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Geo-Engineering Earthquake Reconnaissance (GEER) Association

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GEOLOGICAL ENGINEERING RECONNAISSANCE OF DAMAGE RESULTING FROM THE OCTOBER 15, 2006 EARTHQUAKES, ISLAND OF HAWAII, HAWAII, USA

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1. INTRODUCTION

Two strong earthquakes shook the Island of Hawaii, Hawaii on the morning of October 15, 2006. A geological engineering reconnaissance of earthquake damage resulting from the earthquakes was performed by Dr. Edmund Medley, PE, CEG (Geosyntec Consultants, Oakland) between Friday October 20 2006 and Monday October 23 2006 (Locations as shown on Figure 1). The principal focus of the geological engineering reconnaissance was to document the apparent relationships between the observed geology and the earthquake damage.

The geological engineering reconnaissance was performed after briefings with GEER team members Professor Peter Nicholson, PE (University of Hawaii at Manoa, Honolulu) and Mr. Gary Chock, PE, (Martin Chock Associates, Honolulu) who had already completed their reconnaissances. The contents of this report augment the contributions of Robertson et al (2006) and Chock (2006).

Most paved highways on the Island were traveled at least once during the reconnaissance (Figure 1). About 40 stops were made for more detailed observations (Figure 1). Some 800 photographs were taken with a digital camera, and relevant geometries and site conditions noted. The latitude and longitude coordinates of each stop were recorded using a hand-held Garmin *GPSMap76CS* receiver. Table 1 lists the locations of the stops, their co-ordinates, and other information.

Most of the photographs were taken in stereo (two photographs taken with considerable overlap similar to air photos) to facilitate later analysis and exposition in 3-Dimensions using the software *Pokescope*™. The Appendix provides example stereo images as side-by-side stereographs, requiring stereo glasses such as those used for air photo analysis, and anaglyphs, requiring red/blue glasses[1].

Several locations known to have been damaged by the earthquakes (e.g. Waimea area dams and the Palolo Valley Lookout) were not visited due to a lack of formal permissions. However, entry was granted by the National Park Service to observe the perimeters of the badly damaged stacked rock edifices of the Pu’ukoholā and Mailekini heiaus, located immediately south of Kawaihae.

[1] Red/blue glasses can be obtained via: http://www.3dstereo.com/viewmaster/gla.html

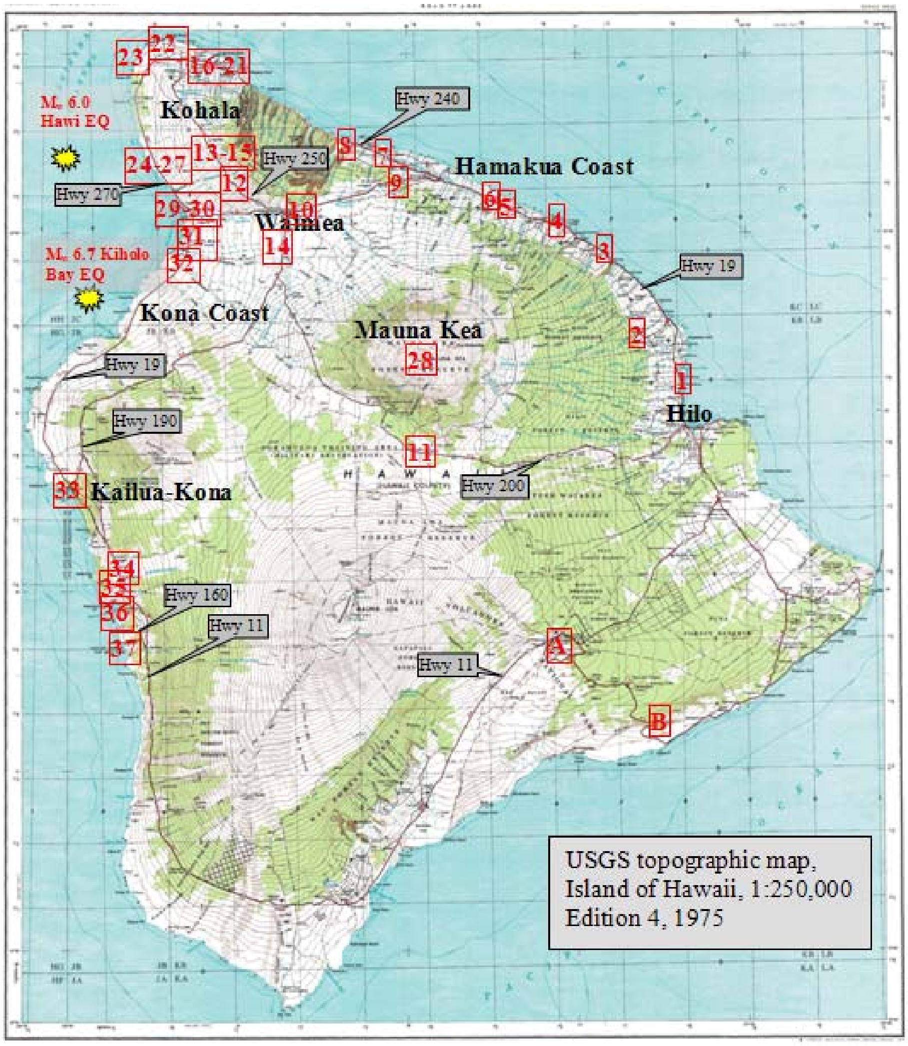

Figure 1: Locations of M6.7 Kiholo Bay and M6.0 Hawi earthquakes of October 15, 2006. Also: locations of geological engineering observation stations, October 21 - October 23, 2006, and route numbers of Highways referred to in the text.

2. ACKNOWLEDGEMENTS

Professor Jonathan Bray of the University of California at Berkeley provided support and guidance for the reconnaissance. The report benefited greatly from the assistance of Michelle Siegel, Erin Vollmer and Dr. Dimitris Zekkos of Geosyntec Consultants, Oakland, California. Funding was provided by Geosyntec Consultants and the Geo-Engineering Earthquake Reconnaissance (GEER) Association via Grant No. CMS-0323914 from the Geoenvironmental Engineering and GeoHazards Mitigation Program (Directors: Dr. Richard Fragaszy and the late Dr. Cliff Astill) of the National Science Foundation.

