Paleoseismology of the Tsunamogenic Long Point Fault, Santa Catalina Island

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Investigators:
Simon L. Klemperer (Stanford University), Mark R. Legg (Legg Geophysical), Danny Brothers (USGS)

I. Project Overview

A. Abstract

In the box below, describe the project objectives, methodology, and results obtained and their significance. If this work is a continuation of a multi-year SCEC-funded project, please include major research findings for all previous years in the abstract. (Maximum 250 words.)

The newly mapped Long Point Fault on and offshore Catalina Island presents a significant tsunamogenic hazard to nearshore communities in the Los Angeles area. We have constrained slip rate and recurrence interval for the Long Point Fault by dating marine terrace deposits transected by the fault. Strata overlying landslide deposits likely triggered by the Long Point fault have been dated using the overlying and underlying sequence boundaries. Even modest tsunamogenic landslides (whether or not seismically triggered) can be very dangerous because of the lack of warning to coastal communities. In June 2015 we conducted 2 days of chirp profiling to locate sequence boundaries within reach of our coring machine, and 2 days of coring and Van Veen grab sampling. The success of these dives motivated two E/V Nautilus ROV dives to collect additional samples that will further refine our chronology. 10 samples have been dated using ^{14}C and U-series geochronology, and we have measured $\delta^{18}O$ and $\delta^{13}C$ on about 50 samples. Samples yielding forams and molluscs have been analyzed and age ranges for several marine terraces have been confirmed, yielding a robust chronology for Catalina's terraces, and demonstrating our ability to use the same approach on other seamounts.

B. SCEC Annual Science Highlights

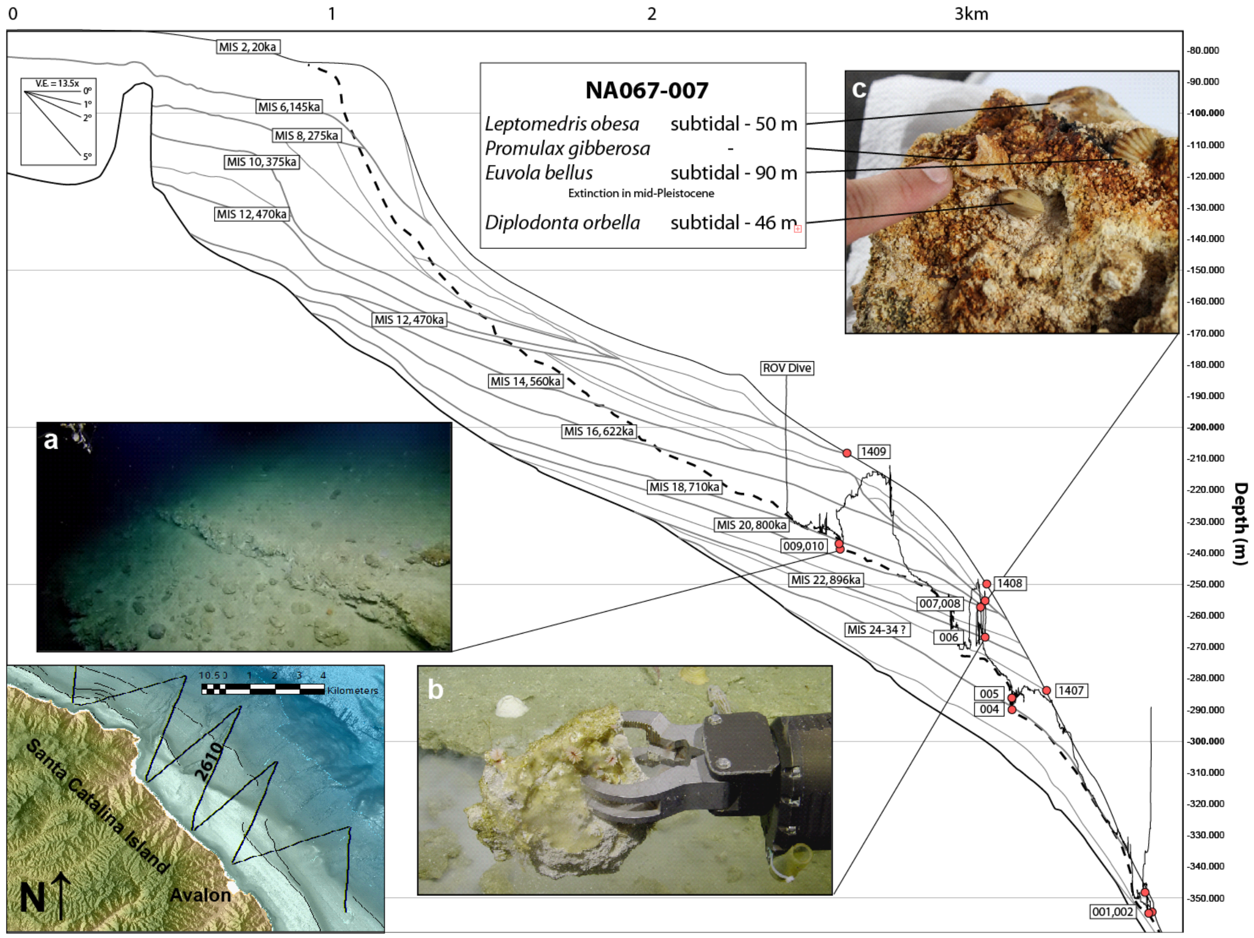
Each year, the Science Planning Committee reviews and summarizes SCEC research accomplishments, and presents the results to the SCEC community and funding agencies. Rank (in order of preference) the sections in which you would like your project results to appear. Choose up to 3 working groups from below and re-order them according to your preference ranking.

