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Frequent landslides from Koolau Volcano: Results from ODP Hole 1223A

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Abstract

Giant landslides on the flanks of oceanic islands are considered relatively rare but potentially devastating natural hazards. The Hawaiian Islands are known to produce some of the biggest landslides on Earth. The Nuuanu slide, largest of the Hawaiian slides, is thought to have removed a substantial part of Koolau Volcano from the island of Oahu. Ocean Drilling Program (ODP) Hole 1223A was drilled to determine the depositional history, timing, thickness and hazards associated with the Nuuanu landslide, the only previously known Koolau slide. Site 1223, located ~260 km northeast of the island of Oahu near the crest of the 500-m-high Hawaiian Arch, was drilled to a depth of 41 m. Eight distinct sandy layers were recovered and more are likely to occur deeper in the section. Contacts of these sandy layers with pelagic clay are sharp at their base and gradational at the top. The layers contain angular fresh glass fragments with compositions that are typical of Hawaiian shield volcanoes, including the distinctive Koolau high SiO_2-type in seven layers. Most glasses (>90%) are degassed (<0.03 wt.% S) indicating that they were probably erupted subaerially. Pleistocene to Early Eocene Radiolaria taxa are present in the Hole 1223A cores, with mixed ages in some intervals. Seven of the sand layers are probably associated with Koolau landslides and were deposited prior to 1.77 Ma. Among the four thicker sand layers (>1.5 m), it is unclear which, if any, are related to the Nuuanu slide. Results from Hole 1223A cores demonstrate that Hawaiian volcanoes collapse repeatedly, and the debris from these many slides can travel great distances (>260 km) across the ocean floor and over significant bathymetric obstacles (~500 m). Thus, landslides from oceanic volcanoes pose a greater risk than previously assumed.

Keywords: Hawaii; Koolau Volcano; Ocean Drilling Program; volcanic glasses; landslides; petrology

1. Introduction

The enormous size (up to 8.5 km of relief and 74,000 km^3; Robinson and Eakins, 2006-this volume), relatively steep submarine slopes (10° to 15°), and rapid growth (~1 to 1.5 Ma; Guillou et al., 1997) of Hawaiian volcanoes cause them to become gravitationally unstable and collapse. These collapses have generated some of the largest landslides on Earth (Moore et al., 1994) and are thought to have produced colossal tsunami waves (>100 m; Satake et al., 2002). Dozens of giant

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landslides, some with deposits extending more than 200 km from their source and with volumes >1000 km^3, have been recognized along the Hawaiian Ridge (Moore et al., 1989, 1994). On average, the Hawaiian Ridge has major landslides every 32 km along its length, which indicates that a major landslide has occurred about every 350 ky (Moore et al., 1994). Hawai‘i has become the type example for this phenomenon. As detailed bathymetry and acoustic images have become available for the flanks and ocean floor around other ocean island volcanoes, large landslides have been recognized on many of these volcanoes (e.g., Reunion, Lenat et al., 1989; Canaries, Watts and Masson, 1995; Krastel et al., 2001). Thus, giant landslides are common feature of ocean island volcanoes and are an important global mass-wasting process. It has been argued that Hawaiian landslides are less frequent but larger in volume than those related to other oceanic islands (e.g., Gee et al., 2001; Krastel et al., 2001).

Here we present a summary of results for ODP Hole 1223A (for details see Shipboard Scientific Party, 2003), which was drilled ~260 km from the island of O‘ahu near the crest of the ~500-m-high Hawaiian Arch (Fig. 1). Drilling at this site was planned for

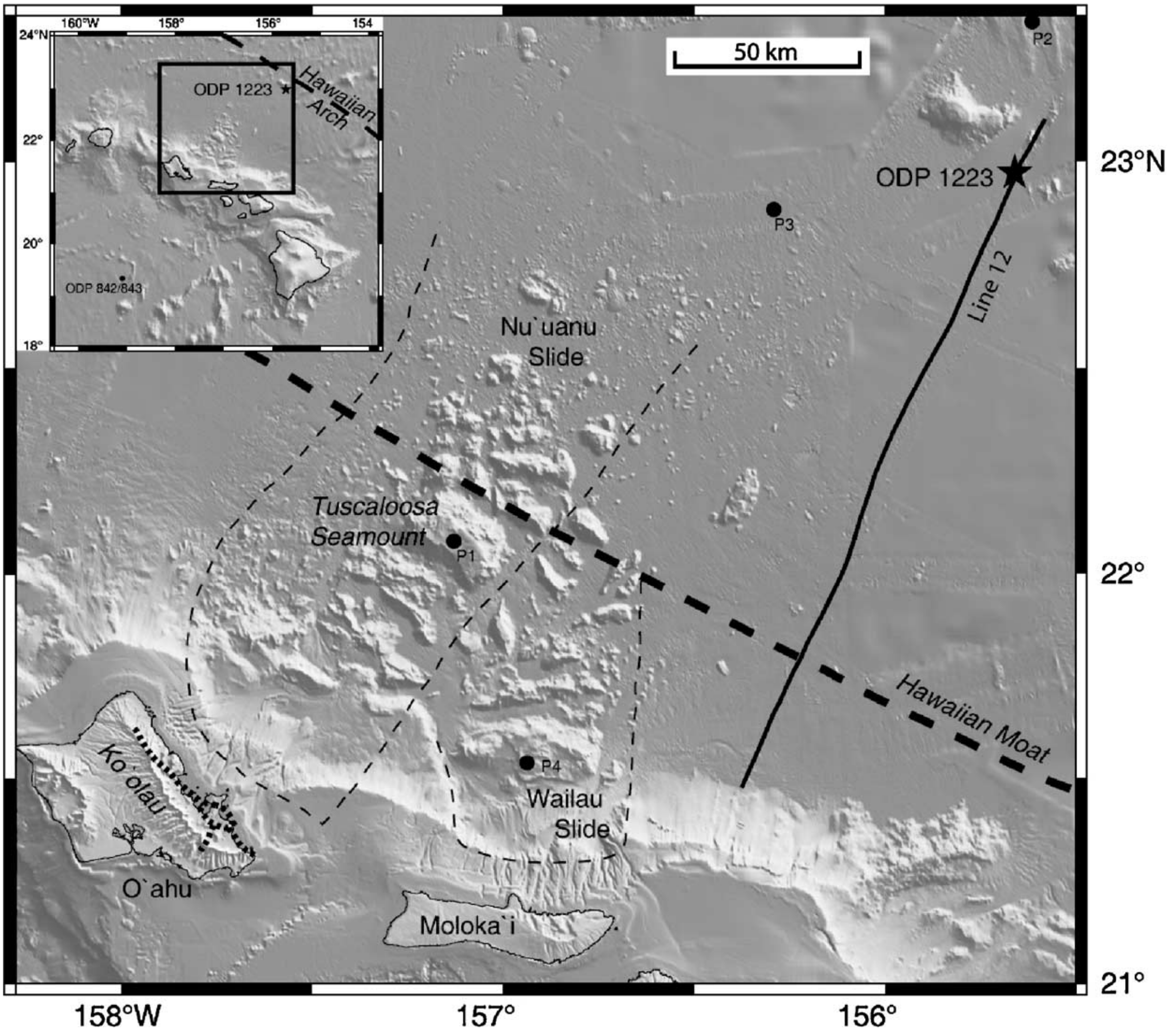

Fig. 1. Shaded relief map showing the location of ODP Site 1223, the islands of O‘ahu and Moloka‘i (outlined by thin black line), the debris fields for the giant Nu‘uanu and Wailau landslides from Ko‘olau and East Moloka‘i volcanoes (thin dashed lines show slide boundaries; Moore and Clague, 2002), the rift zone and caldera locations for Ko‘olau Volcano (heavy dashed lines; Wentworth and Winchell, 1947), the northern Hawaiian Moat, JAMSTEC piston core locations (P1 to P4; Naka et al., 2000), and the seismic line that transects Site 1223 (Fig. 3; Rees et al., 1993). The insert map shows the study area relative to the Hawaiian Islands, ODP Sites 842/843 and the northern Hawaiian Arch.

100 m to determine the depositional history, timing, thickness, and hazards associated with the Nuʻuanu landslide, one of the largest landslides on Earth (Moore et al., 1994). Drilling reached, however, a depth of only 41 m, encountering eight distinct sand layers that were probably associated with landslides of Hawaiian volcanoes. Debris from other landslides may be present at depth in this ~100 m thick, turbidite-rich section based on seismic reflection profiles (Rees et al., 1993). The distinctive Koʻolau high-SiO_2 glass composition in seven of the sands layers indicates that they were probably derived from that distant volcano. Any or none of the four thicker (>1.5 m) turbidite layers recovered in Hole 1223A could be related to the Nuʻuanu slide. The uppermost sand layer is probably related to neighboring East Molokaʻi volcano, which has also collapsed repeatedly (Sherman et al., 2002). The record of all but the last collapses from these two volcanoes is buried. If this history of repeated collapses of Koʻolau Volcano is typical of other Hawaiian volcanoes, then the hazards posed by these unstable islands is much greater than previously envisioned.

2. Geologic setting and previous work

The first geologists to visit Hawaiʻi interpreted the high cliffs along the coasts of some islands as the result of faulting (e.g., Dana, 1891). These cliffs were later reinterpreted as the headwalls of giant landslides (Stearns and Macdonald, 1946). The giant landslide hypothesis was supported by studies of the submarine flanks of Hawaiian volcanoes including the pioneering work of Moore (1964). Subsequent seismic studies of the seafloor around these volcanoes revealed extensive landslide deposits in the Hawaiian Moat and on the flanks of the Hawaiian Arch (e.g., Ten Brink and Watts, 1985). However, not until the 1986–1991 GLORIA surveys to explore the United States exclusive economic zone around the Hawaiian Islands was the extent of these landslides recognized (Moore et al., 1989).

Sand layers associated with turbidites from three major Hawaiian landslides were drilled in 1991 during ODP Leg 136 at two adjacent holes (842, 843) into the western Hawaiian Arch ~250 km southwest of the island of Oʻahu (Fig. 1 inset). The coherent Quaternary to Upper Eocene sediments drilled in these holes resulted in nearly 100% recovery to a depth of ~35 m (Dziewonski et al., 1992). The ages of these turbidites are well constrained by a combination of strong, coherent paleomagnetic signatures in the sediments and well-preserved radiolarians (Garcia and Hull, 1994). The younger sandy sediments (<3 Ma) in these holes contain fresh glass. The geochemistry of these glasses was used to infer the source volcanoes for these turbidites (Garcia, 1996).

The Nuʻuanu landslide originated on the northeast flank of Koʻolau Volcano removing ~2.4 to 3.0 × 10^3 km^3 of the island of Oʻahu (Satake et al., 2002; Robinson and Eakins, 2006-this volume). The debris avalanche associated with this slide had enormous blocks (e.g., Tuscaloosa Seamount is ~30 km long, 17 km wide and at least 2 km tall) that are spread over a wide area of the seafloor (Fig. 2). The Nuʻuanu debris field, and the one associated with the Wailau landslide from nearby East Molokaʻi volcano (Fig. 1) were targets for 1998 and 1999 Japan Agency for Marine-Earth Science and Technology (JAMSTEC) cruises (Naka et al., 2000). In addition to bathymetric surveys (Fig. 2), four piston cores (P1 to P4; Fig. 1), numerous dredge hauls, and several submersible dives were undertaken on the deposits from these landslides (see Takahashi et al., 2002). Only one of these piston cores (P3) is thought to have recovered sediments related to the Nuʻuanu slide (Sherman et al., 2002). However, the fine grain size in this ~1 m thick silty turbidite, led Sherman et al. (2002) to speculate it was related to a secondary collapse of debris from the Nuʻuanu slide. Nonetheless, it was concluded that the distal portions of the deposits related to the Nuʻuanu and Wailau landslides are relatively thin (<1 m; Naka et al., 2000; Sherman et al., 2002). In contrast, Rees et al. (1993) estimated the Nuʻuanu landslide deposits to be nearly 100 m thick near the crest of the Hawaiian Arch based on seismic profiles (Fig. 3). This ambiguity in the thickness of Nuʻuanu sedimentary deposits (<1 vs. ~100 m) creates a large uncertainty in estimates for the volume of the landslide.

