Science Article

IODP Expedition 389: Hawaiian Drowned Reefs

Unlocking the history of sea-level, climate change and reef responses over the last 500,000 years

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The ECORD Faculty Board met in Trieste, Italy on 29-30 September and confirmed that *IODP Expedition 389: Hawaiian Drowned Reefs* will now be rescheduled for 2023 (TBC).

Surrounding the island of Hawai'i are a series of twelve fossil coral reefs that formed as the reef communities successively grew and were drowned by rising sea-levels and/or the near constant subsidence of the crust around the ever-growing volcanic archipelago of Hawaii. Covering important time periods in the Earth's climate history, the information contained in these natural fossil reef archives will help IODP scientists reconstruct sea-level change at higher resolution than previously possible at stable far-field sites. It will also enable them to investigate the links between global sea-level change and global climate change, and therefore the mechanisms that control abrupt climate change. These records of natural climate changes occurring from seasonal and decadal to the much longer-term millennial time scales, will also provide an interpretative framework for understanding the effects of climate change originating from human activity.

Expedition 389 will core in up to eleven locations (Fig 1), to a depth of 150 m below the seafloor, with the aim to address scientific questions across four main themes to: (1) reconstruct sea-level change in the central Pacific over the last 500,000 years; (2) characterize climate variability over the last 500,000 years, as recorded in the fossil corals, to better understand long-term shifts in the background state of sea surface temperature, rainfall and storm tracks and the state dependence of seasonal - inter-annual variability; (3) understand how coral reef systems respond both geologically and biologically to rapid changes in sea-level and climate – for example can reefs turn on and off when they reach certain environmental limits, and how do they recover from disturbances in the system; and (4) better explain the subsidence and volcanic history of Hawai'i. In this article we briefly highlight relevant advances in some of these themes and crucial knowledge gaps that will be addressed by Expedition 389 drilling.

Constraining sea level-changes in the central Pacific over the last 500 kyr.

Significant advances have been made in reconstructing sea-level changes over the past 500 kyrs using continuous deep-sediment archives. However, fossil coral reefs continue to

