RECEIVED
05/27/2020
12:38 pm
STATE OF HAWAII
LAND USE COMMISSION

Appendix 2: Coastal Erosion and Volcanic Hazards Report

GCI

GEOHAZARDS CONSULTANTS INTERNATIONAL, INC.
Appraisal of hazards – reduction of risk

Coastal Erosion and Volcanic Hazards Report
Barry Property
Hawaiian Paradise Park
Puna, Hawai'i
TMK: (3) 01-5-059:059

J.P. Lockwood, Ph.D.

January 2019

AMERICAN INSTITUTE OF PROFESSIONAL GEOLOGISTS
CERTIFICATE NUMBER
9806
AIPG
JOHN P. LOCKWOOD
CERTIFIED PROFESSIONAL GEOLOGIST

P.O. BOX 479 · VOLCANO, HAWAI'I 96785 · USA
TEL: (808) 967-8579 · FAX: (808) 967-8525 · email: geohaz@hawaii.rr.net

Table of Contents

Page No.

Introduction 3

Field Inspection 3

Geology 4

Shoreline Findings..11

Erosion Processes 12

Erosion Rate 14

Effects of Subsidence and Sea Level Rise (SLR) on Shoreline 16

General Coastal Zone Hazards 17

Volcanic Hazards and Risks 17

Summary...20

References Cited..22

Introduction

This report documents the nature of erosion and shoreline migration at the Barry property based on quantitative measurements and observations obtained through field inspection, aerial photography, satellite imagery, and review of the geologic literature. An additional section addressing volcanic hazards and risk was included at the request of the Property owners.

Field Inspection

John Lockwood and Jacob Smith visited the Barry property (hereafter referred to as "the Property") with Kevin and Monica Barry on June 5th, 2018, and again on August 15th and September 11th', 2018. A total of three and a half hours were spent making field observations, surveying with Brunton pocket transit and measuring tape, and obtaining site photography.

The field observations of observed water line on June 5th were taken as the tide rose from +0.9 to +.1.1 feet above the tidal datum (tidal datum for Hilo, Hilo Bay, and Kuhio Bay, HI - *http://tidesand currents.noaa.gov)*. The ocean was characterized by moderate swells (3-4 feet), which generated light surf (Figure 1). The subsequent visits were made at times of higher surf to observe the impact of larger waves. The September 11th visit coincided with the impact of 8-10' swells on the coastline cliff face fronting the Property.

Figure 1. View of coastline fronting the Property – view to south. The vegetation (naupaka) defines the shoreline ("highest reach of waves") fronting the Property, and is as close as 8' to the coastline cliff (Figure 2) at the Property's south boundary. Normal surf does not reach above the coastal cliff, but angular boulders attests to the fact that exceptionally large storms can dislodge cliff edge pahoehoe and place blocks short distances inland, and scour vegetation inland from the cliff face. The coastal bench of bare pahoehoe is as much as 30' wide at the north Property boundary.

