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An amalgamated meter-thick sedimentary package enabled by the 2011 Tohoku tsunami in El Garrapatero, Galapagos Islands

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ABSTRACT

Tsunamis and storms instigate sedimentological and geomorphological changes to the coastal system, both long-term and ephemeral. To accurately predict future coastal hazards, one must identify the records that are generated by the processes associated with these hazards and recognize what will be preserved. Using eyewitness accounts, photographs, and sedimentology, this study documents pre- and post-tsunami conditions and constrains the timing and process of depositional events during and following the 11 March 2011 Tohoku tsunami in the coastal system at El Garrapatero, Galapagos Islands. While the tsunami acted as both an erosional and depositional agent, the thick, fan-like sand sheet in El Garrapatero was primarily emplaced by overwash deposition during high tide from swell waves occurring between 19–25 March and 17–22 April 2011. The swell waves were only able to access the terrestrial coastal system via a channel carved by the 2011 Tohoku tsunami through the barrier sand dune. This combined deposit could result in an overestimation of the hazard if interpreted to be the result of only one event (either tsunami or wind-generated waves). An analogous sand layer, younger than 1390–1530 cal yr BP, may record a similar, prior event.

Introduction

Extreme events, such as tsunamis, often leave complicated geological records. To reliably characterize coastal hazards, sedimentology studies have focused on distinguishing tsunami deposits from other depositional events, typically storms, in order to reconstruct past events (Nanayama et al., 2000; Witter et al., 2001; Goff et al., 2004; Cochran et al., 2005; Morton et al., 2007; Switzer and Jones, 2008; Martin and Bourgeois, 2012). However, by juxtaposing these depositional processes in an effort to distinguish unique sedimentologic characteristics, the possibility of a combined (amalgamated) deposit has been largely ignored. A few recent studies have focused on post-depositional processes that modify or obscure tsunami deposits, such as bioturbation and erosion (e.g., Nichol and Kench, 2008; Szczuciński, 2011; Goto et al., 2012). Additionally, the possibility of overwash adding sediment on top of deposits has been postulated (Goto et al., 2012). Missing still are studies that thoroughly examine processes that augment, alter, or winnow a tsunami deposit.

When an amalgamation of multiple depositional agents responsible for a deposit is not recognized, this can introduce errors into interpretations and calculations of coastal hazards. Tsunami hazard analyses that use sedimentological records stem from our ability to identify a tsunami-derived deposit and can include interpretations of a tsunami's inland penetration, flow depth, and flow speeds. Maps of paleotsunami deposits are crucial for determining inundation areas in past events for hazard analysis (e.g., Clague et al., 2000; González et al., 2009), but are dependent on being able to isolate the paleotsunami deposit in stratigraphy. In addition, recent advances in using a tsunami's thickness and grain size trends to calculate flow depths and flow speeds (Reinhart, 1991; Jaffe and Gelfenbaum, 2007; Moore et al., 2007; Nanayama et al., 2007; Smith et al., 2007; Apotsos et al., 2011; Jaffe et al., 2012) are dependent on deposits not being significantly modified and thus are only valid if original characteristics of the tsunami deposit can be determined and differentiated from other forms of deposition. Therefore, it is imperative for post-event deposition to be studied and accounted for when analyzing past events.

Amalgamated deposits should be expected in low-elevation settings in proximity to the ocean. Quiet-water environments behind coastal barriers are typical places worldwide to look for records of storms and tsunamis (Lui and Fearn, 1993; Sawai, 2002; Bondevik, 2003; Kelsey

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et al., 2005; Switzer and Jones, 2008; Woodruff et al., 2008). In such environments, tsunami and storm erosion are known to breach barriers protecting coastal plains and waterbodies (Cisternas et al., 2005; Atwater et al., 2012), where elevations are similar to local high tide, and typical oceanic processes can significantly alter the sedimentological record of the event deposit after the event. At El Garrapatero, Galapagos Islands, a small, relatively simple coastal system, the 11 March 2011 Tohoku tsunami cut a channel from the beach to a coastal lake, breaching the coastal barrier. This study uses sedimentary structures, geomorphology, photographs and interviews to differentiate the detailed sequence of depositional events and to show that the meter-thick sedimentary package is an amalgamated deposit, rather than solely of tsunami or storm origin.

Background

Both tsunamis and storms are known to break through coastal barriers such as beach ridge, berms, and dunes, and leave behind fan-shaped deposits on the landward side of the breach (Kitamura et al., 1961; Hayes, 1967). The depositional and erosional record of tsunamis or storms depends on the magnitude of the event, coastal topography, and available sediment supply (Schwartz, 1975; Bourgeois, 2009). In general, although there are exceptions, tsunamis tend to cause more widespread erosion and deposition whereas storms are capable of forming thicker deposits, often more restricted in extent (Nanayama et al., 2000; Witter et al., 2001; Goff et al., 2004; Cochran et al., 2005; Morton et al., 2007; Switzer and Jones, 2008).

Coastal erosion by tsunami and wind-generated waves

The potential for tsunamis to dramatically alter the coastal landscape has been seen in numerous examples in recent events, including the 1998 Papua New Guinea, 2006 Kuril Islands, and 2004 Sumatra tsunamis (Gelfenbaum and Jaffe, 2003; MacInnes et al., 2009a,b; Paris et al., 2009). Tsunamis can erode beaches, remove or cut through ridges, alter drainage patterns, destroy vegetation, and transport sediment on- and off-shore (Choowong et al., 2007; Umitsu et al., 2007; Yulianto et al., 2007; Morton et al., 2011). For example, the tsunami from the 2004 Indian Ocean (Mw 9.2) earthquake translated the shoreline up to 500 m inland in parts of Sumatra, removing all landforms including beaches, dunes and wetlands (Liew et al., 2010), although subsidence may have been a factor in such a large event. For smaller events, such as the tsunami from the 2006 Kuril Island (Mw 8.3) earthquake, tsunami erosion still cut through beach ridges, translated the shoreline landward and destroyed vegetation even in cases where run-up was less than 8 m (MacInnes et al., 2009a,b).

Wind-generated waves can also act as agents causing sudden coastal geomorphologic changes, primarily during storms. Similar to tsunamis, storms can also erode beaches, remove or cut through ridges, alter drainage patterns, destroy vegetation, and transport sediment on- and off-shore (Schwartz, 1975; Kumar and Sanders, 1976). The potential of wind-generated waves to change a landscape depends on the duration of the event, the wave height and the stage of the tide during the event (Leatherman, 1981; Nott, 2004).

Deposition associated with barriers and barrier breaches

Tsunami

Tsunamis can breach barriers during their inflow or outflow phase, depositing arcuate or fan shaped features (Kitamura et al., 1961; Yulianto et al., 2007; Morton et al., 2011). On the downflow side of the breach, sediment is generally deposited in a fan where the flow is no longer channelized (Kitamura et al., 1961). Sedimentary structures in fan deposits may include parallel laminae and ripple-drift cross-sets and be >50 cm thick (from the 1960 tsunami in Chile; Yulianto et al., 2007). Back-flow fans, like those studied from the 2010 tsunami in Chile, are typically poorly sorted and massive (Morton et al., 2011). When a tsunami is not channelized as it enters a lake or lagoon, the deposit tends to form as a fining-upward layer, often including or capped by rip-up clasts of organic material, lake and other nearby deposits from along the tsunamis path (Bondevik et al., 1997; Dawson and Smith, 2000; Fujiwara et al., 2000; Morales et al., 2008).