Earthquake Geology
Seismology
Unified Structural Representation (USR)

C. Exemplary Figure

Select one figure from your project report that best exemplifies the significance of the results. The figure may be used in the SCEC Annual Science Highlights and chosen for the cover of the Annual Meeting Proceedings Volume. In the box below, enter the figure number from the project report, figure caption and figure credits.

FIGURE 3: Interpretation of seismic line Stanford 2610, SSW to NNE offshore Avalon, Santa Catalina Island. Bold lines indicate interpreted regressive/transgressive surfaces. Floor of submarine canyon adjacent to location of seismic profile shown as dashed line. Tortuous black line is bathymetric record of ROV dive track, close to the canyon floor but with excursions up the side walls. Red dots indicate locations of samples (both ROV and cores). Interpreted ages of major sequence boundaries labeled. Photos (left to right): a. wave rounded cobbles found in marine terrace deposits, evidence of fossil beaches. b: ROV grab sample of marine terrace, c: NA067-007, fossil bearing bryozoan marl recovered from ROV dive.



D. SCEC Science Priorities

In the box below, please list (in rank order) the SCEC priorities this project has achieved. See *https://www.scec.org/research/priorities* for list of SCEC research priorities. *For example: 6a, 6b, 6c*

1a. Mapping and studying faults in Southern California to determine slip rates for faults at multiple time scales.
1d. Constrain long-term deformation and fault-slip models
4a. Detailed geologic & seismic investigations of fault complexities

E. Intellectual Merit

How does the project contribute to the overall intellectual merit of SCEC? *For example: How does the research contribute to advancing knowledge and understanding in the field and, more specifically, SCEC research objectives? To what extent has the activity developed creative and original concepts?*

The SCEC vertical motion database lacks uplift rates for the numerous submerged seamounts and wave-planed features in the southern California Borderland, and is thus biased toward sampling uplift. Our method of using submerged terraces to investigate paleoseismology and vertical deformation addresses this deficiency and presents a clearer picture of vertical deformation in the SCCB. The submerged marine terrace method we have developed has potential applications in 12% of the borderland, and will elucidate uplift and subsidence records for numerous unexplored regions of the Southern California Borderland, enabling us to better understand evolving styles of deformation, as well as changes in the distribution of slip along the anastamosing faults that dissect the borderland.

F. Broader Impacts

How does the project contribute to the broader impacts of SCEC as a whole? *For example: How well has the activity promoted or supported teaching, training, and learning at your institution or across SCEC? If your project included a SCEC intern, what was his/her contribution? How has your project broadened the participation of underrepresented groups? To what extent has the project enhanced the infrastructure for research and education (e.g., facilities, instrumentation, networks, and partnerships)? What are some possible benefits of the activity to society?*

This SCEC funded project has received lots of publicity, including articles in the LA Times and Newsweek, invited talks at AGU and the Catalina Island Conservancy Symposium. E/V Nautilus Dives (36 hours total) were broadcast worldwide via telepresence to classrooms around the world, and were some of the most popular dives during the season. Our intern, Ethan Williams, participated in CHIRP and coring cruise and completed onshore processing of samples. He gained basic skills in seismic and CHIRP processing, and was trained to conduct U-series chronology in the Stanford ICPMS Facility.

G. Project Publications

All publications and presentations of the work funded must be entered in the SCEC Publications database. Log in at *http://www.scec.org/user/login* and select the Publications button to enter the SCEC Pubications System. Please either (a) update a publication record you previously submitted or (b) add new publication record(s) as needed. If you have any problems, please email *web@scec.org* for assistance.