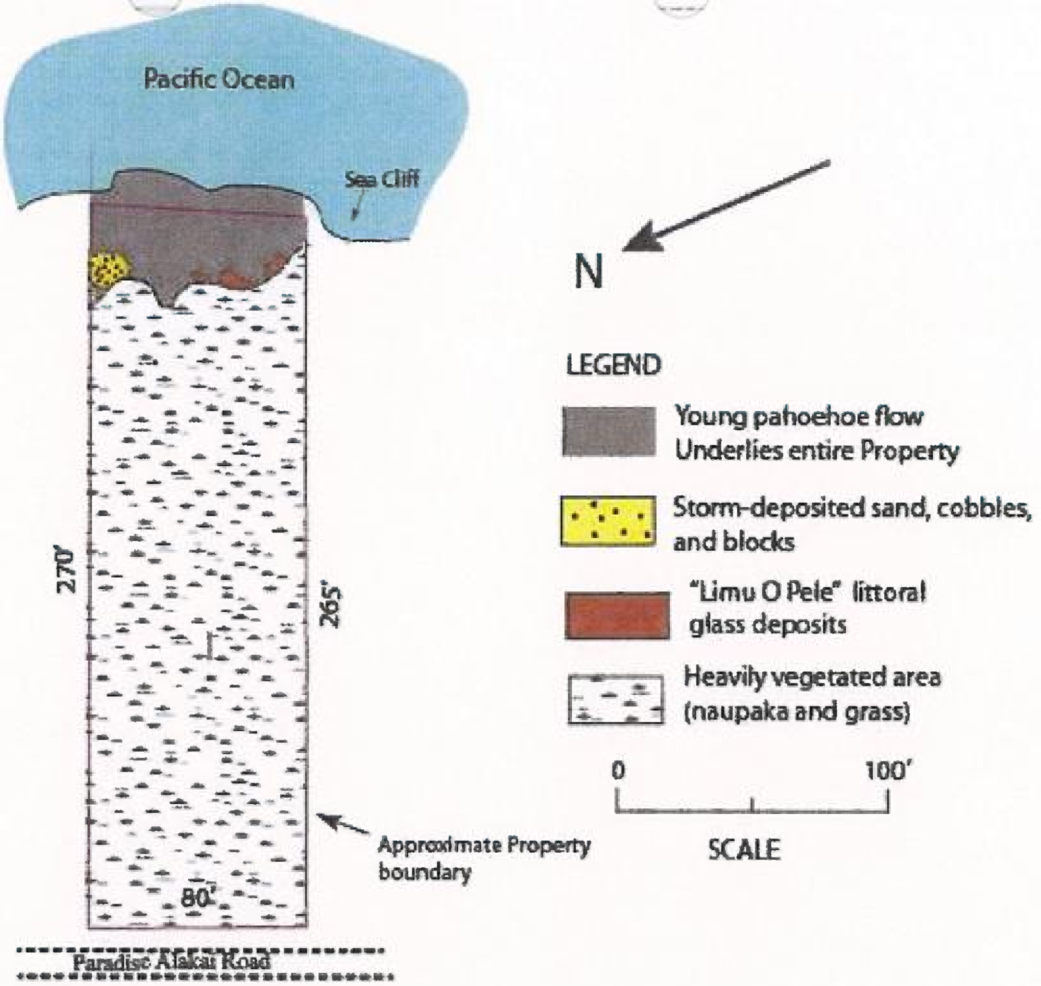

FIGURE 2. Location of Property relative to the coastline and geologic sketch map.

Geology

Lava Flow Nomenclature and Ages

According to Moore and Trusdell's (1991) geologic map of Kilauea's lower east rift zone, the lava flows underlying this area of Puna have estimated ages of 350-500 years before "present" (CE 1950), and belongs to their unit "f6a2". This unit mostly consists of dense pahoehoe lava over a wide area of Puna, extending from Kilauea Iki crater in Hawai'i Volcanoes National Park to the ocean, 20 miles away, where the flows form eight miles of the coastline (Wolfe and Morris, 1996 – their unit P4). The ages of these flows have recently been determined to be older than ages given by Moore and Trusdell, since they are everywhere overlain in Kilauea's summit region by a widespread pyroclastic ash deposit known as the "Keanakakoi Ash" (Swanson and others, 2012), which began to be deposited about 1500 CE. Recent radiocarbon dating and calibration by David Clague (MBARI, pers. communication, 2018) indicates that all of these flows (known as the 'Ai-la'āu flows – Holcomb, 1987, Clague and others, 1999) were emplaced before about 1470 CE, some as old as about 1300 CE. Because of the very young aspects of the upper lava flow at the Property (described below), I shall assign an age of about 550 years before today's date (2018 CE).