Storm

Donnelly et al. (2004) recognized two cases in which wind-wave overwash of coastal barriers occurs. In one case, called run-up overwash, excessive wave run-up overtops the coastal barrier. This leads to an overwash fan or apron, often with parallel laminae deposited by each successive wave. In the other case, inundation overwash, a high storm surge leads to a water level higher than the barrier. In this case the sediment is typically transported farther than in the run-up case, but fans are still a common depositional feature. Typical sedimentary features in fans include approximately parallel laminae that dip steeply at the prograding toe of the fan.

Coastal system recovery from tsunamis and storms

Erosional signatures of tsunami inundation are predominantly ephemeral, as later geomorphic processes can remove or mask the evidence of destruction (Choowong et al., 2009; Di Geronimo et al., 2009; Liew et al., 2010). Ongoing studies of coastal recovery from the 2004 Indian Ocean tsunami show that sandy beaches, in particular, recover quickly following major tsunami inundation. Recovery occurs rapidly at first; study sites show 60% of original beach form being rebuilt in the first 6 months (Choowong et al., 2009). Sand for post-tsunami rebuilding of beaches is derived from offshore (Choowong et al., 2009; Di Geronimo et al., 2009; Liew et al., 2010), allowing beaches to rebuild from background wind and wave processes or from waves acting in combination with storm surges (Choowong et al., 2009; Liew et al., 2010). Inlets filled and beach ridges formed during storm events a few months after the tsunami (Choowong et al., 2009). Within two years after the 2004 Indian Ocean tsunami, most surveyed beaches had returned to their equilibrium profile, although not necessarily at their original position (Choowong et al., 2009; Di Geronimo et al., 2009). Rebuilt berms, low dunes and beach cusps often mimic past geometries in the months to years after the event because the post-tsunami coast experiences the same coastal processes as prior to the tsunami (Liew et al., 2010).

History of tsunamis in the Galapagos Islands

As a volcanic archipelago, the Galapagos Islands have two potential tsunami sources: (1) local tsunamis can be generated by earthquakes, landslides, and volcanic collapse—all possibilities associated with steep submarine slopes and active volcanoes of the Galapagos Islands (Keating and McGuire, 2000); and (2) teletsunamis can arrive from distant, primarily earthquake, sources. In contrast, the Galapagos Islands, being situated near the equator, are not in a region that experiences large storms (Simpson and Reihl, 1981).

The Galapagos Islands have experienced many historical tsunamis (Table 1), albeit the only known locally generated tsunami was from a landslide within a volcanic crater lake (Chadwick et al., 1991). The nearby subduction zone off the coasts of mainland Ecuador, northern Peru and Columbia has generated large, tsunamigenic earthquakes in 1906, 1933, 1953, 1959 and 1979 (Espinoza, 1992; Fig. 1). Tide gauges in the Galapagos Islands recorded over 20 teletsunamis since the 1960 Chilean tsunami (Table 1). Of these, the 11 March 2011 Tohoku tsunami was the largest.

The 2011 Tohoku tsunami in the Galapagos Islands

The first evaluations of the 2011 Tohoku tsunami impact in the Galapagos Islands were performed by a post-tsunami survey team with assistance from the Ecuadoran Instituto Oceanografico de la Armada (INOCAR) and the Galapagos National Park. The team collected

Table 1
Historical tsunamis recorded in the Galapagos Islands. Data from the National Geophysical Data Center accessed 17 September 2011 unless otherwise noted. Tide gauge locations on Fig. 1. Note: not all of the tide gauges have been active for the same period of time or through the whole history represented by this table. X denotes the tsunami was not recorded. Locations of observations are located on Fig. 1B. Tide gauge maximum is half of the wave height (trough to crest).

Year	Source location	Magnitude (Mw)	Location of observation in the Galapagos Islands	Tide gauge maximum (m)
1960	Chile	9.5	San Cristobal Island	0.6
1962	Costa Rica–Panama	6.8	San Cristobal Island	0.1
1964	Alaska	9.2	San Cristobal Island	X
1966	Peru	8.1	*Not noted*	0.2
1966	Chile	7.8	*Not noted*	0.1
1979	Ecuador (from Espinoza, 1992)	7.9	*Not noted*	0.8
1985	Mexico	8.0	Baltra Island	0.11
1986	Alaska	8.0	Baltra Island	0.02
1992	Nicaragua	7.7	Baltra Island	0.55
1995	Mexico	8.0	Baltra Island	0.04
1996	Peru	7.5	Santa Cruz Island	0.2
1996	Mexico	7.1	Baltra Island	0.06
1996	Alaska	7.9	Baltra Island	0.04
2001	Peru	8.4	Baltra Island	0.15
			Santa Cruz Island	0.45
2004	Indonesia	9.1	Baltra Island	0.18
2006	Russia	8.3	Baltra Island	0.3
			Santa Cruz Island	0.33
2007	Russia	8.0	Santa Cruz Island	0.27
2009	Tonga	7.6	Baltra Island	0.03
			Santa Cruz Island	0.14
2009	Samoa	8.0	Baltra Island	0.13
2010	Chile	8.8	Baltra Island	0.35
			Santa Cruz Island	1.08
2011	Japan	9.0	Baltra Island	0.86
			Santa Cruz Island	2.26
2011	New Zealand	7.6	Baltra Island	0.06
			Santa Cruz Island	0.15

~150 measurements of flow depth or runup at 28 sites on the four largest islands in the Galapagos Islands (Lynett et al., 2012). Numerical computations performed prior to the surveys identified focus sites that likely experienced higher than average tsunami waves (Fig. 1). Of the sites surveyed, tide-corrected maximum flow elevations were generally in the range of 3–4 m above sea level; Isabella Island experienced the largest flow elevation of 6 m in a small pocket beach (Lynett et al., 2012). On Santa Cruz Island, tsunami measurements ranged from less than 2 m up to ~5 m above sea level, including maximum flow elevations at El Garrapatero of 3.3 m. The tsunami occurred near high tide within a tidal range of ~2 m (Fig. 1). Coastal dune erosion was widespread and observed on all of the islands visited.

Methods

The El Garrapatero beach and lake were surveyed August 24–26, 2011 with a transit level, zeroed to the water line at high tide on August 24th (Fig. 1). All aspects of the coastal system were surveyed for elevation and location, as they existed in August, including landmarks, surviving vegetation, tsunami water heights, scours, surface details of the deposit, current and former lake levels, and excavations.

