Conducting efficient remote science and planning operations for ocean exploration using Exploration Ground Data Systems (xGDS)

Tamar E. Cohen
KBR Inc.
NASA Ames Research Center
MS 269-3
Moffett Field, CA 94035
tamar.e.cohen@jpl.nasa.gov

Dr. David S. Lees
Carnegie Mellon University
NASA Ames Research Center
MS 269-3
Moffett Field, CA 94035
david.lees@nasa.gov

Dr. Darlene S. S. Lim
NASA Ames Research Center
MS 245-3
Moffett Field, CA 94035
darlene.lim@nasa.gov

Dr. Nicole A. Raineault
Ocean Exploration Trust
215 South Ferry Rd.
Narragansett, RI 02882
nicole@oceanexplorationtrust.org

Dr. Matthew C. Deans
NASA Ames Research Center
MS 269-3
Moffett Field, CA 94035
matthew.c.deans@nasa.gov

Abstract—**NASA Ames' Exploration Ground Data Systems (xGDS) supports rapid scientific decision making by synchronizing information in time and space, including video and still images, scientific instrument data, and science and operations notes in geographic and temporal context. We have deployed xGDS at multiple NASA field analog missions over the past decade.**

In the last two years, we have participated in SUBSEA, a multi-institution collaborative project*. SUBSEA used the research ship E/V *Nautilus* along with its two remotely operated vehicles (ROVs), *Hercules* and *Argus*, to explore deep ocean volcanic vents as an analog for ocean worlds (e.g. Enceladus). This work allowed us to compare the existing oceanographic operations methods and technologies used for ocean exploration with corresponding tools and approaches developed and used at NASA. In the first year of SUBSEA we observed existing remote science operations from the Inner Space Center (ISC). In the second year, we deployed xGDS at ISC to complement existing capabilities with xGDS tools designed to support remote *Nautilus* science operations from the ISC.**

During operations, video, ROV position and instrument telemetry were streamed from the ship to the ISC. As the science team watched dive operations, they could annotate the data with observations that were relevant to their work domain. Later, the team members could review the data at their own pace to collaboratively develop a dive plan for the next day, which had to be delivered on a fixed daily schedule.

The opportunity to compare operations under different conditions enabled us to make several key observations about conducting remote science and planning operations efficiently: (i) Reviewing data collaboratively and interactively with temporal and spatial context was critical for the remote science team's ability to plan dive operations on the *Nautilus*. (ii) Science team members were actively engaged with the remote dive operations because they could interact with the collected data and visualize it as they desired. (iii) Being able to replay past events at accelerated speeds, and jump to points in time and spaced based on search results, provided efficient access to critical points of interest in a massive volume of data, so the remote science team could deliver plans on time.

*** SUBSEA (Systematic Underwater Biogeochemical Science and Exploration Analog) is a multi-institution collaboration supported by NASA, NOAA's Office of Exploration Research (OER), the Ocean Exploration Trust (OET) and the University of Rhode Island's Graduate School of Oceanography (GSO).**

****ISC is GSO's telepresence operations facility.**

TABLE OF CONTENTS

1. INTRODUCTION

The SUBSEA (Systematic Underwater Biogeochemical Science and Exploration Analog) Research Program integrates ocean and space exploration methodologies to identify synergies between each specialty's operations protocols and technologies while conducting real (i.e. non-simulated) ocean science research [1,2]. SUBSEA is a partnership between the NASA Science Mission Directorate's Planetary Science and Technology through Analog Research (PSTAR) program, NOAA's Office of Ocean Exploration and Research (OER), and the Ocean Exploration Trust (OET).

The SUBSEA project conducted two deployments with OET's research ship, the E/V *Nautilus*, and its pair of remotely operated vehicles (ROVs), *Argus* and *Hercules* (Figure 1). The first deployment in August 2018 (Cruise A) was to the Lō`ihi seamount off the coast of Hawai`i. The second deployment in May/June 2019 (Cruise B) explored the mid-ocean Gorda Ridge system off the coast of the California/Oregon border. For both cruises, there was a shipboard science team as well as a remote science team located at the Inner Space Center (ISC) at the University of Rhode Island (URI).

On both SUBSEA cruises, the science team focused on researching venting fluids at isolated seamounts and spreading ridges in the Pacific Ocean as analog environments to volcanically-hosted hydrothermal systems on other Ocean Worlds. Ocean Worlds are places in the outer Solar System that could possess subsurface oceans, such as Enceladus, a moon of Saturn.

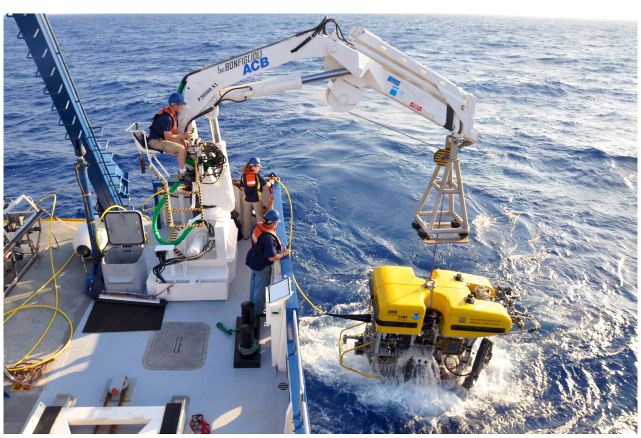


Figure 1. Recovery of ROV *Hercules* onto rear deck of E/V *Nautilus*. *Argus* is at center left of image (Photo Credit: OET).

For both cruises, the science team had *a priori* sonar mapping data of the field sites which they used for strategic planning. These maps were sufficient to identify general areas of interest for the science team's sampling and exploration activities, but were too coarse for further refinement of their pre-cruise site selections. The acquisition of a high resolution characterization of the areas of interest was important to the science team so that they could strategically select the appropriate vents and rocks to sample during each ROV dive. To this end, the science team created dive plans that required repeat visits to the same sites. Within and between these visits, knowledge compounded through a series of imaging, thermal probing, and sampling activities. The increasing knowledge base was used to inform subsequent dive plans and to refine sample site selection.

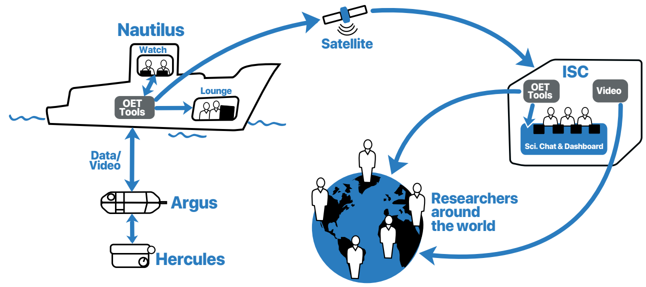


Figure 2. Cruise A System Architecture

The SUBSEA Science Operations research team studied the *Nautilus* operations architecture, distributed teams, and communication during both cruises, embedding observers both on the ship and in the ISC. The Technology research team provided Exploration Ground Data Systems (xGDS) software [Marquez et al. 2019 (Astrobiology paper)] to the ISC-based science team to support integration and visualization of diverse data products and improve support for remote science operations during Cruise B only. This allowed comparison of the Cruise A deployment using existing OET and ISC capabilities, with Cruise B, where the existing capabilities were supplemented by NASA tools and operations practices.

NASA has a rich legacy of terrestrial field analog research, in which various concepts of operations for planetary exploration are studied under real (non-simulated) scientific exploration conditions [3,4,5]. In a typical NASA mission analog, the science team is co-located in one room or location, often close to the field site, sometimes more remote. This science team is responsible for planning and directing their field team's data collection but does not visit the field site directly during operations - analogous to a planetary mission. This is in contrast to the standard operating procedure of OET, where the science staff on ship provides the bulk of the decision making and dive planning, and the lead scientist directs the ROV pilots during operations. When remote scientists do participate, they are truly distributed, often thousands of miles from the ship, and use telepresence to gain situational awareness of the remote operation.

