats, chemosynthetic clams, and what appeared to be authigenic carbonate (Fig. 7A, B; Appendix Table 8). Alignments and groupings of living clams were observed, sometimes in big arcs, as if around a vent. The vent areas appeared to be broad zones of diffuse seepage, not showing bubbles or visible fluid flow, but with enough flux to support the microbial mats and clam communities. The southernmost seep area had a buildup of several meters of carbonate over an area approximately 250 m across. Within this area, crater-like, irregular depressions 30 to 50 m across and 1 to 2 m deep were interpreted to be individual seep vents. Rock, sediment, and shell samples were collected to characterize the vent fluids and authigenic precipitates (Appendix Table 8). Their detailed analyses confirmed active venting at this site and, in conjunction with the interpretation of prior geophysical data, support other studies that suggest that transpression is an important component in the formation and localization of fluid seeps in a strike-slip setting (Conrad et al. 2018, McGann and Conrad 2018).

Catalina Escarpment and Canyon: *Study area*—The major escarpment on the west flank of Catalina Island is associated with the dextral Catalina strike-slip fault. A large, 8 to 9 km releasing stepover separates the escarpment into two sections with an intervening trough, inferred to be a pull-apart basin (Legg et al. 2007). Seismic profiles and linear scarps provide evidence of youthful faulting along the escarpment. Well-defined submerged terraces exist at the crest of the escarpment and around the northwest end of Catalina Island (e.g., Castillo et al. 2015). Catalina Canyon bisects the trough between the two en echelon escarpments.

Objectives—The goal of dive H1460 was to investigate the fault scarps west of Catalina Island and explore for steep fault surfaces and seep-like biology, as well as submerged beach deposits close to the island on the Catalina Escarpment. The Catalina Canyon dive objective (H1555) was to explore for evidence of right-lateral offset of the canyon at the base of the Catalina Escarpment, where the Catalina Ridge Fault crosses and is well-defined in the multibeam data. Beds of glass sponges are suspected to occur on the floor of Catalina Basin, and if encountered, they were to be sampled.

Results and preliminary interpretation—Dive H1460 on the Catalina Escarpment started within the ∼1.5-km-wide trench cut in sediments by the large slide block; most of this area was mud covered (Fig. 7E). However, based on a seismic reflection profile in the area, we anticipated reaching a 15- to 20-m-high scarp along the Catalina Ridge Fault, which might also serve as the headscarp for the landslide. More detailed multibeam bathymetry showed a complex slide area along the steep escarpment below the headscarp. The vertical bedrock scarp was found at ∼744 m depth and was followed for a short distance to observe the biological communities and obtain rock samples (Appendix Table 8). Owing to time constraints, dive H1555 was terminated just as we reached the fault trace. There, we did observe large communities of clams and microbial mats, which may be associated active seepages along the fault zone (Fig. 7C, D; Appendix Table 8).