A series of excavations through the recent deposits in El Garrapatero were hand dug from the position of the breached sand dune to the far side of the lake (Fig. 1). Documentation of the deposit in each excavation includes thicknesses when the basal contact was found and descriptions of sedimentary structures. In total, 12 excavations were dug and described in detail. Supplementary small test pits were used to trace out the deposit extent and thickness across the lakebed. Analysis of the deposits focused on the identification and documentation of sedimentary structures to determine flow conditions during deposition. Deposits were not analyzed for grain size or microfossil identification. Future work will analyze the environmental changes and deeper stratigraphy in more detail.

Additional methods include interviews with Galapagos National Park rangers stationed at El Garrapatero, members of INOCAR stationed in the Galapagos Islands, and participants from the post-tsunami survey who visited El Garrapatero on April 7th, 2011 (Lynett et al., 2012). Information from these sources included prior lake levels and descriptions of the pre- and post-tsunami environment. Photographs from tourists to the area before and after the tsunami were also investigated. The interviews and photographs enable a more complete understanding of the events occurring between March 11th, 2011 and the time of the survey, as well as the coastal system at El Garrapatero before the tsunami.

Results

Observations and history of events in El Garrapatero from 11 March to 26 August 2011

The southward-facing El Garrapatero coastal system is exposed to the south Pacific but otherwise protected on three sides (Fig. 1). Basalt outcrops of the volcanic Santa Cruz Island underlie much of El Garrapatero and are exposed at the periphery of the beach, including a small headland on the east side of the bay. Moderately vegetated sand dunes sit behind the beach in the center of the bay; sand is primarily carbonate in composition. A shallow saline lake, 175 m from the ocean, is connected to the sand dunes (Fig. 2) by a narrow meadow (Fig. 2A1). Forest vegetation surrounds the lake, meadow, dunes and beach.

Prior to the Tohoku tsunami, tourists accessed El Garrapatero beach by a trail that ran along the SE edge of the lake, through the meadow, and over the dune. The trail was sandy and lacked vegetation (Figs. 2B1 and C1). A spur trail also connected the Ranger's hut with the main trail, joining at the landward side of the dunes (Fig. 2 Row E shows this path). The dune crest was approximately at the same elevation along the back of the beach, interrupted only slightly by the lower elevation tourist path. Water level in the lake fluctuated seasonally with rainfall. The lake shoreline during average water level was about 4 m landward of a wooden post (marked in Figs. 1 and 2G2, G3, and G4), according to the National Park ranger. Near this average shoreline of the lake, the pre-tsunami soil transitions from loose and lightly cemented sand to the organic-rich mud of the lake deposits.

The 11 March 2011 Tohoku tsunami brought water over the sand dunes and across the lake. Exact runup and inundation were not measured post-tsunami, but a dead shark was found in the forest near the far side of the lake indicating the tsunami inundated the entire lake area. Flow depths were 0.7–0.8 m (1.9 m above high tide) at the Ranger hut (location in Fig. 1) (Lynett et al., 2012). Erosion by the Tohoku tsunami temporarily connected the lake with the ocean during high tides (Figs. 2A2, C2, D2, and E2). The channel carved by the tsunami occupies the same position that the unvegetated tourist path did. Sand was removed from the beach, lowering the beach surface and causing high tide to reach the base of the sand dune (Fig. 2C2).

Starting on 19 March 2011 and lasting for 4–5 days, a swell, coinciding with spring tides, arrived at the Galapagos Islands. Another period of swell also occurred in late April 17–22. Swells are sets of large wind-generated waves that are typically formed during storms and can travel far from the location of their formation. Large swell waves affect a coastline similarly to storm waves, although unlike in a storm, strong wind, heavy rain, and storm surge are absent during a swell event. The National Park Ranger described the wave heights in March and April as normal heights for swell in the region. Strong swell events average 2–3 m at the outer reef (Glynn and Wellington, 1983) and up to 4.5 m or more. During the combined periods of swell and high tide, sand was seen transported from the beach towards the lake and deposited in the meadow.