2. Cruise A: Current Practices in Remote Ocean Exploration

Cruise A leveraged the existing E/V *Nautilus*, OET and URI telepresence mission architecture and science activities at Lōʻihi [4,5] to gain operational knowledge of the existing ocean exploration telepresence model. In this exploration model, the scientists and navigators on ship worked together to create daily dive plans which would be shared with the shore team the day before execution. Existing OET tools were used for telepresence and collaboration between ship and shore teams (Figure 2).

The OET infrastructure provides a consistent, reliable delivery of all data from available instruments and telemetry readings on both ROVs and the ship over UDP messaging. These data records are always stored in a structured archive of well named and consistent CSV files with extensive documentation. As instruments are changed on the ROVs over time, this consistency provides a reliable way to access data during and after dives.

Several senior members of the science team were on the ship, including the chief scientist and science support staff for lab work and science instrument operation. E/V *Nautilus* staff included OET data engineers, ROV operators, and navigators, ship operations and support teams. The navigators coordinated the needs of the ROV and science teams with the ship's crew and operations team. A data logger tracked observations, metadata, and sample collection, and took frame grabs from the ROVs' video feeds which were recreated on shore. There was also a video engineer who was responsible for monitoring the video and audio (Figure 3).

Figure 3. E/V *Nautilus* control van during ROV operations. Argus and *Hercules* pilots and navigator were seated at the monitors (foreground to background in image). Not pictured: Data logger, chief scientist and watch lead sat in second row (Photo Credit: OET).

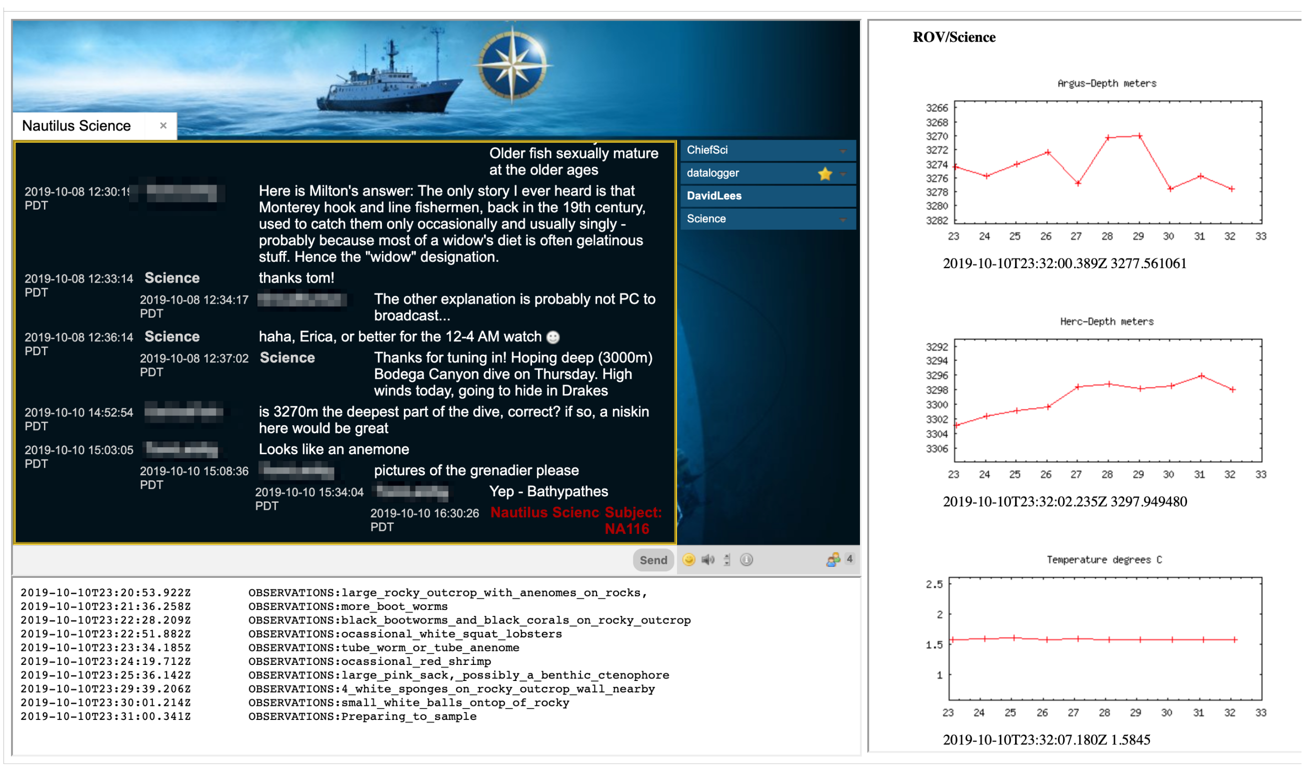


Figure 4. OET Science Dashboard showing chat window (top left), event log (bottom left) and telemetry plots (right column).

When on duty, the team on the ship worked together in the control van; each watch shift was 4 hours long followed by 8 hours off watch. They could immediately view high resolution video from multiple cameras on the ROVs, although they could not rewind or review this video. They had an interactive map on a workstation to visualize ROV location, heading, and depth. Expert operators of the ROVs, navigation and video software were also in the control van. While on watch, scientists could select between different ROV cameras, and speak to the ops team in the control van to request ROV activities such as changing view, taking a sample, probing, etc. They could see high resolution plots of instrument readings (e.g. temperature probe and current ROV depth). The ship team was in constant voice communication with the shore team; this was recorded on the video soundtrack.

Both ship and shore teams used OET's Science Dashboard (Figure 4), which included events from the data logger as well as periodically updated plots of instrument data. It also included the Science Chat, a group chat room where scientists conversed, made observations and requests to the ship.

The shore science team in the ISC (Figure 5) had a reduced set of capabilities and worked from compressed and downsampled data sent via satellite. Three video feeds were transmitted at different compression rates; the highest fidelity (3 Mbps) was used for *Hercules*' main camera; the second level (2 Mbps) was *Argus*' main camera that provided a contextual overhead view of *Hercules*. The most compressed video (1 Mbps) sent a screen capture of the navigator's map, or sometimes a *Hercules* auxiliary camera view (e.g. an instrument on *Hercules*). All video was streamed as fast as it arrived (1.5 - 3 second latency) to the ISC and the first 2 video channels were also available ~30 seconds later via YouTube for the general public and offsite viewing and limited rewind capability. This could be used to take a low resolution screen shot.

Figure 5. Science Team at the ISC during Cruise A. High resolution satellite video of Hercules was shown on the lower screen in front. View of navigator's screen from ship and Google Earth map of ship location location are on upper projector left and right corners. Individual workstations could review public video on YouTube, OET science dashboard or use desktop applications on built-in monitors.

The shore science team used the same OET Science Dashboard that was available on the ship, but this dashboard was driven by data reflected from servers on shore after a minimal delay (~0.5 second). The Science Dashboard rendered information at regular intervals after receipt. Times were displayed along with chat messages and logged events. Data plots refreshed once per minute.

While the shore science team did not have access to the interactive map used on the ship, they could view a map within Google Earth™ which refreshed every 15 minutes. Due to this lag, this map was not useful during a dive as it was not synchronized with the video.

The ship and shore teams could also collaborate via shared file transfer (refreshed every 15 minutes), and they used this to share dive plans, mapped data products and other scientific information with each other. This allowed shore scientists to use GIS software to interact with maps that were created from post processed sonar data on the ship. All of the raw data was also available via the shared file system.