II. Technical Report

SCEC funding enabled us to complete several important objectives that will advance our understanding of deformation along the greater San Andreas Fault system. Submerged marine terraces have been recognized as markers of coastal erosion/deposition that contain a record of tectonic offset (Shepard and Wrath, 1937; Emery, 1968), as well a Quaternary climate record (Milliman et al., 1968), but have remained enigmatic due to the prohibitive cost and difficulty of submarine surveying and sampling. In 2014 Stanford collected numerous high resolution (~0.5 m) seismic profiles near Catalina Island (Figure 1) and six exploratory lines near Pilgrim Banks, a submerged seamount 30 km NW of Catalina Island. These data were capable of showing that Catalina's submerged terraces were indeed the result of Quaternary sea-level fluctutations convolved with tectonic subsidence. However the lack of formal age control created uncertainty in the rate of subsidence. Adding age control to our high-resolution survey around Catalina Island has allowed us to place age constraints on major sequence boundaries that can easily be correlated to other submerged platforms, (eg. Pilgrim Banks). Our detailed marine-terrace chronology allows us to determine offset along major Borderland shear zones which transect terrace sedimentary packages. The two major components of our SCEC funded work, Sampling & Dating, and Paleo-seismology, are described below.

A. Sampling and Dating

During June 2015 we collected numerous samples to constrain the age of Catalina's terraces, specifically the easily accessible sequence boundaries that outcrop at the seafloor. Coring was conducted using a 2-m gravity coring system (on loan from USGS courtesy Danny Brothers George Tate) and/or Van Veen grab sampler as appropriate. We identified ideal locations for coring using Seismic CHIRP. First we searched our seismic data for reflectors that appear to outcrop at the surface. We confirmed the location of these outcrops and evaluated their accessibility using CHIRP (Edgetech 3100 Sub-bottom profiler 2–24 kHz sweeps) data collected in June 2015 (e.g. Figure 2). Confirmed outcrops of major sequence boundaries were sampled using the coring machine or Van Veen sampler (e.g. Figure 3). In order to ensure accurate locations for our cores, we simultaneously ran CHIRP while coring to ensure that we were hit the correct sequence boundary. While monitoring using the CHIRP unit, we could see the position of the coring machine relative to the outcropping sequence boundary, and make minor navigation adjustments.

Cores were split into an archive and sampled halves, and sorted through for dateable fossil material. Van Veen samples were dried and sifted similarly. Of the 52 fossils recovered, we submitted 10 samples to the Lawrence Livermore AMS facility for carbon-14 dating (useful out to ~40 ka, or to demonstrate that "carbon-dead" samples are older than ~40 ka) under the cooperative agreement between SCEC and LLNL; in early September 2015 we received our dates ranging from modern (< 100 a) to radiocarbon dead (>40 ka). With Stanford funds we measured δ^{18}O and δ^{13}C on 28 samples in Stanford's Stable Isotope Biogeochemistry Laboratory, in order to distinguish highstand and lowstand deposits (e.g. Jacobs et al., 2004), and (when combined with radiometric dates) constrain paleo-sea levels during peak Late Wisconsonian glaciation (~ 20-22 ka). We presented the ^{14}C ages and δ^{18}O and δ^{13}C ratios at the SCEC 2015 Annual Meeting (Williams et al., 2015). With Stanford funds we also dated 12 samples using the U/Th-series method (typically useful from ~ 4–400 ka) at the Stanford ICP-MS facility; in early October

2015 we received our dates ranging from modern (< 2000 a) to 238 ka, and presented these results at AGU (Castillo et al., 2015a).

In 2015, our SCEC-funded cruise and widespread publicity (LA Times, 2015; Newsweek, 2015, LiveScience, Phys.org, Rush Limbaugh) of early results (Castillo et al., 2015b) presented at the May 2015 SSA meeting in Pasadena, CA resulted in an invitation from the Ocean Exploration Trust directed by Bob Ballard to design two ROV dives on Catalina. Under their "Scientists Ashore" program, we submitted track-lines and plans for sampling during the August 2015 E/V Nautilus cruise leg from Los Angeles to San Francisco. During "our" dives we received real-time video from the two ROVs and we were able to direct operations and request specific samples with known geologic context (Figure 3). These dives, encouraged by SCEC's support and scientific endorsement, allowed unprecedented access to the internal structure of Catalina's marine terraces, and allowed the collection of dateable material from deep terraces that would have been inaccessible to any other method.