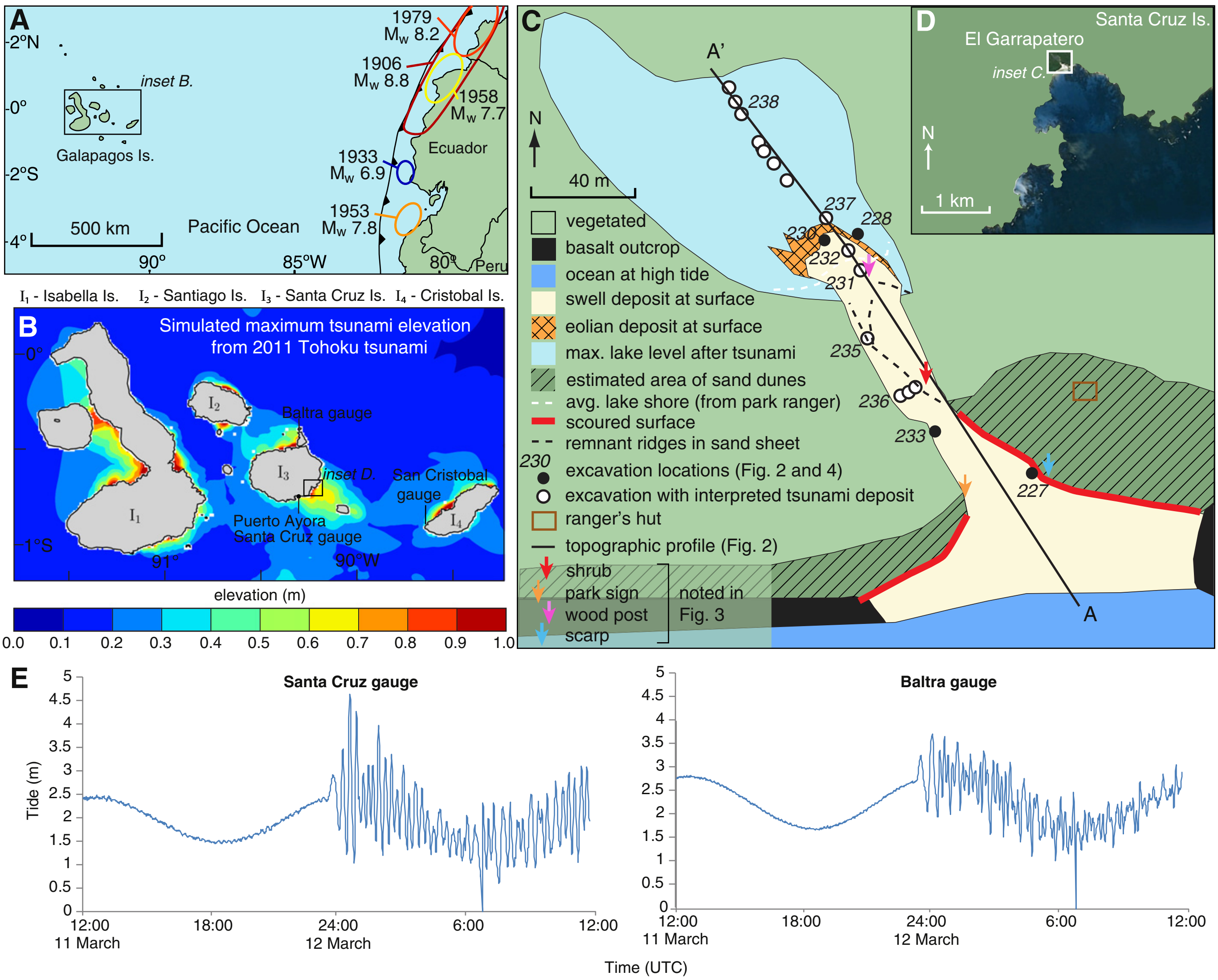


Figure 1. A) Location of Galapagos Islands, Ecuador and tsunamigenic earthquakes on the Ecuadoran subduction zone (Espinoza, 1992; White et al., 2003; NEIC database). B) Simulated maximum wave elevation from the 2011 Tohoku tsunami in the Galapagos Islands (from Lynett et al., 2012). I_1 — Isabella Island, I_2 — Santiago Island, I_3 — Santa Cruz Island, I_4 — Cristobal Island C) Map of the El Garrapatero coastal system with excavations, the profile, and features referred to in the text noted. The map was made in August 2011 and represents the extent of deposits at that time. D) Setting of El Garrapatero. Unlabeled excavations are test pits represented in Fig. 2A but not described in detail. E. Records from tide gauges near the field site (locations in B) showing the arrival of the 2011 Tohoku tsunami at high tide.

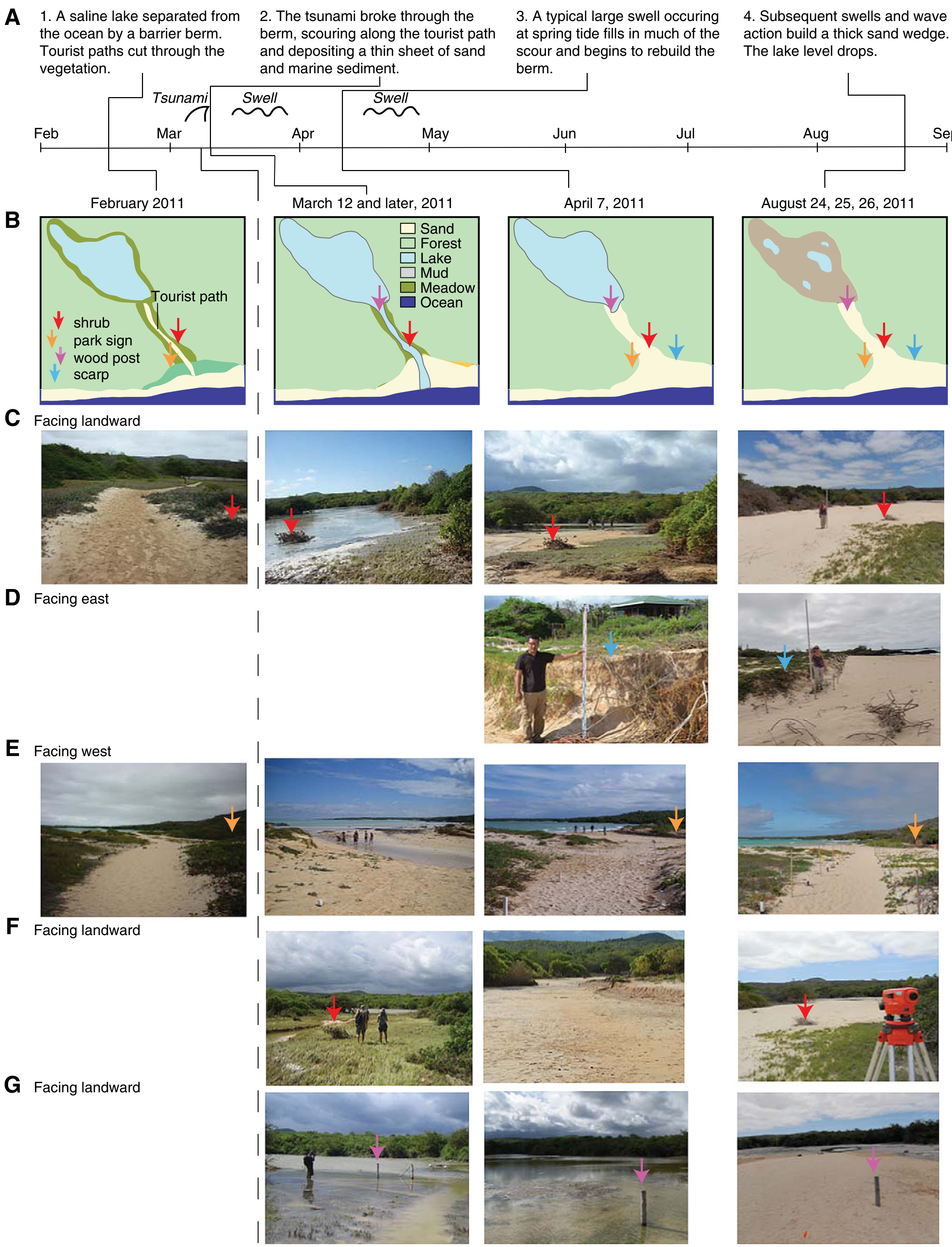
Post-tsunami survey teams visiting El Garrapatero on 7 April 2011 measured the eroded seaward edge of the sand dunes to be 1.4 m high (Fig. 2B3). A continuous sand sheet extended from the dunes to the lake (Figs. 2A3 D3); little remnant meadow existed at the surface. Sand filling the cut/channel through the sand dune had filled to at least high tide (Figs. 2C3, D3, 3). Lake level was higher than normal (Fig. 2E3).

The National Park ranger noted that by June to early July 2011 the channel was filled with sand at a level approximately even with the surrounding surface—roughly the surface measured in late August 2011. Since that time, ocean water had not reached the lake. By August 2011, the sand filling the channel had formed a small berm, reaching above high tide, slightly seaward of the adjacent sand dune crests (Fig. 3).

Deposit observations

As observed from 24 to 26 August, 2011, sand deposited during and after the March 11 tsunami thins rapidly landward (from over 1 m to less than 30 cm thickness in 150 m). The deposit consists of mostly carbonate material and is dominantly fine sand (125–250 μm). Near the actively forming beach berm, the exact thickness of the deposit could not be determined, due to the deposit containing the same size, color and mineralogy of grains in the layer it overlays. Based on estimates from post-tsunami photographs from April and August (Fig. 2D3, D4), the deposit was over a meter thick in the vicinity of the berm. The deposit is thick where it fills the channel scoured by the tsunami and in a fan-shaped wedge at approximately the former lakeshore. Laterally

Figure 2. A) Timeline of events at El Garrapatero. Black lines connect information from the same time period. B) Cartoon map of the changing environments at El Garrapatero. Colored arrows mark the locations on the map with features in the photos. Colors correspond to the key in Fig. 1D. C–F) Column 1: Photographs from before the 11 March Tohoku tsunami, Column 2: Between March 11 and April, Photographs from 12 March (except C2) courtesy of S. Taylor, Column 3: April 7, Column 4: August 2011. Arrows mark landmarks located in (B). Photgraph C2 was taken between March 11 and April 7.
Images C1, C2 and E1 courtesy of I.J. Almeida.