3. CRUISE A: OBSERVATIONS OF THE SHORE SCIENCE TEAM

During Cruise A, the shore science team consistently commented regarding their inability to gain sufficient situational awareness to understand the current state of the ROVs and ship. They also noted their limited ability to provide input to future dive plans [Appendix D].

Dive Plans

Dive plans were authored by the science team and navigators on the ship who were available in person to support plan execution and clarify the intent of the plan. These dive plans included high level science objectives, sample collection instruction and specific geographic waypoints to visit. [Appendix A]. Ship authored dive plans did not include a detailed timeline for plan execution, nor did they explicitly connect sample collection directives with waypoints or science rationale. Dive plans were delivered to shore and discussed via conference call the night before each dive. Even after the call, it was common for the shore team to not have a detailed understanding of the dive plan such that it could be executed without the benefit of input from the science leads.

Ship to Shore Communication

The continuous voice communication was a critical part of giving the shore team any situational awareness of the dive. The shore scientists often had questions about what was happening along with clarification about what should be happening. A great deal of critical, but ephemeral, information about dive status was communicated only by voice. If science team members were not in the room when dive status was reported, they would have to ask colleagues for information or repeat a request to the ship. Many requests from shore pertained to changing views or video displays to provide more context to the shore science team with information that they could not see (e.g. switching the low-res feed from map view to temperature probe chart when recording the temperature of a hydrothermal vent).

Map

The lack of resolution and interactivity of the map hampered the science team's ability to understand where the ROVs and ship were in relation to the sea bed, each other, and the dive plan. When a compressed video of the navigator's HYPACK® map was sent from ship to shore, the resolution was not sufficient for the shore team to comprehend the map or read any figures or markup on that map. The shore team also could not control the map at all (change zoom level or view different overlays) since it was a video view of the navigator's screen on the ship.

Geolocating and Correlating Information

The shore science team had access to KML maps in Google Earth™ which refreshed every 15 minutes. These maps aggregated position and depth information with observations, frame grabs, and collected samples. We initially observed the shore science team attempting to use Google Earth™, but since the maps were out of sync with the live video feed and with the information in the OET Science Dashboard, they caused confusion and were abandoned.

The Science Dashboard did not provide a fully synchronized display of the rapidly changing data for the science team to synthesize. It also did not support searching or rewinding of data.

The archived data were periodically available via the shared file system, typically as CSV log files. It was possible to manually retrieve values for instrument readings, map locations, chat messages and logged events at specific times. This process was cumbersome for two reasons: (i) It could not be completed fast enough to provide useful information during a dive, i.e. to provide expert guidance to the ROV team before they left the relevant site. (ii) Expert skills and knowledge were required to locate and understand the content of the raw data files. To understand and work with the well structured archived data, the data would have to be imported into some software tool (Excel ™, Matlab ™ for example) or processed by custom software providing analysis capabilities to pull out relevant information.

Recording Observations

The data loggers on the ship could record observations, frame grabs or sample collection events, which were saved with timestamps and correlated with ROV positions. The shore side science team could not record formal observations in the data loggers' system. Instead, they used the Science Chat to record observations with custom keywords. A post processing script was written to associate these records with ROV positions in a CSV file. These observations could then be manually reviewed.

4. CRUISE B: NASA PRACTICES APPLIED TO REMOTE OCEAN EXPLORATION

For Cruise B, we extended the existing telepresence infrastructure by applying operations technology and practices adopted from NASA mission analogs. Critical science decision making was also shifted to the shore which made our operations practices more analogous to planetary exploration (Figure 6).

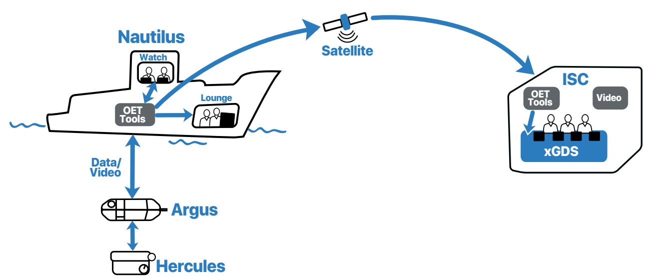


Figure 6. Cruise B System Architecture

The chief scientist and leads for all the science theme areas were co-located at the ISC. They were required to deliver a detailed science plan to the ship on a daily schedule. The crew on the ship had general expertise in the science focus areas, but were instructed to adhere as best as possible to the instructions in the dive plan sent from shore. Throughout Cruise B, we observed and evaluated the shore science team's situational awareness, ability to plan effectively, and actively control the exploration taking place on the ship.

For three of the seven dive days on Cruise B (Mode 1), the shore team could only communicate to the ship via a dive plan delivered nightly, and were not permitted to use real time voice or chat communication with the ship. The ship team also sent a daily dive report to shore after each dive. The shore team could hear what was said by the watch team on the ship as the soundtrack on the video feed, and had access to all of the video, map and telemetry data. The successful execution of the dive and sample collection therefore depended entirely on the information provided in the dive plan.

For the remaining four dive days (Mode 2), live voice and chat communication were permitted. The ship team was still required to follow a detailed dive plan and deliver a dive report but could also talk or text chat with the shore team anytime to clarify information that was communicated through the dive plan or dive report.

The shore science team used xGDS, provided by the NASA technology team, in place of the OET Science Dashboard and map delivery systems. xGDS synchronized information in time and space, including video and still images, scientific instrument data, and science and operations notes, displaying them interactively in geographic and temporal context. xGDS presented this information in a format that enabled the science team to gain rapid situational awareness during the dives (Figure 7).

During each dive, the seven member shore science team monitored execution of the dive they had planned, watched sample collection, recorded observations, captured frame grabs from video and marked up maps to assist with dive planning for subsequent dives. xGDS provided flexible interactive data access and facilitated searches for the critical information needed to create the daily dive plans and deliver them on schedule to the ship.

Figure 7. Shore science team in ISC during Cruise B using xGDS to review and annotate dive activity and interactively explore maps of the dive site. Full resolution live satellite video was shown on projector as in Cruise A

Capabilities provided to the SUBSEA team included:

Recording of telemetry from the ship

xGDS integrated directly with the UDP messages coming from the ship which included the telemetry from the ROVs and ship along with several instruments (CTD, O2S, TempProbe). This data was recorded and stored in xGDS' database, and broadcast upon receipt to all users.

Recording of video

xGDS leveraged the existing infrastructure at ISC, subscribing to HLS video files from the Wowza™ video server recording the video transmitted from the ship over satellite. These HLS files allowed xGDS to embed and control interactive, web playable video via JW Player™. Since there was about a 30 second delay for the video to be encoded by Wowza™, the science team could watch the live video directly on ISC monitors with correlated live telemetry in xGDS or could use the recorded HLS video in xGDS for replay and frame grabs, correlated with the telemetry from the same time (Figure 8).

Interactive map viewer

xGDS supports a user-authored 'Map Tree' - consisting of folders and nodes which can be GeoTiffs, KMLs, map layers authored within xGDS, plans or dynamic layers. xGDS also includes an interactive map view on most of its pages, currently built on OpenLayers. This map view allowed users to pan, zoom and measure, and control visibility and transparency of layers, of their own individual map view. They could also view the locations of search results as well as live updates of ROV and ship positions and headings (Figure 9).