Erosion of the sea cliff fronting the Property reveals that these pahoehoe lobes overlie an older, massive, dense lava, along a sharp contact (Figure 3). This older flow could not be inspected because of dangerous surf conditions, and its origin is uncertain. It was probably erupted by an earlier phase of the same long-term ʻAi-laʻāu eruption that formed the overlying pahoehoe. The top of this underlying flow shows red oxidation (Figure 3) indicating some significant passage of time before emplacement of the overlying flow. Its age is not known, but I shall assume it erupted about 1350 CE (about 670 years ago) – one of the earliest ʻAi-la'āu flows.

Figure 3. Seacliff fronting the Property, showing the younger, overlying pahoehoe flow lobes that form the surface of the entire Property (above arrow) – view to northeast. The contact with the underlying dense, massive lava flow is marked by a red oxidized surface zone, which demonstrates substantial time elapsed between emplacement of the two flows.

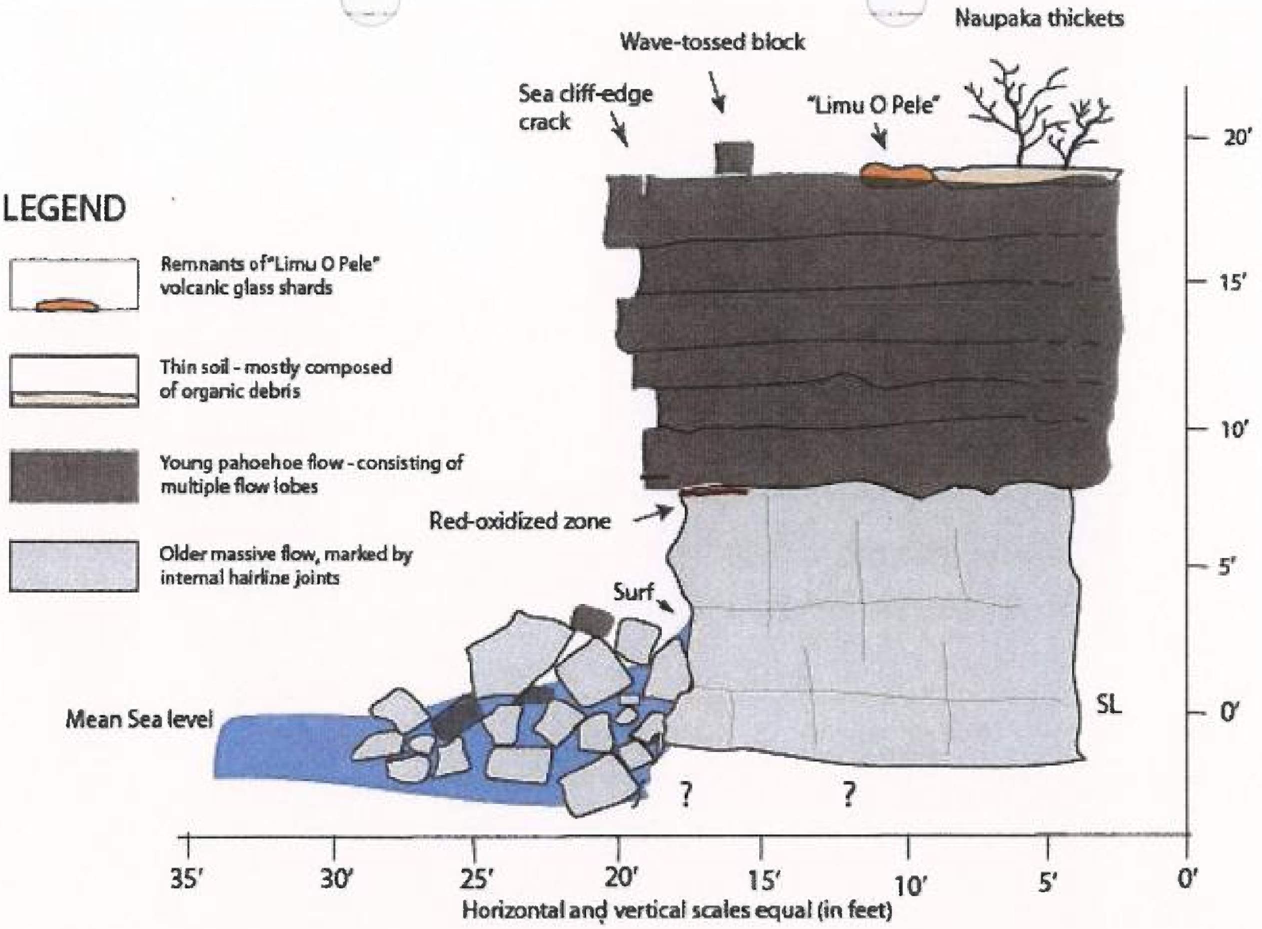

Figure 4. Geologic cross-section of typical coastal cliff fronting the Property - view to southwest.

Flow Lithology

The surface lava flow underlying the entire Property consists of multiple flow sheets of pahoehoe, all emplaced during the same eruption. These pahoehoe lava flows that form the surface of the entire Property (Figs. 1, 3) are dense, aphanitic (crystal-free) basalt typical of many of the 'Ai-la'āu flows that form Kaloli Point. The very fine-grained matrix "sparkles" with fine crystallites – probably consisting of plagioclase and clinopyroxene. Thick black glass marks some flow surfaces, especially inland of the naupaka-defined shoreline. Some of this glass is up to almost ½' in thickness – suggesting that it may have been quenched by either heavy rainfall or surf splashing.

Flow Internal Structures

The overlying pahoehoe flow consists of 5-8 individual flow sheets where exposed along the shoreline cliff (Figures 3, 4). Each one of these flow lobes erupted during the same eruption, but probably over an interval of only a few weeks or months. Individual flow lobes have black glassy surfaces at both tops and bottoms to half-inch thicknesses, but have nearly