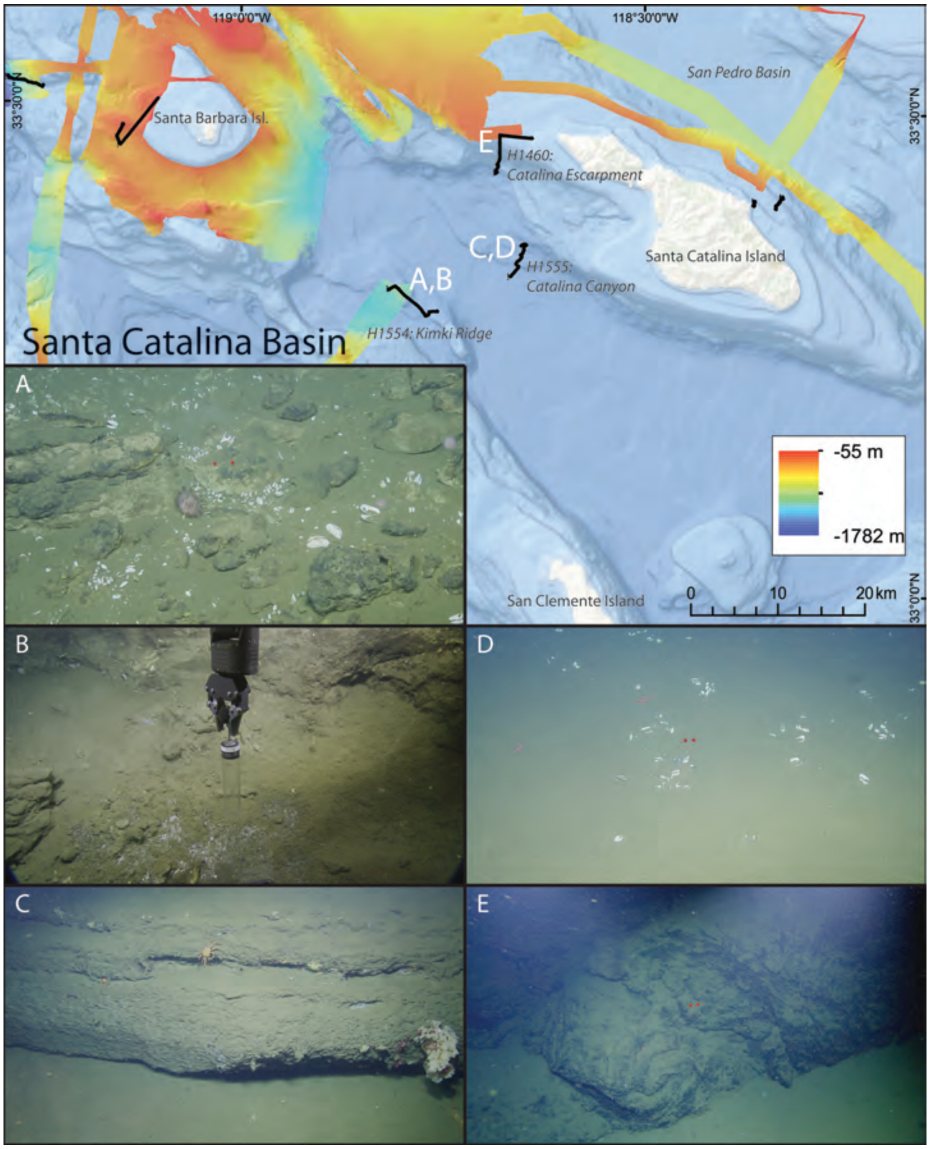

Fig. 7.—Santa Catalina Basin. Top: Newly acquired multibeam bathymetric data (colored swaths) and *Hercules* dive tracks (black lines). Select still frames from *Hercules*: **A)** Clams, anemones, and other faunas were found living on likely authigenic limestone associated with hydrocarbon seeps on Kimki Ridge. **B)** *Hercules* collecting a push core inside a "crater" on Kimki Ridge for further analysis (sample NA075-092); the core locations are surrounded by microbial mats, clam shells, and authigenic limestone. **C)** Heavily sedimented ledge with obvious sediment layers on the wall of Catalina Canyon from which a sediment core (sample NA075-098) was taken. **D)** View of seabed with clams, empty shells, and microbial mats indicating the possible presence of a seep approaching the Santa Cruz–Catalina Ridge Fault at 1146 m in Catalina Canyon. **E)** This black outcrop yielded a sample of limestone encrusted with manganese (sample NA067-015). For scale, red scaling dots are 10 cm apart (A, D, E); the claw at the end of the manipulator arm is 18 cm long (B); panoramic frames are approximately 8–10 m across (C).

San Nicolas Basin and Escarpment

Study Area: Lying approximately 110 km offshore southern California, San Nicolas Island is the westernmost of the southern Channel Islands and is composed chiefly of Eocene marine sandstone and siltstone beds with minor conglomerate and mudstone (Vedder and Norris 1963). A large canyon to the southeast of the island was selected for exploration. New multibeam data collected on the same cruise provided the needed base map for dive planning in this largely unexplored area (Fig. 8).

Objectives: The purpose of this San Nicolas Escarpment dive was to investigate the geology of the largest canyon southeast of San Nicolas Island as well as to inspect the San Nicolas Island Fault Zone, which intersects the escarpment at midheight, as suggested from existing seismic profiles (e.g., De Hoogh et al. 2019).

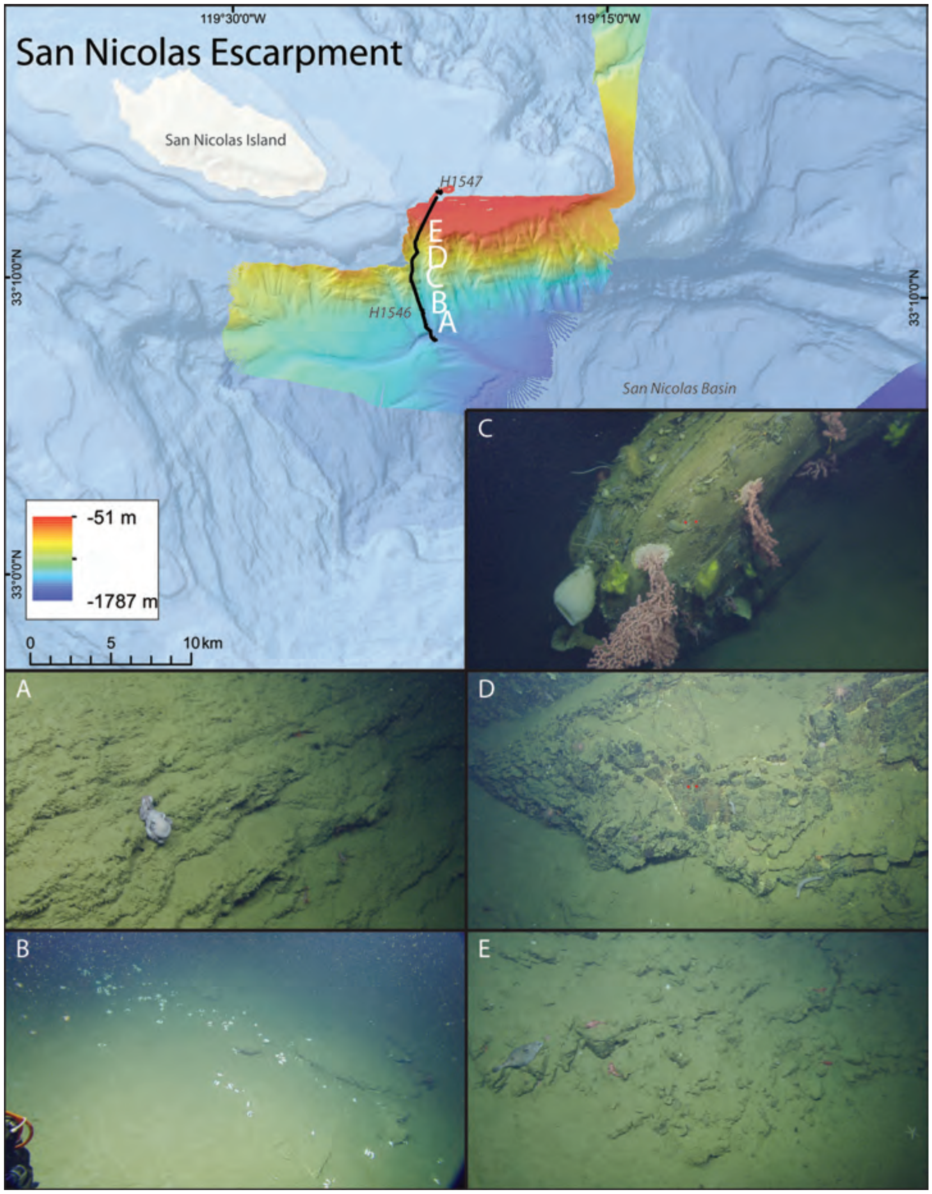

FIG. 8.—San Nicolas Escarpment. Top: Newly acquired multibeam bathymetric data (colored swaths) and *Hercules* dive tracks (black lines). Select still frames from *Hercules*: **A)** The steep canyon walls at the beginning of the dive exhibited horizontal bedding and were heavily sedimented. **B)** Many shells of dead clams inside this gully could be related to abandoned seepage in this area. **C)** Two rock samples were collected on this outcrop encrusted with glass sponges and deep-sea corals (samples NA075-036, NA075-037). **D)** *Hercules* came across this vertical rock face in close proximity to the San Nicolas Island Fault Zone, from which it collected angular rock samples (samples NA075-038, NA075-039). **E)** The upper extent of the canyon was heavily sedimented with periodic outcrops of crumbly rock, probably sandstone or carbonate, and was home to an abundance of brittle stars, other invertebrates, and rockfish. For scale, panoramic frames are approximately 8–10 m across (A, B, E); red scaling dots are 10 cm apart (C, D).