Another uncertainty is the age of the Nuʻuanu landslide, which must be equal to or less than that of Koʻolau Volcano. Normark et al. (1993) inferred an age for the slide of 1.4 to 2.6 Ma based on 1.8 to 2.7 Ma K–Ar ages for Koʻolau lavas (McDougall, 1964; Doell and Dalrymple, 1973). However, many of the younger Koʻolau ages have very low K values indicating that these samples probably lost K during weathering (Haskins and Garcia, 2004). New K–Ar ages indicate the shield volcanism probably ended by 2.2 Ma (Ozawa et al., 2005) and new Ar–Ar ages extend the age of subaerial Koʻolau volcanism to at least 2.9 Ma (Haskins and Garcia, 2004). A younger age limit for the slide is older than the overlying Wailau slide deposit, estimated to be ~1.5 Ma (Clague et al., 2002; Sherman et al., 2002). Kanamatsu et al. (2002) used paleomagnetic data for three JAMSTEC piston cores,

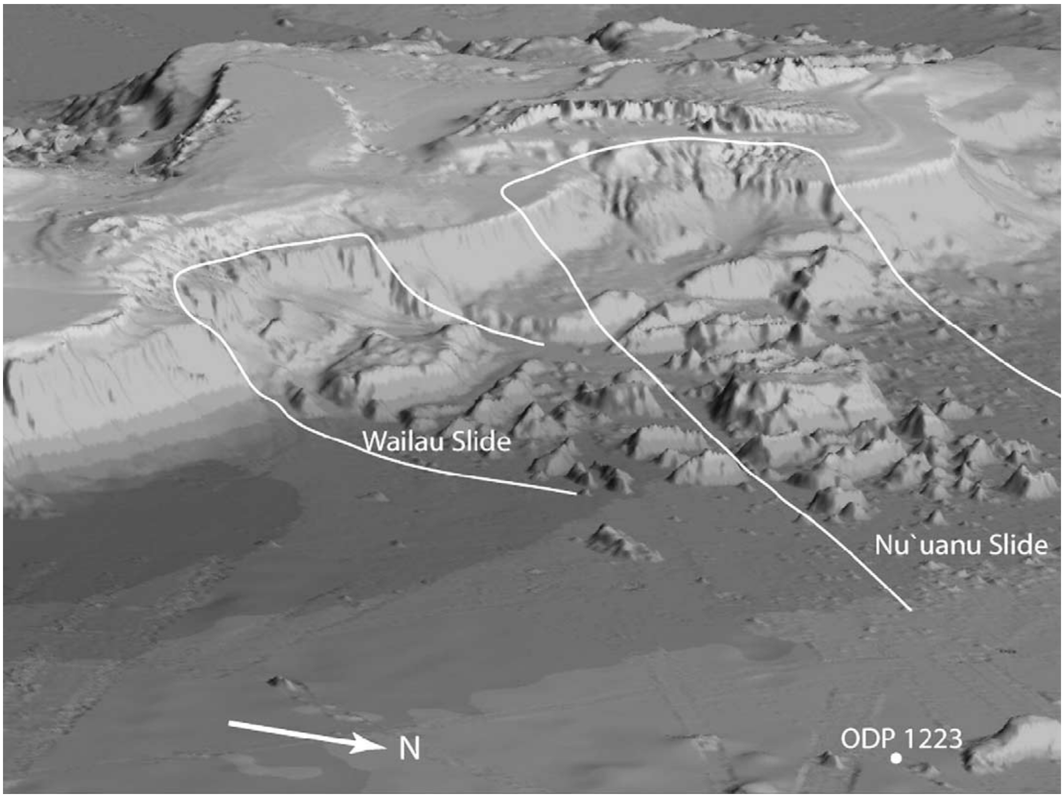

Fig. 2. Shaded relief map showing a three-dimensional perspective view of the Nuʻuanu and Wailau landslide debris (white lines are the boundaries of the debris fields; Moore and Clague, 2002). The slides were derived from the flanks of shield volcanoes on Oʻahu and Molokaʻi, respectively. The perspective looks southwest from near ODP Site 1223. Constructed from bathymetric data from Smith and Satake (2002) and Eakins et al. (2003). A north arrow is provided for reference.

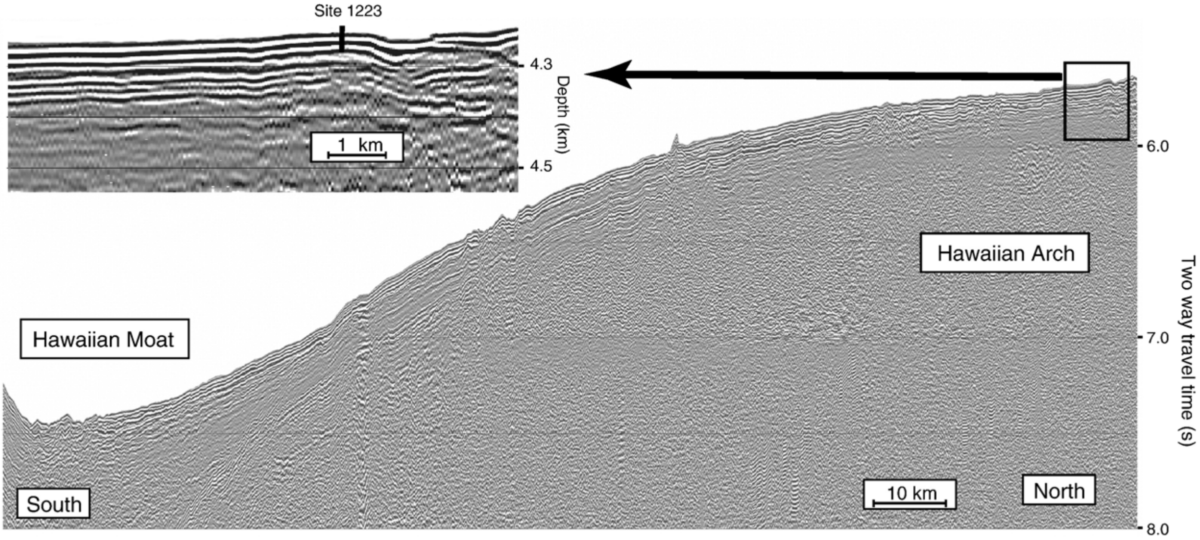

Fig. 3. Two-way travel time seismic reflection profile (in seconds) across the Hawaiian Moat and Arch. This profile is line 12 from Rees et al. (1993). See Fig. 1 for the location of the line. The inset is a depth-converted section of the seismic line that shows the location of ODP Site 1223. Note that there are at least 60 m of bedded sediments beneath the base of the drill hole.

and both constant- and variable-rate models for sedimentation to infer ages for the Nu‘uanu slide of >2.58 or >1.77 Ma, respectively. A new study of microfossils in a mantling deposit on top of a Nu‘uanu slide block suggests that the age of the slide is between 2.55 and 3.09 Ma (Morgan et al., 2006-this volume). Hole 1223A was designed to determine the thickness and age of the Nu‘uanu slide.

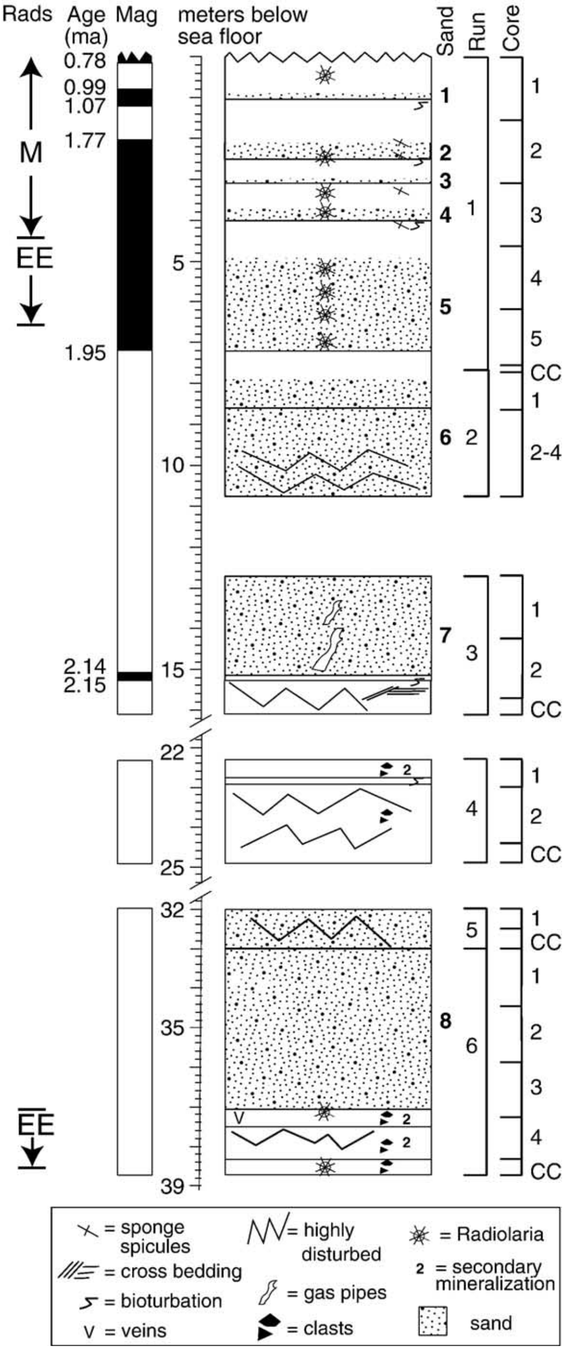

Fig. 4. Graphic log for ODP Hole 1223A. There are gaps in the section from 16 to 22 m below the sea floor (mbsf), and 25 to 32 mbsf. The mudline was missed in the first core (shown by the sawtooth pattern at the top of the section), so only lowermost part of the section deposited during the Brunhes chron was recovered. Prominent unconsolidated sand layers are numbered 1 to 6. They have sharp basal contacts and gradational upper contacts with pelagic clay. The upper and lower volcaniclastic sandstones are labeled 7 and 8. The Radiolaria (Rads) included mixed assemblages (Eocene and younger; M) and only Early Eocene (EE) taxa. The ages are based on the magnetic reversals. See the box for an explanation of the symbols used in the graphic log (modified after Shipboard Scientific Party, 2003).

3. Drill core results and analysis

3.1. Drilling operations

Hole 1223A was planned to piston core to a depth of ~100 m, which according to seismic interpretations (Rees et al., 1993) would penetrate the entire sedimentary sequence associated with the Nu‘uanu landslide (Fig. 3). Unfortunately, only a ~41-m hole could be drilled within the 42 hours allotted for this location because indurated sediments were encountered at a depth of 12.7 m. These hard rocks required switching from coring with the advanced piston core (APC) system to an extended core barrel (XCB) system. Drilling remained slow and recovery went from ~86% for the APC-cored section to 45% for the XCB-cored interval with major section gaps in Cores 3X and 4X (6–7 m; Shipboard Scientific Party, 2003). The mudline was missed at the start of the APC coring, so the top of the section is absent.