A
1. A saline lake separated from the ocean by a barrier berm. Tourist paths cut through the vegetation.
2. The tsunami broke through the berm, scouring along the tourist path and depositing a thin sheet of sand and marine sediment.
3. A typical large swell occuring at spring tide fills in much of the scour and begins to rebuild the berm.
4. Subsequent swells and wave action build a thick sand wedge. The lake level drops.
Tsunami
Swell
Swell
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
February 2011
March 12 and later, 2011
April 7, 2011
August 24, 25, 26, 2011
B
Tourist path
shrub
park sign
wood post
scarp
Sand
Forest
Lake
Mud
Meadow
Ocean
C
Facing landward
D
Facing east
E
Facing west
F
Facing landward
G
Facing landward

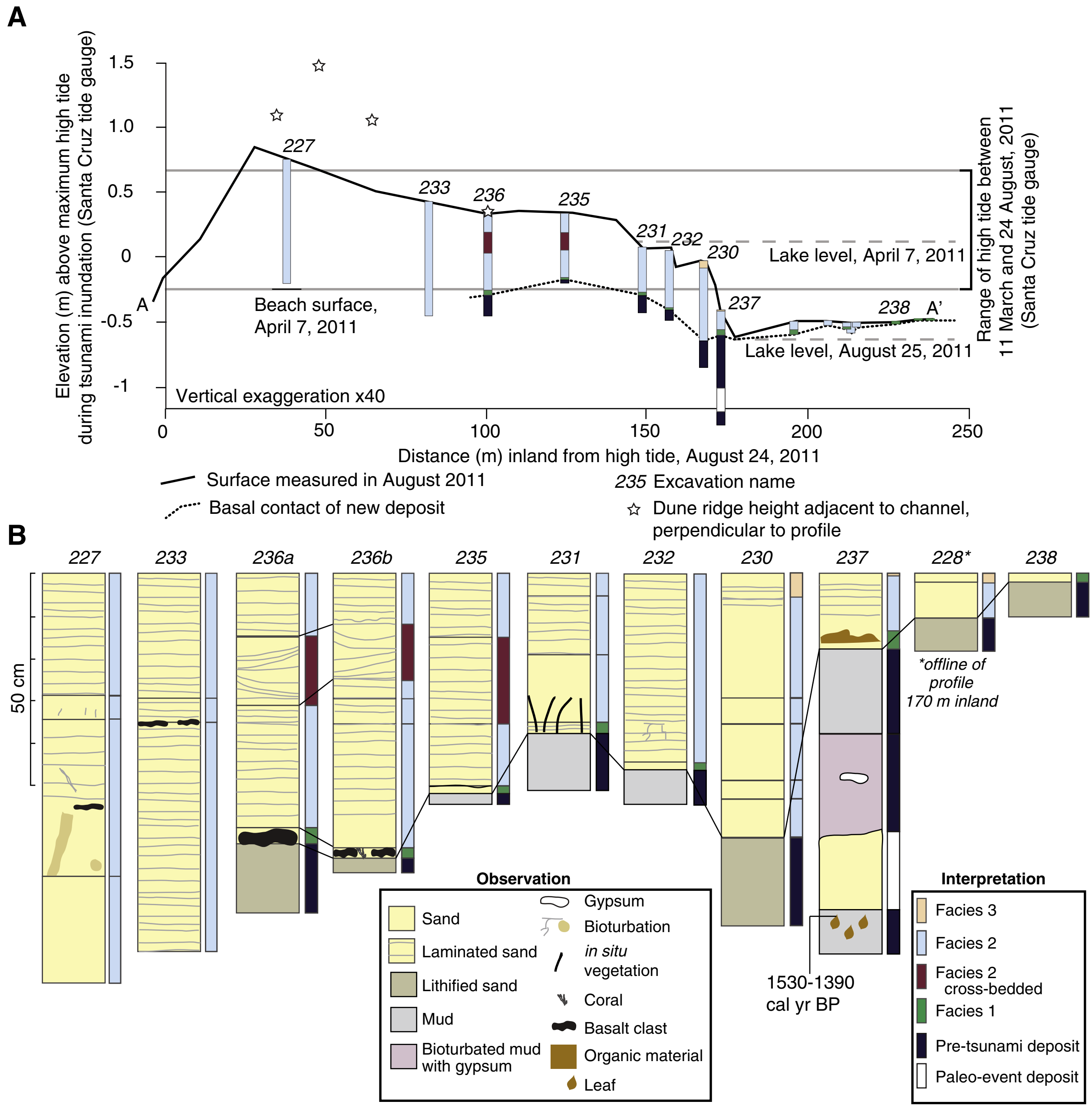


Figure 3. A) Topographic profile from the ocean to the lake including depths and interpreted facies of excavations. Profile location in Fig. 1. B) Stratigraphic sections from excavations in August 2011. For each excavation there are two columns: to the left, a stratigraphic column of observations of grain size, sedimentary structures and defining characteristics; to the right, color blocks of the interpreted facies of the stratigraphic column.

and landward of these features, the deposit thins to less than 20 cm in the lake area. By the landward (north) side of the lake, the deposit thins to 1–2 cm (Fig. 3A). Test pits in the lake bed, not described in detail, are plotted on Fig. 3A and were similar in character to excavation 238 (Fig. 4F). In most locations, the basal contact of the deposit is erosional. An exception to this is where vegetation was not eroded during the tsunami event, such as in excavation 231 (Fig. 3).

At the seaward (south) end of the profile, fining upward laminae and laminae of differing grain sizes dominate the deposit. Thickness of the laminae is highly variable but typically 1–2 cm thick with gradational contacts. Laminae thin upwards. At the beach and within the dunes, there is little to no soil formation and the deposit unconformably overlies sandy berm and dune sediments. Basalt cobbles are present in the seaward-most excavations (227 and 233, Fig. 4). Excavation 227 shows evidence for post-depositional bioturbation by crabs (Fig. 3).

The deposit in the middle of the channel (excavations 236a, b, and c, Fig. 4C) unconformably overlies muddy fine sand and basalt cobbles and boulders. Prior to the tsunami this area was a coastal meadow with some soil formation. In excavation 236b, clasts of coral up to 4 cm long were found in gaps between the basalt clasts at the base of the deposit. The basal 3 to 5 cm of the deposit and the space between the basalt is filled with a mix of fine to coarse sand and shell fragments. The rest of the deposit consists of fine sand containing 30 to 40 cm parallel-laminated sand overlain by 15 to 20 cm of cross-laminated sand, in turn overlain by 12 to 15 cm of parallel-laminated sand. Laminae are 0.5–1.5 cm thick and alternate between thicker, coarser laminae and thinner, fine sand laminae.