Results and Preliminary Interpretation: Geological samples, as well as opportunistic biological samples, were collected below and above the fault zone (Fig. 8; Appendix Table 9). The dive began at 1416 m in the San Nicolas Basin, where we observed sedimented scarps (Fig. 8A) and seafloor with many trails present, likely of biological origin, as well as shells of dead clams (Fig. 8B). As we moved upslope along the steep western wall of the canyon, we observed crumbly, rocky outcrops, possibly composed of sandstone or carbonates, on which abundant glass sponges and cold-water corals are thriving (Fig. 8C). From 1400 to 1000 m, the terrain was characterized by steep canyon walls and terraces alternating with heavily sedimented gullies. We sampled a black angular rock from the presumed San Nicolas Island Fault Zone (NA075-039), at ~1000 m depth (Fig. 8D). Due to time constraints, we towed the vehicles in the midwater from 880 to 700 m water depth. From 700 to 505 m, we observed a relatively featureless, sedimented slope with punctuated outcrops, one of which was sampled (Fig. 8E; NA075-041).

San Diego Trough

Study Area: San Diego Trough is a 30-km-wide, 1100-m-deep basin that lies between the Thirtymile and Coronado Banks offshore San Diego. It is bisected by the dextral San Diego Trough Fault Zone, one of several fault systems that accommodate motion between the Pacific and North American plates (Ryan et al. 2012). The Del Mar Seep was discovered in 2012, 48 km off Del Mar, California, and it occurs within the northern region of the San Diego Trough Fault (Grupe et al. 2015). Recent investigations of that seep have documented the distinct habitats of sulfur-oxidizing microbes and folliculinid ciliates, clam beds, polychaetes, protozoan tube beds, and methanogenic carbonate rocks. Fish species previously observed here include dover sole (*Microstomus pacificus*), thornyheads (*Sebastolobus* spp.), and sablefish (*Anoplopoma fimbria*).

Objectives: Six *Hercules* dives were conducted in the San Diego Trough, primarily focused on the deep ecosystems in the region, and we report on three of these dives here. Dive H1444 on the Del Mar Seep was planned to recover experimental pieces of wood, whale bone, and carbonate rock placed on the seafloor in 2013 (Levin et al. 2016), to survey the West Mound by collecting near-bottom video imagery along transects on and off the active seep, and to obtain imagery of different habitats and organisms. The goal of dive H1445 was to survey the seafloor on and off the seep, sampling representative fauna, taking push cores, and collecting water samples at and off the seep. During the La Jolla Canyon dive (H1449), we planned to visually survey canyon organisms and habitats along depth and oxygen gradients, collecting characteristic organisms, and viewing sediment features.

Results: The 2015 dives H1444 and H1445 on the Del Mar Seep conducted visual observations and limited biological sampling to help constrain the full habitat heterogeneity of this site (Fig. 9A, B; Appendix Table 10). The wood, bone, and carbonate experiments collected showed clear differences in colonization of wood-boring clams (*Xylophaga* sp.) between the actively seeping site compared to the inactive site (Levin et al. 2016). During the La Jolla Canyon dive, we documented and sampled the different habitats and biota in changing oxygen levels through the local OMZ from 700 to 425 m depth, showing strong benthic zonation based on oxygen concentration (Fig. 9C, D; Appendix Table 10) (Levin et al. 2016).

Outer Borderland

Arguello Canyon: *Study area*—Arguello Canyon (Von Huene 1969, Marsaglia et al. 2019) is a major submarine canyon offshore Point Arguello, California (Fig. 10A). It was a high-priority dive area because it is within the boundaries of the proposed Chumash Heritage National Marine Sanctuary (Collins 2015), which met national significance criteria described in the 2015 NOAA National Marine Sanctuary nomination process (Sanctuary Nomination Process 2018).

Objectives—Dives were planned to investigate the seafloor morphology and geological character of the canyon; conduct timed transects at fixed altitude/speed/direction while collecting consistent imagery for coral counting; collect coral samples from the canyon floor and walls; and collect sediment and bedrock samples from the canyon floor and walls.

Results—*Hercules* dove twice in Arguello Canyon, H1537 and H1539, within a newly mapped area outside the CINMS in a region under consideration for management and conservation (Fig. 10). We conducted several transect locations along the canyon axis and along different geomorphologic zones, but at similar depth ranges to characterize hard- and soft-bottom habitat along a fault-bounded offset in the canyon axis. Abundant deep-water coral reefs were discovered (Fig. 10A), and representative sediment push cores, hard rock samples, and biological samples were collected to better characterize this previously unexplored region (Appendix Table 11).

Trask Knoll: *Study area*—Trask Knoll is a 20-km-long NW–SE-elongated rise in the outer California Borderland, located SW of Santa Rosa Island (Fig. 10B). Previous work suggested that Miocene sedimentary rock comprises much of the knoll, but at the center of the knoll, metamorphic rocks have been sampled that resemble the Catalina Schist basement complex (Vedder et al. 1974, Crouch 1981). The Catalina Schist is considered to be deep subduction complex rocks that were underplated beneath the North America margin during subduction of the Farallon plate (Grove et al. 2008) and then unroofed during Miocene extension.

Objectives—The purpose of dive H1558 was to conduct an exploratory dive along the fault bordering Trask Knoll to the west and then explore upslope to the top of the knoll, collecting geological and biological samples along the way.

Results—We sampled various formations during a transect dive across the west side of Trask Knoll (Fig. 10B; Appendix Table 11). The dive track intersected the Trask Knoll Fault at the base of the knoll and progressed up to the ~600-m-deep summit. The multibeam bathymetry data show continuation of the fault another 7 km to the NW beyond the knoll along a narrow ridge that may represent a pressure ridge (Legg et al. 2016). Nine rock samples were collected on the slopes of Trask Knoll to better understand the geological history of this feature.