ROV sampling was conducted during August 2015 in a submarine canyon near Avalon. ROV sampling allowed us to collect additional samples between sequence boundaries sampled during June 2015, further refining our chronology. We completed two dives: Dive 1 collected dateable material from terraces northeast of Catalina between 350–230 m depth, but was unable to continue up the canyon due to commercial fishing equipment. Dive 2 started west of Catalina in the scarp of a 1.3 km^3 landslide, looking for exposed stratigraphy, then continued across the surface of the 270-m terrace and continued up to 130 m collecting samples of exposed stratigraphy, wave rounded cobbles, and biogenic carbonates (Raineault et al., in review) (Figure 3). All Nautilus samples are archived at URI's Ocean Exploration Center, but in October 2015 Castillo travelled to URI to sample the archived material, bringing back to Stanford a substantial collection of carbonate fossils for identification and radiometric dating, as well as samples of basement (Catalina schist) for sectioning and petrographic analysis by Dan Francis (CSU Long Beach) (e.g. Francis et al. 1990;Francis & Legg, 2010). Molluscs have been used to date onshore Pleistocene marine terraces in California by Chuck Powell (USGS emeritus) (Powell, 1994; Powell et al., 2004); he has already identified the pectinid *Euvola bellus* that went extinct in the mid-Pleistocene in material from a deeper terrace (Figure 3). This suggests an age ~ 780 ka that we hope to refine by U-series dating in 2016, confirming our hypothesis that deeper terraces are older terraces. Marine microfauna recovered from samples have been identified with the help of Prof. Jim Ingle (emeritus, Stanford University) who is an expert on the Neogene and Quaternary paleontology and paleoecology of the Pacific Coast (e.g. Green-Nylen et al., 2001; Halfar et al., 2002). Samples from deeper terraces include *Neogloboquadrina inglei* which went extinct no later than 700ka, confirming the mid-Pleistocene age for Catalina's deeper terraces.

B. Marine Terrace Paleseismology

The purpose of our cruise was to develop methodologies for constraining vertical motion along faults or subsiding tectonic blocks, to augment the marine paleoseismology toolkit and improve the SCEC Geologic Vertical Motion Database (VMDB) (Niemi et al., 2008). We have successfully constrained the subsidence rate of Santa Catalina Island to be ~0.2 mm/yr, and Pilgrim Banks ~2.0 mm/yr.

The Long Point Fault (LPF) provided an opportunity to apply marine terrace paleoseismology to constrain the age of offset along this fault, and improve a methodology for establishing slip rates on other faults in the SCCB. Our seismic profiles collected over the newly mapped (LPF) (e.g. Figures 1, 2) during June 2014 clearly demonstrate the presence of a shear zone that forms the NE coastline of Catalina Island (Figure 1). The deepest marine terraces are offset by ~25m by the LPF, with progressively less separation upsection. The uppermost sediments are gently folded and the sediment-water interface is undeformed by the LPF. Despite the lack of observed deformation in the uppermost sediments, seismicity on the LPF indicate that this shear zone extends to at least 12 km depth (Figure 1). The LPF has been mapped over a distance of 24 km from Two Harbors to south of Avalon suggesting the potential to nucleate a M6.5 or greater. On our bathymetric maps we identify a 15m scarp that offsets what may be the Last Glacial Maximum (LGM), 19–23ka terrace, a fault not mapped in the USGS "Quaternary Fault and Fold Database". Combining all the information resulting from the SCEC-funded 2015 cruise, we can constrain the age of last significant motion on the Long-Point Fault to be 642–710 ka (Castillo et al., 2015a). The last tsunamogenic landslide as observed in seismic must have occurred between 560 and 710 ka (Figure 4). We also successfully constrained our subsidence model for Santa Catalina Island using diverse sampling and chronologic methods. These results will result in a paper and partial PhD thesis (Castillo et al., in prep.), an undergraduate honors thesis and likely AGU presentation (Williams et al., 2015). Implications for paleosealevel at MIS 6 (~145 ka) will appear as a separate study with Jerry Mitrovica's group (Castillo et al., in prep.)

The most powerful utility of having a dated marine terrace record is the ability to constrain the ages of faults on other islands and seamounts by correlating major sequence boundaries island to island (or seamount) (Figure 5). Marine terrace morphology and internal structure are governed primarily by the sea level history and dynamics of transgression/regression, as well as fluctuations in sediment supply and sea state, which affect wave base and the amount of erosive energy imparted by waves. Terraces on Catalina exhibit variability in their morphology and internal architecture, some being easily distinguishable in profiles surrounding Catalina Island. This allowing us to identify several major sequence boundaries and correlated to other islands. In summer 2016 we plan to collect CHIRP seismic data at Pilgrim Banks, then samples using the E/V Nautilus ROV that will help us to prove that terrace correlation can be reliable (Figure 5).