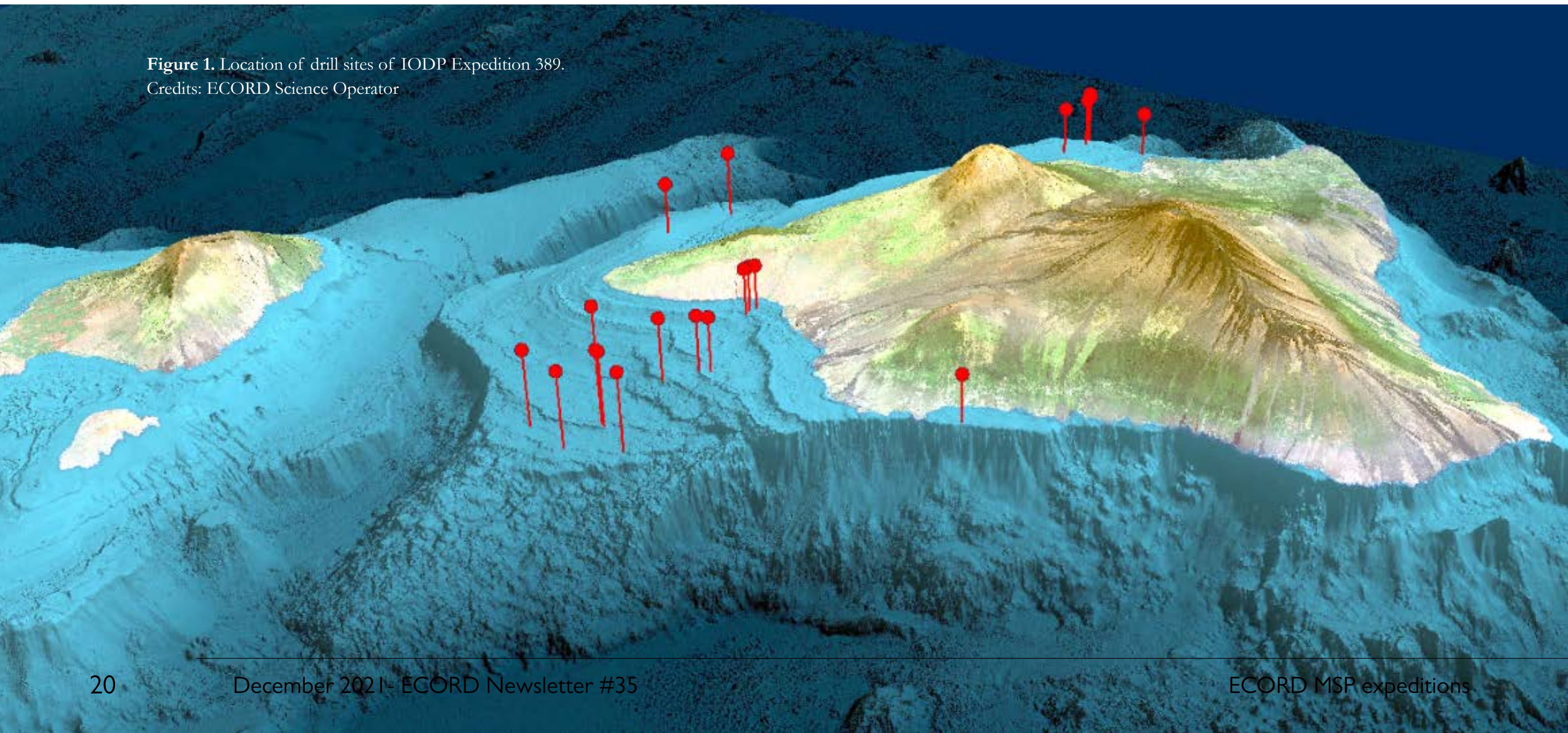

Figure 1. Location of drill sites of IODP Expedition 389.
Credits: ECORD Science Operator

offer more precise temporal resolution than achievable from deep-sea sediment reconstructions and may also provide more accurate constraints on the vertical position of past sea level (Woodroffe and Webster, 2014). There have been several recent reviews of the global fossil coral sea level data (e.g., Fig. 2). Despite significant progress in understanding sea level variability, ice sheet dynamics and global isostatic adjustment (GIA) over the last 150 ka – particular during MIS 5e and the last deglaciation (Barbados, Expedition 310 Tahiti, Expedition 325 GBR), crucial questions remain in part due to the lack of appropriate absolute coral sea-level data. Figure 2A-C highlights: (1) the bias towards high sea-level events (i.e. highstands); (2) the lack of temporal coverage earlier than 150 ka – particularly during interstadial/ stadial and lowstand sea levels; and (3) a major bias towards either co-seismically uplifted sites and/or relatively stable sites with condensed reef sections. Expedition 389 will provide the most comprehensive and absolute record of sea levels during the different interglacial, interstadial/ stadial, glacial maxima, and deglacial intervals over the last 500 kyrs, including the abrupt meltwater pulse events (MWP's) (Fig. 2) which are proving difficult and controversial to resolve. For example, recent work off the western coast of Hawai'i confirms that the H1d reef terrace (-150 m) drowned ~14.75 ka, coeval with the deglacial MWP-1A timing derived from the Expedition 310 Tahiti reef record but not Barbados at 14.1 ka (Fig. 3). New sea level data are vital to better calibrate and tune dynamical models that simulate ice sheet mass loss and predict the rate and amplitude of future global sea rise.