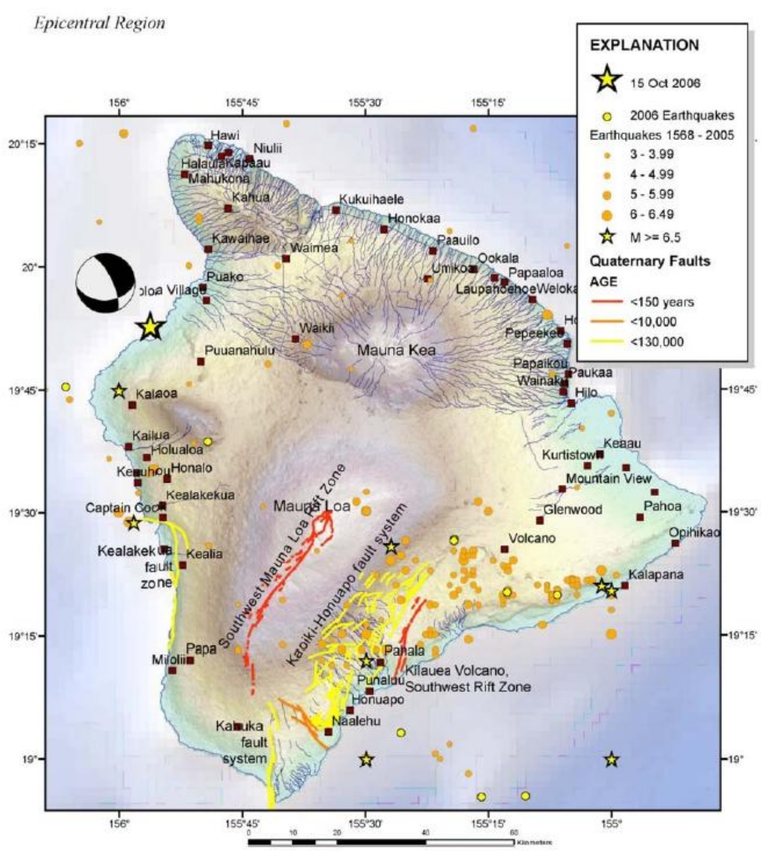

Figure 2: The Big Island of Hawai'i: locations of towns, volcanoes, principal historical earthquakes, major faults and Kiholo Bay Mw6.7 earthquake of October 15, 2006. (Chock, 2006; after USGS).

3. EARTHQUAKE CHARACTERISTICS

At 7:07:48 a.m. (local time) on Sunday October 15, 2006 an M_w 6.7 earthquake struck off-shore of the west coast of the island of Hawaii. The earthquake originated at N 9.820°, W156.027°s and a depth of about 29 km (18 miles).[2] The epicenter was about 11 km (7 miles) north-northwest of Kalaoa, in Kiholo Bay (Figure 1, Figure 2, Figure 3), 99 km (62 miles) from Hilo and 250 km (155 miles from Honolulu) (Figure 3[3]). Numerous aftershocks occurred, including a M_w 6.0 event at 07:14 a.m. at N20.129°, W155.983° and depth of 19 km (12 miles), referred to as the separate Hawi earthquake by Robertson et al (2006) (Figure 1).

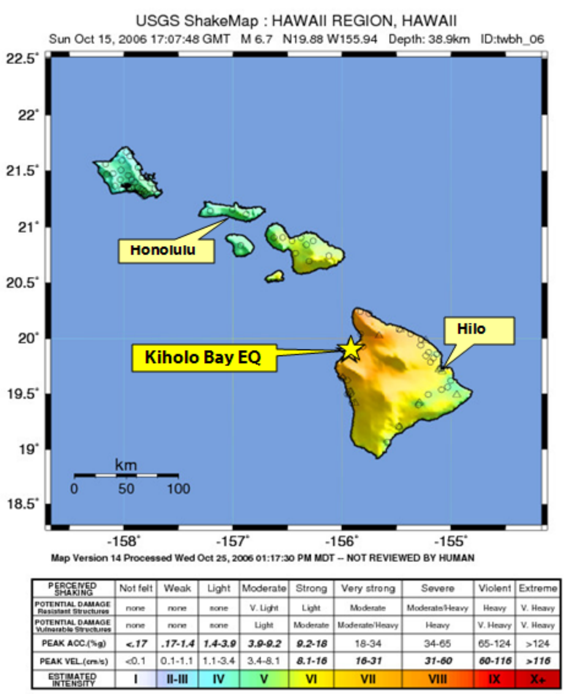

Figure 3: USGS ShakeMap for the M6.7 Kiholo Bay earthquake (after USGS).

As shown on Figure 3, the strongest shaking (MMI VII-VIII) was felt at the northwestern part of Hawaii. Damage resulting from the two largest earthquakes was concentrated on the western Kona Coast (Figure 1), the northern Kohala region, and the eastern Hamakua Coast north of Hilo, (Figure 1, and Figure 2). It should be noted that the thickest soil development is along the Hamakua Coast (windward and wet) and in the Kohala area (on the oldest Hawaii rocks).

[2] Details at: USGS website http://earthquake.usgs.gov/eqcenter/recenteqsww/Quakes/ustwbh.php

[3] Source of Figure 2: http://earthquake.usgs.gov/eqcenter/shakemap/shakemap.display.php

Figure 4: Hwy 270, near Keokea Bay Beach Park access road: Highway blocked by rock fall.

Figure 5: Failed rock cut: massive a'a block undermined by raveled a'a clinker (Chock, 2006; after Robertson et al, 2006)

Shaking from the earthquake and the aftershocks were also felt at several places in the State (Figure 3). The felt effects of the Hawaii earthquake were reported to be "...as severe as, or even worse, than those of the Kiholo Bay event" (Robertson et al, 2006). Damage was reported at the eastern end of the island of Maui, located to the northwest of Hawaii.

The earthquakes effects also included loss of electrical power on Maui and Oahu. As of October 26, the cumulative damage attributed to the earthquakes was some $146 million (Chock, 2006).

The principal observations reported here are related to the failure of road cut slopes (Figure 4 and Figure 5), landslides, and the failure of stacked rock structures. Only a few observations are presented of the failure of buildings, bridge structures and approaches, which are reported in fuller detail by Robertson et al (2006) and Chock, 2006.

4. FAILED ROAD CUT SLOPES

Most of the reconnaissance was performed along Island highways (Figure 2) between six to nine days after the earthquake, and after most of the more disruptive slides had been cleared. Despite the considerable proportion of highway alignments bounded by cuts, the proportion of seriously failed road cuts appeared to be relatively low.

In general, slope cuts are steep in Hawaii: even in soils the slopes exceed 1:1 (45 degrees: Figure 4). Many virtually vertical slopes were observed in deep cuts. Based on the reconnaissance, there appeared to be strong relationships between slope heights, geology and the occurrence of failures. That rockfalls from road cuts are apparently common was implied by the many highway signs warning of "Rock Fall" that were observed during the reconnaissance.

1.1 Failed Rock Cut Slopes

Being less than about 1 to 2 million years old, Hawaii is the youngest island in the Hawaiian chain. The island was formed from the merging and superposition of basalt rocks produced by the island's five volcanoes: Kohala, at the north, being the oldest and Kilauea, at the south, being the youngest. Kilauea is the source of current eruptions at the southwest portion of the island. The other three volcanoes are Hualalai, Mauna Kea, and Mauna Loa (Figure 2).

Generally, Hawaiian basalts are either *a'a*[4] or *pāhoehoe*. A'a basalts are characterized by alternating layers and inclusions of massive, very hard and strong basalt, surrounded by various thicknesses of clinker, composed of poorly to loosely welded, irregularly-shaped and rough-surfaced rocks ranging between gravel to boulders in size (Figure 6)

Figure 6: Location 11, Saddle Road (Hwy 200). Lava flow of *a'a* clinker and dry stacked wall of clinker composed of a'a blocks.

[4] In the Hawaiian language, the word *aa* is correctly spelt *a'a*: (pronounced "ah-ah") with the apostrophe being a glottal stop, or slight pause. Accented letters in Hawaiian words (such as the ***ā*** *in pāhoehoe)* are stressed.

Figure 7: Location 32, road cut at Hwy 11. Massive basalt in *a'a* flow.