C. References

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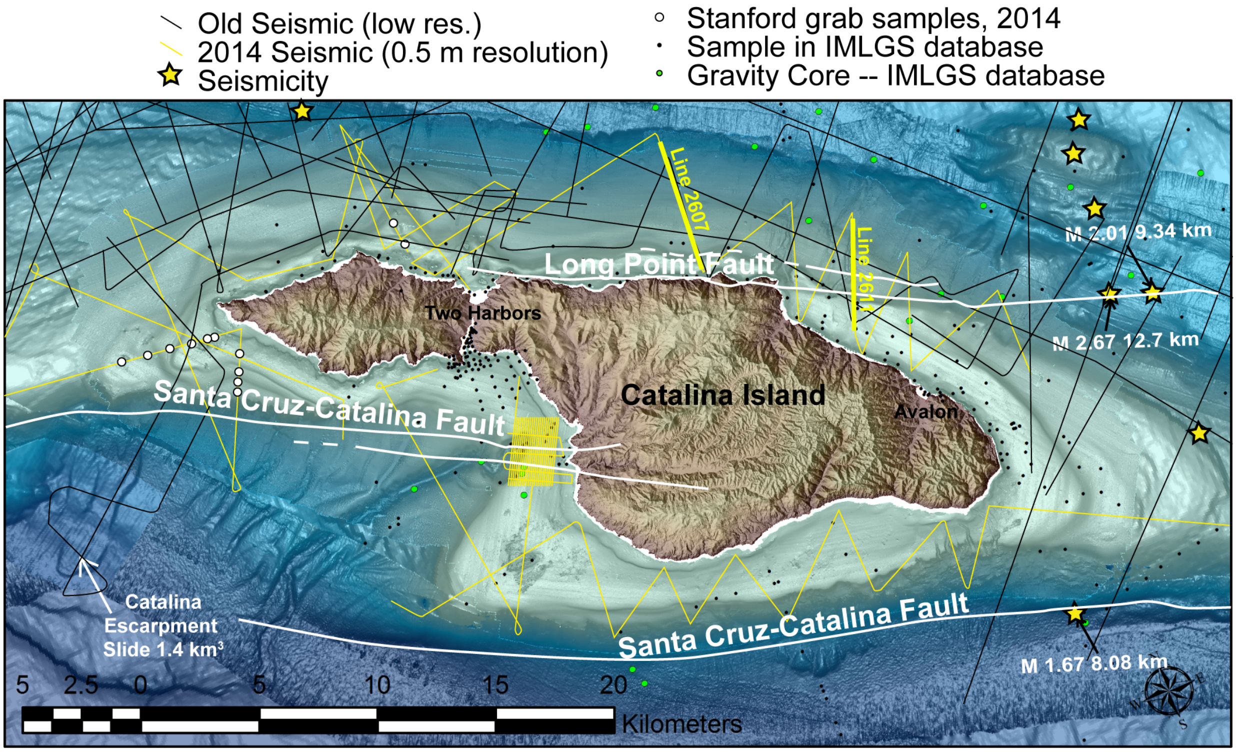

Figure 1 Slope-enhanced shaded relief map of Catalina Island and surrounding bathymetry, including major faults in white, available seismic data, seismicity, cores and both collected and available bottom samples.