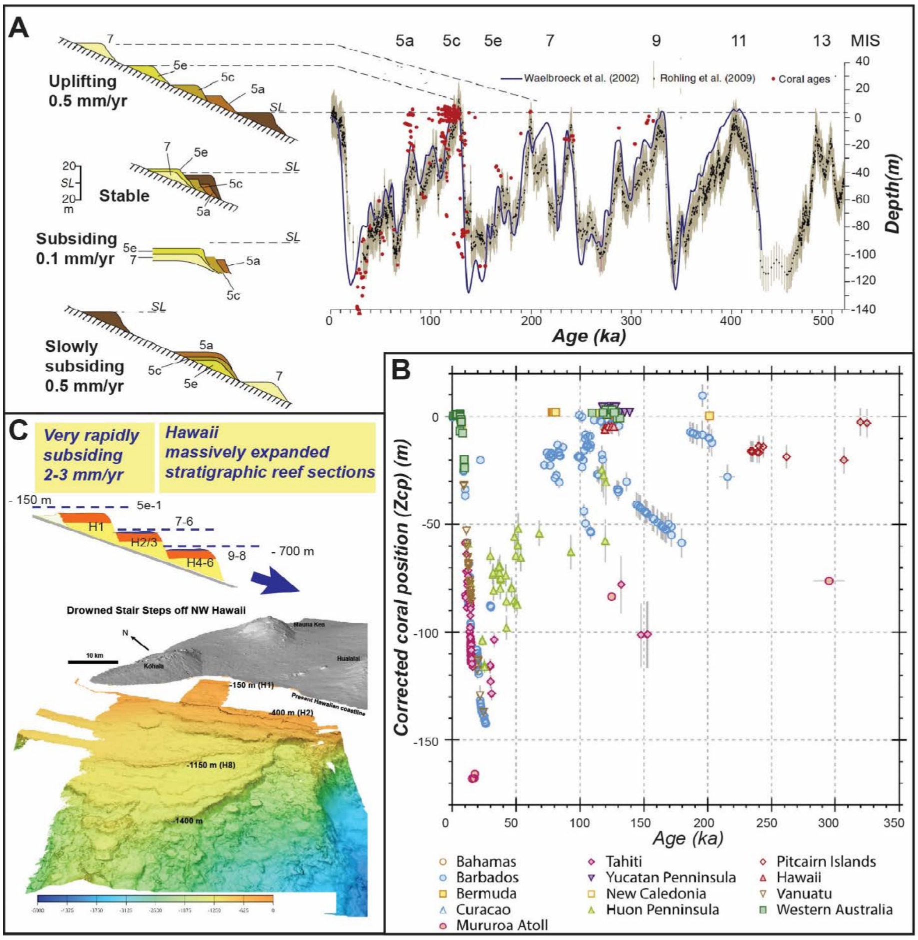

Figure 2. (A) Review of the response of coral reefs to sea level changes (after Woodroffe and Webster, 2014 and see for original sea level data sources). Reconstructions of sea level over the past 500 ka based on continuous records, compiled from the Red Sea, and the coral-calibrated deep-sea benthic δ18O records. The distribution of the most reliably dated corals (coral that have been U-series dated and have δ234U values within the range 137–157‰) are shown for those samples >25 ka. **(B)** Reconstructed relative sea levels for fossil corals, without GIA correction, from both near and far-field locations that pass an initial screening (δ234U initial, calcite 2% and 232Th concentration 2 ppb) with their respective uncertainties intervals (95%) based on a recent synthesis by Hibbert et al., (2016). Note both reviews clearly highlight lack temporal coverage back past ~150 ka – particularly during interstadial/stadial and lowstand sea levels, and the major bias towards either co-seismically tectonic uplifted sites and/or relatively stable sites with condensed reef sections. **(C)** Schematic showing the drowned reef terraces and greatly expanded reef sections (see (A) for comparison) in Hawai'i due to the relationship between reef growth, sea level oscillations and very rapid subsidence. 3D multibeam image, see the current coastline, showing the series submerged reefs to drilled by Exp. 389, formed over the last 500 ka, deepest at 1400 m below present sea level (after Webster et al., 2009).

Reconstruct paleoclimate variability for the last 500 kyr and establish the relationship between the mean climate state and seasonal-interannual variability.