A'a clinker commonly surrounds discontinuous and contorted massive inclusions of irregularly fractured, extremely strong basalt. Road cuts in a'a generally require blasting, which induces mechanically-induced fractures in the massive rock inclusions additional to the natural discontinuities (Figure 7).

There is a considerable difference in the mechanical properties of the a'a clinker and massive basalt. During the earthquakes, loose a'a clinker raveled and rolled away from beneath massive basalt blocks, removing support from the overlying massive blocks (Figure 8). Although the integrity of massive blocks is influenced by the extent, spacing and nature of the internal discontinuities,

Figure 8: Location 25, Hwy 270 north of Kawaihae. Cantilevered block of massive a'a basalt, undermined by raveled clinker

Figure 9: Location 32, Hwy 11. Failure of massive basalt rock overlying weaker weathered rock (baked zone).

blocks are capable of sustained significant cantilevers. However, with the removal of raveled supporting clinker, many overhanging blocks failed during the earthquakes (Figure 8). It was these large and heavy blocks, rather than the soil-like clinker, that represented the greater hazard to traffic.

The baked contact between lava flows and pre-existing ground surfaces is often marked by a zone of red soil and highly weathered rock resulting from accelerated weathering. A number of road cut failures were observed where the weaker basal soils failed, undermining the stronger rock above, in a fashion similar to that above described for aa/massive basalt sequences (Figure 9 and Figure 10).

The other major form of basalt in Hawaii is *pāhoehoe*, often known as "ropy lava" (Figure 11). Being less viscous than a'a lava, pāhoehoe flows tend to be thinner. With smoother or inter-flow contact surfaces, there is also considerably less clinker and a greater proportion of massive rock. Hence, road cuts in pāhoehoe are generally more stable than those in a'a sequences (Figure 12 and Figure 13), although relatively few road cuts in pāhoehoe sequences as fresh as those illustrated were observed. Rockfall from cuts in obvious pāhoehoe sequences were relatively isolated blocks of rock.

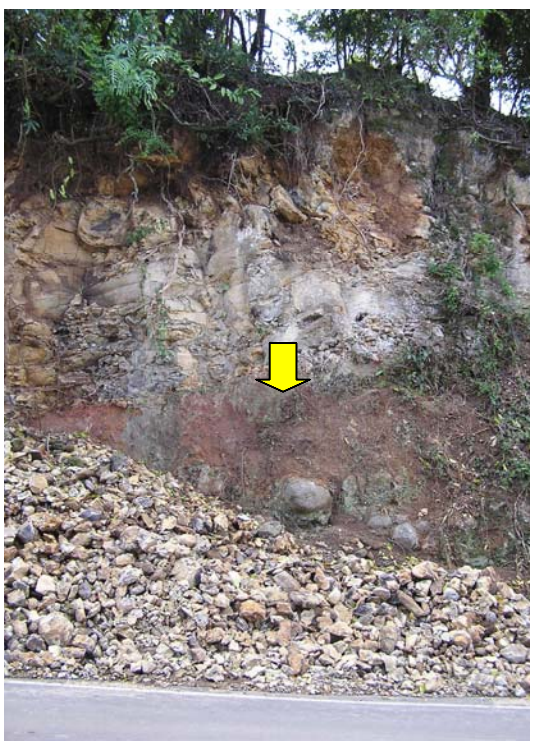

Figure 10: Location 18, Hwy 270 at Makapala. Failure of stronger rock underlain by baked zone soil, with weathered boulders (arrow).

Figure 11 Vicinity Location B, Hawaii Volcanoes National Park. Pahoehoe basalt (ropey lava).

At Location 13 on Hwy 250, (Milepost 8, Kohala Mountain Road) a very high and steep road cut appeared to have sustained little distress during the earthquake (Figure 14). The rock is a pyroclastic assemblage of welded volcanic ash and other volcanic debris (Figure 15).

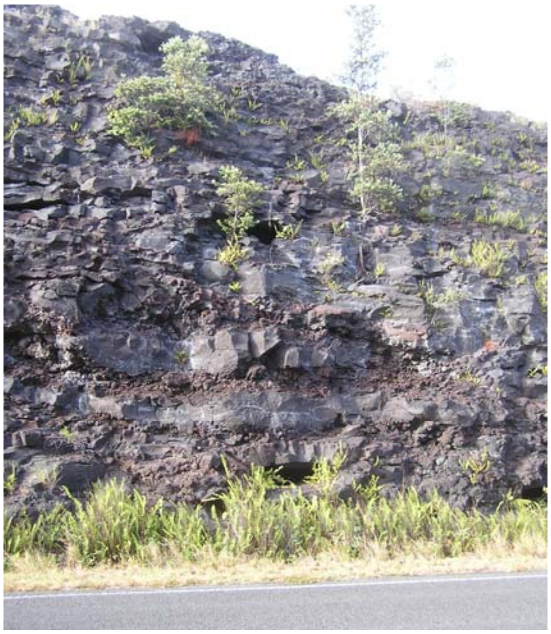

Figure 12: Location B, Hawaii Volcanoes National Park. Stacked sequence of pahoehoe lava flows with lava tubes.

Figure 13: Location 37, Hwy 160. Pāhoehoe in road cut.

Figure 14: Location 12, Milepost 8, Hwy 250. Stable steep and high road cut.

Figure 15: Location 13, Milepost 8, Hwy 250. Rock at road cut is a pyroclastic assemblage of ash and other volcanic debris.

Weathered rock was often found to have failed along fractures occupied by tree roots. The effect was more clearly evident at slope failures in soil, as described below.

Lava tubes are common in pāhoehoe. One lava tube beside Highway 240 (Figure 16) showed remarkably little apparent disruption of wall and roof rock mass, despite a span of several meters and fractured rock exposed at the cave surfaces. The degree of rockmass failures in caves and tunnels due to the earthquake is unknown. The vulnerability of tunnels to rockfall during large earthquakes is an important lifeline issue given that Statewide, many water supply routes occupy tunnels. Water supply to the Waipio area was interrupted by collapse of a major ditch in the Kohala area (according to news reports).

1.2 Failed Soil Cut Slopes

Soil development on the island of Hawaii is most apparent at the older northern end of the island (Kohala region) and along the wetter eastern side (Hamakua Coast). For the purposes of this report, and using a commonly understood definition, "soil" is the material that can be excavated by conventional earthwork equipment. Accordingly, moderately to completely weathered rock is considered soil, a range which includes residual soil and saprolites, which to varying degrees preserve a rock-like appearance and the legacy of the original rock mass discontinuities. Such soils thus have the worst qualities of both geo-materials: the weakness of soil and the built-in failures surfaces of rock.

Figure 16: Location 7, Hwy 240, near Kapulena, north of Honokaa. Lava tube, with apparently little rockfall from roof and walls.

Figure 17: Location 4, old Hwy 11 near Ookala, Modern Hwy 11 viaduct above. Soil slide in very steep road cut in vicinity of abutment of viaduct, typical of many slides along this road.