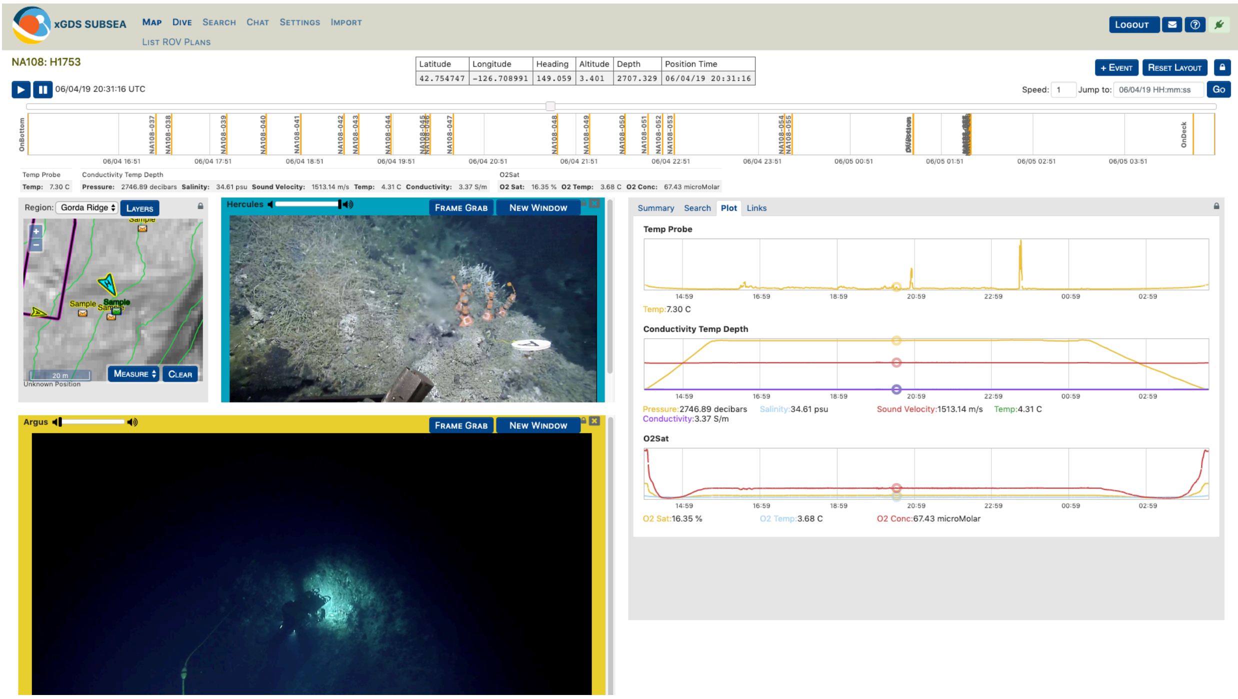


Figure 8: xGDS dive monitor/replay view showing video correlated with ROV and ship tracking and instrument data plots.

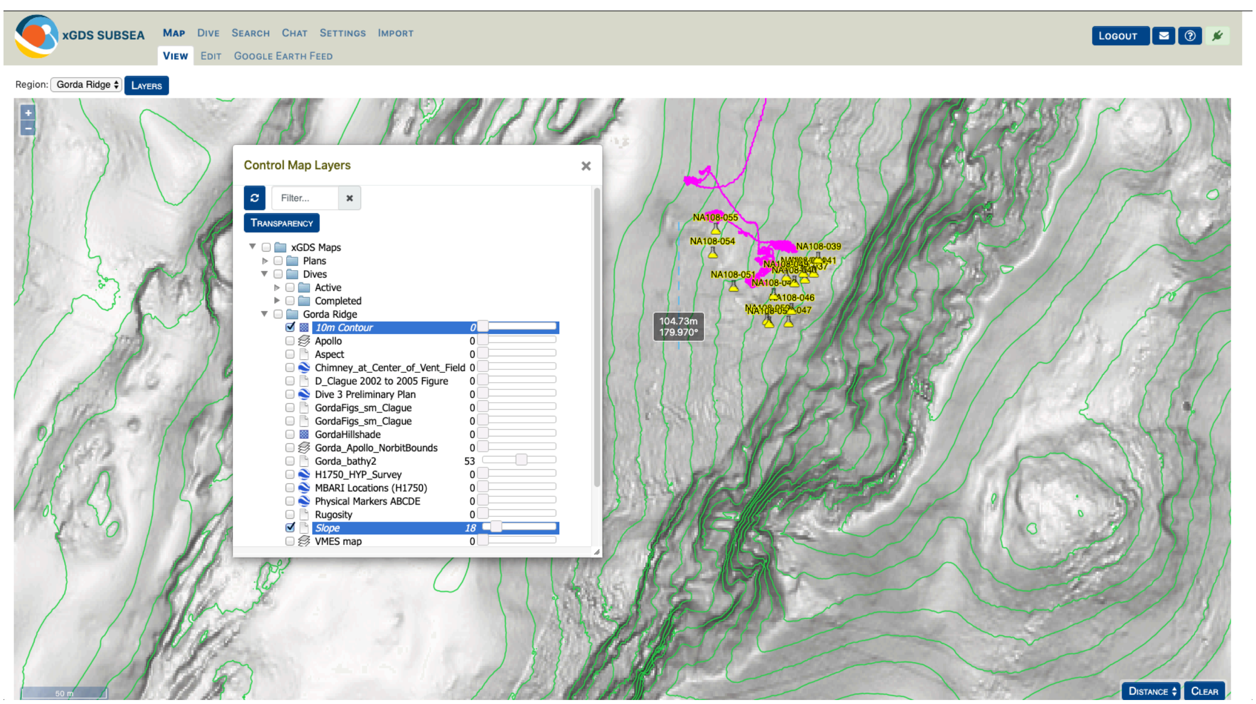


Figure 9: xGDS Map viewer showing layer selection, track, markers and measurement