3.2. Core stratigraphy

Two basic lithologies were recovered at Site 1223: fine-grained sediments (clay and silt), and volcanic sand (Fig. 4). In the upper part of the hole (<12.7 m), the sediments are unconsolidated. In the deeper part of the hole the fine-grained sediments are weakly consolidated and the sands are indurated. The two indurated sand units were called tuffs by the Shipboard Scientific Party (2003). As discussed below, the heterogeneity of the glass composition and other features of these units led us to conclude they are volcaniclastic sandstones. Core 1H contains five prominent, dark-gray sand layers interbedded with yellowish-brown pelagic clay (Fig. 4). Core 2H contains disturbed sand under a thin brown clay layer. A volcaniclastic sandstone was encountered in Core 3X but its top contact was not recovered and at least 6 m of section are missing from this core run (Fig. 4). The sandstone overlies a bioturbated claystone and a volcaniclastic sandy siltstone with cross-bedding. In Core 4X, three claystone units with variable amounts of volcaniclastic silt were recovered, although recovery was also poor (~7 m of section missing; Fig. 4). The drill bit jammed during drilling for Core 5X and only about 1 m of weathered and disturbed material from the lower volcaniclastic sandstone was recovered. Core 6X contained about 4 m of a second volcaniclastic sandstone overlying about 2 m of volcaniclastic claystone and siltstone (Fig. 4).

The five sandy layers in Core 1H have sharp basal contacts and gradational upper contacts with the overlying yellowish-brown pelagic clays (Fig. 5). These sand layers range in thickness from 11 to 232 cm and are generally normally graded (Table 1). Three, very thin (<1 cm) sandy intervals occur just below layer 4 (Fig. 5). Sand layer 5 is internally complex with numerous thin (0.5 to 2 cm thick) light and dark bands of varying grain size and composition overlying a basal carbonate gravel. The basal contact of sand layer 5 has a rip-up of the underlying dark-brown clay. Sandy layer 6 in Core 2H is highly disturbed, with a poorly consolidated lower interval (Fig. 4).

Underlying these unconsolidated sand layers are two volcanic sandstones and several volcaniclastic claystone units (Shipboard Scientific Party, 2003). The thickness of the two sandstones is uncertain because of incomplete recovery. The top of the upper volcaniclastic sandstone unit was lost during APC drilling. The switch to XPC drilling allowed a 2.36-m-thick section of the upper

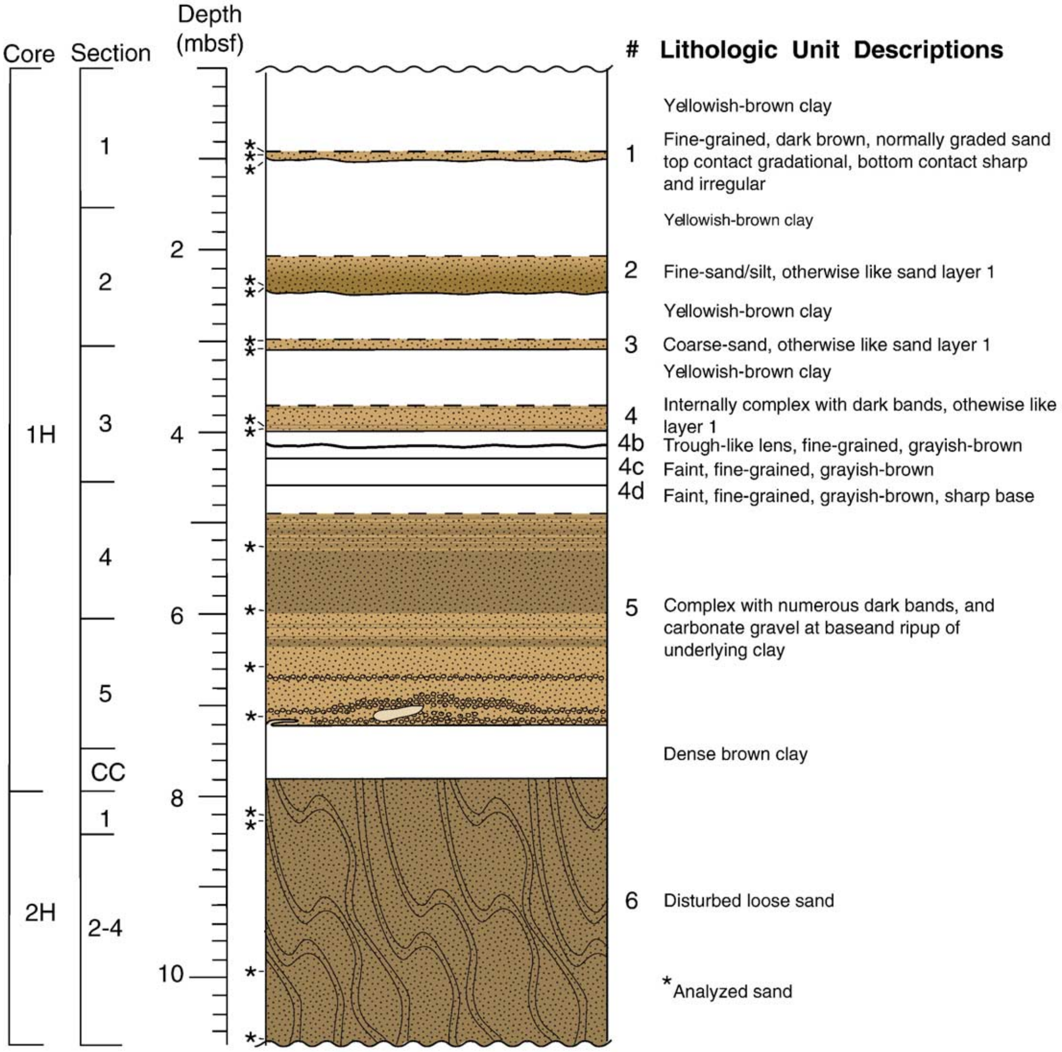

Fig. 5. Graphic log of the soft sediment section (cores 1 and 2) from ODP Hole 1223A showing sedimentary features and locations where sand samples were taken for petrography and microprobe analyses (*). Sand layers 1–5 have sharp basal contacts (layers 1, 2 and 5 have irregular, scoured contacts) and gradational upper contacts. Layer 5 also has carbonate gravel and rip-up structures at its base. Layers 1–3 are normally graded. Units 4 and 5 are internally complex with multiple light and dark bands ~1 cm thick. Layer 6 is internally disrupted. Gray intensity reflects color of sand.

Table 1
Sand layer characteristics for ODP Site 1223

Layer	Thick (cm)	Contacts		Size grading	Other	Depth (m)	Modes (volume %)						#
		upper	lower				lithics	vitric	glass	oliv	plag	pyx	
1	11	gradational	sharp	normal	finer sand	1.0	27	23	6	33	10	1	30
2	45	gradational	sharp	normal	coarser sand	2.4	15	15	40	23	7	<1	105
						2.5	30	10	32	17	7	4	
3	12	gradational	sharp	normal	finer sand	3.0	<1	<1	46	34	16	2	117
						3.1	1	<1	53	27	17	1	
4	28	gradational	sharp	normal	four dark bands	3.9	1	<1	33	41	26	–	77
						4.0	7	1	26	52	13	1	
5	232	gradational	sharp	normal	internally complex with 20 dark and 4 light bands; micrite pebbles and clay rip-ups at base	5.2	4	1	46	41	8	1	196
						7.2l	16	<1	24	46	11	2	
						7.2d	11	3	24	47	12	3	
6	>150	gradational	absent	none	coherent upper part, disturbed lower section	8.0	3	4	48	37	7	<1	147
						9.3	7	<1	63	22	6	<1	
7	>240	absent	sharp	normal	gas pipes in weakly altered upper sandstone	13.8	14	27	34	23	2	–	132
						14.9	26	20	31	19	2	2	
8	>500	absent	sharp	normal	highly (top) to moderately weathered (base)	33.7	4	19	56	19	2	–	32
						36.7	8	11	65	15	<1	–	

Petrography for sand- and silt-size components only based on at least 300–600 points/sample; layers 7 and 8 are 1000 points/sample with most (>90%) of their glass altered to palagonite (after Shipboard Scientific Party, 2003); #glasses analyzed by microprobe (summary given in Table 2); l- light-colored sand; d- dark-colored sand.

sandstone to be recovered. The sandstone is moderately indurated, matrix-supported, normally size-graded (medium to very coarse grained, maximum size of 2.2 mm, average ~1 mm), with angular to subrounded fragments of fresh glass (some with thin clay rims), minerals (mainly fresh olivine), and vitric and lithic clasts in a radiolarian-bearing brown clayey matrix. The sandstone also contains pipe-like voids that were interpreted as gas pipes by the Shipboard Scientific Party (2003). These voids are oriented in various directions including nearly horizontal and are coated with mud.

The lower volcaniclastic sandstone was encountered at ~32 m below seafloor (mbsf) in Core 5X (sandy unit 8 in Fig. 3). Its upper part is poorly consolidated and was highly disturbed by drilling. The lower part in Core 6X is well lithified. Overall, the lower sandstone is similar in character to the upper sandstone except for the more advanced stage of glass alteration, and the absence of pipe-like voids. In addition, the sediments just below the lower sandstone are reported to contain wairakite and some Radiolaria have been replaced by opal-CT (Shipboard Scientific Party, 2003). For additional core stratigraphy information, see the Shipboard Scientific Party (2003) descriptions.

3.3. Biostratigraphy

Biostratigraphic analyses were not conducted on the *JOIDES Resolution* during Leg 200, although the presence of Radiolaria and sponges were noted in Cores 1H and 6X (Shipboard Scientific Party, 2003). In order to more precisely determine the nature and distributions of the fossil assemblages in this hole, a total of 99 smear slides at approximately 10 cm intervals have been examined from the following intervals: Core 1H (79 slides from 0.08–7.81 mbsf); Core 3X, Section 2 (15.13–15.62 mbsf); Core 4X, Section 1(22.84–22.9 mbsf) and Core 6X, Sections 3-CC (37.03–38.64 mbsf). Significant numbers of Radiolaria in a state of preservation adequate for identification were observed only in Cores 1H and 6X. Other microfossils were too rare and too poorly preserved throughout these intervals to provide biostratigraphic control.

Radiolaria are intermittently rare to common, and moderate- to well-preserved in two intervals in Core 1H: 3.02-3.96 and 5.10–6.70 mbsf. The lower of these intervals occurs in the middle to upper portions of sand layer 5 (Figs. 4 and 5), where it is represented by an Early Eocene assemblage with good preservation and without observable contamination by older or younger faunas. The assemblage is characteristic of the *Buryella clinata* Zone, which is reported to range in age from 50.3 to 52.85 Ma by Sanfilippo and Nigrini (1998). The abrupt change in both the concentration and state of preservation of Radiolaria in this interval of Core 1H in contrast to the general condition in the upper sediment column is striking. This phenomenon can be explained by the differences in age and original depositional environments of the sediment. The sediments above sand layer 5 are generally barren of Radiolaria or contain only trace occurrences in states of degraded preservation. The exception is the yellowish-brown clay bed between sand layers 3 and 4, which contains intermittently common occurrences of Radiolaria in moderate preservation states. The radiolarian assemblage from this interval differs from the lower interval described above in that both Eocene and Pliocene taxa are present. Forty of the 54 Eocene species identified in sand layer 5 also occur in Section 3, and the ages of the two Eocene faunas are believed to be the same. Additionally, 32 taxa are present that have stratigraphic ranges restricted to the Neogene (Popova-Goll and Goll, in press). The presence of *Eucyrtidium matuyamai* at 3.15 mbsf indicates an assignment to the *E. matuyamai* Zone of Hays (1970), which occurs in magnetochrons C2n–C1r2r and has an age range of 1.95 to 1.05 Ma according to Morley and Nigrini (1995; time scale revised to Cande and Kent, 1995). These authors also reported a last occurrence age of 1.79 Ma for *Lamprocyrtis heteroporus*, which is also present in this fauna.