Many small slides of soil were observed during the reconnaissance, although the majority of these were generally of a few cubic meters in volume only. It is not clear how many of the observed failures were directly related to the earthquakes, how many to subsequent heavy rainfall, and how many due to the combination of these influences. Many road cut soil slides were observed to have occurred within larger and older failure features. As indicated above, soil slopes were generally inclined as steeply as rock cuts, greater than 50 degrees (Figure 17). Composite slopes, where soil overlay rock or weathered rock, generally showed failure of the soil only (Figure 18). Where the soil/rock profile varied laterally at road cuts, failures predominated in the soil sections. Where slopes had been stable long enough for tree roots to take hold in fractures, sections of the sloes peeled off to expose the roots. The waving of trees due to prolonged shaking may also have contributed lateral loading to the failed veneers (Figure 19).

Figure 18: Location 4: old Hwy 11 near Ookala. Failure of soil above rock. Note inclusions of rock within soil.

Figure 19: Location 16, Near Kapaau (Kohala), Hwy 270. Tree roots within fractures influenced instability in road cuts in soil.

Fresh to moderately weathered rocks, in which hard blocks of rock are surrounded by weaker soil (Figure 10 and Figure 18); or rock masses composed of massive blocks of basalt within an a'a clinker matrix (Figure 9) are complex geological mixtures. As shown by Wakabayashi and Medley (2004)[5] such rock/soil mixtures have a *block-in-matrix*

[5] Wakabayashi and Medley, 2004 paper at: http://bimrocks.geoengineer.org/resources.html

rock (bimrock[6]) fabric when the blocks are larger than about 5 percent of a characteristic dimension indicating the scale of engineering interest (such as the height of road cut) and have an appreciable volumetric proportion. The seismic response of a slope composed of blocks of rock surrounded by weaker matrix is as yet poorly understood, despite the common and worldwide occurrence of road cuts in rock/soil mixtures. Further research is warranted.

Figure 20: Location 2, Akaka Falls, Hamakua Coast. Bald scars in the cliff face may not all be attributable to the earthquake.

[6] bimrocks: for more information see http://bimrocks.geoengineer.org

5. LANDSLIDES

Because of the abundance of steep and high slopes, high rainfall conditions, weak soils and weathered rock, there were likely many landslides in the Kohala and Hamakua areas of Hawaii initiated by the earthquakes: only few were observed during the reconnaissance.

Apparently recent slides were observed on the cliff face of the Akaka Falls (Figure 20). Other earthquake effects at the State Park property were apparently limited to fallen trees and damaged hand railings. At Waipio Valley, the coastal cliffs show evidence of older landslides which have deposited debris that is at least 35 years old[7] (Figure 21). However, prominent large scars may not be a result of the earthquake since at the time of the reconnaissance, the water at the toe of the cliff was not muddy. The alignment of the failed cliffs in Figure 21 suggests a mega-landslide head scarp or a fault scarp, although the faceted spurs may also be due to erosion.

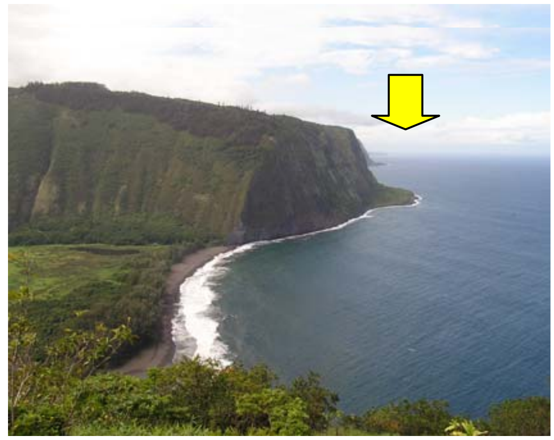

Figure 21: Location 8, Waipio Valley cliffs. Debris from an older slide (arrowed) in the background. Apparently recent scar in the closer truncated spur is not a result of the earthquakes since the water is not muddy.

Figure 22: Location 19, Keokea Bay. Cliffs failed during the earthquake: Note displaced trees (arrow) and slide scars.

At Keokea Bay, the pavilion at the Keokea Beach Park was red-tagged because of structural damage caused by the earthquakes. Adjacent the Park, the

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[7] The debris is obvious in the oblique aerial photograph (and is referred to in the caption) of Figure 185 of *Volcanoes in the Sea- The Geology of Hawaii* (MacDonald and Abbott, 1970).

freshly scarred cliff faces, trees that had slid to the shore and muddy near-shore waters were clear indicators of recent slides resulting from the earthquakes. (Figures 22 and 23).

Closer to the epicenters, the seismic activity resulted in landslides and tension cracks several feet from the cliff top along the trail between Honoipu Landing and Puakea Ranch (Figure 24 and Figure 25). The cliff failures also damaged the dry stacked rock wall structure supporting part of the parking area for shoreline access at the nearby Puakea Ranch residential development.

A dramatic earthquake-triggered landslide occurred at Kealakekua Bay (Figure 26), south of Kailua-Kona from the Pali Kapu o Keōua, a fault trace and the head scarp of the Alika mega-landslide that occurred about 100,000 years ago. The area seaward and landward of the cliffs was closed by the State and so was not investigated during the reconnaissance.

Figure 23: Headland to the northwest of Location 19, Keokea Bay. Cliff top slid into the ocean, indicated by the displaced tree and the almost submerged toe debris.

Figure 25: Location 23, Kuakini Trail. Tension cracks behind cliff top (arrow).

Figure 24: Location 23, failed cliff south of Honoipu Landing (Kuakini Trail).

Figure 26: Location 36, Napo’opo’o, facing the Pali Kapu o Keōua, a fault/mega-landslide scarp.

6. LIQUEFACTION AND LATERAL SPREADING

The harbor area at Kawaihae suffered considerable distress from the earthquakes, as fully detailed by Robertson et al (2006), so only passing reference is made here. Figures 27 and Figure 28 show examples of lateral spreading, ground fissuring and ejection of liquefied sand resulting from the earthquakes, still evident a week after the event.

Figure 27: Location 27, Kawaihae Small Boat Harbor, showing ground crack resulting from lateral spreading.

Figure 28: Location 27, Kawaihae Small Boat Harbor parking lot, adjacent boat yard at south side. Liquefied (white) sand was ejected from ground crack.

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7. PERFORMANCE OF STACKED ROCK STRUCTURES

In Hawaii, dry stacked rock structures built of stone placed without mortar are common, being the heritage of an ancient art (*uhau humu pohaku*) used to craft walls, temples, and platforms. Stacked rock walls, sometimes weakly mortared, are also evident in old churches and more modern structures such as retaining walls and boundary fences. The rocks used in the walls vary between a'a clinker (Figure 29) to segments of columnar jointed basalt (Figure 30).

Figure 29: Location 11, Saddle Road (Hwy 200). Stacked rock wall of *a'a* clinker.

Although the earthquake damaged many stacked rock structures, the observed effects were inconsistent. The overall impression was that most damage was suffered by tall and/or steep structures close to the earthquake epicenters, and where the contacts between rocks were minimal.

Figure 30: Location 33, Moku'aikaua Church, Kailua-Kona. Finely constructed stacked rock perimeter wall.

The Pu'ukoholā Heiau, located south of Kawaihae (Figure 31), is an excellent example of a well-constructed stacked rock structure. The heiau, an important cultural edifice in Hawaii, is a ritual temple commissioned by Kamehameha I between 1790 and 1791. The edifice was constructed using water-rounded cobbles and boulders, apparently transported hand-to-hand from Pololu Valley some 20 miles away. The reconnaissance was performed around the perimeters of the structures since only native

Figure 31: Location 29. Mailekini Heiau in middle ground, and Pu'ukoholā Heiau on top of hill.