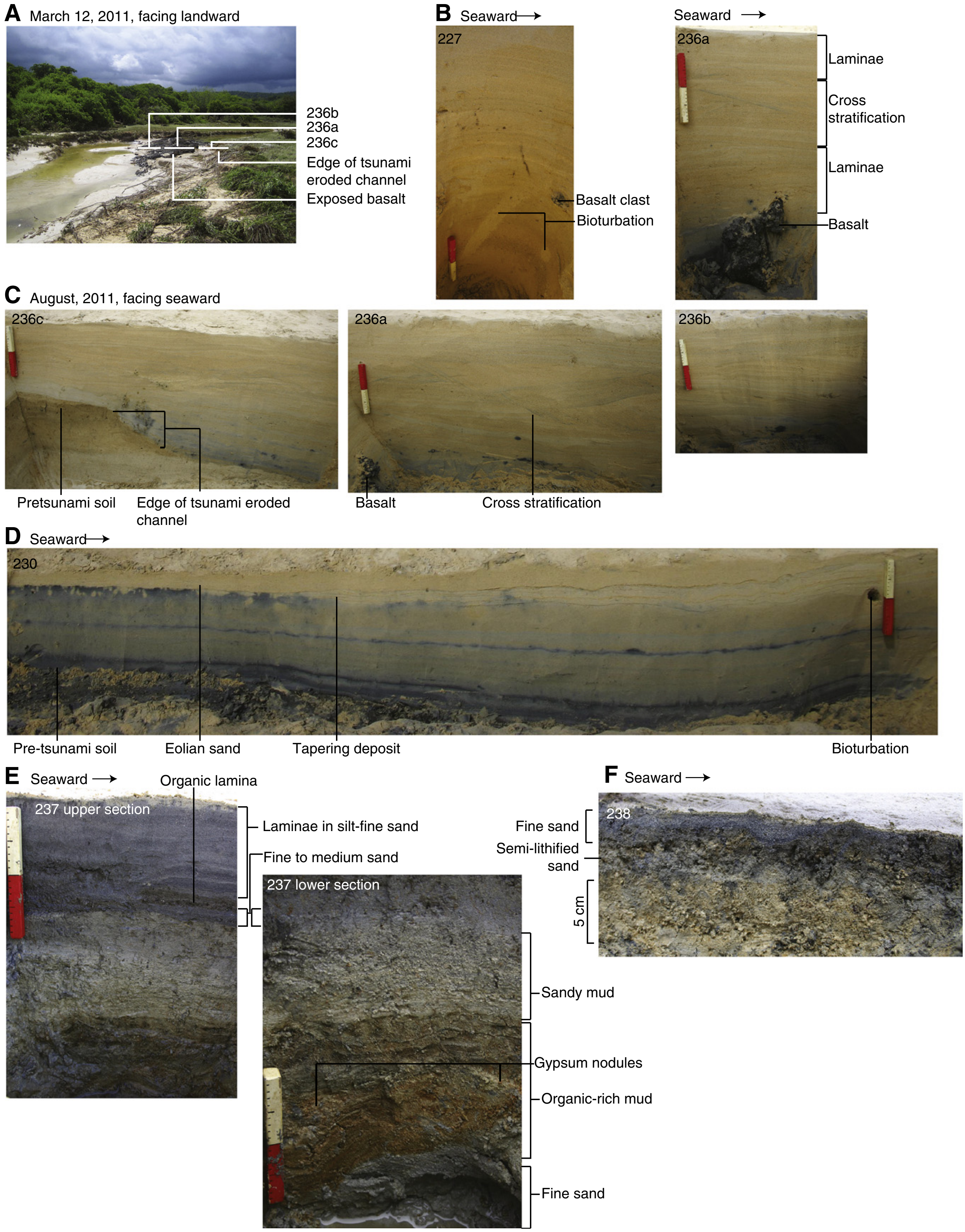


Figure 4. Photographs of excavations. A) The tsunami cut channel from 12 March 2011 with the locations of excavations 236a, b and c from August 2011. Photograph courtesy of S. Taylor. B–F) Photographs of excavations from August 2011 from closest to the beach (B) to the middle of the lakebed (F). B) Excavation 227 detailing the laminated deposits and the onset of bioturbation. C) Excavation 236a, b and c showing the edge of the tsunami-cut channel and the cross-stratified sand that filled the channel in the months after the tsunami. D) Excavation 230 detailing laminated units pinching out. The darker sediment is not due to a change in sediment type but is due to reduction. E) There are two photographs of excavation 237 — to the left is the upper portion of the excavation and to the right is the lower portion. The photos are aligned and scaled the same. This excavation shows both the upper and a portion of the lower sand layers. F) Excavation 238 is a typical representation of the sand deposit in the lake bed. The sand is a few centimeters thick.

Farther landward, the deposit overlies the vegetated surface with *in situ* plant stems embedded in the deposit (excavation 231). Mottling from reduction is associated with this organic material. The plants are rooted into a sandy mud. The basal 1 to 3 cm of the overlying deposit is fine to medium sand (250–500 μm) capped by a <1-cm-thick organic lamina. The overlying 15 cm contains few sedimentary structures. The upper 19 cm of sand is laminated, with the uppermost 6 cm of laminae less well-defined. The upper 6 cm of laminae fine upwards.

Near the edge of the former lakeshore, at the break in slope of the fan (excavation 230), the basal 55 cm of the deposit are faintly laminated due to variation in grain size. The deposit sediment is overlain by 0 to 10 cm of strongly laminated sands that pinch out landward. The upper 5 cm of the deposit is massive (Fig. 4D). Mottling from reduction is common. The pre-tsunami sediments consist of sandy mud, semi-cemented in some locations, that grades into an organic rich mud towards the lake (Figs. 3A and B).

As the deposit thins into the lake, it becomes more massive. The strongly laminated portion of the deposit thins to 13 cm. The laminae are typically separated by mud partings and are approximately 1 cm thick. In excavation 237, 2 to 3 cm of organic material separates the upper laminated, fine-grained sand from a lower, more massive, fine to medium sand with scattered coarse grains and organic material (Fig. 4E).

In seaward end of the lake but perpendicular to the channel, the deposit thins to 10 to 12 cm. In excavations, 228 and 229, the fine sand deposit contains but does not completely bury *in situ* grass (Fig. 4G). Following the trend of the channel, the deposit thins across the lakebed (Fig. 3); near the landward lakeshore the deposit is 1 to 2 cm with typically massive or upward fining sedimentary structure (excavation 238, Fig. 4F).

Underlying stratigraphy

Where excavations reached a basal layer, the lower deposit was typically muddy sand along the channel and mud or semi-consolidated sandstone in the lake area. In excavation 237 (Figs. 3 and 4E), the gray bioturbated muddy fine sand that underlies the sand deposit grades down into a slightly pink, organic-rich muddy, fine to coarse sand (125–1000 μm). The muddy sand contains gypsum nodules and is highly bioturbated. Below the muddy sand, from 65 to ~85 cm depth, is an unconsolidated, clean fine sand layer underlain by mud with well-preserved leaves and roots. Similar to the other sand deposits, the unconsolidated, clean fine sand contains well-rounded sand-sized fragments of shells. Fragments of crab shell were also found in this layer. Leaf fragments from the top 3 cm of the lower mud (~85 to 88 cm depth) yielded an age of 1530–1390 cal yr BP (1590 ± 30 ^{14}C yr BP using AMS, Beta Analytic sample 312635; calibrated using INTCAL09, Reimer et al., 2009).