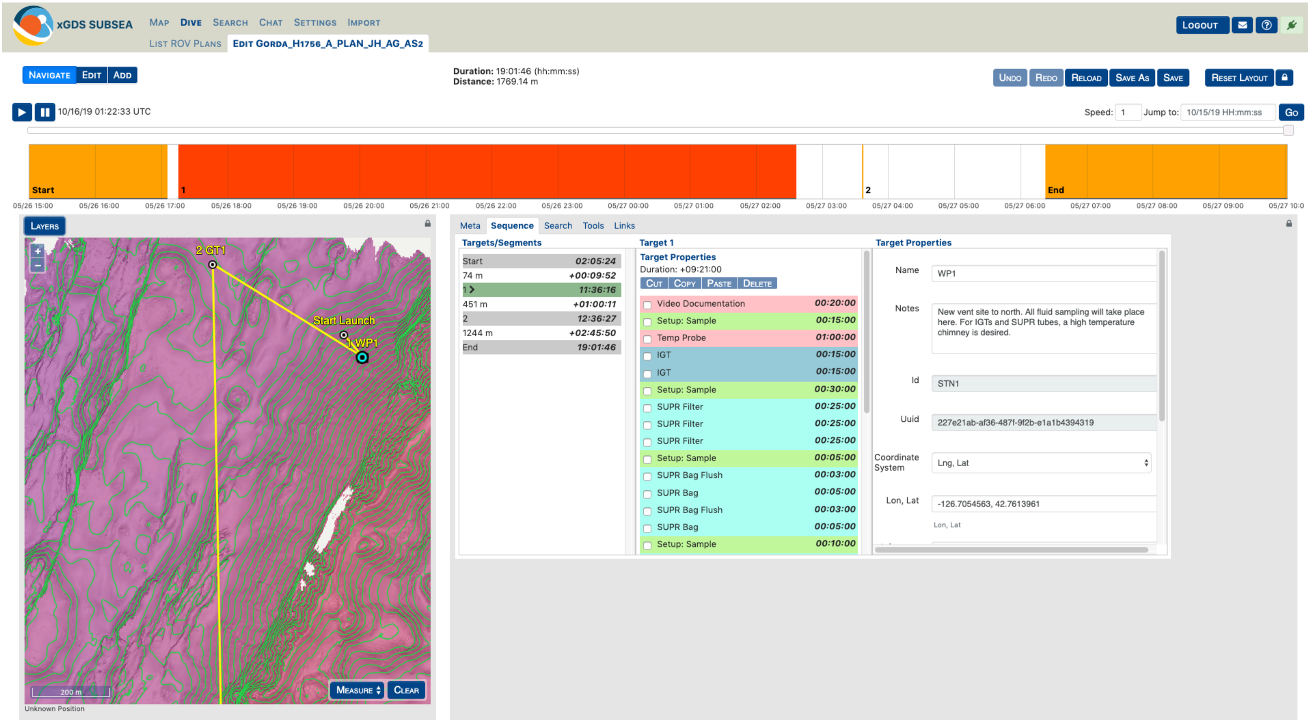


Figure 10: xGDS planner with interactive map, timeline and activity editing

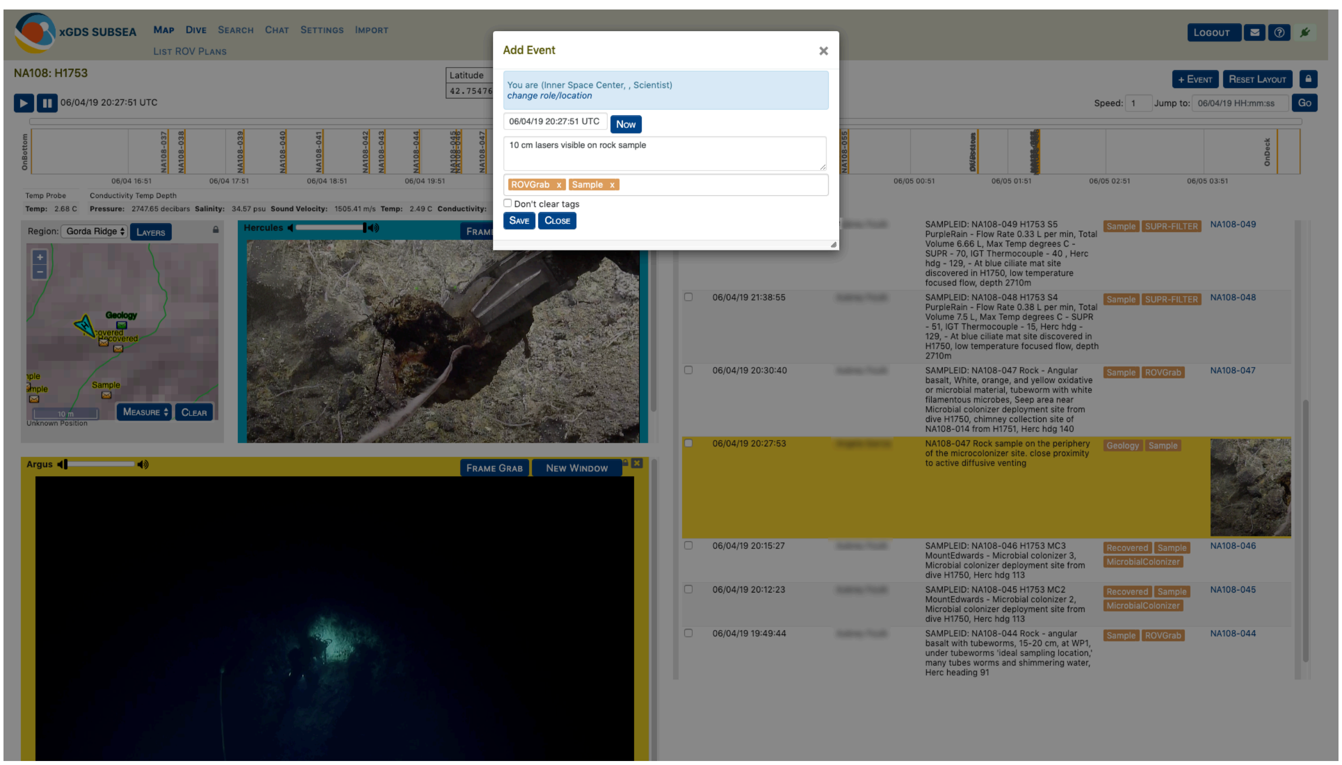


Figure 11: Adding and viewing events in xGDS

Science Chat

xGDS embedded the existing OET Science Chat client and subscribed to Science Chat traffic to record all chat messages, display them on a map and allow them to be easily searched post-dive.

xGDS Planner

The science team used the xGDS planner to efficiently collaborate to build ROV plans which simulated dive execution time and distance. ROV plans were exported and included in a PDF dive plan [Appendix B] showing a list of waypoints and activities in the dive, along with science rationale and supporting images. Plans were also exported into a format compatible with the HYPACK® navigation software used on the ship. The shore science team consulted with an expert ROV navigator to ensure their dive plans were achievable (Figure 10).

5. Cruise B: Observations of the Shore Science Team

Compared to Cruise A, we observed improved situational awareness when the shore science team was using xGDS to view and interact with data from the ship [Appendix D]. A survey conducted at the end of each cruise showed improvements in the science teams' ability to understand, correlate and access data during Cruise B. With the support of xGDS, they were able to accomplish their tasks within the constraints of their daily schedule.

Map

Within xGDS, the shore science team controlled interactive maps, authored map mark up and created custom layers to overlay on the sonar base map, ROV locations, sample markers and other mapped data. Each science team member individually controlled views of the maps (layers, pan and zoom level).

xGDS' map tools are not a full featured replacement for GIS systems. They are designed to facilitate rapid review and search of data in context to support decision making or for export of key data to other tools for detailed analysis. As an example, the geology team extracted information from xGDS along with a previously acquired high resolution base map to analyze in external GIS tools. By doing this they were able to identify geologic formations that they anticipated to be of interest purely by looking at map data. They then created a dive plan to explore their proposed area of interest and discovered a new vent field, named the Apollo vent field. [cite Ashley Shield's AGU abstract]. Based on interviews with the geology team, xGDS allowed them to quickly narrow down a region of interest so they could focus on it using full-featured GIS tools and deliver timely input to the dive plan.

Dive Planning

The shore science team extensively used the planning tools in xGDS to collaboratively build dive plans. Each science theme area team added tasks (e.g. sampling, imaging) to a shared plan and then passed control to the next team. Collectively, they built a unified representation of the next day's dive activities and timeline. Scientists did not need specialized GIS expertise or tools to do the planning. All of the map layers and collected data from previous dives were available in xGDS for search and display during the planning process.

xGDS' planner simulated durations based on an activity dictionary customized for Hercules and the specific science activities for SUBSEA. This supported live display of rough estimates of the duration of the plan and of each activity within the plan, including descent, ascent and transits. As scientists dragged waypoints around the map, the durations automatically updated. Addition or modification of sampling activities would automatically update duration calculations.

Position Accuracy

Inaccuracies with position estimation caused confusion between the shore and ship teams. Two different sensing methods were used to determine the geographic position of the ROVs based on their proximity to the sea floor. Near the sea floor (~10 meters), doppler velocity log (DVL) position sensing was used. When not near the sea floor, ultra short baseline sonar (USBL) was used. The USBL data was very noisy, but was the positioning data that xGDS was subscribing to. Therefore the positions represented in xGDS were noisy and imprecise relative to the size of the work area (~+/-10m position accuracy in a 50m wide work area).

Despite these challenges, the shore science team was able to deliver useful plans. They worked around the positioning challenges by importing target files from the HYPACK® software on the ship; which included positions based off of USBL and refined by DVL. These positions along with depths, headings and images from ROV video were included in the dive plans.