San Juan Seamount: *Study area*—Unlike the other features visited by *Hercules* during the 2015–2016 field seasons, San Juan Seamount is situated beyond the western limit of the Southern California Continental Borderland (Fig. 10C). San Juan Seamount is one of several elongated volcanic structures in that area with a distinctive NE–SW alignment sitting directly onto the oceanic crust at the foot of the Patton Escarpment; these elongated seamounts are thought to have erupted in response to crustal extension at the continental margin related to transtensional tectonics (Davis et al. 2010). San Juan Seamount is the largest of these seamounts, rising ~3500 m above the 4000-m-deep surrounding seafloor. High-precision $^{40}Ar/^{39}Ar$ ages indicate episodes of volcanic activity mainly from ~11 to ~7 Ma, but they also document one eruption as recent as 2.8 Ma (Davis et al. 2010). Its summit ridge probably emerged at some point as a line of eight small islands, one of them standing at least 140 m above sea level (Paduan et al. 2009).

Objectives—The goal of the San Juan Seamount dive H1529 was to explore the eastern side of the seamount, including a visual transect up the southeast slope; collection of representative fauna samples; collection of water samples for environmental deoxyribonucleic acid (eDNA, the DNA expelled by organisms through feces, mucus, carcasses, etc.) analysis, collection of images and representative coral samples; and collection of representative lava samples for dating.

Results and preliminary interpretation—Multibeam and backscatter data revealed a distinct caldera about halfway up the southeast face of San Juan Seamount (~2050 m) and possible flat terraces just below, which were explored and sampled for the first time on this dive (Appendix Table 11). *Hercules* began this dive at a depth of 3350 m, well below the caldera, on the southeast base of San Juan Seamount, where the seafloor was characterized by soft, light-colored sediments, which were sampled with a short push core. Continuing upslope, the seafloor transitioned into muddy sediment with local gouges, similar

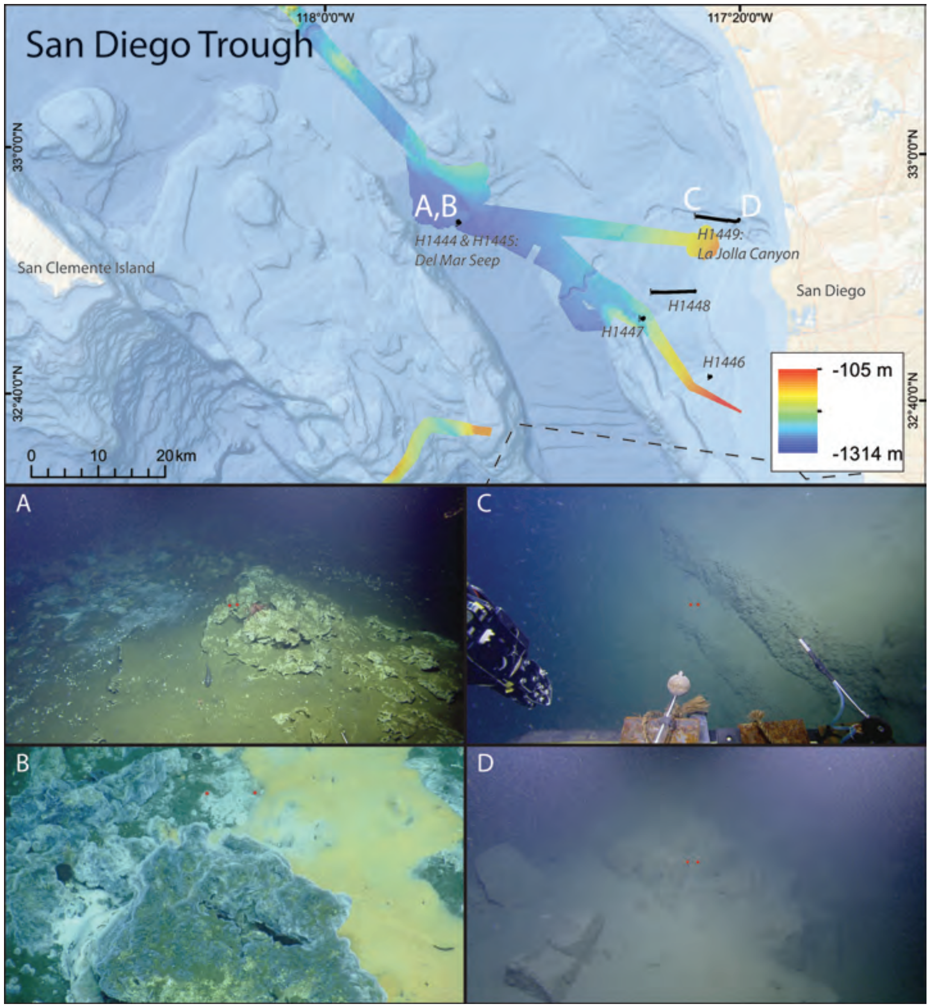

FIG. 9.—San Diego Trough. Top: Newly acquired multibeam bathymetric data (colored swaths) and *Hercules* dive tracks (black lines). Select still frames from *Hercules*: **A, B)** First discovered in 2012 (Grupe et al. 2015), the Del Mar Seep lies along the San Diego Trough fault, a dextral strike-slip fault. Carbonate outcrops were probably formed by now-extinct seeps, and active seeps are colonized by gray, white, and yellow microbial mats, as well as other faunas, such as crabs and deep-sea fishes. **C)** Outcrops of bedded sediment found in La Jolla Canyon, which was heavily sedimented and filled with extremely turbid water. **D)** Further up the La Jolla Canyon, blocky sandstone(?) boulders were observed. For scale, panoramic frames are approximately 8–10 m across (A, C, D); red scaling dots are 10 cm apart (B).

to those ascribed to beaked whale scours (Auster and Watling 2010). The sediment cover thinned at ~2960 m, revealing what were interpreted to be basaltic cobbles and pillow lava. Large exposures of these basaltic features were observed along the steeper ridge faces starting at 2840 m depth (Fig. 10C). As *Hercules* approached the possible terrace features, more pillow lava fields were observed. Further upslope, *Hercules* explored a sedimented plateau, possibly an eroded beach terrace. About halfway up the seamount, the large sediment-filled crater was explored. Core samples of the inner sediment were collected (2009 m), as well as a piece of rock from the basaltic crater rim (2075 m). The uppermost slope of San Juan Seamount consisted of many steep ridges with intermittent pillow lava regions and sediment patches. The summit was relatively flat with consistently sized basalt cobbles along the southwest ridgeline.