Determining paleoclimate conditions in the open ocean subtropical Pacific remains a high priority for testing climate theory and for validating the ability of fully coupled IPCC-class climate models to hindcast the regional expression of global climate change. This has profound implications for predicting storm distribution, frequency and intensity, and therefore for water resource management and geohazard prevention. Recent work shows that numerical simulations of the amplitude of North Pacific storm tracks is model-dependent because of model-to-model differences in grid spacing and in the ability to calculate accurate temperature gradients; paleoclimate studies can thus provide a test bed to evaluate individual and ensemble model behaviour. Studies focused on MIS 5 predict that, at Hawai'i, there should have been changes in the mean and seasonality of sea surface temperature (SST) due to changes in Greenland ice sheet size and greenhouse gas concentrations and in storminess and winter precipitation. Modelling results of the last glacial maximum (LGM) predict that Hawaiian coral records should reflect a southward shift in storm tracks, a precipitation anomaly, and SST responses to changes in ice albedo and greenhouse gas forcing. In addition, model simulations of Heinrich 1, interstadial and stadial events, and the LGM, suggests that although extratropical teleconnections to ENSO variability could have changed under different boundary conditions in many locations, Hawai'i is one of the few regions where interannual variability is consistently coupled to tropical ENSO variability. In all, existing modelling studies provide a firm theoretical framework for interpreting the mean, seasonal, and interannual variability that can be derived from the fossil corals targeted by Expedition 389.

With respect to data-based paleoclimate studies, the open-ocean subtropical Pacific remains one of the most important regions for which there is almost no data to compare to other regional data or to models due to the lack of appropriate geological samples. Relevant advancements in data-based paleoclimate work are sparse, but include evidence from a Mauna Kea ice core for a strong atmospheric temperature response to millennial-scale climate changes, from a sub-tropical west Pacific sediment core for significant changes in SST since the LGM related to Asian monsoon dynamics, and from MIS 7 corals for changes in seasonal and interannual variability. In addition, there have been a number of tropical ENSO reconstructions that can be compared to Hawaiian coral records to test ideas regarding the nature of extratropical teleconnections.

Recent advancements in coral geochemistry have provided a better handle on the complexities of metal and isotope uptake and therefore will enhance the ability of Hawaiian fossil corals to provide robust paleoceanographic reconstructions. For example, there is a better understanding of which coral species are best suited for palaeoclimate reconstruction. Additionally, the boron geochemistry of coral skeletons offers a potential method to reconstruct the dissolved inorganic carbon (DIC) chemistry of the coral calcification fluid from which the skeleton precipitates and reconstruct past DIC e.g. seawater pH. Coral nitrogen and phosphorous isotopes are also increasingly being used as novel proxies for reconstructing nutrient input and upwelling. Finally, although Sr/Ca measurements in some species of corals are not thought to provide reliable SST data, there are promising new proxies like Li/Mg and Sr-U that can provide robust SST estimates.