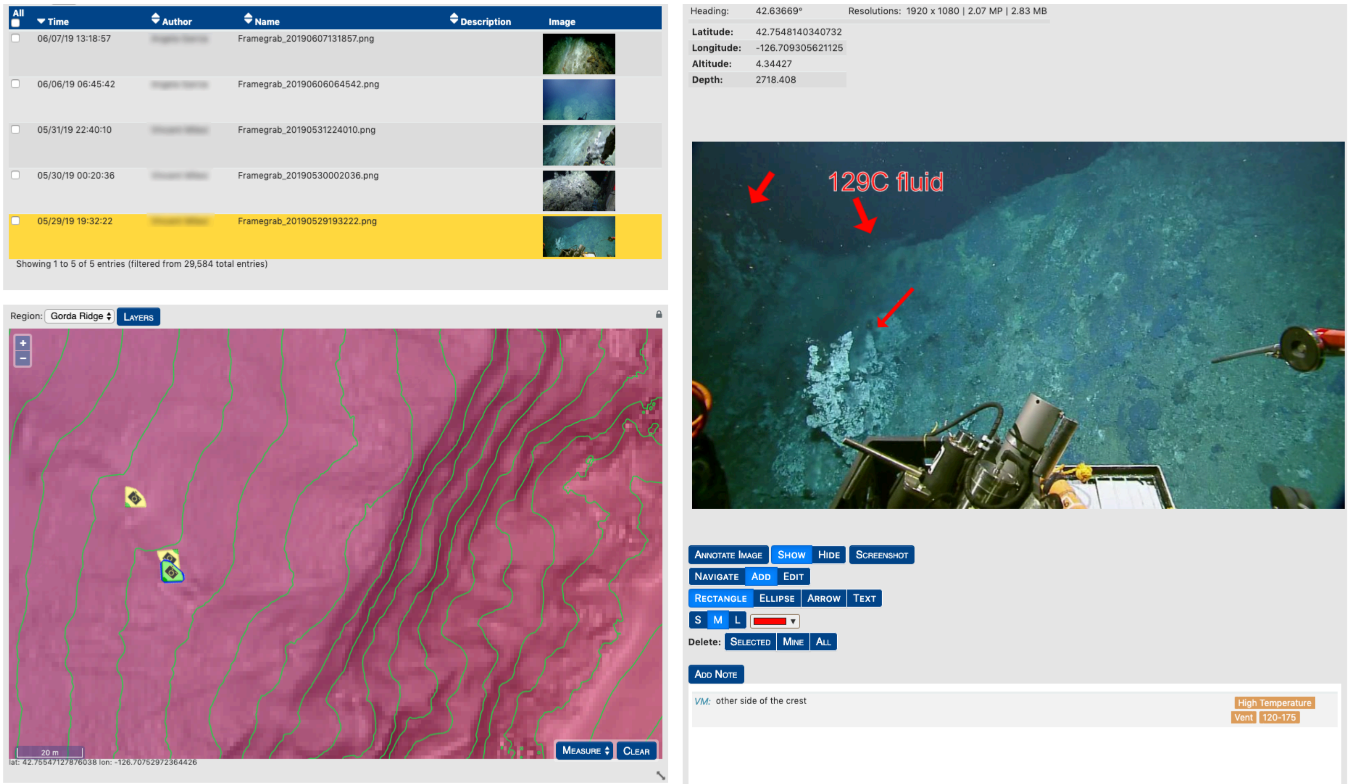


Figure 12: Frame grab with annotations

Improved engagement

Science team members were actively engaged with the remote dive operations because they could interact with the collected data and visualize it as they desired. Shore scientists used xGDS to create their own geolocated, time stamped and tagged events, which facilitated searching for key data and made planning and correlation of information more efficient. They could record events in xGDS, independently from the data logger on the ship (Figure 11). This allowed them to use the Science Chat for its primary purpose as a communication tool.

Shore scientists used the video frame grab capability extensively to snapshot specific views of the sea floor for illustration and planning. They annotated (marked up) these frame grabs and included them in the dive plans (Figure 12).

Appendix A shows xGDS usage statistics for Cruise B for both planning and data annotation and review. These results are for shore team usage only (i.e. in addition to over 1000 still images and events logged on the ship) and show how actively the shore science team was engaged with dive operations when given tools to interact with and understand live events as they happened and efficiently locate and correlate data products for planning.

Interactive data access with temporal and spatial context

The shore science team was able to synthesize information coming from disparate sources and understand the data that the ROVs were gathering in context. With one set of controls in xGDS they could manipulate video synchronized with the geographic context of ROVs and other data, updating instrument readings and plots, and tagged observations along with a timeline. xGDS provided a user interface to simplify searching for and filtering data.

Being able to replay past events at accelerated speeds, and jump to points in time and spaced based on search results, provided efficient access to critical points of interest in a massive volume of data, so the remote science team could deliver plans on time.

The shore science team often used xGDS to rewind and replay the dives from any time, along with the video, position in the map, the plot data from instrument values, and the logged events. The dives could be replayed up to four times actual speed, to speed up review of a dive or locate key events needed for planning.

6. CONCLUSION

SUBSEA successfully demonstrated that NASA exploration methods and operational practices are effective and beneficial when applied to remote ocean exploration. Conversely, ocean exploration is an excellent research platform and analog for space exploration. The operations model and technologies used for SUBSEA Cruise B are directly applicable to future Ocean Worlds exploration.

The requirement to follow strict communications protocols and develop a highly structured dive plan forced the shore science team to capture all necessary information for plan execution within their daily dive plans. These restrictions drove a more rigorous process when authoring dive plans. xGDS helped the science team achieve their goals even with once per day communication via file transfer with the ship team. The cadence and task load for the shore science team was supported by capabilities provided by xGDS.

User interfaces and capabilities that streamline and improve the efficiency of the process of observing, tagging, reviewing and organizing massive volumes of data support rapid comprehension and data analysis. This is critical when teams have limited time to make effective science decisions while data collection is underway (e.g. during ROV dives or EVAs in space).

During exploration, there is a higher level of focus and attention to exploration events and data than afterwards when teams have disbanded. Tagging and annotating this data as it arrives drastically increases its utility both during and after exploration, providing keywords and metrics for search and further analysis.

Lastly, as discoveries are made during exploration, it is paramount to share these findings through outreach efforts. OET has built a robust and effective platform which engages the public via web, social media and YouTube™ platforms, along with the support of dedicated Science Communication Fellows and staff. Future integrations between tools like xGDS and outreach programs such as OET's could provide higher levels of engagement and encourage more active citizen scientist participation around the world.

APPENDICES

A. EXCERPT OF CRUISE A DIVE PLAN

Vital Stats

- **Expected launch time:** 00h00 HST
- **Expected length of dive:** 16 hours
- **Max allowable dive time:** On deck by 16h00 HST on 08 29 2018
- **Expected depth at launch:** 1322 meters
- **Expected max depth:** 1350 meters
- **On bottom Lat:** 18.90661°N **Long:** 155.25781°W

Dive Plan and Objectives

a) dive to center of Pele's Pit crater at depth of 1322m

b) drive ESE to to Marker 38 area, relocated in Dive H1705

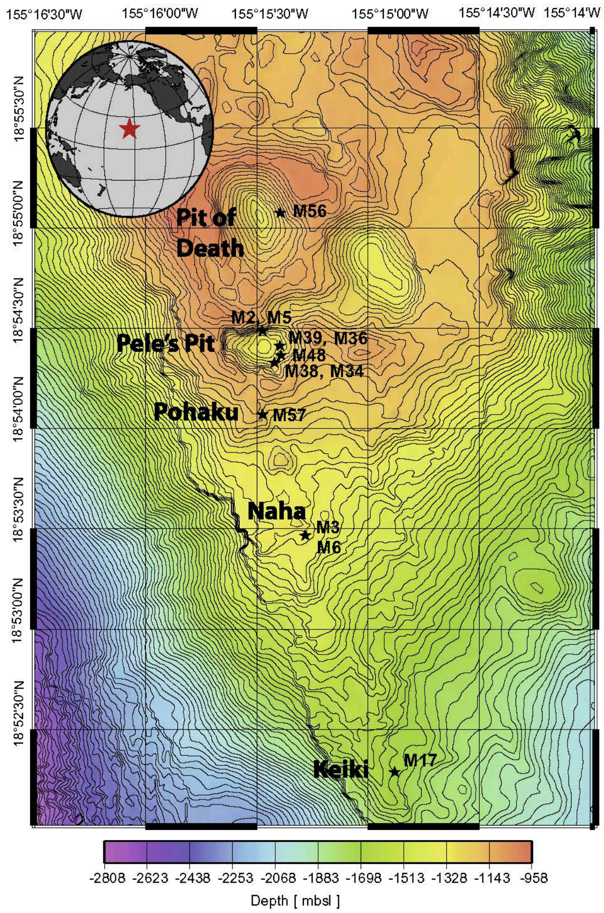
c) conduct Temperature survey with ROV T-probe to select an orifice for sampling