Hawaiians may enter or walk on the heiaus.

The Pu'ukoholā heiau and the neighboring older Mailekini heiau (Figure 31 and Figure 32) were both badly damaged by the earthquakes. The worst damage at the Pu'ukoholā heiau was to the access steps on the north side (Figure 32). At the Mailekini heiau, much of the interior face of the east wall slumped and raveled (Figure 33).

The long axes of the heiaus are oriented approximately north-south. The stacked rock structures range between 1.5 m to over 10 m high and 1.5 m to more than 12 m wide at the tops. Rock sizes range between a few inches to more than 1 m with most boulders being in the 0.3 m to 0.6 m size range.

Earthquake damage was in the form of slumps and ravels of the wall faces (Figure 34 and Figure 35). The unfailed side slopes are inclined at about 40 to 50 degrees (Figure 34). The angle of repose for the slumps was about 30 degrees, with run-outs extending to 5 m and greater from the original toes of the inclined walls. Many wall bulges were observed where the slopes approached vertical (Figure 35), which suggests vulnerabilities to increased rock face instability and eventual collapse from future earthquakes or creep deformation.

Figure 32: Location 29, Pu'ukoholā heiau, north side: Earthquake caused collapse of access step structure.

Figure 33: Location 29, Mailekini heiau. Significant raveling and slumping of interior face of the eastern wall (outlined).

Figure 34: Location 29, Pu'ukoholā heiau, northeast corner. Dashed lines indicate boundary of ravel zone.

As reported by Robertson et al (2006), dramatic damage occurred at the Kalāhikiola Congregational Church in Kapa'au, which was largely constructed of weakly grouted stacked rock (Figure 36).

At Spencer Beach Park, south of Kawaihae, a tall free-standing grouted stacked rock wall appeared to have accommodated earthquake-related deformation (Figure 37). No other walls at the park showed damage, although none seemed unrestrained like the one pictured.

Failed stacked rock retaining walls were observed in several locations, such as that shown in Figure 38 in Captain Cook, on Hwy 11 south of Kailua-Kona. Virtually no stacked rock wall (or road cut) failures were observed on Hwy 11 between Captain Cook and Hilo. Only minor damage to trails was reported at Hawaii Volcanoes National Park (Location A, Figure 1).

Figure 35: Location 29, NE corner Puukohola Heiau. Bulging of rock face approaches 90 degree inclination as indicated by yellow line. Bulge is clearly seen in stereo (see Appendix).

Figure 36: Location 21, Kalāhikiola Congregational Church, Kapa'au. Weakly cemented stacked rock walls failed dramatically.

Figure 37: Location 30, Spencer Beach Park, south of Kawaihae. Apparent earthquake damage of partially mortared rock wall.

Figure 38: Location 35, Captain Cook. Failed stacked rock retaining wall.

8. BRIDGE APPROACHES AND EMBANKMENTS

Robertson et al (2006) and Chock (2006) reported many structural and geotechnical reconnaissance observations related to earthquake-related bridge and embankment distress. The geological engineering reconnaissance also revealed earthquake distress due to the poor performance of fills adjacent at bridges. Some examples are presented:

At Mile Post 35 on Hwy 11, near Pa'auilo, an embankment for the southern approach failed (Figure 39).

Figure 39: Location 6, Mile Post 35, Hwy 11 near Pa'auilo. Failure of fill at makai (east) side of southern approach to bridge.

At Mile Post 9.4 on Hwy 250 (Kohala Mountain Rd), the makai (west) side embankment failed at several locations over several hundred meters (Figure 40). There is a narrow shoulder for this road, and the bridge itself is single-lane. The road was closed at this location after the earthquake. Since Hwy 270 was also closed, there was no route open for traffic in or out of Kohala.

Figure 40: Location 15, north of Mile Post 9.4 Hwy 250. Slump failure of embankment on makai (west) side road.

At the crest of a steep embankment near Makapala on Hwy 270, tension cracks and a head scarp about 0.3 m high were observed (Figure 41). The high embankment was on the makai (north) side of the road, and had side slopes of greater than 45 degrees.

At the bridge located at approximately Mile Post 28, Hwy 270, cracks in the road surface appeared to match the locations of the cut/fill transitions of underlying subgrade (Figure 42). At one location, cracked asphalt concrete pavement was thrust over adjacent pavement (Figure 43). The west bridge abutment headwall had suffered some spalling at apparent pre-existing cracks (Figure 44).

At the Mauna Kea Observatories complex at the summit of Mauna Kea, (about 4,260 m elevation), no apparent distress was observed at the high earthwork embankment adjacent the Keck Observatory building, although recent spalling had occurred at the exterior (Figure 45).

Figure 41: Location 18, Hwy 270 near Makapala, makai side. Arrow indicates tension cracks and short head scarp (12 inches) at crest of steep and high fill slope.

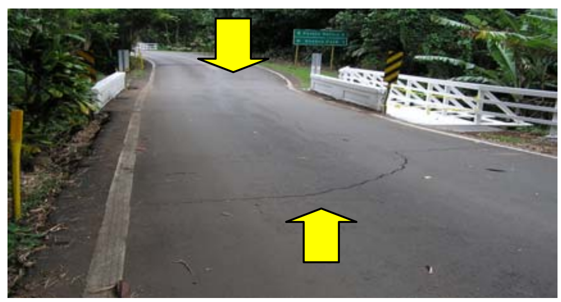

Figure 42: Location 20, bridge at approximately MP 28, Hwy 270. AC pavement cracked at approximately the cut/fill transition lines of underlying subgrade (cracks in AC).

Figure 43: Location 20, bridge at approximately MP 28, Hwy 270. Thrusting of AC pavement.

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Figure 44: Location 20, bridge at approximately MP 28, Hwy 270. At SW corner of bridge, looking upward. Wooden plank sidewalk above. Significant spalling of bridge abutment headwall.

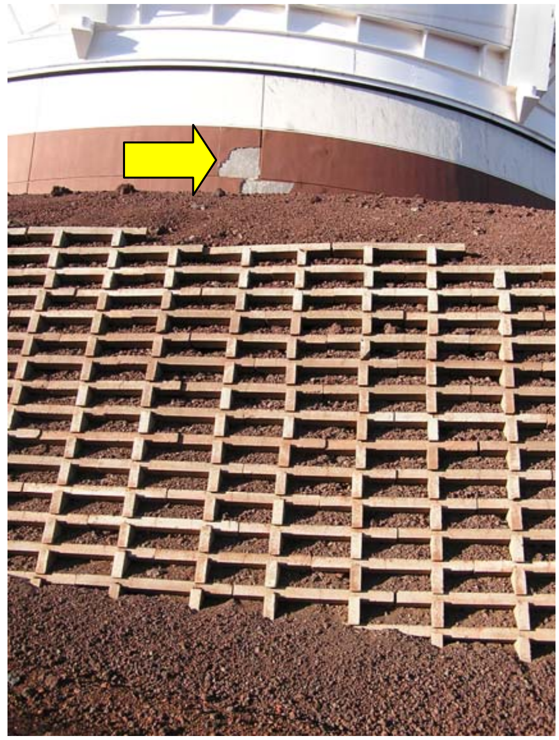

Figure 45: Location 28, Keck Observatory, Mauna Kea summit. No apparent distress to high embankment beside the observatory. Spalled stucco evident at two places on the exterior wall of the building (one arrowed).