Patton Escarpment: *Study area*—The western extent of the Outer California Borderland is marked by the steep Patton Escarpment, a NW–SE-striking feature that rises from deeper than 4000 m to ~1000 m. It represents the preserved trench slope of the former subduction zone that once marked the boundary between the Farallon and the North American plates, a plate boundary that remained active since before 100 Ma (Atwater 1970). Little of this area had been mapped or sampled, except for scant dredge samples, nearby Deep Sea Drilling Project (DSDP) drilling sites 468 and 469, and two prior ROV cruises (Fig. 10; Vedder et al. 1981, Marsaglia et al. 2006, Clague et al. 2019). Cruise NA075 was the first to conduct a visual ROV survey of the northwestern section of the Patton Escarpment.

Objectives—The objectives of dive H1559 were to conduct a transect up the slope of the Patton Escarpment in an area previously unexplored using ROV technology; collect representative rock samples for later characterization; and conduct a visual survey for vertical changes in the deep-sea ecology.

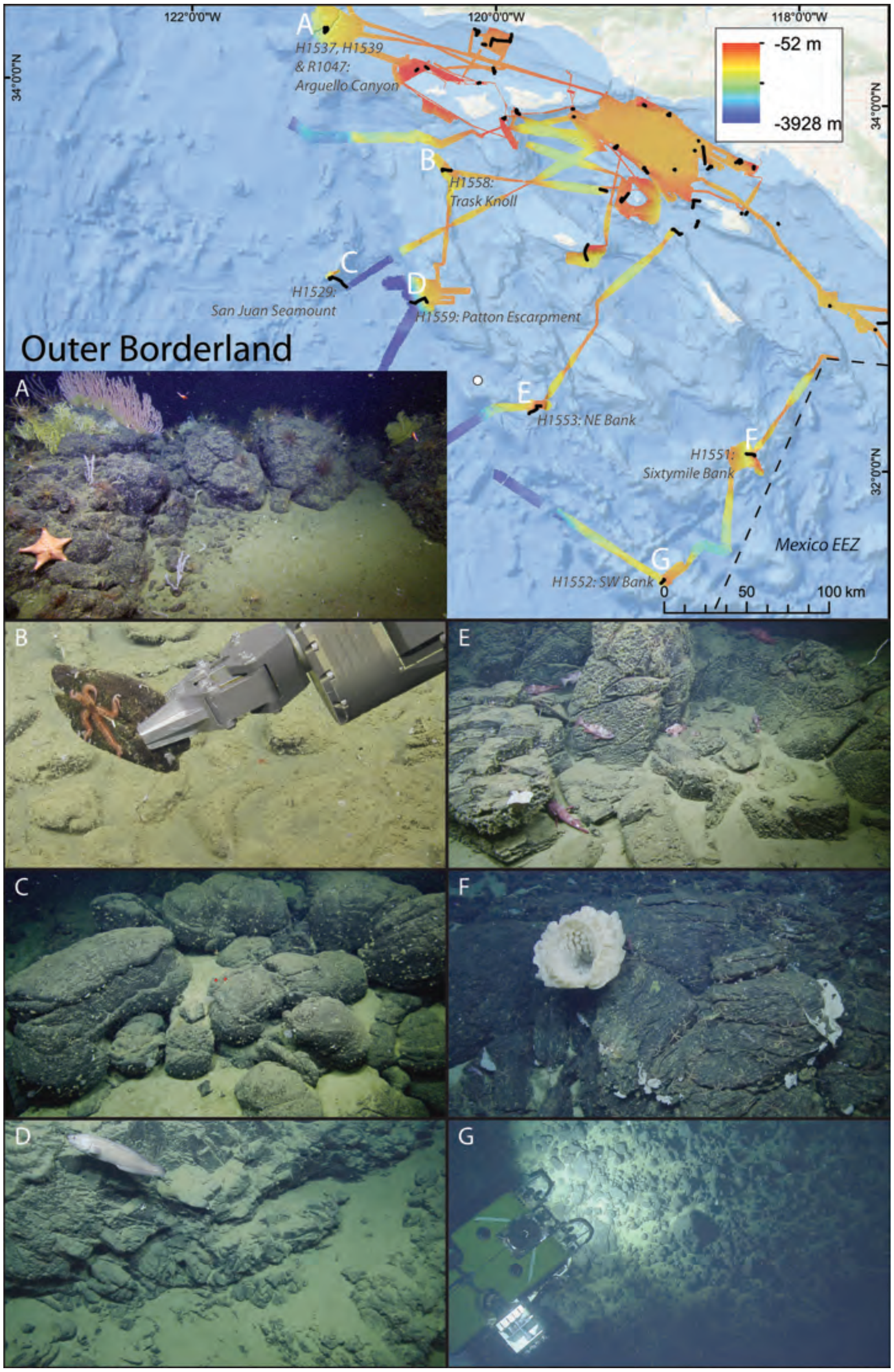

FIG. 10.—Outer Borderland. Top: Newly acquired multibeam bathymetric data (colored swaths) and *Hercules* dive tracks (black lines). White dot indicates the approximate location of DSDP Site 468, between Northeast Bank and Patton Escarpment. Select still frames from *Hercules*: **A)** At 1500 m on rocky outcrops in Arguello Canyon, a high abundance of life was present with a diverse array of corals, echinoderms, sponges, crustaceans, and octopuses. **B)** This slab-like rock (schist?) was sampled from a fragmented cliff face on Trask Knoll (sample NA075-136). **C)** Large black rock outcrops, probably pillow basalts, on San Juan Seamount. **D)** Nearly vertical slope of black rock and sediment-covered small boulders on Patton Escarpment. **E)** Rocky outcrop on Northeast Bank with an abundance of rockfishes in the crevices. **F)** Foliated, possibly folded, black rocks on Sixtymile Bank, colonized by sea stars, glass sponges, and other benthic fauna. **G)** *Hercules* collecting a black rock on the slope of Southwest Bank (sample NA075-068). For scale, panoramic frames are approximately 5–10 m across (A, C, D, E, F); the claw at the end of the manipulator arm is 18 cm long (B); *Hercules* is 1.8 m wide (G).