aphanitic (no large crystals) interiors where the lava cooled more slowly. A fine sparkly texture in the interiors reveal microlites of probable olivine and clinopyroxene. Abundant vesicles are rounded to sub-rounded throughout the lobes, attesting to the highly fluid nature of this pahoehoe when emplaced. The pahoehoe flow appears to be too thin to contain pyroducts ("lava tubes") beneath the Property, but about 100 yards to the south-southeast, where the flow is thicker, a probable pyroduct extending inland at the head of an embayment was noted.

Although the dense lava flow underlying the surface pahoehoe could not be inspected directly, it consists of a single thick, dense flow of unknown thickness. The sections exposed at the sea cliff consist of very dense, erosion resistant "blue rock" in the normal wave impact zone (Figure 3). Angular blocks of this unit at the foot of the sea cliff indicate the presence of very fine fracture joints that control block failure (following section).

Younger Deposits

The uppermost pahoehoe flow is overlain by three types of sedimentary deposits – coeval remnants of fragmental volcanic glass debris, scattered patches of cobbles, gravel and sand that have been deposited by exceptional storm wave activity, and a colluvial, organic rich soil found inland beneath vegetation.

Discontinuous deposits of volcanic glass fragments in deposits up to three inches in thickness are found in grass-covered pockets just makai of the naupaka-defined shoreline. These deposits consist of a unique material called "limu o Pele" (Mattox and Mangan, 1997), and were formed by the explosive interaction of seawater and fluid pahoehoe when the underlying flow entered the ocean 300-500 years ago. The rapid expansion of steam entering molten lava formed large "lava bubbles", which formed thin sheets of glass and fine particles as they exploded (Figure 5).

Figure 5. Bursting bubble of molten lava where seawater interacted explosively with fluid pahoehoe lava entering the sea along Kilauea's south coast during a 1990's eruption. Such explosions form the windborn fragmental debris uncommonly preserved on the Property as "limu O Pele". Photograph supplied by Tari Mattox, but photographer unknown.