9. CONCLUSIONS AND RECOMMENDATIONS FOR FURTHER WORK

The geological engineering reconnaissance prompts the following preliminary conclusions and recommendations:

1. The failure of road cut rock slopes was much influenced by the presence of a'a clinker. Where clinker underlay massive basalt blocks, there was a tendency for the loose clinker to translate, rotate and ravel downslope, thereby undermining the blocks. Where the massive blocks could not sustain a critical cantilever, they dislodged as well. Even if the blocks did not fail, their overhang is a future traffic hazard and they should be reviewed by an engineering geologist (or geotechnical engineer knowledgeable in rock engineering) and removed if necessary;
2. The performance of road cuts in soil slopes was generally better than that of rock slopes;
3. There are some parallels between the geomechanical behavior of clinker rock masses and the behavior of stacked rock structures: slope angle, slope height, particle size and nature and proportion of inter-particle contacts govern performance for both. Analysis of failure modes and modeling of vulnerabilities would be ideally suited to discontinuous deformation analysis (DDA) or other discrete element numerical methods commonly used in geological/geotechnical engineering; and.
4. Although many stacked rock walls likely will be repaired relatively easily, some historical and cultural structures (such as the Pu'ukoholā and Mailekini heiaus) will require detailed, culturally-sensitive and inter-disciplinary assessments of damage and scope of repairs. Initial nom-intrusive damage surveys could be performed using LiDAR and/or photogrammetric surveying using terrestrial stereo-photography.

10. REFERENCES

Chock, G., (ed). "Preliminary Observations on the Hawai'i Earthquakes of October 15, 2006", EERI Special Earthquake Report, Learning from Earthquakes; EERI, Oakland, CA: http://www.eeri.org/lfe/pdf/usa_kona_hawaii_eeri_prelim_report.pdf

MacDonald, G.A, and Abbott, A.T. *Volcanoes in the Sea – The Geology of Hawaii*, University of Hawaii Press, Honolulu, HI; (1970) 441 pp.

Robertson, I.N., Nicholson, P.G. and Brandes, H.G. "Reconnaissance following the October 15th, 2006 Earthquakes on the Island of Hawaii". Research Report UHM/CEE/06-07, University of Hawaii College of Engineering, Department of Civil and Environmental Engineering; October 26, 2006. 65 pp. (2006)

Wakabayashi, J. and Medley, E.W. "Geological Characterization of Melanges for Practitioners," Felsbau Rock and Soil Engineering-Journal for Engineering Geology, Geomechanics and Tunneling, vol. 22, No. 5 (2004).

11. TABLE OF RECONNAISSANCE LOCATIONS

Station	Date	Location	Latitude (N degs)	Longitude (W degs)	Feature	Photo Numbers	Comments
A	20 Oct. 2006	Volcanoes Nat. Park	20.4333	155.2500		21-26	Was told by 4 separate Park personnel that no damage other than minor rock falls or trails; no damage at Observatory.
B	9 Aug. 2006	Volcanoes Nat. Park: Chain of Craters Road	20.3250	155.1333	Pāhoehoe sequences exposed in high road cut	9 Aug 2006 photos	In Aug 2006: observed almost vertical cuts in pāhoehoe sequences; assume no significant failures based on info from Park personnel **NOT OBSERVED IN OCT 2006.**
1	21 Oct. 2006	Onomea Scenic Drive	26.8083	155.0833	Road cut slide	1-8	(Due to recent rain?) many seen along Scenic Drive, traffic coned.
		Pepeekeo Sugar Mill			Stack standing, Lighthouse too.		
2	21 Oct. 2006	Akaka Falls	19.9538	155.1894	Landslide at Falls	9-18	Due to recent rain?? EQ caused trees to topple, which damaged railings.
3	21 Oct. 2006	S. of Kepehu Camp	19.9571	155.1971	Road cut slides	19-34	Slides within pre-existing slide bounds; 3-5 foot thick slides; soil failed over weathered rock.
		Laupahoehoe				35-36	No damage observed in Park.
4	21 Oct. 2006	Near Ookala, old road beneath Hwy 11 bridge	20.0106	155.2881	Road cut slides	37-50	Soil slope failed across road? Top 1/3 of slope.
5	21 Oct. 2006	Near Kukaiau, Hwy 11, MP 32	20.0273	155.3394	Road cut slides	51-57	Several small slides not contained by pre-existing netting??
6	21 Oct. 2006	Near Paauilo, MP 35 Hwy 11	20.0335	155.3553	Embankment at bridge	58-79	Fill at south approach to bridge failed.

Station	Date	Location	Latitude (N degs)	Longitude (W degs)	Feature	Photo Numbers	Comments
7	21 Oct. 2006	Near Kupalena, Hwy 240, MP 6.3?, Honokaa-Waipio	20.1067	155.5373	Lava tube	80-89	Remarkably little rock fall.
8	21 Oct. 2006	Waipio valley access road	20.1165	155.5875	Rock fall	90-101	Sole rock fall seen on very steep 4x4 access road, high slope.
9	21 Oct. 2006	Honokaa-Waimea, Hwy 19	20.0712	155.4942	Rock fall	101-114	Active rockfall clearance; tree roots in rock fractures.
10	21 Oct. 2006	East side Waimea, Hwy 19	20.0459	155.5867	Landslides (?)	115-119	Unknown if these fresh scarps are result of EQ: many observed.
11	21 Oct. 2006	Saddle Road near intersection with Mauna Kea access Road	19.6933	155.4930	Rock wall (intact)	120-132	Intact rock walls across extensive a'a fields.
	22 Oct. 2006	Waimea area			Views of Waimea area (from Saddle Road)	1-2 and 348	
12	22 Oct. 2006	Scenic Lookout Kohala Mt. Road, Hwy 250	20.0704	155.7599	Views of Waimea-Kona coast-Kohala coast (from Kohala Mt Road)	3-6	
13	22 Oct. 2006	near Scenic Lookout Hwy 250	20.0719	155.7605	Road cut (intact)	7-18	Little evidence of slope failures: massive cut, >100 feet high in volcanic ash/tuff.