Results—The dive began at 3368 m depth and revealed a different fauna from that observed at shallower depths during previous dives (Fig. 10D). Observed faunas included purple acorn worms (*Tergivelum baldwinae*), sea pigs (*Scotoplanes globosa*), predatory tunicates (*Megalodicopia hians*), and large stalked glass sponges. The dark, smooth rock outcrops present along most of the dive track were initially interpreted to be volcanic in origin, but closer examination of the samples collected with the ROV revealed them to be sandstone or siltstone covered with a surprisingly thick manganese crust (Appendix Table 11).

Northeast Bank: *Study area*—Northeast Bank, a guyot located more than 200 km off San Diego, California, is an isolated volcanic seamount with a flat top that is now at 400 m below the sea surface; this feature resulted from wave erosion before it subsided below sea level (Fig. 10E). Northeast Bank is thought to have erupted during the Miocene near a triple junction, where the Pacific–Farallon spreading center interacted with the North American plate (Marsaglia et al. 2006). Rising ~1000 m above the surrounding seafloor, this bank affects local currents and is thought to support local biodiversity. Previous dives by MBARI explored the southeastern rim of this feature and documented a paleoshoreline, lava flows, and volcaniclastic sediments (Paduan et al. 2007, 2009).

Objectives—The purpose of dive H1553 was to explore the geology and benthic fauna associated with two volcanic cones on the SW flank of the guyot and explore a possible volcanic lava flow area at the summit of the western edge of the Northeast Bank.

Results—During the transect up the western flank, we observed and sampled volcanic rocks, some basaltic, as well as bedded volcaniclastic sandstone (Fig. 10E; Appendix Table 11). There are a series of isolated cones on the seafloor adjacent to this guyot that may be worthy of future exploration.

Sixtymile Bank: *Study area*—Sixtymile Bank sits at the boundary between the Inner and Outer California Borderland (Fig. 10). Rising over 1200 m above the adjacent seafloor to a water depth of approximately 130 m, the summit of this bank would have been subaerial during the Last Glacial Maximum, which would explain its flat top. This bank is located at the edge of the Inner Borderland, where previous studies elsewhere in the offshore borderland (e.g., Crouch and Suppe 1993) suggest that Miocene tectonic uplift may have resulted in exhumation of metamorphic rock from within the relict subduction zone.

Objectives—Dive H1551 was conducted to sample biological and geological features along a transect of the steep (~18°) western slope of Sixtymile Bank, which may be controlled by faulting.

Results and preliminary interpretation—Planar rock outcrops dominate the flattened summit of this feature, consistent with wave erosion during sea-level lowstand. We collected nine geological samples, many from in situ exposed rock faces, but also some loose samples during long intervals where nothing but talus was encountered (Fig. 10F; Appendix Table 11). Closer examination of these samples at the URI Marine Geological Samples Laboratory revealed lithologies ranging from siltstone to schist, all of them coated with a thick manganese crust. The presence of metamorphic rock seems to confirm the tectonic uplift and exhumation hypothesis. Slurp samples collected near the summit area of Sixtymile Bank at 537 m and 139 m water depth consist of calcareous sand and carbonate shell hash, respectively.

Southwest Bank: *Study area*—Southwest Bank is the southern flank of the Velero Basin, the deepest basin in the Outer California Borderland (Fig. 10G). The bank features a flat summit at ~500 m depth, probably indicating a wave-cut platform that formed when the area was subaerial prior to regional subsidence. Existing seismic profiles suggest the flanks of the escarpment are controlled by faults within the Ferrelo Fault Zone (Legg et al. 2015; C.C. Sorlien, personal communication, May 2017). However, the activity of this branch of the Ferrelo Fault Zone, one the longest fault zones offshore southern California, is poorly constrained.

Objectives—The objectives of dive H1552 on Southwest Bank were to confirm the fault origin of some of the features hinted at in the seismic profiles and to characterize the geology of the bank by collecting rock samples.

Results and preliminary interpretation—The dive began below 1200 m and crossed over the top of a sharp linear ridge at approximately 1005 m, where we encountered and collected heavily weathered breccia, possibly volcaniclastic (Fig. 10G; Appendix Table 11). This narrow ridge abuts the west side of Southwest Bank and represents, in all likelihood, a pressure ridge related to transpression across a branch of the Ferrelo Fault system. Fault-related features similar to those previously identified along the Santa Cruz–Catalina Ridge Fault Zone (see section "Hillside Valley") were observed along that pressure ridge, including fields of brecciated rocks. These features may indicate recent activity of this branch of the Ferrelo Fault Zone. At the dive termination near 555 m depth, there was evidence of a formerly subaerial paleoshoreline in the form of rounded cobbles, sculpted rocks, and semiconsolidated conglomerate consisting of clasts of various lithologies similar to those previously interpreted as characteristic of a former shoreline at other seamounts in the offshore California Continental Borderland (Paduan et al. 2009).

CONCLUSIONS

Digital data and physical samples await further analysis, but preliminary observations made during the 2015–2016 *Nautilus* expeditions across the Southern California Continental Borderland reveal several major findings. The high-resolution multibeam bathymetric data clearly highlight, in exquisite detail, the traces at the seafloor of several presumably active strike-slip faults, coincident with the locations of effusive seeps. For instance, seeps are associated with the San Clemente Fault at Kimki Ridge, with the San Pedro Basin Fault NE of Redondo Knoll and at the SE corner of Santa Monica Basin, and the Santa Cruz–Catalina Ridge Fault Zone SE of Catalina Island. Furthermore, observed faunal assemblages appear to be associated with distinct biogeographical provinces newly defined by this study for the southern California Borderland; for example, the fauna observed along the foot of the Patton Escarpment was quite distinct from that observed in the Inner Borderland. Geologic samples collected across the region will add to understanding the distribution of bedrock, whereas sediment samples collected from submerged marine terrace sequences may constrain the ages and positions of paleoshorelines in various locations. We look forward to other scientists utilizing data collected by *Nautilus* to contribute to a better understanding of the Southern California Continental Borderland.