The limu o Pele deposits consist of sedimentary remnants of pure volcanic glass that were once apparently widespread above the upper pahoehoe flow. They consist entirely of medium to coarse sand-size, glass fragments, and would have been scoured away by storm waves long ago if they were not protected by dense mats of an unidentified, presumably native grass whose rootlets permeate and stabilize the underlying loose glass fragments (Figures 6, 7). These deposits indicate that the original coastline when the underlying flows were emplaced could not have been too much farther seaward.

Scattered cobbles are widespread above the surface pahoehoe (note a few in Figure 6), and have accumulated to nearly a foot depth in one small area along the Property's northwest boundary (Figures 2, 8). These unconsolidated sediments are partially vegetated, and are only deposited or moved about by very infrequent storm waves that have over-topped the sea cliff in this area. On most of the vegetated areas of the Property, the pahoehoe flow is overlain by a discontinuous soil zone up to five inches thickness, consisting mostly of organic debris intermixed with very minor amounts fine silt- and clay-size mineral material, likely derived from the accumulation of windblown dust.

Figure 6. Limu O Pele deposit preserved 10' inland from cliff edge. These deposits, preserved by storm wave erosion by overlying grass mats, consist of sand-size volcanic glass fragments, and were formed by the explosive interaction of the underlying fluid lava with seawater. Their presence indicates that the original coastline when the underlying flows were emplaced could not have been too much farther seaward.

Figure 7. Limu O Pele deposit detail. Fragments consist entirely of fresh, brown volcanic glass fragments up to 1 mm diameter. Note the grass rootlets that permeate the deposit. Thinner glass films common in modern limu O Pele deposits have apparently been dissolved away, leaving only coarser fragments behind.