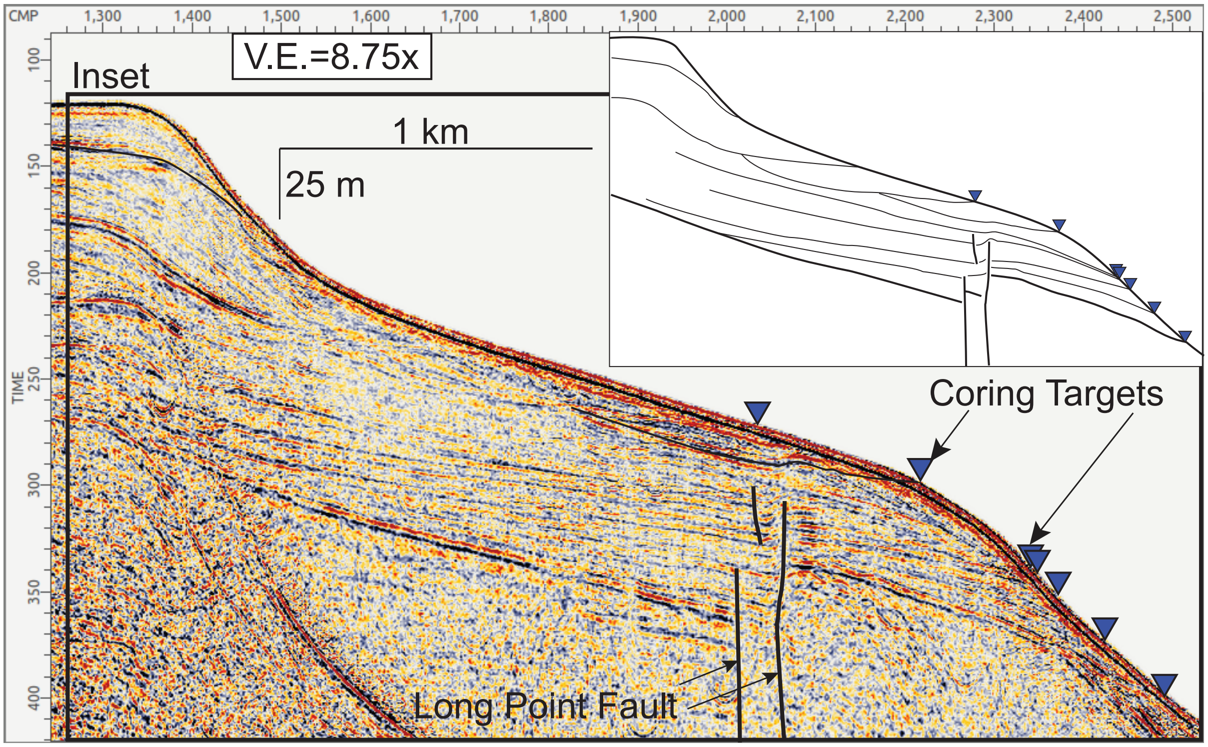

Figure 2 Prestack migration of Stanford line 2611 over Long Point Fault.