Radiolaria are generally common in the volcaniclastic silty claystone and clayey siltstone underlying sand layer 8 of Core 6X at 37.03–38.64 mbsf. The state of preservation of this assemblage indicates that the original glassy skeletal composition has been replaced by opal-CT. Only six taxa have been identified from this interval, but the presence of *B. clinata* is taken as strong evidence that this fauna has the same age as that of the lower radiolarian-bearing interval of Core 1H.

Fossils preserved in sediments interpreted as having been displaced by turbidity currents can provide information only for the age of the sediment entrained by the displacement event, although they provide a maximum age for the redistribution event itself. Thus, the Neogene radiolarian fauna present in the sediments between 3.02 and 3.96 mbsf indicate that the turbidites of sand beds 1–3 were emplaced after 1.79–1.95 Ma. In contrast, the pure Early Eocene radiolarian fauna of sand bed 5 does not significantly constrain the age of transport of this unit, although it sheds some light on the origin of the fine-grained sediments entrained in this turbidite complex.

3.4. Magnetostratigraphy

The magnetostratigraphy for Hole 1223A was determined from paleomagnetic measurements made every 1 cm along the archive-half core sections and on 25 discrete samples (~1–7 cm^3) collected from the working-half core sections (Shipboard Scientific Party, 2003). Hole 1223A cores appear to record all the major chrons and subchrons from Chron C1n (the Brunhes Chron; 0.0–0.78 Ma) into Chron 2r (1.95–2.581 Ma). The Brunhes normal polarity interval spans only the top 14 cm of Core 200-1223A-1H, which is thinner than expected by ~1 m based on prior piston coring in the vicinity (Kanamatsu et al., 2002). It seems probable that the upper meter or so of the sedimentary section was not recovered, but there was insufficient time during Leg 200 to core a second hole and test this interpretation. The termination and onset of Chron 1r.1n (the Jaramillo Subchron; 0.99–1.07 Ma) are located at 0.80 and 1.23 mbsf, respectively and the termination and onset of Chron C2n (the Olduvai Chron; 1.77–1.95 Ma) are located at 2.02 and 7.19 mbsf, respectively.

The section recovered below 7.19 mbsf is interpreted to be entirely reversed polarity, although some intervals are ambiguous because the magnetic overprint related to drilling (e.g., Acton et al., 2002) could not be completely removed by magnetic cleaning. Throughout this lower interval, the paleomagnetic inclinations were either negative after magnetic cleaning, which is indicative of reversed polarity, or migrated from the steep positive inclinations related to the drilling overprint to shallow inclinations before becoming unstable or too weak to measure. The latter is also indicative that the underlying primary magnetization is reversed polarity, but is not fully isolated by magnetic cleaning. If some intervals below 7.19 mbsf were normal polarity, we would have expected the inclination to migrate from steep positive values to moderate positive values (~40°) as AF or thermal magnetic cleaning progressed. Because coring gaps of several meters are present below Core 1H and hiatuses in the section are likely given the nature of the erosional and depositional processes associated with turbidites, some polarity intervals may not have been recovered or are missing. Radiometric dates on glass taken from the unconsolidated sand from Core 2H and from the upper vitric tuff in Core 3X give ages ranging from 2.5 to 4 Ma (G. Acton, unpublished data), suggesting that these units were deposited since 4 Ma. The simplest interpretation is that the interval below 7.19 mbsf was deposited within Chron C2r (1.95–2.581 Ma), although the data are consistent with deposition in a reversed polarity interval as old as Chron C2Ar (3.58–4.18 Ma).

3.5. Petrography

Sand layers from Hole 1223A contain abundant basalt detritus including fresh glass, olivine, and plagioclase fragments. At least two polished thin sections were made from each sand layer (Fig. 5) to determine their petrography and glass chemistry. For unconsolidated sediments from sand layers 1–6, sections were made of only the sand- and silt-size fractions. The rock fragments in these sand layers are cryptocrystalline (vitric) to microcrystalline (lithic) and typically contain plagioclase, magnetite, olivine and pyroxene. The glass fragments are mostly light brown in color, translucent (sideromelane), and crystal-free, although some glasses contain olivine or plagioclase crystals or are darker brown in color. Single grains of unaltered olivine, plagioclase and more rarely pyroxene are present and are generally about the same size as the rock fragments. Individual sand grains range in size from 0.05 to 0.2 mm, with most 0.1–0.2 mm in diameter giving the sand layers a well sorted character. The sand grains are angular with blocky to flaky shapes. Some rock and glass fragments in all layers are partially altered to clay.

Three hundred point count modes were made of the Hole 1223A unconsolidated sands and 1000 point counts were made on the two volcaniclastic sandstones for two samples for each layer except the thin uppermost sand layer. These modes show a wide range in the components between the sand layers (Table 1). The amounts of glass (or its alteration products) range from 6 to 65 vol.%, rock fragments (lithic and vitric: 1–50 vol.%), olivine (15–52 vol.%), plagioclase (<1–26 vol.%), pyroxene (0–4 vol.%), magnetite (<1 vol.%), with very rare fossils ($\ll 1\%$). Vesicles in the rock and glass grains are rare (<1 vol.%). Sand layer 1 is distinct from the other sand layers with its abundant rock fragments and sparse glass (Table 1). The other sand layers have abundant glass (or their alteration products). Layers 3, 4 and 6 are noteworthy for their relatively sparse rock fragments (total lithics and vitric grains <10 vol.%). The only consistent trends in clast type within individual sand layers are increasing lithics and decreasing vitrics with depth (Table 1). The light and dark intervals in sand layer 5 are surprisingly similar petrographically. The indurated volcaniclastic sandstones are petrographically similar to unconsolidated sand layers except for their more advanced stages of alteration and lithification, and the presence of zeolites in voids and rare chlorite grains ($<1\%$).

3.6. Glass major element and S compositions

The composition of the glass sands from Hole 1223A was determined by microprobe using methods described by Sherman et al. (2002). The 838 glass sands that were analyzed are all tholeiitic and typical of Hawaiian shield volcanoes (Table 2). The compositional fields for each layer overlap significantly at 6–8 wt.% MgO (Fig. 6), the common range for Hawaiian tholeiitic glasses (e.g., Clague et al., 1995; Davis et al., 2003). However, the compositional range at any level of fractionation (e.g., 7 wt.% MgO content) is greater than generally observed for individual Hawaiian shield volcanoes (e.g., 49–55 vs. 51–53 wt.% SiO_2). Hawaiian volcanoes typically have limited subaerial exposures of stratigraphic sections (<500 m) compared to the sizes of landslide scars on these volcanoes (e.g., 1.6 km for the Ka Lae landslide on Mauna Loa; Garcia et al., 1995). Three glasses with unusually high MgO (up to 12.3 wt.%) were found in layer 2 (Fig. 6). These values are indicative of relatively primitive magma compositions (e.g., Clague et al., 1991) and high quenching temperatures (~1295°C) based on the geothermometer of Montierth et al. (1995), which is appropriate for these bulk compositions. A few glasses from layers 2 and 3 have high SiO_2 (up to 69 wt.%), which are extremely rare in Hawai‘i (e.g., Wright and Fiske, 1971). CaO contents also range widely (2–12 wt.%; Fig. 6), although Al_2O_3 shows much less variation (12–16 wt.%; Table 2), suggesting that clinopyroxene fractionation is more important than plagioclase in the strongly evolved glasses.

Sulfur contents were measured in the Site 1223A glasses to determine their depth of eruption based on the pioneering work of Moore and Fabbi (1971) and subsequent studies (e.g., Swanson and Fabbi, 1973; Garcia et al., 1989; Moore and Clague, 1992; Davis et al., 2003). These studies found that undegassed Hawaiian tholeiitic magmas typically have S contents >0.09 wt.% compared to <0.03 wt.% S for subaerially erupted lavas. The vast majority of the Site 1223A glass sands ($>90\%$) have low S contents (>0.03 wt.%; Fig. 7) indicating that they were erupted subaerially.

3.7. Mineral compositions

Microprobe analyses were made of minerals from some of the sand layers from Hole 1223A, especially layers 1 and 6, to characterize their compositions. The methods used are the same as for the glasses, except a focused beam was employed. Olivine sand compositions range widely from forsterite 89 to 80 (Table 3), which is typical of Hawaiian tholeiitic lavas (Clague et al., 1995; Garcia, 1996) including those from Ko‘olau Volcano (Garcia, 2002). The CaO contents of layer 6 olivines (0.24–0.27 wt.%) overlap those of typical Ko‘olau olivines (0.17–0.27 wt.%; Garcia, 2002), although layer 1 olivine CaO contents are somewhat higher (0.26–0.30 wt.%; Table 3). Likewise, compositions of clinopyroxene sands from Hole 1223A are typical of Hawaiian tholeiites (e.g., Fodor et al., 1975; Clague et al., 1995; Garcia et al., 2000), although rare differentiated compositions (e.g., pyroxene end members; enstatite 33.6%,

Table 2
Representative microprobe glass analyses of Site 1223 sands. Depth in meters

Layer	Depth	SiO_2	TiO_2	Al_2O_3	FeO	MnO	MgO	CaO	Na_2O	K_2O	P_2O_5	S	Sum
1	0.9	49.69	2.88	13.22	11.77	0.16	8.15	12.03	1.75	0.37	0.23	0.059	100.31
1	0.9	50.27	2.72	13.62	10.67	0.16	7.06	11.97	2.15	0.26	0.22	0.001	99.09
1	0.9	52.29	3.60	12.76	15.43	0.21	5.24	5.73	3.07	0.54	0.36	0.004	99.25
2	2.4	49.22	2.03	12.04	11.60	0.17	12.13	10.20	1.81	0.24	0.14	0.052	99.63
2	2.4	53.66	1.72	14.39	9.29	0.12	7.03	10.01	2.56	0.22	0.16	0.011	99.18
2	2.4	51.03	3.26	13.64	11.47	0.15	5.63	9.90	2.73	0.54	0.38	0.146	98.88
2	2.5	49.50	2.26	13.04	10.93	0.16	9.00	11.60	2.04	0.26	0.15	0.118	99.06
2	2.5	53.76	2.17	13.45	9.26	0.17	6.89	10.08	2.65	0.33	0.21	0.018	98.98
2	2.5	60.74	1.73	15.12	6.54	0.10	3.00	5.86	3.49	3.16	0.24	0.007	99.98
3	3.0	51.51	2.19	13.76	10.17	0.13	8.26	10.54	2.38	0.44	0.20	0.002	99.56
3	3.0	54.30	2.02	14.62	8.80	0.12	6.91	10.32	2.63	0.37	0.16	0.001	100.24
3	3.0	57.42	1.57	15.32	7.25	0.12	4.27	7.85	3.09	1.91	0.16	0.000	98.95
3	3.1	50.77	2.18	13.22	10.97	0.17	8.48	10.84	1.99	0.24	0.16	0.065	99.09
3	3.1	53.52	2.09	14.07	9.46	0.12	7.45	10.17	2.49	0.31	0.16	0.016	99.87
3	3.1	57.93	1.52	15.06	7.47	0.10	4.72	8.05	3.03	1.82	0.17	0.000	99.89
3	3.1	69.02	0.50	14.05	2.66	0.04	0.90	2.13	3.50	4.74	0.10	0.000	97.65
4	3.9	50.30	2.24	13.25	10.88	0.12	8.32	11.22	2.03	0.26	0.12	0.064	98.81
4	3.9	53.58	2.02	14.44	9.45	0.13	7.02	10.42	2.57	0.35	0.23	0.005	100.22
5	5.2	52.00	2.23	13.73	10.35	0.16	7.57	10.63	2.39	0.36	0.27	0.007	99.70
5	5.2	53.97	2.38	15.02	9.47	0.14	6.06	8.72	3.11	0.57	0.23	0.005	99.66
5	5.2	54.18	2.63	14.83	10.24	0.07	5.42	7.34	3.29	0.67	0.27	0.008	98.95
5	5.9	51.02	2.18	13.06	10.64	0.16	9.47	10.29	2.10	0.46	0.19	0.033	99.61
5	5.9	50.82	2.47	13.85	10.81	0.17	7.53	10.98	2.21	0.33	0.25	0.000	99.41
5	5.9	53.39	2.28	14.23	9.23	0.14	6.83	10.71	2.43	0.36	0.18	0.000	99.78
6	8.0	52.14	2.30	13.51	9.93	0.16	8.08	10.41	2.38	0.39	0.23	0.004	99.54
6	8.0	54.03	1.82	14.42	9.93	0.14	6.55	10.15	2.62	0.29	0.17	0.010	100.13
6	8.0	54.31	2.56	15.05	10.42	0.14	5.44	7.57	3.24	0.72	0.28	0.001	99.74
6	8.1	49.42	2.17	12.31	11.63	0.18	10.96	10.00	2.00	0.36	0.21	0.039	99.30
6	8.1	53.77	1.94	14.04	9.63	0.19	7.05	10.02	2.44	0.29	0.16	0.012	99.54
6	8.1	51.32	2.91	13.11	12.20	0.15	6.02	10.52	2.41	0.47	0.22	0.013	99.35
6	9.3	51.33	2.43	14.07	10.15	0.13	7.44	11.50	2.25	0.37	0.21	0.000	99.89
6	9.3	53.90	2.08	14.27	8.99	0.12	7.15	10.45	2.51	0.26	0.19	0.027	99.95
6	9.3	53.90	2.84	15.39	10.34	0.12	5.59	7.45	3.21	0.66	0.33	0.014	99.85
6	10.3	52.34	2.34	13.90	10.41	0.13	7.94	10.06	2.46	0.39	0.21	0.001	100.18
6	10.3	53.95	2.10	14.49	9.14	0.13	6.79	10.28	2.60	0.39	0.24	0.016	100.13
6	10.3	60.24	1.60	15.41	6.73	0.08	3.73	6.59	3.77	2.35	0.16	0.002	100.66
7	13.1	54.14	2.10	14.22	10.13	–	6.44	10.29	2.66	0.28	0.21	0.004	100.48
7	13.8	53.40	2.55	15.09	8.78	–	5.36	12.04	1.92	0.01	0.26	0.010	99.42
7	14.9	52.42	2.16	14.00	10.14	–	6.89	10.64	2.47	0.41	–	0.017	99.15
8	34.6	51.66	2.53	14.47	9.78	0.15	7.26	11.47	2.53	0.34	0.27	–	100.46
8	34.6	52.29	2.72	14.00	9.66	0.16	6.80	11.10	2.72	0.43	0.27	–	100.15
8	34.6	52.25	3.50	13.78	10.64	0.13	5.18	9.04	3.07	0.83	0.47	–	98.89