Station	Date	Location	Latitude (N degs)	Longitude (W degs)	Feature	Photo Numbers	Comments
14	22 Oct. 2006	Hwy 250	20.0807	155.7635	Road cut failure	19-30 + stereo	
15	22 Oct. 2006	Hwy 250, MP 9.34 bridge over Kawaihae Uka	20.0902	155.7677	Embankment failure (near bridge)	31-40	Failures at top of road embankments north of bridge on makai side.
15a	22 Oct. 2006	North of Sta 15	20.0910	155.7689	Embankment failure	41-55	Failures at top of road embankments for several hundred feet north of bridge on makai side.
16	22 Oct. 2006	Hwy 270 east of Kapaau	20.2288	155.7705	Soil cut failure	56-76	Detrimental effects tree roots in soil failures.
17	22 Oct. 2006	Hwy 270 east of Kapaau	20.2206	155.7539	Soil cut failure	77-80	Detrimental effects tree roots in soil failures.
18	22 Oct. 2006	Hwy 270 Makapala area	20.2089	155.7388	Rock cut failures, embankment failure	81-97, 103	
18a	22 Oct. 2006	Hwy 270 Makapala area, Waiapuka Gulch bridge	20.2089	155.7388	Intact bridge - typical	98-102	No evidence of distress at bridge though abutment approach fill has tensions cracks (see Sta 18).
19	22 Oct. 2006	Keokea Beach Park	20.2276	155.7453	Sea Cliff failures	104-115	Large blocks of cliff top slid down cliff faces, includes block to west at headland of Keokea Bay.
19a	22 Oct. 2006	Keokea Beach Park			Pavilion failure	116-122	Cracked pavilion columns.
20	22 Oct. 2006	Hwy 270 MP 27.3 Bridge 407	20.2206	155.7484	Bridge failure	123-159	Thrust ac; abutment fill problems; bridge damage includes widening (?) of old cracks.

Station	Date	Location	Latitude (N degs)	Longitude (W degs)	Feature	Photo Numbers	Comments
21a	22 Oct. 2006	Kapaau King Kam statue			Structure Intact		
21	22 Oct. 2006	Kapaau Kalahikiola Church	20.2225	155.7948	Structure failure	162-189	Ungrouted rock in walls failed.
22	22 Oct. 2006	Road to Upolu Airport	20.2607	155.8563	Structures intact	190-192	9 of 16 windmills working and Silos still standing. Any windmills damaged? Could not check Kamehameha birthplace heiau due to impassable access road.
23	22 Oct. 2006	Ala Kahaki trail between Honoipu Landing and Parking area at Puakea Point	20.2433	155.8892	Sea cliff failures	193-212	Cracks in cliff top; failures in weathered clinker; failures of rock structure below ac parking lot at rock walls.
23a	22 Oct. 2006	Lapakahi Heritage Park	20.1750	155.9167	Structures intact	213-220	According to docent: no distress to historic Hawaiian village except minor wall failures; no damage observed.
24	22 Oct. 2006	MP 8 Hwy 270 S of entrance Kohala Ranch Estates	20.0743	155.8563	Rock cut failures, embankment failure?	221-233	Embankment failure due to recent rainfall??
25	22 Oct. 2006	Hwy 270 north of Kawaihae, near entrance Kohala Estates	20.0647	155.8484	Rock cut failures	234-260	Extensive road cut failures, some retreat of road cut crest toward structure??

Station	Date	Location	Latitude (N degs)	Longitude (W degs)	Feature	Photo Numbers	Comments
26	22 Oct. 2006	Honokoa Gulch bridge, Hwy 270 MP 4.98	20.0513	155.8393	Bridge failure	261-307	Bridge distress makai side; minor failure approach fill south side.
27	22 Oct. 2006	Kawaihae Small Boat Harbor	20.0394	155.8311	Lateral spreading, liquefaction, boils	308-347	Much evidence of liquefaction and lateral spreading.
28	23 Oct. 2006	Mauna Kea Keck Observatory	20.8250	155.4833	Structure damage, earthwork intact??	1-47	Some damage observed to stucco at Keck Observatory; none obvious at earthwork structure adjacent.
29	23 Oct. 2006	Pu'ukoholā heiau Kawaihae area	20.0263	155.8200	Rock Wall (Structure) Failures	48-122, 156, 178-179	First co-ord is Visitor Center: damage at various places around structure; photos 48-51 general views incl rock wall near Entrance.
29-1	23 Oct. 2006	Pu'ukoholā heiau south side	20.0277	155.8211	Rock Wall (Structure) Failures	52-54	South side.
29-2	23 Oct. 2006	Pu'ukoholā heiau: east side, NE corner	20.0279	155.8213	Rock Wall (Structure) Failures	55-75	East side and NE corner.
29-3	23 Oct. 2006	Pu'ukoholā north side	20.0275	155.8217	Rock Wall (Structure) Failures	74-82, 84-94	North side; most damage is to collapsed access stairs; previously blocked off and had laser security system??

Station	Date	Location	Latitude (N degs)	Longitude (W degs)	Feature	Photo Numbers	Comments
29-4	23 Oct. 2006	Pu'ukoholā heiau west side heiau, SW and NW corners	20.0276	155.8217	Rock Wall (Structure) Failures	95-122	West side and SW, NW corners.
29b	23 Oct. 2006	Mailekini Heiau, Kawaihae	20.0281	155.8222	Rock Wall (Structure) Failures	83, 123-177	Shows extensive failures in older structure; also views of Leaning Stone (not damaged by EQ) and other shots of adjacent Royal Compound.
		Mailekini Heiau east side, NE corner			Rock Wall (Structure) Failures	130-142	East side and NE corner.
29b-1	23 Oct. 2006	Mailekini Heiau NW corner	20.0283	155.8222	Rock Wall (Structure) Failures	143-155	North side; NW corner.
29b-2	23 Oct. 2006	Mailekini Heiau west face, SW corner	20.0275	155.8224	Rock Wall (Structure) Failures	159-172	West side and extensive failures of interior face east wall.
30	23 Oct. 2006	Spencer Beach Park, south of Kawaihae	20.0249	155.8227	Rock Wall (Structure) Failures??	180-186	Leaning free standing rock wall; formed from grouted two courses. EQ damage?? Block missing near base, evidence recent failure?? No tags… No other leans seen, but no others wall are free standing.
31	23 Oct. 2006	Mauna Kea Hotel South side	20.0075	155.8249	Structure damage	187-201	EQ damage at south building; terrain flat: possible soft ground??
32	23 Oct. 2006	Hwy 19 Q. Kaahumanu Hwy	19.9570	155.8260	Road cut failure	202-224	Typical of raveling a'a; massive blocks poss. cracked prev. by blasting; slopes to 90 degrees.

Station	Date	Location	Latitude (N degs)	Longitude (W degs)	Feature	Photo Numbers	Comments
33	23 Oct. 2006	Hulihee Palace, Kailua Kona	19.6393	155.9939	Structure failure	225-230, 240-241	Cracks at exterior; could not access property.
33b	23 Oct. 2006	Moku'aikua Church, Kailua Kona	19.6393	155.9939	Structural failure?; and intact stone walls	231-240; 242-252	Cracks at exterior, recently repaired; grouted rock masonry; intact rock walls in Hawaiian style.
34	23 Oct. 2006	Kealakekua, Hwy 11	19.5306	155.9253	Rock wall failure	253-258	Failed wall adjacent private property.
35	23 Oct. 2006	Captain Cook, Hwy 11	19.5006	155.9201	Rock wall failures	259-261	Failed walls adjacent private property: typical of the few seen.
36	23 Oct. 2006	Napoopoo Beach Park	19.4738	155.9195	Sea cliff failure	262-275	Views of failures (poor light) from old landslide scarp (Pali Kapu o Keoua, head of Alika landslide; 100k to 105k yBP).
37	23 Oct. 2006	Scenic Lookout Hwy 160, near City of Refuge	19.4167	155.9167	Intact slopes	276-284	Intact slopes in pāhoehoe; rock wall under construction.