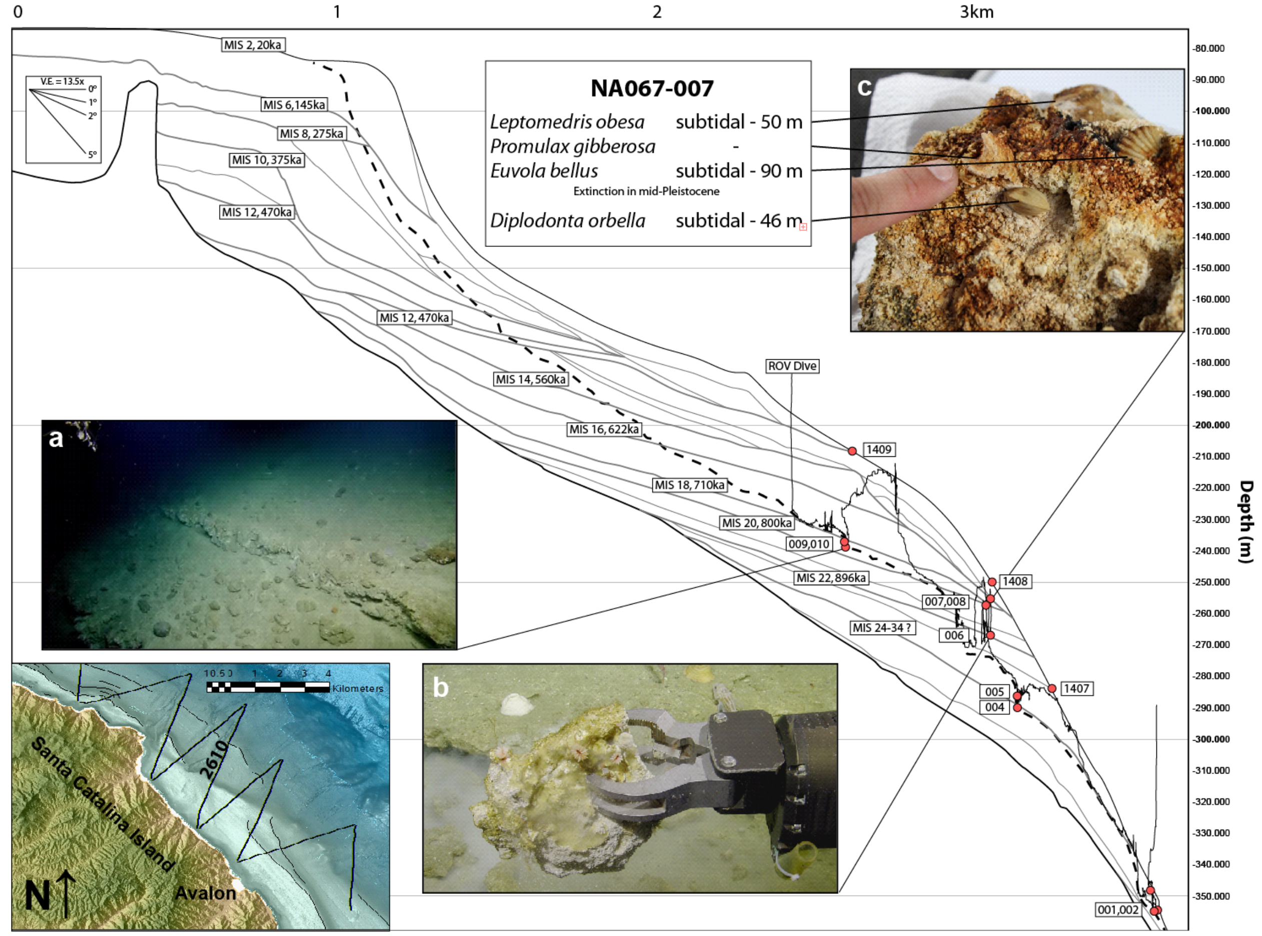

Figure 3. Interpretation of seismic line Stanford 2610, SSW to NNE offshore Avalon, Santa Catalina Island. Bold lines indicate interpreted regressive/transgressive surfaces. Floor of submarine canyon adjacent to location of seismic profile shown as dashed line. Tortuous black line is bathymetric record of ROV dive track, close to the canyon floor but with excursions up the side walls. Red dots indicate locations of samples (both ROV and cores). Interpreted ages of major sequence boundaries labeled. Photos (left to right): **a.** wave rounded cobbles found in marine terrace deposits, evidence of fossil beaches. **b:** ROV grab sample of marine terrace, **c:** NA067-007, fossil bearing bryozoan marl recovered from ROV dive.