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TABLE 3.—Samples collected in the Santa Barbara Basin.

Operating Area	Dive	Push cores	Grab Samples	Suction Samples	Niskin Samples
Santa Barbara Basin	H1462	NA067-027 NA067-028 NA067-029 NA067-030 NA067-031 NA067-032 NA067-033	—	—	—
Santa Barbara Basin	H1463	—	—	—	—
Santa Barbara Basin	H1525	NA073-002 NA073-003 NA073-004 NA073-005 NA073-006 NA073-007	NA073-001 (NS) NA073-008	NA073-009	—
Santa Barbara Basin	H1527	NA073-018 NA073-019 NA073-020 NA073-021 NA073-022 NA073-023	—	NA073-024	—
Santa Barbara Basin	H1530	NA073-056 NA073-057 NA073-058 NA073-059 NA073-060 NA073-061	—	NA073-062 NA073-063 (NS) NA073-064 NA073-065	—
Santa Barbara Basin, Southern Shelf	H1535	—	NA074-038 NA074-039 NA074-040 (NS) NA074-041 (NS)	—	—
Santa Barbara Basin, Southern Shelf	H1536	—	NA074-042 NA074-043 NA074-044 NA074-045	—	—
Santa Barbara Basin, Southern Shelf	H1538	—	NA074-069 NA074-071 NA074-072 NA074-073 NA074-074 NA074-076 NA074-077 NA074-078 NA074-079	—	NA074-070 NA074-075
Goleta Landslide Complex	H1526	—	—	NA073-010 NA073-011 NA073-014 NA073-015	NA073-012 NA073-013 NA073-016 NA073-017

NS = no sample (sample lost, discarded, otherwise does not exist).

TABLE 4.—Samples collected in the Santa Cruz Basin.

Operating Area	Dive	Push cores	Grab Samples	Suction Samples	Niskin Samples
NW Santa Cruz Basin	H1533	NA074-015 NA074-016	NA074-009 NA074-010 NA074-012 NA074-013 NA074-014 NA074-017 NA074-018 NA074-019 NA074-021 NA074-022	NA074-011 NA074-020	—
NW Santa Cruz Basin	H1540	—	NA074-103 NA074-105 NA074-106 NA074-109 NA074-110 NA074-112 NA074-113 NA074-114 NA074-115 NA074-116 NA074-117 NA074-118 NA074-119 NA074-120 NA074-121 NA074-122 NA074-123 NA074-124 NA074-126	NA074-108 NA074-111	NA074-104 NA074-107 NA074-125
SE Santa Cruz Basin	H1532	—	NA074-001 NA074-002 NA074-003 NA074-004 NA074-005 NA074-006 NA074-007 NA074-008	—	—
SE Santa Cruz Basin	H1557	—	NA075-119 NA075-120 NA075-121 NA075-122 NA075-123 NA075-124 NA075-125 NA075-126 NA075-127	—	—

TABLE 5.—Samples collected in the Santa Cruz–Catalina Ridge.

Operating Area	Dive	Push cores	Grab Samples	Suction Samples	Niskin Samples
Northwestern Banks	H1534	—	NA074-023	—	NA074-025
			NA074-024		NA074-026
			NA074-027		NA074-032
			NA074-028		NA074-033
			NA074-029		NA074-034
			NA074-030		NA074-035
			NA074-031		
			NA074-036		
			NA074-037		
Northwestern Banks	H1541	—	—	—	—
Northwestern Banks	H1544	—	NA075-019	NA075-017	—
			NA075-021	NA075-018	
			NA075-022	NA075-020	
			NA075-025	NA075-023	
			NA075-026	NA075-024	
			NA075-028	NA075-027	
			NA075-030	NA075-029	
			NA075-031		
Northwestern Banks	H1545	—	—	—	—
Hillside Valley	1543	NA075-012	NA075-005	NA075-006	—
			NA075-008	NA075-007	
			NA075-009		
			NA075-010		
			NA075-011		
			NA075-013		
			NA075-014		
			NA075-015		
			NA075-016		

TABLE 6.—Samples collected in the Santa Monica Basin.

Operating Area	Dive	Push cores	Grab Samples	Suction Samples	Niskin Samples
Point Dume	H1454	NA066-126	NA066-124	NA066-129	NA066-125
		NA066-127	NA066-135 (scoop)	NA066-134	NA066-130
		NA066-128	NA066-136	NA066-137	NA066-139
		NA066-131	NA066-138		NA066-140
		NA066-132			NA066-141
		NA066-133			NA066-142
Point Dume	H1456	NA066-157	NA066-164 (scoop)	NA066-155	NA066-160
		NA066-158		NA066-156	NA066-161
		NA066-159		NA066-163	NA066-162
		NA066-167 (NS)		NA066-170	NA066-165
		NA066-168 (NS)			NA066-166
		NA066-169			
Point Dume	H1457	—	—	—	—
Point Dume	H1528	NA073-025	NA073-031	NA073-027	NA073-033 (NS)
		NA073-026	NA073-036	NA073-030	NA073-035 (NS)
		NA073-028	NA073-037	NA073-032	
		NA073-029	NA073-039	NA073-041	
		NA073-034		NA073-042 (NS)	
		NA073-038			
		NA073-040			
Redondo Knoll	H1451	NA066-101	—	NA066-100	NA066-099
		NA066-102		NA066-103	
Redondo Knoll	H1455	—	NA066-143	NA066-150	NA066-146
			NA066-144	NA066-151	NA066-147
			NA066-145 (scoop)	NA066-152	NA066-153
			NA066-148		NA066-154
			NA066-149		
Redondo Knoll	H1461	—	—	—	—
Redondo Knoll	H1542	NA075-001	NA075-002	NA075-003	
			NA075-004		
Santa Monica Basin Seep	H1548	NA075-045	—	NA075-043 (NS)	NA075-044 (NS)
		NA075-046		NA075-049 (NS)	
		NA075-047		NA075-050 (NS)	
		NA075-048		NA075-051 (NS)	

NS = no sample (sample lost, discarded, otherwise does not exist).