Interpretation

Interpretation of sand deposits

The sand unit at El Garrapatero can be generalized into three dominant sedimentary structures: (1) massive to fining upward, with a mix of fine to coarse sand at the base, (2) faintly to strongly laminated fine sand, and (3) massive upper sand near the seaward edge of the lake (Fig. 4D). The interpretation of these three facies are (1) the coarser base likely represents higher energy processes, such as tsunami deposition or deposition while the channel was still open to high tide, (2) the laminated sands are overwash deposits from wind-generated waves, and (3) the upper massive sand is eolian.

The coarser sand in the facies 1, especially in the lakebed, was more likely deposited by the tsunami due to the layers extent, grain size and stratigraphic location. Based on a shark carcass and other marine debris found in the vegetation on the landward side of the lake, the tsunami inundated for at least 10s of meters beyond the lake. Tsunamis transport sand as suspended load for a significant percent of their inundation distance (MacInnes et al., 2009b), even in cases of shallow standing water (Higman and Bourgeois, 2008). The potential for sand transport and deposition across the lake after the tsunami is low. Based on post-tsunami photos from the days after the tsunami and in April (Figs. 2E2, E3), the breach of the sand dunes by the tsunami led to the flooding of the lower elevation lake. Standing water impeded cross-lake transport of sand by post-tsunami depositional agents, such as wind-generated waves or eolian processes. For example, wind-generated waves, when exiting the channel into standing lake water would lose their energy, dissipate, and drop their sediment load forming a fan (Kitamura et al., 1961). In addition, facies 1 is coarser than the upper sand units indicating either higher energy transport or a different source for the sediment.

The tsunami was also the most likely agent of deposition for facies 1 in excavations into the old meadow area. Photos of the meadow from immediately after the tsunami (Figs. 2C2, F2, G2) show grasses not yet buried in sand, but with a thin deposit present. In the lake (excavation 237), the layer of organic material within the sand deposit may be analogous to organic material and plant fragments in tsunami sediments deposited in a lake by the Storegga landslide (Bondevik et al., 1997). If analogous, the organic material represents strong erosive forces (to tear up the material) and later quiescence allowing the material to settle. Facies 1 fines inland: coarse grains such as coral fragments several centimeters long were found at the base of the deposit in excavation 236 but no such coarse grains were found in the lakebed.

The laminated facies, facies 2, is most likely the result of deposition by wind-generated waves (Fig. 3, and 4B, C, D). Pre- and post-tsunami photos from March (Figs. 2C1, E1, C2–G2) do not show the presence of the thick sand unit of this facies, indicating it had not yet been deposited. Two large swells, one in March and one in April, likely resulted in the majority of the deposition. Based on interpretations of deposits and discussions with National Park rangers, both inundation and run-up overwash (terminology after Donnelly et al., 2004) from wind-generated waves led to deposition at El Garrapatero. Inundation overwash occurred after the tsunami breached the coastal berm and formed the channel. During this stage, waves were channelized and deposited a fan between the beach and lake. As the channel filled in and the coastal berm rebuilt, swell waves at high tide would have been large enough to still overtop the berm as run-up overwash. During this period, deposition was more concentrated near the beach.

The sedimentary structures within facies 2 of the deposit support the two processes for overwash deposition. Individual parallel laminae are traceable for meters, indicating they may be the result of single waves. The cross-laminated sand subset of facies 2, best exemplified in excavations 236a, b, and c, potentially represent braided-stream-like conditions, occurring during the transition from inundation to run-up overwash (Fig. 4C). This interpretation is based on the variable dip directions of the cross bedding and the identification of multiple filled channels. Three filled channels can be seen in the shore parallel photograph of excavation 236a in Fig. 4C and a filled channel of a different orientation is evident on the shore perpendicular photograph of the same excavation in Fig. 4B. As the tsunami-cut channel filled, the area transitioned from constant connection with the ocean (inundation overwash) to run-up overwash as deposition rebuilt the beach berm. Braided-stream-like deposition would occur when the flow depth was reduced as the berm was rebuilt, but while sedimentation rate remained high. The parallel laminae overlying the cross laminae indicate the berm had built to a point that deposition had become exclusively run-up overwash.

The upper massive facies, 3, is likely the result of eolian deposition. Active eolian winnowing of the deposit was observed in August 2011 from the beach to the upper break in slope of the fan. Some of this wind-transported sand was deposited where the slope steepened, and some on the damp exposed lakebed. At excavation 230 (Fig. 4D), which was dug along the toe of the fan, the upper, massive sand thickens landward.

There are two potential sources for the sand deposits—terrestrial and shallow marine. The bay at El Garrapatero is shallow and partially covered in sediment (predominantly fine to coarse sand) and basalt outcrops based on interpretation of satellite images and grab samples from less than 2 m water depth. The second source is the berm that contributed sediment to the tsunami flow as it was eroded. The tsunami deposit is likely a combination of the eroded berm and sediment from the bay. The overwash deposit is likely a combination of sediment from the bay and sediment deposited on shore and in the bay during the tsunami.

Excavation into the lakebed (excavation 237) revealed a possible repeating sequence of a clean sand layer separating different depositional environments (Figs. 3, and 4E). At approximately 65 cm below the surface, a 20-cm-thick sand unit unconformably overlies organic-rich mud with mangrove leaves and rootlets (Figs. 3 and 4E). Overlying the sand is bioturbated mud with gypsum nodules, the gypsum indicating a restricted and evaporative environment such as a saline lake. The gypsum nodules may indicate seasonal drying of the lake in the past. This gypsum-forming variation in lake level would have been greater than the seasonal variation that occurred before the tsunami described by the National Park ranger. Environmental variations within the lake stratigraphy and the lower sand unit deserve further study.

Discussion

Implications of the sand sheet at El Garrapatero

For future post-tsunami surveys

Caution should be exercised in interpreting terrestrial deposits near the shoreline, as the records of storms, tsunamis and coastal recovery may be ambiguous. As shown in other studies (Choowong et al., 2009; Di Geronimo et al., 2009; Liew et al., 2010), coastlines can recover rapidly from large disturbances such as storms and tsunamis. This study highlights the potentially complex series of depositional events that may influence the geological record of coastal disturbances by storms and tsunamis. The deposit in El Garrapatero is interpreted to have formed dominantly post-tsunami as the coastal system recovered from tsunami erosion; however, without the assistance of contemporary observations, the depositional agent of the fan deposit likely would have remained an enigma. Although the equatorial setting of El Garrapatero excludes the likelihood of large storms (Simpson and Reihl, 1981) as agents of deposition, the parallel lamina and cut and fill structures in the deposit indicates that wind-generated wave deposition dominated (Morton et al., 2007; Switzer and Jones, 2008). The tsunami was the most uncommon and most energetic of the three agents of deposition (tsunami, wind-generated wave, and eolian); however, little of its depositional record is distinguishable from the other processes. This is, in part, due to the coastal berm cut and low-elevation lake allowing swell deposition to augment and overlay the tsunami deposit. Topography rising from the coast would not allow such swell deposition. Similar combined depositional events may be possible in other settings such as coastal lakes, lagoons, and bays protected by spits or coastal berms.