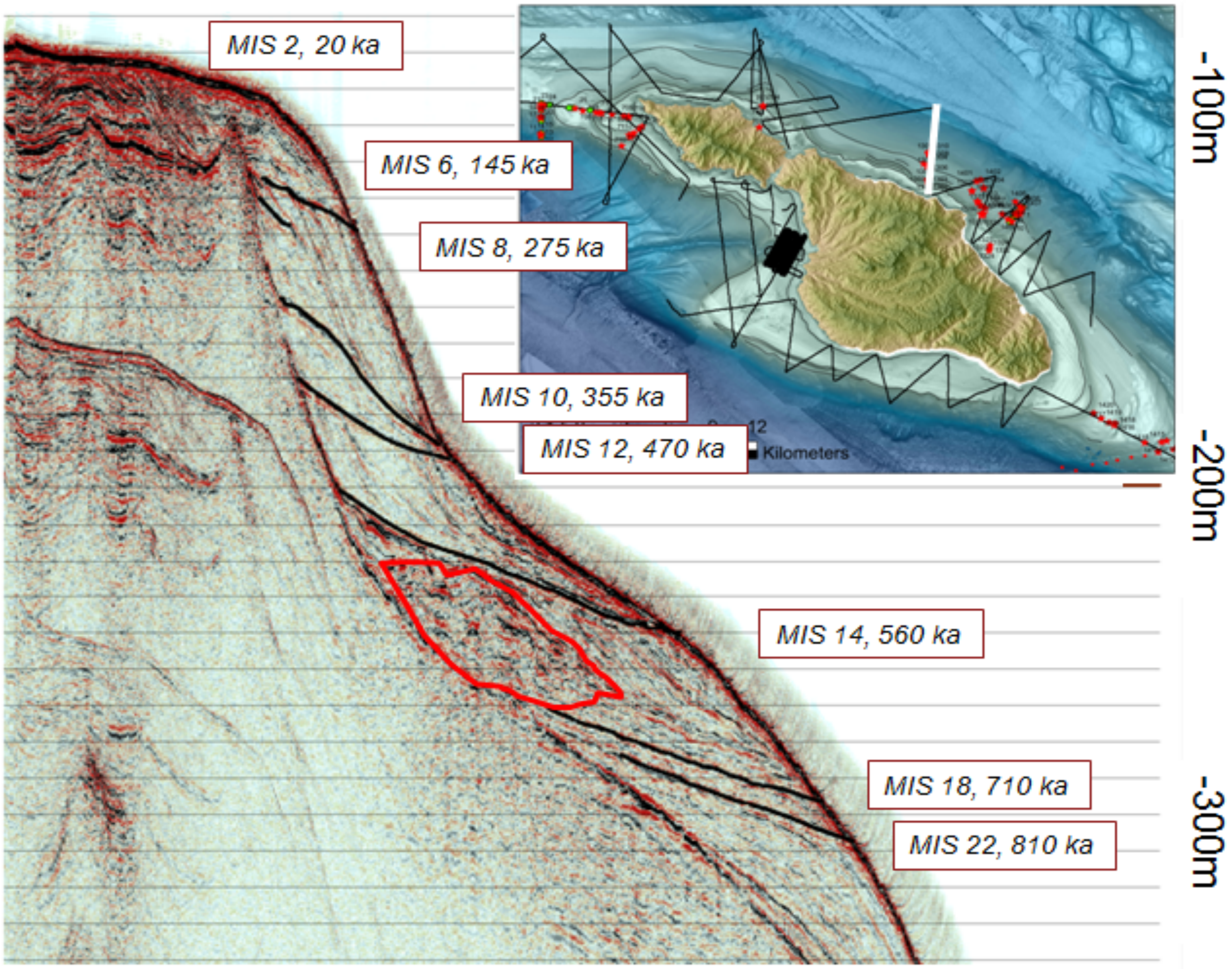

Figure 4: Interpreted prestack time migration of Stanford 2607 with major sequence boundaries interpreted (Black lines) and ages assigned. Red outline is ~0.4 km3 landslide that would have sent a tsunami at southern California. Inset: Map of Catalina Island and seismic coverage (black lines). Location of seismic line shown in white.

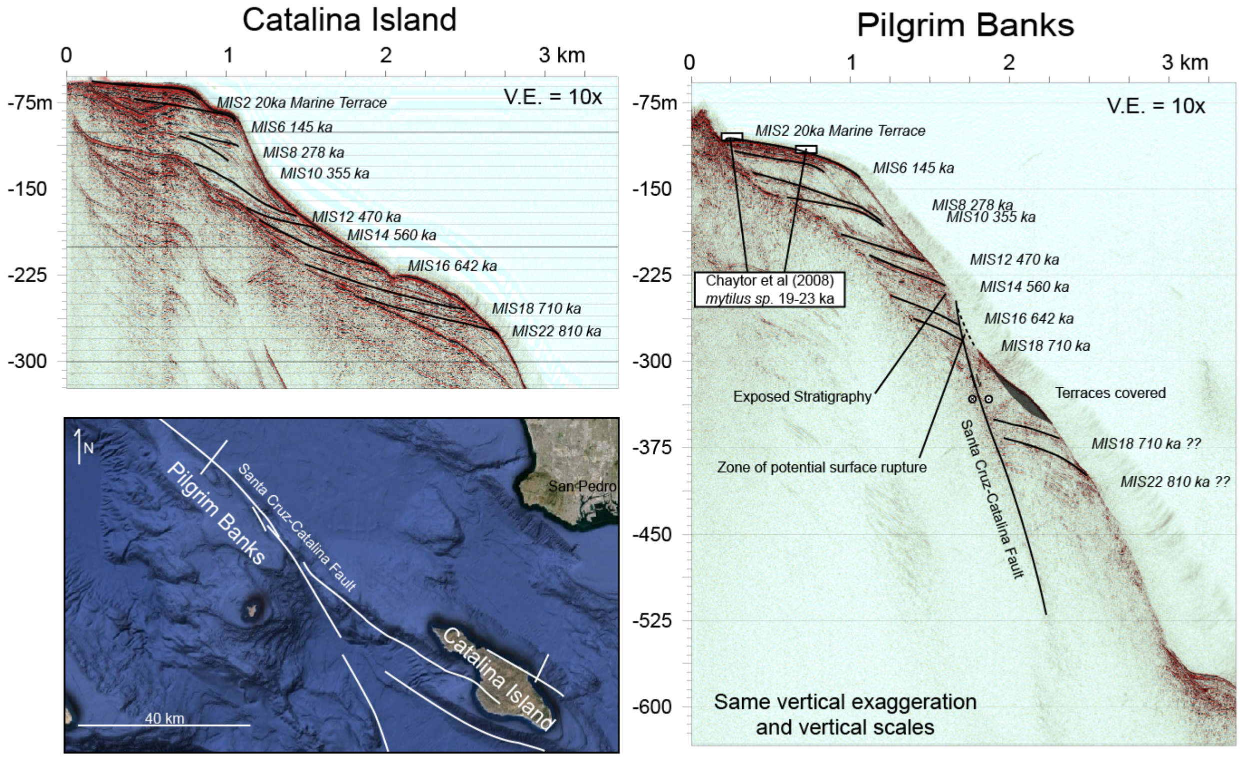

Figure 5: Correlation of sequence boundaries from Catalina Island to Pilgrim Banks. Both images prestack time migration with interpreted sequence boundaries in black lines and assigned ages listed. Fossil constraints from ROV dive or other publications labeled.