wollastonite <40%) do occur. Compositions of plagioclase sands also range widely (anorthite 48–80), although most are in the range of anorthite 60–75 (Table 3) typical of Hawaiian tholeiitic lavas (e.g., Clague et al., 1995).

4. Discussion

4.1. Mechanism of deposition and source of Hole 1223A sand layers

Early studies of the sediment on the abyssal plains around the Hawaiian Islands recognized the importance of sand in these deposits (e.g., Menard, 1964; Moore, 1964; Horn et al., 1969; Schreiber, 1969). Sands of probable Hawaiian origin have been found more than a 1000 km from the Islands (e.g., Rehm and Halbach, 1982). The discovery of numerous sand layers in core from Hole 1223, >220 km from the nearest island (Moloka‘i) and near the crest of the ~500 m high Hawaiian Arch was unexpected and presents several challenges. Various mechanisms have been proposed for transporting sands long distances from their presumed Hawaiian Island source including wind (Rehm and Halbach, 1982) and turbidity currents (e.g., Moore, 1964; Schreiber, 1969). The low vesicularity of glass

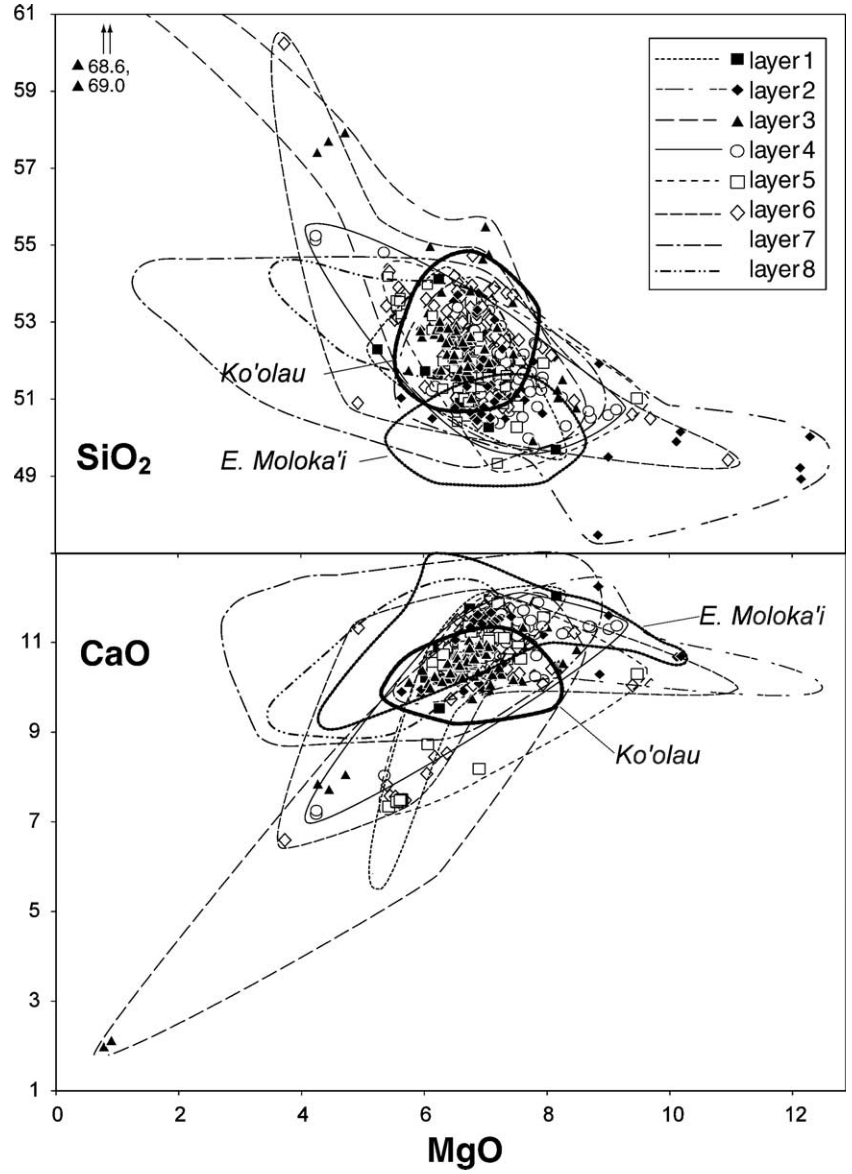

Fig. 6. MgO vs. SiO_2 and CaO variation diagrams for glass sands from layers 1–8 of ODP Hole 1223A. All values are in weight %. Note the wide but overlapping variations for the compositions of each layer. Only fields are given for layers 7 and 8. The wide compositional variations indicate that large sections of the volcano were sampled by these sand layers. Most of the glasses from sand layers 2–8 have compositions similar to Koʻolau Volcano, whereas most glasses from layer 1 are similar to East Molokaʻi volcano. Fields for Koʻolau are from Haskins and Garcia (2004); the East Molokaʻi fields are from Sherman et al. (2002).

sand in sediment around the Hawaiian Islands (Garcia, 1996; Sherman et al., 2002), and the location of some sites upwind and long distances from the islands (e.g., Site 1223; Fig. 1) makes it unlikely that the glasses are of explosive, windblown origin or were derived by fragmentation during eruption into shallow water (e.g., Carey et al., 1994).

The Hawaiian Moat was thought to present an insurmountable barrier for turbidity currents (Schreiber, 1969). Subsequent lab experiments and theoretical studies demonstrated that it is possible for turbidity currents to climb up and over ridges of significant height (~1000 m; Muck and Underwood, 1990). The viability of this hypothesis is supported by several field studies (e.g., Dolan et al., 1989; Garcia and Hull, 1994; Sherman et al., 2002) showing that sand has been transported up and over major bathymetric highs (≥500 m).

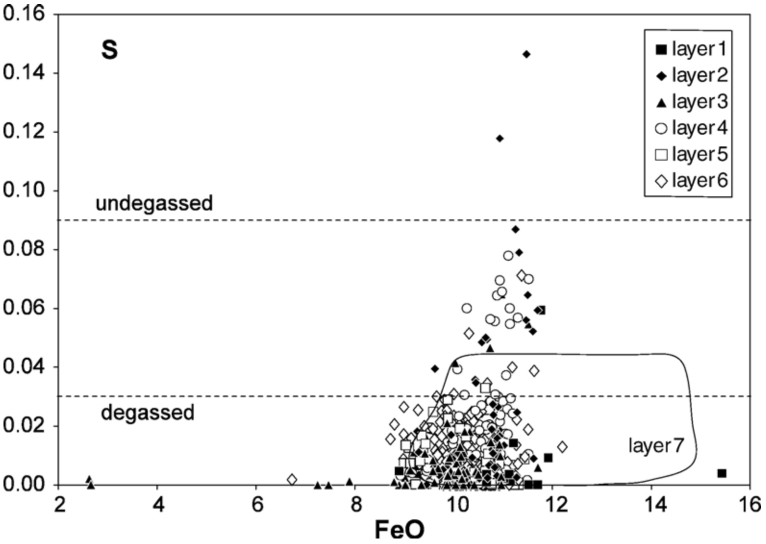

Fig. 7. S vs. FeO variation diagram for glasses from ODP Hole 1223 sand layers 1–7. All values are in weight %. Only a field is shown for layer 7 and no S data are available for sand layer 8. The vast majority of the glasses from sand layers 1–7 are degassed (<0.03 wt. S; Moore and Fabbi, 1971). Field boundary for undegassed glasses is from Garcia and Hull (1994).

Several factors suggest landslides as a likely source for the sands in Hole 1223A. The composition of the glass sands indicate that the Hawaiian Islands, more than 220 km away, are their probably source (Fig. 6) and that the eruptions were probably subaerial to account for the low S content in the glasses (Fig. 7). The abundance of glass and its angular shape in the Hole 1223A sand layers is analogous to the volcaniclastic deposits found in the upper 1 km of the submarine section of Hawaiian volcanoes (Bridges, 2004). Unlike some of the individual units in these deposits (Bridges, 2004), the Hole 1223A sands have a remarkable range in composition (Fig. 6); thus, they are not related to individual eruptions (e.g., Kīlauea, 1983 to present; Garcia, 1996). Indeed, the extreme range of SiO_2 and MgO in these glasses (Fig. 6) compared to surface lavas on typical Hawaiian volcanoes (e.g., Wright and Fiske, 1971; Frey et al., 1994; Garcia et al., 1995), argues that a major section of the volcano has been sampled. The mixed age assemblages and anomalous old Radiolaria in the Hole 1223A sediments indicates that sediments of various ages have been combined, perhaps as the result of scouring by debris avalanches associated with a major landslide. Although a 500-m high barrier stands over 200 km away from the source for the sands, this barrier probably acts as a filter allowing only energetic currents, such as those related to major landslides, to deposit sand at Site 1223.