An additional implication of this study is a caution for post-tsunami surveys that do not occur immediately after an event. While post-tsunami surveys may not be possible soon after a tsunami event for logistical and ethical reasons, these surveys and other detailed studies of tsunami sediments need to mitigate for post-tsunami alteration and enhancement of deposits. In the weeks to months after a large storm or tsunami, the coastal zone can be more vulnerable to other events. In the case of El Garrapatero, the site would need to have been visited within nine days for the deposit left only by the tsunami to be accurately identified. By March 20th, swell waves combined with spring high tides were transporting sand across the meadow along the channel.

For a potential record of older events

The potential for this deposit to be preserved in the geological record decreases along profile from the lake to the beach. Already, the deposit's bounding surfaces are difficult to identify at the seaward end of the profile because of the similarities in sediment characteristics between the new deposit and the dune sands. Bioturbation in this region is beginning to disrupt the integrity of the new deposit (Fig. 3B), and likely will continue to erase or blur sedimentary structures and deposit contacts. Furthermore, nearest to the beach, the deposit can be reworked during future events or from fluctuations in sea level.

The lake has the highest potential for preserving the record of the 2011 Tohoku tsunami. As seen in other tropical locations, ephemeral and permanently wet environments preserve tsunami deposits (Jankaew et al., 2008; Monecke et al., 2008). The difference in lithology between the underlying lake mud and the sandy tsunami and swell deposit allows for easy recognition. Future deposition of fine-grained lake sediments will possibly cover and preserve the tsunami and swell deposit. Although it is unknown if the drying of the lake is a long-term effect of the tsunami, environmental changes associated with the sand layer would be analogous to other tsunami and storm impacts in protected coastal water bodies (Atwater et al., 2012).

For tsunami deposit taphonomy

Tsunamis that flood low-elevation lakes behind barriers in other geographic locations may leave similar records to what was found at El Garrapatero. Previous studies of the changes to tsunami deposits after deposition show preservation only in favorable environments (Nichol and Kench, 2008; Szczuciński, 2011; Goto et al., 2012). At sites where thin tsunami deposits may not otherwise be preserved, thicker deposits laid down soon after protect lower layers from bioturbation and other post-depositional alteration (Arcos, 2012). In other cases, post-tsunami thickening of the deposit may be ultimately indistinguishable from the tsunami deposit, such as the case where the deposits of the 2004 Sumatra tsunami within 100 m of the shore were found to be thicker five years after the event (Goto et al., 2012). As active eolian processes move sand into the lake and the deposit is gradually bioturbated, further investigation of the El Garrapatero site is warranted to monitor how the sand sheet evolves before it is buried in the stratigraphic record. The preservation of an older, similar sand layer in the lake may indicate that at least the toe of the fan could eventually be preserved there.

For paleo-tsunami studies and Pacific tsunami hazard analysis

Paleo-deposits that are an amalgamation of sediments from multiple depositional processes could be misinterpreted as a single event resulting in an overestimation of the size of the event if the greater thickness is interpreted to indicate a larger event. Neither the 3.3-m-high tsunami nor later swell waves at El Garrapatero were large events. A 1-m-thick deposit in El Garrapatero, if assumed to be all from tsunami deposition, may imply a much larger and more hazardous event than what actually occurred. Similarly, if the breach of the coastal berm and deposit are assumed to be only from wind-generated waves, the depositional record also implies much larger waves than actually occurred. Credence should be given to the hypothesis that a series of smaller events can combine to form a record that can be misinterpreted as of a single larger event.

The presence of an older sand deposit in the lake suggests the potential for a similar series of tsunami erosion followed by overwash deposition and ecological change to have occurred at least once in the past of El Garrapatero, although other sources of the sand layer cannot be ruled out at this time. The change in environment associated with the sand deposit may represent the closing off of the lake area to the ocean, an event that can be precipitated by a storm or tsunami (e.g., Atwater et al., 2012). Additional work in El Garrapatero to test the tsunami-origin hypothesis of the older sand layer could be a valuable contribution to Pacific tsunami hazard studies.

Predictions of future recovery

Initial recovery post tsunami occurred rapidly, an observation similarly made after other tsunamis (e.g., Choowong et al., 2009). Based on photographs (Fig. 3), the channel had filled and a beach berm grew to at least 60% of the height of the surrounding sand dunes in the 6 months post-tsunami. Presumably, the dunes will fully recover, based on work by Morton et al. (1994) in Texas, although the recovery processes including revegetation could take several years. The geometry of the coast after recovery will likely mimic the pre-tsunami counterpart, as observed in other post-tsunami studies (Liew et al., 2010).

Conclusions

The 11 March 2011 Tohoku tsunami overtopped the coastal sand dunes (dune height ~1.5 m above high tide) at El Garrapatero, Galapagos Islands by around 0.8 m and carved a channel through the dunes to a small saline lake by exploiting an unvegetated tourist path. By forming the channel, the tsunami set off a series of depositional events that could not have otherwise occurred. The subsequent overwash deposition of swell waves during spring high tide left a sand sheet up to a meter thick between the sand dunes and the lake. The sedimentologic record of the Tohoku tsunami that is likely to be preserved in El Garrapatero will be this amalgamated deposit rather than the tsunami deposit in isolation.

Although small in scale, the coastal environment at El Garrapatero is similar to other quiet-water environments behind coastal barriers that are typical places worldwide to look for records of storms and tsunamis (Lui and Fearn, 1993; Sawai, 2002; Bondevik, 2003; Kelsey et al., 2005; Switzer and Jones, 2008; Woodruff et al., 2008). Deposits with characteristics similar to those at El Garrapatero for example, those of unusual thickness, or those with cross- and planar lamination in similar settings should also be considered candidate amalgamated deposits and treated accordingly in coastal hazard analysis.

Sedimentary fans may form from a variety of processes both during and after erosive events. Other surveys have demonstrated that both storms and tsunamis can leave fan-shaped sediment wedges where they break through coastal barriers and ridges (Schwartz, 1975; Morton et al., 2011). We would like to add that similar fan deposition can occur during coastal recovery from a tsunami and likely post-storm as well.

Tsunamis can alter coastal systems such that typical processes can leave atypical sedimentary records. Swells of a typical size for the Galapagos Islands generated a large sedimentary fan at El Garrapatero after the 2011 Tohoku tsunami. Fan deposition was atypical, as a similar sedimentary deposit had not formed for approximately 1000 years before the 2011 event. Although the tsunami did not directly form the fan, the infrequent recurrence of the similar deposits indicates an atypical event. Because the Galapagos Islands do not predictably experience large storm waves, the distinction between tsunami recovery and storm deposition may be possible. In parts of the world that experience both storms and tsunamis, the distinction may not be as simple, although amalgamated deposits should be expected in low-elevation settings in close proximity to the ocean.

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