Waypoints

Site	Lat	Long	Depth (m)	Heading	Tmax (°C)
Marker 2	18 54.531	155 15.459	1175	241	40.7
Marker 36	18 54.390	155 15.415	1300	124	Ambient
47°C Vent	18 54.382	155 15.414	1298	38	47.1

Vent-fluid Sampling for Geochemistry

Sample	Interested party	Processing
2 replicate IGT Fluid Samples at site of active fluid flow selected from ISC	Names	Record T° at time of sampling; Shipboard chemistry; Shorebased chemistry


155°16'30"W
155°16'00"W
155°15'30"W
155°15'00"W
155°14'30"W
155°14'W
18°55'30"N
18°55'00"N
18°54'30"N
18°54'00"N
18°53'30"N
18°53'00"N
18°52'30"N
Pit of Death
M56
M2, M5
Pele's Pit
M39, M36
M48
M38, M34
Pohaku
M57
Naha
M3
M6
Keiki
M17
-2808
-2623
-2438
-2253
-2068
-1883
-1698
-1513
-1328
-1143
-958
Depth [mbsl]

B. Excerpt of Cruise B Dive Plan

Vital Stats

- **Expected launch time (UTC):** 11h00 UTC
- **Expected length of dive:** 16 hours
- **Expected Science Objectives:** 4 Objectives
- **Max allowable dive time:** 16 hours
- **Expected depth at launch:** 2732m
- **Expected max depth:** 2732m
- **On bottom Lat:** 42.7549129°N **Long:** 126.7096505°W

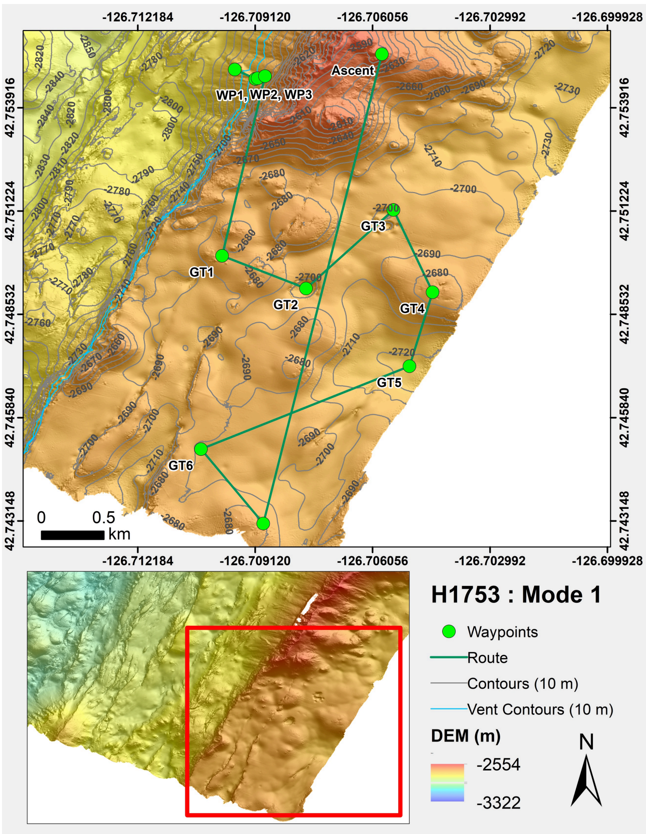
Science Objectives

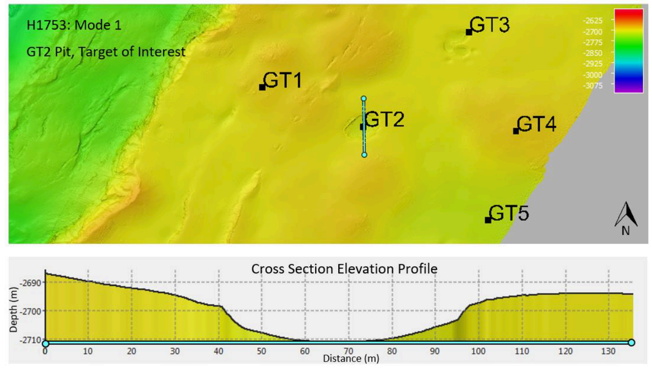
2. Conduct low temperature fluid & rock sampling at a first diffuse flow site.
- 2 x IGT
- 3 x SUPR Filters
- 2 x SUPR bags
- Deploy marker
- 1 x rock
3. Recover the first two of the six colonization experiments at Marker A

Notes	This fourth dive to Gorda Ridge has 6 objectives. (1) Ensure that the ROV is back on deck by 20h00 Ship's Time; (2) Conduct low temperature fluid and rock sampling at/around a patch of bluelilac ciliate mats, uphill from the highT vents sampled on dive H1752 along the same ridge with chimneys that leads up to the colonization experiments at Marker A; (3) Recover the first two of the six microbial colonization experiments deployed on Dive H1750; (4) Conduct low temperature fluid and rock sampling at a second location identified from Dive H1751; (5) Conduct a series of Geotransits on the bathymetric platform uphill from the SeaCliff site, including pits that are targets of interest along the suggested Geotransit path; (6) Collect Niskin water column samples during the ascent, as close together as possible without interrupting the ascent, as soon as (but NOT before) the vehicle has risen to shallower than 2100m.
Duration	21:48:35
Distance	3714.34 m

WP ID	Lat/Lon	Depth	HDG°	BRG°/ Dist	Notes	Activity / Duration	Cum. Time
Target STN1: WP1	42.754668 126.709112	2706.00 m	120.00°	66.73°	Lilac Mat: This area was seen on Dive 1750 at ~2706m depth. See Figure 1 for descriptions of site and what to look for. Heading uphill from the landing site, the target area should be found on the ridge that hosts multiple chimneys along a heading of ~120160 on the way from the highT site sampled on H1752, before you get to the incubation experiments put out on H1750 at Marker A. If you are going along the ridge and end up in basalt and tubeworms, you have gone too far.		
Activity SUS: WP1					Use *Hercules* temperature probe and visual cues for shimmery flow to find area of hydrothermal diffuse flow among the purple ciliate mat. Please note that there is some very hot focused flow near here and we do not want to sample that flow. We want to sample the shimmery, lower temperature flow among the purple ciliates. This needs to be in the range of 1050 C. See Figures 1AD.	+00:15:00	02:26:11

Segment SEG5: Geotransit				202.21 m	Continue geotransit.	+00:26:58	11:15:38





GT2 elevation profile of target of interest (see detailed dive plan). This is included to give you a sense of the depth of the pit as you go by. We'd like to see the interior wall during exit from the pit; don't worry about driving backwards to look at the wall as you arrive at the pit.