One surprising feature of the Hole 1223A cores is the indurated nature of the volcaniclastic sandstone units at 12.7 mbsf, whereas coring just above this interval recovered loose sand. In addition, the identification of wairakite in the siltstone below the lower sandstone, and the presence of “gas pipes” in the upper volcaniclastic sandstone led to the suggestion that the sandstones were deposited hot (or at least warm) following two collapses and eruptions of Ko‘olau Volcano, similar in nature to the 1980 Mt. St. Helens eruption (Shipboard Scientific Party, 2003). To test this hypothesis, we examined thin sections near the base of the unit and just below it for evidence of thermal metamorphism. None was found. The glasses and clays in these areas showed the same petrographic features as the rest of the unit and the other sand layers. Likewise, the ranges of glass compositions in the sandstones are similar to those for the unconsolidated sand layers suggesting no dominant composition, as would be expected from an eruption (e.g., Garcia, 1996). An examination of the pipes in the upper sandstone showed they have variable orientations (horizontal to vertical), rather than being preferentially oriented vertical from the escape of hot gases. Also, there were no vapor deposits lining the pipes. Thus, it is likely that these pipes formed from the escape of water within the upper sandstone units during deposition from a turbidity current. The induration of the sandstones may be related to clay formation as observed in the Hawaiian Scientific Drilling Project core (DePaolo et al., 2001). However, the abrupt change below 12.7 m in level of sediment solidification is striking and may indicate a time break in the section related to scouring by sand layer 6. Also, the replacement of opal-A in the radiolarian tests with opal-CT (cristobalite) below the lower indurated volcaniclas-

Table 3
Microprobe analyses of minerals in Site 1223 sand layers. Fo—forsterite; En—enstatite; Wo—wollastonite, An—anorthite

Layer	Depth	SiO_2	TiO_2	Al_2O_3	FeO	MnO	MgO	CaO	Na_2O	K_2O	Sum	Fo
Olivine (cm)												
1	93	40.60	0.06	0.05	14.57	0.20	45.05	0.26	0.00	0.00	100.78	84.6
1	93	38.07	0.00	0.03	19.11	0.22	42.31	0.30	0.00	0.00	100.04	79.8
1	93	39.33	0.02	0.05	17.99	0.23	41.84	0.33	0.00	0.01	99.80	80.6
5	678	39.59	0.03	0.04	17.70	0.23	41.94	0.30	0.00	0.00	99.84	80.8
5	717	40.45	0.00	0.05	12.75	0.15	45.65	0.21	0.02	0.01	99.27	86.2
6	800	40.50	0.02	0.03	13.23	0.16	45.73	0.26	0.00	0.00	99.93	86.0
6	800	39.80	0.00	0.00	15.44	0.21	43.85	0.24	0.00	0.01	99.55	83.5
6	800	39.71	0.06	0.00	16.53	0.24	42.92	0.25	0.00	0.00	99.71	82.2
6	815	40.04	0.02	0.03	15.96	0.24	43.50	0.27	0.03	0.00	100.08	82.9
6	1027	41.41	0.02	0.02	10.22	0.13	48.14	0.24	0.00	0.00	100.18	89.4
6	1027	40.72	0.05	0.02	15.36	0.16	43.64	0.25	0.02	0.00	100.21	83.5
8	3420	39.35	–	–	16.63	0.24	43.89	0.27	–	–	100.38	85.5
8	3420	38.95	–	–	17.38	0.24	43.14	0.31	–	–	100.02	81.6
Clinopyroxene										Sum	En	Wo
1	93	51.90	1.03	2.31	12.45	0.26	17.83	14.66	0.15	100.58	50.4	29.8
1	93	49.23	1.85	3.47	10.14	0.18	14.16	20.47	0.30	99.79	41.0	42.6
1	93	50.24	1.37	7.64	9.39	0.19	11.42	18.36	1.26	99.87	38.2	44.2
1	105	53.05	0.61	1.81	7.35	0.16	17.29	19.33	0.20	99.81	49.0	39.4
1	105	52.17	0.73	2.54	5.56	0.12	16.95	21.29	0.22	99.59	47.9	43.3
1	105	51.01	1.25	4.03	7.71	0.18	16.89	18.32	0.19	99.57	49.1	38.3
1	105	52.29	0.83	1.74	11.26	0.18	14.69	18.80	0.22	100.00	42.5	39.2
1	105	51.61	1.49	6.23	10.39	0.18	9.67	18.45	1.74	99.77	33.6	46.1
4	393	51.47	1.01	2.72	10.05	0.24	17.75	16.98	0.19	100.41	49.9	34.3
6	800	51.67	1.05	3.11	8.55	0.19	16.59	18.22	0.19	99.56	48.1	38.0
Plagioclase											Sum	An
1	93	48.18	0.03	31.93	0.83	0.00	0.18	16.60	2.27	0.07	100.10	79.8
1	93	50.57	0.10	29.24	0.74	0.00	0.20	15.98	2.81	0.06	99.70	75.6
1	93	53.15	0.11	28.48	0.70	0.05	0.19	12.66	4.23	0.33	99.91	61.2
1	105	48.71	0.02	31.08	0.52	0.01	0.17	16.75	2.18	0.07	99.52	80.6
1	105	50.23	0.06	30.16	0.72	0.00	0.20	15.67	2.74	0.08	99.84	75.6
1	105	50.81	0.07	29.85	0.46	0.00	0.00	14.73	3.37	0.18	99.47	70.0
1	105	51.61	0.04	29.64	0.69	0.00	0.04	13.81	3.69	0.23	99.74	66.6
1	105	54.55	0.17	27.32	0.53	0.01	0.13	12.39	4.64	0.22	99.94	58.9
1	105	55.59	0.16	26.57	0.88	0.00	0.20	11.03	5.01	0.27	99.70	54.1
1	105	56.50	0.13	26.32	0.54	0.00	0.02	9.98	5.68	0.54	99.71	47.8
2	253	51.63	0.11	29.45	0.59	0.02	0.26	14.26	3.58	0.09	100.00	68.4
2	253	52.34	0.18	28.78	0.80	0.02	0.32	13.75	3.81	0.12	100.12	66.1
6	800	53.92	0.05	28.13	0.59	0.01	0.15	13.11	4.20	0.18	100.34	62.6
6	800	53.92	0.05	27.55	0.59	0.01	0.15	13.11	4.20	0.18	99.75	62.6

tic sandstone may require elevated temperatures (~50 °C; Behl and Garrison, 1994). The Shipboard Scientific Party (2003) speculated that a widespread blanket of hot material provided a compressive load and an impermeable barrier to fluids, which may have lead to the induration of these layers.

Glass composition is a potential tool for determining the source of the sands from Hole 1223A. It has been used in numerous studies to fingerprint the sediment source for submarine deposits (e.g., Carey and Sigurdsson, 1978; Garcia, 1996; Sumita and Schmincke, 1998). The geochemistry of lavas from Koʻolau Volcano on the island of Oʻahu is especially distinctive with their relatively high SiO_2 (e.g., Frey et al., 1994; Sherman et al., 2002). However, a 679-m deep drill hole into Koʻolau found that beneath an ~250-m-thick carapace, the lavas and glasses have lower SiO_2 lavas (Haskins and Garcia, 2004), although most are compositionally distinct from those of neighboring East Molokaʻi volcano (Fig. 6). If a major landslide occurred on the flanks of heterogeneous Koʻolau Volcano, sampling many hundreds of its thin lavas (average thickness ~2 m; Wentworth and Winchell, 1947; Frey et al., 1994), a wide compositional range with high SiO_2 glasses would be expected. Indeed, Hole

1223A glass sands have a remarkably large compositional range (Table 2). Many of the glasses have relatively high SiO_2 contents (>53 wt.%; Fig. 6) and most are higher in SiO_2 than glasses from the other likely source of sand for Hole 1223, East Moloka‘i (49–52 wt.%; Sherman et al., 2002). Also, most glasses from Hole 1223A have relatively low FeO and CaO contents (Table 2), which are typical of Ko‘olau glasses (Sherman et al., 2002; Haskins and Garcia, 2004). Overall, most of the glass sands have compositions, including the distinctive high SiO_2-type consistent with a Ko‘olau origin for all sand layers with the exception of layer 1.

Glasses from layer 1 have lower SiO_2 (all but 2 of the 30 glasses analyzed have <52 wt.%) and their average CaO (Fig. 6) and FeO contents are higher than in the other layers (Table 2). Layer 1 glasses are similar in composition to those reported from the ~60 cm thick sand layer in JAMSTEC piston core P3 taken ~60 km west of Site 1223, which was interpreted to have originated from East Moloka‘i volcano (Sherman et al., 2002). Also, the olivines from layer 1 have higher CaO contents than Ko‘olau olivines (ave. 0.32 vs. 0.22 wt.% at forsterite 81; Garcia, 2002). Thus, the sands in the relatively thin (11 cm) layer 1 probably originated from East Moloka‘i volcano, although they are not related to the ~1.5 Ma Wailau landslide (Sherman et al., 2002; Clague et al., 2002) based on the ~1.0 Ma age for this deposit inferred from paleomagnetic data (Fig. 4). However, results from JAMSTEC piston core P4 near the island of Moloka‘i show that island has repeatedly collapsed (22 volcaniclastic layers; Sherman et al., 2002) since the Wailau slide, so layer 1 in Hole 1223A may be related to one of these younger collapses.

Degassed lavas can travel considerable distances down the submarine flank of Hawaiian volcanoes (at least 10 km; Garcia and Davis, 2001) and even erupt on the submarine flanks of Hawaiian volcanoes at depths of ~1 km (Davis et al., 2003; Wanless et al., 2006-this volume). The low S content (>0.03 wt.%) of over 90% of the Hole 1223A glasses (Fig. 7) and the high glass content of the sands (Table 1) indicates that many of the lavas forming the sands were probably subaerially erupted but quenched rapidly in the ocean. Thus, the landslides that produced these sands probably originated on the shallow submarine flanks of Ko‘olau and East Moloka‘i volcanoes.

4.2. Sedimentation rates north of the Hawaiian Islands

A wide range of sedimentation rates have been estimated for the seafloor in the vicinity of the Hawaiian Islands (<1 to 17.7 m/my; e.g., Siebold and Berger, 1996; Kanamatsu et al., 2002). Paleomagnetic data for Hole 1223A can and has been used to infer the sedimentation rates, although some assumptions are needed. For example, if sedimentation was constant for the entire section, the uppermost normal polarity interval is the Brunhes chron (most of this part of the section was missed in coring), and the rest of the section (0.2–38.7 mbsf) was deposited during the Matuyama reverse polarity chron (0.78–2.58 Ma; Shipboard Scientific Party, 2003), then an overall rate of 21.4 m/my is obtained. This is at least 10 times the estimated sedimentation rates for red clays in the central North Pacific (15–25°N, which vary from 1.3 to 2.1 m/my; Opdyke and Foster, 1970; Berger, 1973). After subdividing the section into subchrons, sedimentation rates of 0.2 to 60 m/my were estimated by the Shipboard Scientific Party (2003). The highest rates (28.7–60.0 m/my) are for sections with major gaps in core recovery (Fig. 4). Removing these intervals from the section leaves rates of 0.2–5.5 m/my for Core 1H, which had continuous recovery beneath the truncated Brunhes chron (Shipboard Scientific Party, 2003). These rates are similar to those estimated for the same time period for the turbidite-bearing JAMSTEC piston cores in the vicinity of Site 1223A (2.7–3.8 m/my; Kanamatsu et al., 2002) and those from ODP Holes 842 and 843 on the opposite side of the Hawaiian Islands on the crest of the southern Hawaiian Arch (~7 m/my; Helsley, 1993), based on paleomagnetic data and a constant deposition model. These relatively high sedimentation rates, compared to North Pacific red clay rates, have been related to the proximity of these sites to the Hawaiian Islands (e.g., Helsley, 1993). However, these estimates include sand layers that were rapidly deposited (e.g., sand layers comprise ~52% of the recovered core in Hole 1223A). Thus, we calculated sedimentation rates by removing the sand layers from Core 1H for the period 0.78 to 1.95 Ma. This yields a sedimentation rate of 3.2 m/my, still somewhat higher than the estimates of sedimentation rates for the Pacific sea floor outboard of the Hawaiian Arch. Although our estimate ignores the effects of scouring by the sand layers and does not consider the effects of bioturbation (which appear to be minor in Core 1H except just below the sand layers; Fig. 4), it still indicates that the contribution of fine sediment to the ocean floor 260 km from the Hawaiian Islands is significant, comparable to the pelagic sedimentation rate.