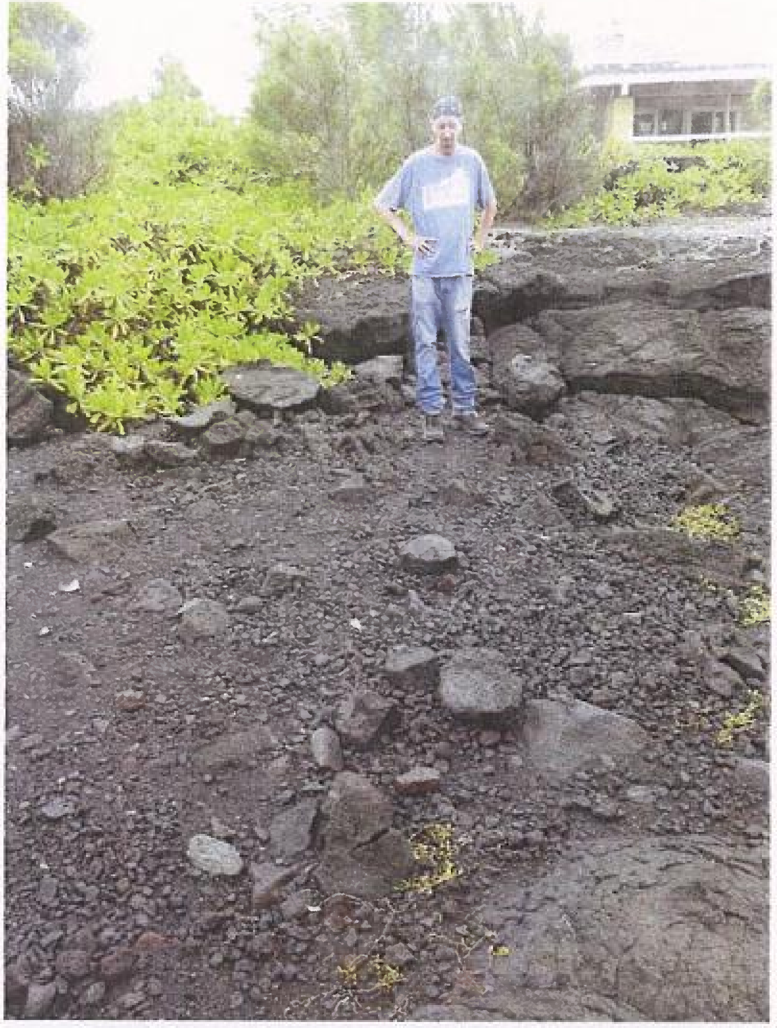

Figure 8. Small area of storm wave-deposited cobbles, gravel, and sand along the northwest-most boundary of the Property.

In summary, the two relatively young, prehistoric lava flows underlying the Property are of typical Kilauea compositions, and were erupted from Kilauea's summit area 500-700 years ago. They were not derived from Kilauea's recently active East Rift Zone, nor is the Property threatened by future eruptions from that rift. Sparse deposits of volcanic glassy debris found near the shoreline show that the original coastline was not located far offshore from its present position, and place limits on the amount of coastal erosion that has occurred since flow emplacement.

Shoreline Findings

The shoreline is legally defined in Hawai'i as "*the upper reaches of the wash of the waves, other than storm and seismic waves, at high tide during the season of the year in which the highest wash of the waves occurs, usually evidenced by the edge of vegetation growth, or the* *upper limit of debris left by the wash of the waves . . . .*" (HAR §13-5-2). In this case the shoreline has been assumed to be the edge of vegetation growth (Figures 1-3), which also coincides with the most mauka impact of storm waves. The vegetation-defined shoreline lies 8-30' back from the sea cliff makai of the Property boundary.

The vegetation inland from this shoreline is dense coastal naupaka (*Scaevola taccada)* with some minor young ironwood (*Casuarina equisetifolia*) scattered about. Ironwoods are fast-growing alien species that can block viewscapes and eliminate native vegetation – they should be uprooted and destroyed wherever found. The naupaka ("naupaka kahakai") grows everywhere on the Property inland from the shoreline, and is underlain by unconsolidated soil, which indicates no erosion is taking place mauka of the shoreline. Along the front of the Property there is no "debris line" that would mark the shoreline as along the sandy beaches on older islands such as Oahu and Kauai.

Over the very long-term (since the emplacement of the lava flow underlying the property about 550 years ago) coastal erosion has caused the shoreline to migrate mauka, but the present low erosion rate (discussed below) has limited this migration and it does not threaten the safety or integrity of the Property.

Erosion Processes

The sea cliff fronting the Property is resistant to erosion, and negligible erosion occurs during normal sea conditions. During times of major storms, however, the impact of waves can cause some mechanical and abrasional erosion, although even this is likely rare. Cracks near the edge of the sea cliff in several places (Figure 9) indicate where the cliff edge is unstable, and susceptible to failure when impacted by powerful storm waves. A few scattered blocks of angular pahoehoe up to two feet diameter were noted above the coastal plain and as much as ten feet inboard of the shoreline (Fig. 1). These were formed when powerful waves impacted the top of the sea cliff, injected high-pressure water into the contacts between flow lobes, and through the process of "hydraulic ramming" loosened blocks and moved them short distances inland.