APPENDIX

STEREO PHOTOGRAPHS

Figure S2: Location 29: Puukohola Heiau. Bulge at NE corner.

ANAGLYPH

Figure S3: Location 25. Road cuts near Kohala Ranch Estates, Hwy 270.

STEREO PAIR

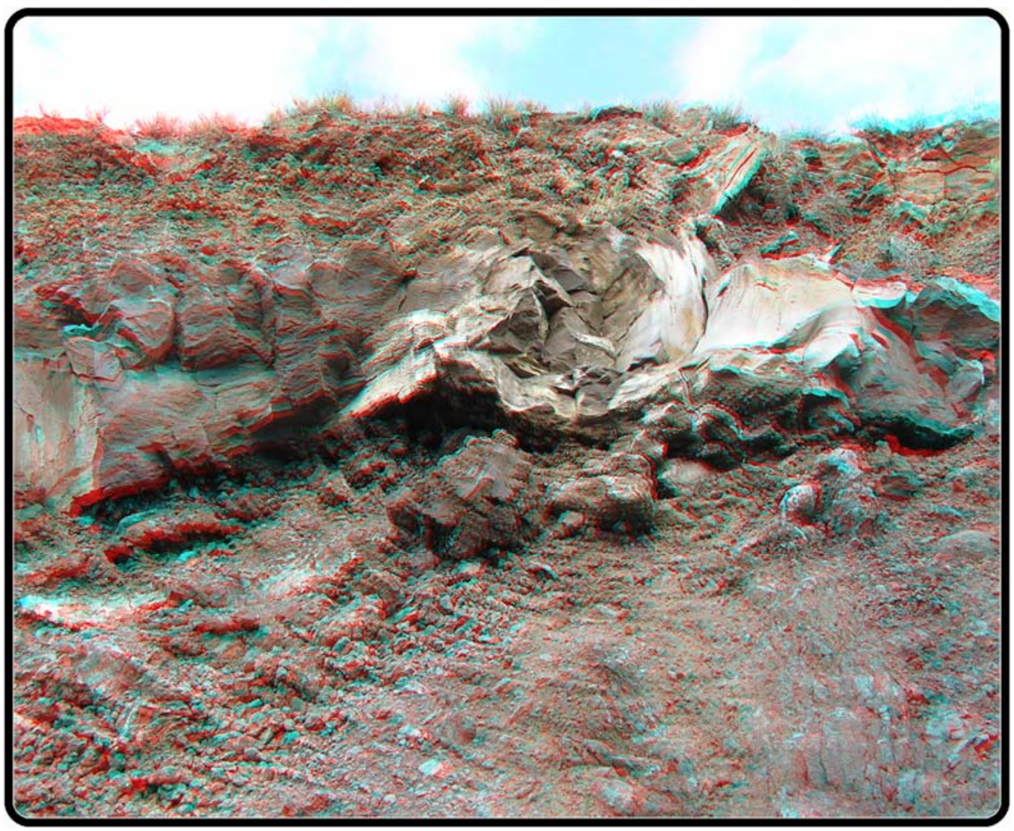

Figure S4: Location 25. Road cuts near Kohala Ranch Estates, Hwy 270.

ANAGLYPH

Figure S5: Location 20. Bridge at MP 28, Hwy 270. Looking upward at spalled concrete structure.

STEREO PAIR

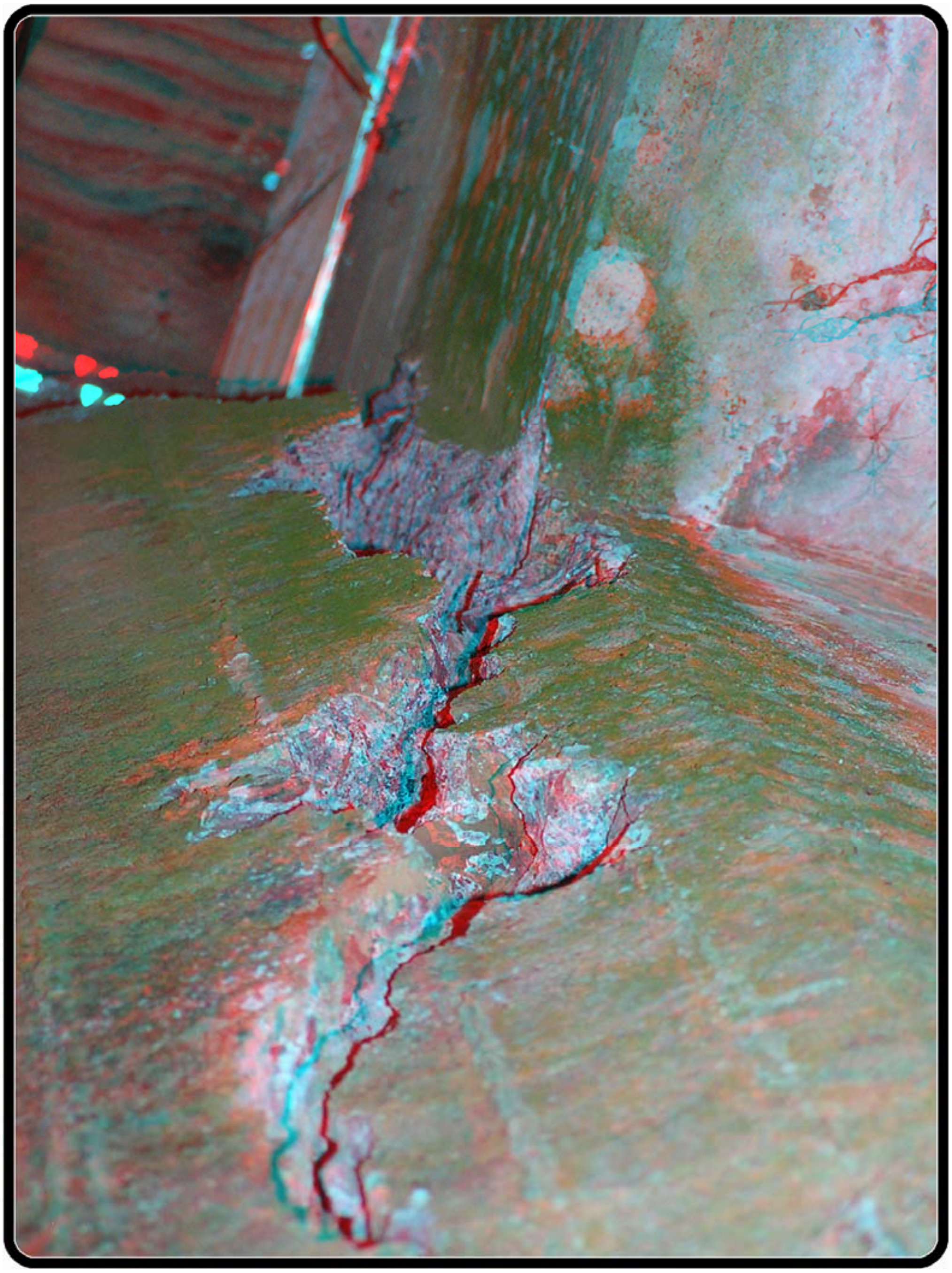

Figure S6: Location 20. Bridge at MP 28, Hwy 270. Looking upward at spalled structure.

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