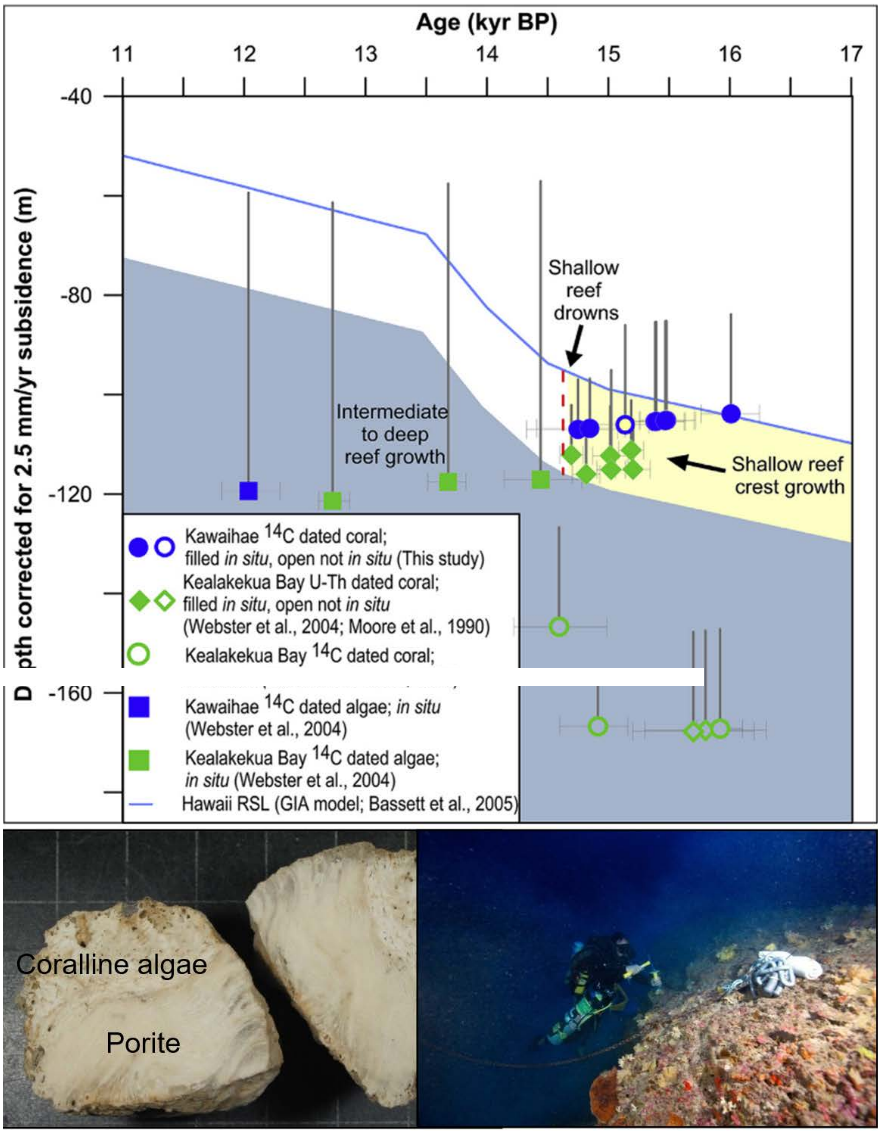

Figure 3. Summary of chronologic data from Kawaihae (blue symbols) and Kealakekua Bay (green symbols) including the new radiocarbon dated corals, published ages from Kealakekua Bay. Vertical error bars represent paleowater depth of the coral or algae samples, and horizontal errors denote 2σ age range. The transition from shallow (yellow) to deep (blue) facies growth is shown with shading (top panel). Deep diver photographs of sample recovery on H1d and examples of shallow water reef crest facies characterised by Porites samples with associated encrusting coralline algae (CAR) and vermetid gastropods (after Sanborn et al., 2017 and see for other data sources).

Geologic and biologic responses of coral reef systems to abrupt sea-level and climate changes.

Considerable progress has been made in understanding the role of coral reef systems as valuable archives of past sea-level and environmental changes, and how reefs were impacted by these changes (Camoin and Webster, 2015; Woodroffe and Webster, 2014). However, important questions still remain about: (1) what processes control high-resolution spatio-temporal variations in reef architecture and composition – particularly in response to millennial-scale sea-level and climate changes; (2) what causes reefs to "turn-on" or "turn-off" (i.e. drowning) and what are their climatic and ecologic thresholds; and (3) how reef communities reassemble following disturbances on interglacial/glacial vs. millennial times scales. There is an urgent need for further research, not only to decipher processes driving past sea-level and climate change and its geographical variability, but also to better understand how coral reefs might respond in the context of future global climate changes (Camoin and Webster, 2015). The combination of Hawaii's unique geological setting (rapid subsidence, expanded stratigraphic sections, sensitivity to drowning, contrasting local environmental conditions), recent advances in dating techniques (diagenetic vetting – hyperspectral imaging and micro-scale carbonate mineral mapping, U/Th isotope systematics, Laser-Ablation ICP-MS), the novel use of reef assemblages, proxies (endolithc borers) and statistical tools to better constrain reef accretion, palaeowater depth estimates, and sophisticated 3D numerical reef modelling, make the prospect of Expedition 389 all the more exciting.