TABLE 7.—Samples collected in the San Pedro Basin.

Operating Area	Dive	Push cores	Grab Samples	Suction Samples	Niskin Samples
Palos Verdes	H1452	NA066-109	NA066-105	NA066-104	NA066-111
		NA066-110	NA066-115	NA066-106	NA066-112
		NA066-113	NA066-119	NA066-107	NA066-120
		NA066-114		NA066-108	
		NA066-116		NA066-118	
		NA066-117			
Palos Verdes	H1531	—	NA073-066	—	NA073-068
			NA073-067		
Palos Verdes	H1453	—	NA066-121	—	NA066-122
					NA066-123
Long Point Fault	H1458	—	—	—	—
Long Point Fault	H1459	—	NA067-001	—	—
			NA067-002		
			NA067-003		
			NA067-004		
			NA067-005		
			NA067-006		
			NA067-007		
			NA067-008		
			NA067-009		
			NA067-010		
Long Point Fault	H1556	NA075-101	NA075-100	NA075-105	—
		NA075-116	NA075-102	NA075-114	
		NA075-117	NA075-103	NA075-115	
			NA075-104		
			NA075-106		
			NA075-107		
			NA075-108		
			NA075-109		
			NA075-110		
			NA075-111		
			NA075-112		
			NA075-113		
			NA075-118		

TABLE 8.—Samples collected in the Catalina Basin.

Operating Area	Dive	Push cores	Grab Samples	Suction Samples	Niskin Samples
Kimki Ridge	H1554	NA075-092	NA075-086 NA075-088 NA075-089 NA075-090 NA075-091 NA075-093 NA075-094 NA075-095	NA075-087	—
Catalina Escarpment and Canyon	H1460	—	NA067-011 NA067-012 NA067-013 NA067-014 NA067-015 NA067-016 NA067-017 NA067-018 NA067-019 NA067-021 (scoop) NA067-022 NA067-023 NA067-024 NA067-025	NA067-020	—

TABLE 9.—Samples collected in the San Nicolas Basin.

Operating Area	Dive	Push cores	Grab Samples	Suction Samples	Niskin Samples
San Nicolas Basin & Escarpment	H1546	NA075-033	NA075-035 NA075-036 NA075-037 NA075-038 NA075-039 NA075-040 NA075-041 NA075-042	NA075-032 NA075-034	—
San Nicolas Basin & Escarpment	H1547	—	—	—	—

TABLE 10.—Samples collected in the San Diego Trough.

Operating Area	Dive	Push cores	Grab Samples	Suction Samples	Niskin Samples
San Diego Trough	H1444	NA066-006	NA066-003	NA066-012	NA066-001
		NA066-010	NA066-004	NA066-015	NA066-002
			NA066-005	NA066-016	NA066-011
			NA066-007		NA066-017
			NA066-008		NA066-018
			NA066-009		NA066-019
			NA066-013		
			NA066-014		
San Diego Trough	H1445	NA066-020	NA066-022	NA066-023	NA066-026
		NA066-021	NA066-033	NA066-024	NA066-027
		NA066-030		NA066-025	NA066-028
		NA066-031		NA066-032	NA066-029
San Diego Trough	H1449	NA066-081	—	NA066-083	NA066-089
		NA066-082		NA066-084	NA066-090
		NA066-085		NA066-088	
		NA066-086			
		NA066-087			

Table 11.—Samples collected in the Outer Borderland.

Operating Area	Dive	Push cores	Grab Samples	Suction Samples	Niskin Samples
Arguello Canyon	H1537	NA074-046	NA074-054	NA074-048	NA074-059
		NA074-052	NA074-056	NA074-049	NA074-060 (NS)
		NA074-053	NA074-057	NA074-050	NA074-066
			NA074-058	NA074-051	NA074-067 (NS)
			NA074-061	NA074-055	
			NA074-062		
			NA074-063		
			NA074-064		
			NA074-065		
			NA074-068		
Arguello Canyon	H1539	NA074-090 (NS)	NA074-080	NA074-086	NA074-087
		NA074-091	NA074-081	NA074-088	
		NA074-097	NA074-082	NA074-089	
		NA074-098	NA074-083	NA074-099	
			NA074-084	NA074-101	
			NA074-085		
			NA074-092		
			NA074-093		
			NA074-094		
			NA074-095		
			NA074-096		
			NA074-100		
			NA074-102		
Arguello Canyon	R1047	—	—	—	—
Trask Knoll	H1558	—	NA075-128	—	—
			NA075-129		
			NA075-130		
			NA075-131		
			NA075-132		
			NA075-133		
			NA075-134		
			NA075-135		
			NA075-136		
San Juan Seamount	H1529	NA073-043	NA073-044	NA073-049	NA073-045
		NA073-048	NA073-046	NA073-050	NA073-051
			NA073-047		NA073-052
			NA073-053		NA073-054
					NA073-055
Patton Escarpment	H1559	—	NA075-137	—	—
			NA075-138		
			NA075-139		
			NA075-140		
			NA075-141		
			NA075-142		
			NA075-143		
			NA075-143		
			NA075-144		
			NA075-145		
Northeast Bank	H1553	—	NA075-076	—	—
			NA075-077		
			NA075-078		
			NA075-079		
			NA075-080		
			NA075-081 (NS)		
			NA075-082		
			NA075-083		

Table 11.—*Continued*.

Operating Area	Dive	Push cores	Grab Samples	Suction Samples	Niskin Samples
			NA075-084		
			NA075-085		
Sixtymile Bank	H1551	—	NA075-052	NA075-059	—
			NA075-053	NA075-060	
			NA075-054	NA075-060	
			NA075-055	NA075-064	
			NA075-056		
			NA075-057		
			NA075-058		
			NA075-061		
			NA075-062		
			NA075-063		
Southwest Bank	H1552	—	NA075-065	NA075-067	—
			NA075-066	NA075-074	
			NA075-068		
			NA075-069		
			NA075-070		
			NA075-071		
			NA075-072		
			NA075-073		
			NA075-075		

NS = no sample (sample lost, discarded, otherwise does not exist).