4.3. Implications of sand layers for landslide history of Ko‘olau Volcano

The original goal of this study was to document and understand the processes associated with the Nu‘uanu landslide. Based on the results from the distal JAMSTEC piston coring (P2 and P3), we expected to encounter two sand layers at Site 1223: an upper layer from the East Moloka‘i volcano's Wailau landslide and a lower layer from the Ko‘olau Volcano's Nu‘uanu landslide. Thus, it was surprising to recover eight distinct layers more than 10 cm thick in Hole 1223A (Table 1). Sand layer 1, unlike the other sand layers, has geochemical similarities to East Moloka‘i glasses. All the other layers appear to be of the appropriate age (1.8–2.58 Ma vs. 2.2–2.9 Ma for subaerial Ko‘olau lavas) and composition (Fig. 6) to have been derived from Ko‘olau Volcano. Among the thicker layers (>1.5 m), layer 5 is especially attractive as a potential Nu‘uanu landslide product given its basal carbonate gravel and rip up structures, and its complex internal structure of numerous light and dark sediment bands. However, the two indurated sandstones and the unconsolidated layer 6 are also viable candidates. Unfortunately, these other sandy layers were incompletely recovered, so the details of their internal features are unknown. Thus, we are left with no compelling reason to prefer one sand layer as the product of the Nu‘uanu slide over another. Furthermore, seismic results indicate that Site 1223A is underlain by ~100 m thick sedimentary section (Fig. 3), so coring at this site may not have encountered the deposits from the Nu‘uanu slide. However, we concur with Sherman et al. (2002) that the thin silt layer in JAMSTEC piston core P3 is probably not a direct deposit of the Nu‘uanu slide.

Previously, it was assumed that the mapped surface deposits around the Hawaiian Islands revealed their landslide history and that the slide frequency was much lower than for the Canary Islands (e.g., every 350 ky vs. 50 to 75 ky; Moore et al., 1994; Gee et al., 2001). This observation was at odds with the much higher eruption rate and size of Hawaiian volcanoes, so it was suggested that the higher volatile content of Canary Archipelago magmas created more volcaniclastic deposits on these islands making them less stable (Krastel et al., 2001). Deep drilling (3 km) into a Hawaiian volcano has shown that they also contain abundant volcaniclastics in their submarine sections (~55%; Bridges, 2004), so this is not a factor. The recognition of numerous sand-rich layers (four >1.5 m thick) with diverse glass compositions at Site 1223A demonstrates that Ko‘olau Volcano had produced at least four major and three other significant landslides during a period of ~0.7 million yrs. Thus, major landslides on Hawaiian volcanoes are more common than previously assumed.

It is known that landslides can occur at any time in the history of a Hawaiian volcano, from the preshield stage (e.g., Lō‘ihi) to well after it has ceased erupting (Moore et al., 1989). However, the largest slides are anticipated during the final stages of shield development when the volcano has reached its peak size (Moore et al., 1989). The partial filling of the scar on the flanks of Ko‘olau Volcano, in contrast to the obvious gap on the north flank of East Moloka‘i volcano (Fig. 1), suggests that all of the collapses of Ko‘olau Volcano occurred during its growth stage (2.2 Ma to at least 2.9 Ma). This interpretation is consistent with the ages for the Site 1223 unconsolidated sand layers inferred from paleomagnetic data (1.77 to 2.58 Ma; Fig. 4). The sandstones may be from the same age range or the next oldest reversely magnetized period, 3.58–4.18 Ma. The gaps in section do not allow us to assign a specific age for these units.

Lastly, it should be emphasized that more sand layers from other landslides, including possibly the Nu‘uanu slide, probably lie at depth at this site (Fig. 3). Deeper drilling is needed to more fully evaluate the history of Hawaiian landslides including their distribution and volumes. However, existing data indicate that large landslides are common (~100,000 yrs) on some Hawaiian volcanoes. Dividing this estimate by the number of active or recently active subaerial Hawaiian volcanoes (5) indicates that landslides are an important geologic hazard in the Pacific basin, especially considering the number of young volcanic islands in this region.

5. Conclusions

The discovery of eight sand layers from ODP Hole 1223A has important implications for the mass wasting history of typical Hawaiian volcanoes. The geochemistry of the glasses and minerals in the sand layers indicate that all but the youngest layer was derived from Ko‘olau Volcano. The wide diversity of glass compositions implies that a major section of the volcano was sampled by each layer. It is unclear which, if any, of these layers is related to the Nu‘uanu slide. The geochemistry of the relatively thin (11 cm) sand layer 1 is similar to East Moloka‘i and the glass sands in its ~1.5 Ma giant Wailau slide. However, the inferred age for layer 1 (~1.0 Ma) makes it too young to be related to that slide. Radiolarian tests from several intervals in the cores yield ages ranging from Quaternary to Early Eocene indicating that the turbidity currents that deposited the sands eroded older sediments around the Hawaiian Islands. All of the landslides must have been of significant size to have generated turbidity currents that ran out more than 220 km, crossing the Hawaiian Moat and scaling the ~500 m high Hawaiian Arch to reach Site 1223. The four older and thicker sand layers (>150 cm) are probably related to giant landslides (e.g., Moore et al., 1994) from Koʻolau Volcano. The ages for two of these landslides are between 1.77 and 2.58 Ma based on paleomagnetic results. The two reversely magnetized volcaniclastic sandstones may have been deposited sometime from 1.95–2.58 Ma or 3.58–4.18 Ma. Gaps in the section prevent us from assigning a more specific age.

One alarming discovery from the Hole 1223A drilling results is that Hawaiian volcanoes can undergo repeated major collapses. If Koʻolau Volcano, a moderate size volcano is typical of other Hawaiian volcanoes, then the frequency of landslides is much greater than previously assumed (one major landslide every 350 ky somewhere along the Hawaiian ridge). Koʻolau Volcano alone produced at least four major and three other slides during a period of ~0.7 million yrs. The still growing Mauna Loa volcano on the island of Hawaiʻi has experienced at least one major landslide and repeated smaller collapses in the last few hundred thousand years. Thus, although more coring is needed to confirm the extrapolation of the Hole 1223A results to other Hawaiian volcanoes, existing data argue that large landslides are a common occurrence (~100 ka). Dividing this estimate by the number of active or recently active subaerial volcanoes (5) indicates that landslides on oceanic islands are an important geologic hazard.

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References

Acton, G.D., Okada, M., Clement, B.M., Lund, S.P., Williams, T., 2002. Paleomagnetic overprints in ocean sediment cores and their relationship to shear deformation caused by piston coring. J. Geophys. Res. 107. doi:10.1029/2001JB000518.

Behl, R.J., Garrison, R.E., 1994. The origin of chert in the Monterrey Formation of California. Proc. 29th Intern. Geol. Cong. Part C, pp. 101–132.

Berger, W.H., 1973. Cenozoic sedimentation in the eastern tropical Pacific. Geol. Soc. Am. Bull. 84, 1941–1954.

Bridges, K.P., 2004. Submarine growth of a Hawaiian shield volcano based on volcaniclastics in the Hawaiian Scientific Drilling Project 2 core. MS Thesis, Univ. Hawaiʻi, 176 pp.

Cande, S.C., Kent, D.V., 1995. Revised calibration of the geomagnetic polarity time scale for the Late Cretaceous and Cenozoic. J. Geophys. Res. 100, 6093–6095.

Carey, S., Sigurdsson, H., 1978. Deep-sea evidence for distribution of tephra from the mixed magma eruption of the Soufiere of St. Vincent, 1902: ash turbidites and air fall. Geology 6, 271–274.

Carey, S., Maria, T., Cornell, W., 1994. Processes of volcaniclastic sedimentation during the early growth stages of Gran Canaria based on sediments from Site 953. In: Weaver, P.P.E., Schmincke, H.-U., Firth, J.V., Duffield, W.A. (Eds.), Proc. ODP Sci. Results Leg 157. Ocean Drilling Program, College Station TX, pp. 183–197.

Clague, D.A., Weber, W.S., Dixon, J.E., 1991. Picritic glasses from Hawaii. Nature 353, 553–556.

Clague, D.A., Moore, J.G., Dixon, J.E., Friesen, W.B., 1995. Petrology of submarine lavas from Kilauea's Puna Ridge, Hawaii. J. Petrol. 36, 299–349.

Clague, D.A., Moore, J.G., Davis, A.S., 2002. Volcanic breccia and hyaloclastite in blocks from the Nuuanu and Wailau landslides, Hawaii. In: Takahashi, E., Lipman, P.W., Garcia, M.O., Naka, J., Aramaki, S. (Eds.), Hawaiian Volcanoes: Deep Underwater Perspectives. Am. Geophys. Union Geophys. Monogr. 128, 279–296.

Dana, J.D., 1891. Characteristics of Volcanoes. Dodd and Co., New York, 399 pp.

Davis, M.G., Garcia, M.O., Wallace, P., 2003. Volatiles in Mauna Loa glasses: implications for magma degassing and contamination, and growth of Hawaiian volcanoes. Contrib. Mineral. Petrol. 144, 570–591.

DePaolo, D.J., Stolper, E., Thomas, D.T., 2001. Deep drilling into a Hawaiian volcano. EOS, Trans. Am. Geophys. Union, vol. 82, pp. 149–155.

Doell, R.R., Dalrymple, G.B., 1973. Potassium–argon ages and paleomagnetism of the Waianae and Koʻolau Volcanic Series, Oʻahu, Hawaii. Geol. Soc. Am. Bull. 84, 1217–1242.

Dolan, J.E., Beck, C., Ogawa, Y., 1989. Upslope deposition of extremely distal turbidites: an example from the Tiburon Rise, west-central Atlantic. Geology 17, 990–994.

Dziewonski, A., Wilkens, R., Firth, J., et al., 1992. Proc. ODP., Init. Repts. Leg 136. Ocean Drilling Program, College Station, TX. 99 pp.

Eakins, B.W., Robinson, J.E., Kanamatsu, T., Naka, J., Smith, J.R., Takahashi, E., Clague, D.A., 2003. Hawaii's volcanoes revealed. U.S. Geol. Surv. Geol. Invest. Series I-2809.

Fodor, R.V., Keil, K., Bunch, T.E., 1975. Contributions to the mineral chemistry of Hawaiian rocks. Contrib. Mineral. Petrol. 50, 173–175.

Frey, F., Garcia, M.O., Roden, M., 1994. Geochemical characteristics of Koʻolau Volcano: Implication of intershield geochemical differences among Hawaiian volcanoes. Geochim. Cosmochim. Acta 58, 1441–1462.

Garcia, M.O., 1996. Turbidites from slope failure on Hawaiian volcanoes. Geol. Soc. London, Spec. Publ. 110, 281–294.

Garcia, M.O., 2002. Submarine picritic basalts from Koʻolau Volcano, Hawaii: Implications for parental magma composition and mantle source. In: Takahashi, E., Lipman, P.W., Garcia, M.O., Naka, J., Aramaki, S. (Eds.), Hawaiian Volcanoes: Deep Underwater Perspectives. Am. Geophys. Union Geophys. Monogr. 28, 391–401.

Garcia, M.O., Davis, M.G., 2001. Submarine growth and internal structure of ocean island volcanoes based on submarine observations of Mauna Loa volcano, Hawaii. Geology 29, 163–166.

Garcia, M.O., Hull, D., 1994. Turbidites from giant Hawaiian landslides: results from Ocean Drilling Program Site 842. Geology 22, 159–162.