Expedition 389 is also concerned with elucidating the nature of living and ancient microbial communities in the reefs and their role in reef building. Microbial activity led to the precipitation of significant amounts of carbonate (microbialite) in cavities formed by primary reef builders (corals and encrusters, like coralline red algae, vermetids, and bryozoans), as shown by Expedition 310 (Tahiti), and also coevally on the seafloor by the Expedition 325 (GBR) cores. The microbial carbonate is locally the major component of the Tahiti reef, and some stratigraphic intervals of the GBR reef, contributing significantly to framework development and preservation. Biomarkers in fossil microbialite from Tahiti, GBR and other deglacial reefs indicate a key role of sulfate reducing bacteria in calcite precipitation. Analysis of global microbialite development in reef structures during the LGM-deglaciation suggests a strong correlation between microbial carbonate precipitation and carbonate saturation state of shallow ocean waters but this must be tested through previous glacial/interglacial cycles. Finally, the energy dynamics and role of different microorganisms within carbonate-precipitating microbial mats remains to be solved.

Reef foundations, subsidence and volcanic history Hawai'i.

Over several decades, researchers have used the surface ages and depths of the various drowned shorelines around Hawaii to determine the rate of subsidence of the island. These empirical data, along with recent numerical modelling studies, are consistent with constant subsidence over time periods of hundreds of thousands of years. Over a million-year timeframe, however, the island does not subside uniformly because the center of mass of the active volcanoes is slowly but systematically shifting towards the southeast as older volcanoes stop growing and new volcanoes form. Overall, the evolutionary history of Hawaiian volcanoes remains surprisingly poorly known; although the sequence of eruptive stages is well documented, their timeframe is not. Expedition 389 will obtain well-dated volcanic samples from the base of each hole to: (1) refine the variation through space and time of the subsidence of Hawaii, and; (2) contribute to understanding the volcanic evolution of the island.

The promise of Expedition 389, seabed rock drills and expedition planning.

The implementation of Expedition 389 around the rapidly subsiding island of Hawai'i has the potential to unlock a unique and largely unexploited archive of sea-level and climate changes. The scientific potential of Expedition 389 is supported by a wealth of bathymetric, submersible, ROV observations, sedimentary and radiometric data collected over the last 30 years by many workers (Fig. 3). The drilling platform to be used on Expedition 389 is yet to be finalised, however, there have been significant advances in the seabed rock drill technology used for research and commercial applications (i.e. MeBo 200 – MARUM; RD2 – BGS; PROD1-3 – Benthic; Seafloor drill – Fugro, and the new BMS50M (Benthic Multi-coring System – JOGMEC). Most recently, as a "proof of concept" that seabed rock drills can recover high quality cores from challenging reef lithologies such as heterogeneous reef frameworks and cavities, e.g. friable grainstones, and coralline algal facies, our group investigated a unique suite of cores that were collected by the PROD drilling system as part of a geotechnical survey in ~80 m water (~30 m penetration, ~80% recoveries) on the North West Shelf of Australia (Fig. 4). On the basis of economic cost, environmental/ cultural sensitivities, seabed depths, penetration depths and the need for high quality reef cores, the preferred platform for Expedition 389 is a seabed rock drill deployed from a ship.

In summary, Expedition 389 is well positioned to directly address several key Strategic Objectives and Flagship Initiatives in the 2050 Science Framework: Exploring Earth by Scientific Ocean Drilling by investigating the mechanisms that control rapid sea level and climate change as well as the relationship between changes in mean climate state and high frequency (seasonal-decadal) climate variability. As ECORD Science Operator now moves forward with expedition planning, finalizing the ship and drill system logistics, and environmental permitting please stay tuned for the call to join the Expedition 389 Scientific Party and be part of this exciting new phase of IODP coral reef drilling.

Acknowledgments.

We acknowledge the other proponents on the original proposal IODP proposal #716-Full2 (Drowned corals reefs around Hawaii: a unique archive of sea-level, climate change, and reef response over the last 500 kyr).

Fig. 4. Representative core images showing the high quality core recovery in a range of very challenging fossil reef lithologies using a sea bed rock drill (Webster et al., In Press 10/09/21). These MIS 3 to 4 reef cores were recovered from the North West Shelf of Australian using the seabed drilling system PROD in ~-80 m water.

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