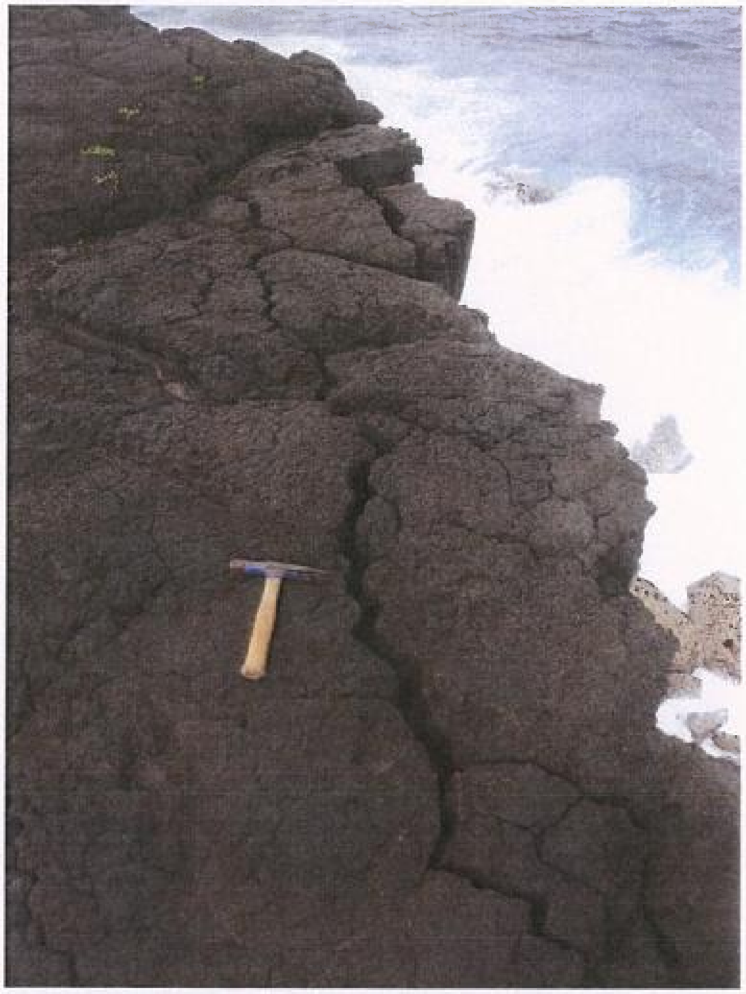

Figure 9. Extension cracks present at the Property's coastal cliff edge. These cracks, which are common along this stretch of coastline, develop as stresses are relieved at the cliff face, and contribute to the susceptibility of this upper pahoehoe flow to rare storm waves that impact the cliff face and force sea water into the horizontal contacts between flow lobes.

The dense lava underlying the pahoehoe flows is highly resistant to wave impact forces, but also has internal joint fracture planes that can be exploited by the impact of particularly powerful waves. This type of mechanical erosion is rare, but can occur, as indicated by the presence of very large (up to five feet diameter) angular, subangular, and sub-rounded blocks found at the base of the sea cliff fronting the Property (Figures 3, 10).

These erosional processes are normal for the storm-wave exposed rocky coastlines of Puna, and are of no particular concern for this Property over the short-term (the next several decades).

Figure 10. Detailed view of eroded blocks at the base of the coastline cliff. Most of the blocks have slightly subrounded edges, indicating abrasion by surf action. The large block marked with an "X" is about three feet in diameter, with uniformly angular edges, and must have fallen within the past few years – long ago enough to be covered with marine algae. These large blocks serve to block and attenuate the force of impacting waves – forming protection from erosion.

Erosion Rate

A rigorously quantitative approximation of the shoreline erosion rate at the Property is not statistically feasible using the methods outlined by Hwang (2005) because of the relatively low rates of erosion and the inadequacy of available high-resolution aerial photography. Shoreline determinations must rely upon alternative indicators – primarily observation of active erosion of the coastal sea cliff makai of the shoreline – and factors such as freshly cut cliff faces or presence of angular erosional debris as discussed above. Shoreline erosion is, however, not a continuous process that can be characterized by simple "erosion rates". Mechanical erosion of the coastline is episodic, related to the uncommon impact of especially strong storm activity.