Dive 1753: SUPR Diffuse Flow Sampling Site #2

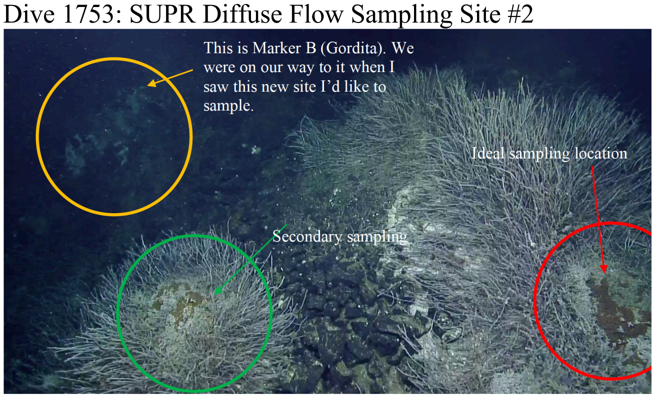


Fig. 1AD. 20190530211539 Sampling site of interest for second SUPR sampling site, Heading 107, with Gordita for help in finding. If too difficult to get into ideal sampling location, use second choice, indicated in green.

C. xGDS Usage Statistics for Cruise B

Activity	Count
Still images captured from satellite video feed	~1000
Interactive access to map layers	~700
Observations and tags on data streamed from ship	~600
Accesses to video replay page	~230
ROV dive plan drafts	53
Final plans delivered	7
Typical dive duration	16 hours
Maximum dive duration	24 hours

D. Survey Results

After each cruise, participants were surveyed and asked the same questions. These questions were rated on a Likert scale where 5 was the strongest positive value and 0 was the strongest negative value. The table below summarizes some of the key responses for both cruises. The fractional values show the proportion of respondents who selected that classification.

Question	Cruise A	Cruise A Score	Cruise B	Cruise B Score
Understand status of ship and ROV operations	.75 somewhat able .25 fairly able	3.25	.2 often unable .2 somewhat able .6 fairly able	3.4
Understand dive plan objectives	.75 fairly able .25 completely able	4.25	.2 fairly able .8 completely able	4.8
Understand dive plan timeline	.5 often unable .5 fairly able	3	.2 fairly able .8 completely able	4.8
Locate ROVs on a map	.5 often unable .25 somewhat able .25 completely able	3	.2 fairly able .8 completely able	4.8
Locate frame grabs on a map	.5 completely unable .25 often unable .25 fairly able	2	.4 fairly able .6 completely able	4.6
Locate logged events on a map	.5 completely unable .25 often unable .25 somewhat able	1.75	.2 somewhat able .2 fairly able .6 completely able	4.4
Read and review logged events	.5 often unable .25 somewhat able .25 fairly able	2.75	1 completely able	5
Follow sample collection progress	.5 often unable .25 somewhat able .25 fairly able	2.75	.2 often unable .4 fairly able .4 completely able	4
Understand what samples had been collected	.5 often unable .25 somewhat able .25 fairly able	2.75	.2 fairly able .8 completely able	4.8
Satisfied with ability to work with logged events	.75 dissatisfied .25 neutral	2.25	.4 satisfied .6 very satisfied	4.6
Satisfied with ability to understand temporal information during a dive	.25 dissatisfied .25 neutral .5 satisfied	2.75	.2 very dissatisfied .6 satisfied .2 very satisfied	3.6
Satisfied with ability to access information during a dive	.75 dissatisfied .25 neutral	2.25	.8 satisfied .2 very satisfied	4.2
Satisfied with ability to correlate information during a dive	.5 dissatisfied .25 neutral .25 satisfied	2.75	.2 neutral .4 satisfied .4 very satisfied	4.2

ACKNOWLEDGEMENTS

SUBSEA is funded by the NASA Planetary Science and Technology Through Analog Research (PSTAR) Program (NNH16ZDA001N-PSTAR) grant (16-PSTAR16_2-0011) to D. Lim and in-kind support by NOAA - OER and the Ocean Exploration Trust.

The authors greatly appreciate the support of all SUBSEA team members, collaborators and organizations for supporting their xGDS research and integration with E/V *Nautilus* for SUBSEA deployments:

- NOAA Office of Ocean Exploration Research
- Ocean Exploration Trust
- University of Rhode Island, Graduate School of Oceanography

REFERENCES

[1] S.E.K. Nawotniak, D.S.S. Lim, et. al., "Project Introduction for SUBSEA: Systematic Underwater Biogeochemical Science and Exploration Analog", *Ocean Worlds 2018*, Houston TX, May 2018.

[2] D.S.S. Lim, N. A. Raineault, et.al., "SUBSEA 2018 Expedition to Lōʻihi Seamount, Hawaiʻi", *Oceanography*, v32, n1, pp. 48-49, March 2019 Supplement.

[3] D. S. S. Lim, A. L. Brady, A. F. Abercromby, D. T. Andersen, et al., "A historical overview of the Pavilion Lake Research Project—Analog science and exploration in an underwater environment," *GSA Special Paper*, vol. 483, pp. 85–115, 2011.

[4] D.S.S. Lim, A.F.J. Abercromby, et al., "The BASALT Research Program: Designing and Developing Mission Elements in Support of Human Scientific Exploration of Mars", *Astrobiology,* v19, n3, March 2019.

[5] J. Heldmann, A. Colaprete, et. al., "Lunar polar rover science operations: Lessons learned and mission architecture implications derived from the Mojave Volatiles Prospector (MVP) terrestrial field campaign", *Advances in Space Research*, pp. 545-559, v58, n4, August 2016.

[6] T. Cohen, D. Lees, et. al., "Integrating Time-Synchronized Video with Other Geospatial and Temporal Data for Remote Science Operations", *2018 IEEE Aerospace Conference*, Big Sky MT, March 2018.

BIOGRAPHY

Dr. David S. Lees *is a researcher in the Intelligent Robotics Group at NASA Ames and a Senior Project Scientist at Carnegie Mellon University's Silicon Valley campus. His research background is in human-robotic interaction and user interfaces for terrestrial and space applications. While at Ames, he has supported the development, study and deployment of ground systems tools including xGDS at multiple NASA field analogs. He has also developed and deployed 3D visualization tools to support the MER and MSL Mars missions. He received a BS degree in EECS from Johns Hopkins University, followed by an MS and Ph.D. in Mechanical Engineering from Stanford University.*

Dr. Matthew C. Deans *is deputy lead of the Intelligent Robotics Group (IRG) at NASA Ames Research Center. Dr. Deans has many years of experience in robotic mapping, localization, navigation, machine vision in unstructured environments, and remote operation of rovers. He leads the xGDS work within the Intelligent Robotics Group, building and testing technologies for remote rover operations and science. Dr. Deans has significant experience with field robotics, participating in field experiments in Chile, Antarctica, the Arctic, Canadian Rockies, Hawaii, and the continental US.*

Dr. Darlene S. S. Lim *received her PhD from the University of Toronto during which she conducted climate change research in the Canadian High Arctic. She is now based at the NASA Ames Research Center, and her work as a geobiologist has since extended to include the development of operations concepts and capabilities in support of human-robotic scientific exploration of our Solar System. Darlene has spent over two decades leading field research around the world and is the Principal Investigator of SUBSEA.*

Tamar E Cohen *received a B.S. in Computer Science from Cornell University in 1991 and a M.A. in Art from George Mason University in 1993. She has been with SGT, Inc for more than 10 years, supporting research at NASA Ames Research Center's Intelligent Robotics Group as well as JPL. Her work focuses on bridging the gap between robots and humans. She designs and implements software to provide situational awareness for remote robotic operation. Tamar has been a senior contributor on the Mars 2020 rover mission, xGDS platform and VERVE. Prior to working at SGT, she has written SDKs for educational toy companies, tools for web based collaboration, and 3D interactive games.*

Dr. Nicole Raineault *received her PhD from the University of Delaware in geological sciences. She is the Chief Scientist and VP of Exploration and Science Operations for the Ocean Exploration Trust, the non-profit organization that owns and operates the E/V Nautilus. In the last decade, Nicole has lead or been involved in over 40 expeditions at sea.*