Garcia, M.O., Muenow, D.W., Aggrey, K., O'Neil, J., 1989. Major element, volatile and stable isotope geochemistry of Hawaiian submarine tholeiitic glasses. J. Geophys. Res. 94, 10,525–10,538.

Garcia, M.O., Hulsebosch, T., Rhodes, J.M., 1995. Olivine-rich submarine basalts from the southwest rift zone of Mauna Loa Volcano: implications for magmatic processes and geochemical evolution. In: Rhodes, J.M., Lockwood, J.P. (Eds.), Mauna Loa Revealed: Structure, Composition, History and Hazards. Am. Geophys. Union Geophys. Monogr. 92, 219–239.

Garcia, M.O., Pietruszka, A.J., Rhodes, J.M., Swanson, K., 2000. Magmatic processes during the prolonged Puu Oo eruption of Kilauea Volcano, Hawaii. J. Petrol. 41, 967–990.

Gee, M.J.R., Watts, A.B., Masson, D.G., Mitchell, N.C., 2001. Landslides and the evolution of El Hierro in the Canary Islands. Mar. Geol. 177, 271–293.

Guillou, H., Garcia, M.O., Turpin, L., 1997. Unspiked K–Ar dating of young volcanic rocks from the Loihi and Pitcairn seamounts. J. Volcanol. Geotherm. Res. 78, 239–250.

Haskins, E.H., Garcia, M.O., 2004. Scientific drilling reveals geochemical heterogeneity within the Koʻolau Shield, Hawaiʻi. Contrib. Mineral. Petrol. 147, 162–188.

Hays, J.D., 1970. Stratigraphy and evolutionary trends of Radiolaria in North Pacific deep-sea sediments. In: Hays, J.D. (Ed.), Geological Investigations of the North Pacific. Geol. Soc. Am. Mem. 126, 185–218.

Helsley, C.E., 1993. Paleomagnetic results from Leg 136. In: Wilkens, R.H., Firth, J., Bender, J., et al.,Proc. ODP Init. Repts., vol. 136. Ocean Drilling Program, College Station TX, pp. 45–50.

Horn, D.R., Delach, M.N., Horn, B.M., 1969. Distribution of volcanic ash layers and turbidites in the North Pacific. Geol. Soc. Am. Bull. 80, 1715–1724.

Kanamatsu, T., Herrero-Bervera, E., McMurtry, G.M., 2002. Magnetostratigraphy of deep-sea sediments from areas adjacent to the Hawaiian Islands: implications for ages of turbidites derived from submarine landslides. In: Takahashi, E., Lipman, P.W., Garcia, M.O., Naka, J., Aramaki, S. (Eds.), Hawaiian Volcanoes: Deep Underwater Perspectives. Am. Geophys. Union Geophys. Monogr. 128, 51–63.

Krastel, S., Schmincke, H.-U., Jacobs, C.L., Rihm, R., Le Bas, T.P., Alibes, B., 2001. Submarine landslides around the Canary Islands. J. Geophys. Res. 106, 3977–3997.

Lenat, J.-F., Vincent, P., Bachelaery, P., 1989. The offshore continuation of an active basaltic volcano: Piton de la Fournaise. J. Volcanol. Geotherm. Res. 36, 1–36.

McDougall, I., 1964. Potassium–argon ages from lavas of the Hawaiian Islands. Geol. Soc. Am. Bull. 75, 107–128.

Menard, H.W., 1964. Marine Geology of the Pacific. McGraw-Hill, New York, 271 pp.

Montierth, C., Johnston, D.A., Cashman, K.V., 1995. A glass geothermometer for Mauna Loa lavas. In: Rhodes, J.M., Lockwood, J.P. (Eds.), Mauna Loa Revealed: Structure, Composition, History and Hazards. Am. Geophys. Union Geophys. Monogr. 92, 207–217.

Moore, J.G., 1964. Giant submarine landslides on the Hawaiian Ridge. U. S. Geol. Surv. Prof. Pap. 501-D, D95–D98.

Moore, J.G., Clague, D.A., 1992. Volcano growth and evolution of the island of Hawaiʻi. Geol. Soc. Am. Bull. 104, 1471–1484.

Moore, J.G., Clague, D.A., 2002. Mapping the Nuʻuanu and Wailau landslides in Hawaii. In: Takahashi, E., Lipman, P.W., Garcia, M.O., Naka, J., Aramaki, S. (Eds.), Hawaiian Volcanoes: Deep Underwater Perspectives. Am. Geophys. Union Geophys. Monogr. 128, 233–244.

Moore, J.G., Fabbi, B.P., 1971. An estimate of the juvenile sulfur content of basalt. Contrib. Mineral. Petrol. 33, 118–127.

Moore, J.G., Clague, D.A., Holcomb, R.T., Lipman, P.W., Normark, W.R., Torresan, M.E., 1989. Prodigious submarine landslides on the Hawaiian Ridge. J. Geophys. Res. 94, 17,465–17,484.

Moore, J.G., Normark, W.R., Holcomb, R.T., 1994. Giant Hawaiian landslides. Annu. Rev. Earth Planet. Sci. 22, 119–144.

Morley, J.J., Nigrini, C., 1995. Miocene to Pleistocene radiolarian biostratigraphy of north Pacific Sites 881, 885, 886, 887. In: Rea, D.K., et al. (Eds.), Proc. Ocean Drilling Program, Sci. Res. 145, 55–91.

Morgan, J.K., Resig, J.M., Siesser, W.G., 2006. Microfossil assemblages on Tuscaloosa seamount and their constraints on the age of Nu?uanu landslide, north of O?ahu, HI. J. Volcanol. Geotherm. Res. 151, 269–278. doi:10.1016/j.volgeores.2005.07.031.

Muck, M.T., Underwood, M.B., 1990. Upslope flow of turbidity currents: a comparison among field observations, theory, and laboratory models. Geology 18, 54–57.

Naka, J., Takahashi, E., Clague, D., (with 30 coauthors), 2000. Tectono-magmatic processes investigated at deep-water flanks of Hawaiian volcanoes. EOS, Trans. Am. Geophys. Union vol. 81, pp. 227–230.

Normark, W.R., Moore, J.G., Torresan, M.E., 1993. Giant volcano-related landslides and the development of the Hawaiian Islands. U.S. Geol. Surv. Bull. 2002, 184–196.

Opdyke, N.D., Foster, J.H., 1970. Paleomagnetism of cores from the North Pacific. Geol. Soc. Am. Mem. 126, 83–95.

Ozawa, A., Tagami, T., Garcia, M.O., 2005. Unspiked K–Ar ages of Honolulu rejuvenated and Koʻolau shield volcanism on Oʻahu, Hawaii. Earth Planet. Sci. Lett. 232, 1–11.

Popova-Goll, I.M., Goll, R.M. in press. Radiolarian biostratigraphy of ODP Hole 1223A. In: Stephen, et al., (Eds.), Proc. ODP 200, Sci. Res., College Station TX (Ocean Drilling Program).

Rees, B.A., Detrick, R.S., Coakley, B.J., 1993. Seismic stratigraphy of the Hawaiian flexural moat. Geol. Soc. Am. Bull. 105, 189–205.

Rehm, E., Halbach, P., 1982. Hawaiian-derived volcanic ash layers in equatorial northeastern Pacific sediments. Mar. Geol. 50, 25–40.

Robinson, J.E., Eakins, B.W., 2006. Calculated volumes of individual shield volcanoes at the young end of the Hawaiian Ridge. J. Volcanol. Geotherm. Res. 151, 309–317. doi:10.1016/j.volgeores.2005.07.033.

Sanfilippo, A., Nigrini, C., 1998. Code numbers for Cenozoic low latitude radiolarian bistratigraphic zones and GPTS conversion tables. Mar. Micropaleontol. 33, 109–156.

Satake, K., Smith, J.R., Shinozaki, K., 2002. Volume estimate and tsunami modeling for the Nu‘uanu and Wailau landslides. In: Takahashi, E., Lipman, P.W., Garcia, M.O., Naka, J., Aramaki, S. (Eds.), Hawaiian Volcanoes: Deep Underwater Perspectives. Am. Geophys. Union Geophys. Monogr. 128, 333–348.

Schreiber, B.C., 1969. New evidence concerning the age of the Hawaiian Ridge. Geol. Soc. Am. Bull. 80, 2601–2604.

Seibold, E., Berger, W.H., 1996. The Sea Floor—An Introduction to Marine Geology. Springer-Verlag, Berlin, 219 pp.

Sherman, S.B., Garcia, M.O., Takahashi, E., 2002. Geochemistry of volcanic glasses from piston cores taken north of O‘ahu and Moloka‘i islands, Hawaii. In: Takahashi, E., Lipman, P.W., Garcia, M.O., Naka, J., Aramaki, S. (Eds.), Hawaiian Volcanoes: Deep Underwater Perspectives. Am. Geophys. Union Geophys. Monogr. 128, 263–277.

Shipboard Scientific Party, 2003. Leg 200 summary. In: Stephen, R.A., Kasahara, J., Acton, G.D. et al., (Eds.), Proc. ODP, Init. Repts., vol. 200. Ocean Drilling Program, College Station TX. 72 pp.

Smith, J.R., Satake, K., 2002. Multibeam bathymetry and sidescan data of the Hawaiian islands, 1998–1999 (explanation of accompanying CD-ROM). In: Takahashi, E., Lipman, P.W., Garcia, M.O., Naka, J., Aramaki, S. (Eds.), Hawaiian Volcanoes: Deep Underwater Perspectives. Am. Geophys. Union Geophys. Monogr. 128, 3–9.

Stearns, H., Macdonald, G.A., 1946. Geology and groundwater resources of Hawaii. Hawaii Div. Hydrography, Bull. 9, 363 pp.

Stephen, R.A., Kasahara, J., Acton, G.D., et al., 2003. Proc. ODP, Init. Repts., 200 [CD-ROM]. Available from: Ocean Drilling Program, Texas A&M University, College Station, TX 77845-9547, USA.

Sumita, M., Schmincke, H.-U., 1998. Tephra event stratigraphy and emplacement of volcaniclasitic sediments, Mogan and Fataga stratigraphic intervals. In: Weaver, P.P.E., Schmincke, H.-U., Firth, J.V., Duffield, W.Proc. ODP Sci. Res., 157. Ocean Drilling Program, College Station TX, pp. 219–265.

Swanson, D.A., Fabbi, B.P., 1973. Loss of volatiles during fountaining and flowage of basaltic lava at Kilauea Volcano, Hawaii. U.S. Geol. Surv. J. Res. 1, 649–658.

Takahashi, E., Lipman, P.W., Garcia, M.O., Naka, J., Aramaki, S. (Eds.), 2002. Hawaiian Volcanoes: Deep Underwater Perspectives, Am. Geophys. Union Geophys. Monogr., vol. 128, 418 pp.

ten Brink, U.S., Watts, A.B., 1985. Seismic stratigraphy of the flexural moat flanking the Hawaiian Islands. Nature 317, 421–424.

Wanless, V.D., Garcia, M.O., Rhodes, J.M., Weis, D., Norman, M., 2006. Alkalic lavas from Mauna Loa volcano, Hawaii. J. Volcanol. Geotherm. Res. 151, 141–155. doi:10.1016/j.volgeores.2005.07.027.

Watts, A.B., Masson, D.G., 1995. A giant landslide on the north flank of Tenerife, Canary Islands. J. Geophys. Res. 100, 24,487–24,498.

Wentworth, C.K., Winchell, H., 1947. Ko‘olau basalt series, O‘ahu, Hawaii. Geol. Soc. Am. Bull. 58, 49–77.

Wright, T.L., Fiske, R.S., 1971. Origin of the differentiated and hybrid lavas of Kilauea volcano, Hawaii. J. Petrol. 12, 1–65.