One perspective can be derived from estimates of the coastal erosion that has taken place since the emplacement of these lava flows. The uppermost pahoehoe flow has been eroded back since emplacement an estimated 550 years ago, but the distance eroded is not precisely quantifiable. The presence of littoral explosion-derived limu O Pele above the pahoehoe shelf suggests the original coastline was not far away. I assume that the coastline was 100' away at the time of flow emplacement (this estimate is based on observations of historical limu o Pele deposits associated with recent pahoehoe ocean entries associated with the Pu'u O'o eruption – Mattox and Mangan, 1997). Such an assumption would imply an overall erosion rate of 0.18 feet, or 2.2 inches/year over the past 550 years.

Careful inspection of available aerial photographs (Table 1) to measure coastline positions relative to internal fixed distances (between roads) provides another erosion rate. These photos indicate that slight erosion of the coastline (coastal sea-cliff) has occurred since the earliest 1954 photos, but migration of the shoreline (vegetation line) is not measureable. The large scale and limited resolution of the available aerial photographs makes precise analyses of fine-scale morphological changes of the shoreline or sea-cliff impossible, but a trend is apparent (Table 2).

Date	**Agency**	**Flight Line**	**Frames**
1954	USN-USGS	017	1755, 1756
1961	USGS	GS-VSJ 6	155, 56
1965	USDA	EKL-11CC	198, 199
1977	USGS	GS-VEEC 6	119, 120
2017	Google Earth	16 March, 2017 image	----

Table 1. Available aerial photography.

Differences in tidal level and surf conditions at the times individual photography was obtained also contributes to the lack of precision. It is thus doubtful that horizontal changes of less than 10 feet could be documented, although greater changes should be apparent, especially when the morphology of prominent coastal features change with time. So far as migration of the shoreline, there are no resources to evaluate the migration of the vegetation that defines the shoreline, but dead naupaka roots near the coastline suggests that this vegetative marker migrates with time in response to climatic as well as storm wave impacts.

Analyses of coastline migration yield erosion rates varying from 1.5-5.5 inches/year (Table 2) with an average erosion rate of the coastline cliff at 3.0 inches/year. This compares favorably with the less rigorous rate of 2.2 inches/year described above. Such rates are very low compared to the rapid rates of sandy beach shoreline erosion that can occur when impacted by severe storms on the older, low-lying islands of Maui, Oahu and Kauai (up to 20 feet in a single storm – Hwang, 2005).

Time interval	Road-→ Coastline Distance (ft)	Change since Aerial photo (ft)	Years elapsed	Indicated erosion (inches/year)
1954-→2017	286'	-12'	63	2.3"
1961-→2017	280'	-06'	56	1.3"
1965-→2017	299'	-24'	52	5.5"
2017	274'	----	----	
			Average erosion rate:	3.0"/year

Table 2. Coastal erosion estimates based on analyses of historical aerial photography between different photo sets. The differing erosion rates (Column 5) reflect measurement uncertainties related to low photograph resolution.

Effects of Subsidence and Sea Level Rise (SLR) on Shoreline

Hwang et al (2007) use a figure of .16 in/yr in their assessments of present-day SLR for Oahu, but an overall global rise in sea level of 3.3 feet by the end of the 21st century has been proposed by Fletcher (2010) and implies higher, increasing rates. SLR for any particular area depends heavily on local factors (water temperatures, ocean currents, salinity, etc.). Anderson and others (2015) predict a doubling of SLR rates for Hawaiʻi within 30 years.

Relative SLR, of course, is a result of the combined water rise and land subsidence. The Big Island of Hawaiʻi is sinking into the Earth's mantle because of the gravitational, isostaic load of it's growing volcanoes. A subsidence rate of 2-3 mm/year (0.08-0.12 inches/year) related to isostatic sinking has been determined by submersible studies of drowned reefs off west Hawaiʻi (Moore and Fornari, 1984), but that rate is higher for the Puna coastline, where volcanic loading activity is greater. Coastline subsidence can be accelerated by sudden events such as the 1975 Kalapana earthquake that caused land in Kapoho to drop 0.8 feet (based on Hawaiʻi Volcano Observatory (USGS) data in Hwang *et al.* 2007). Such *episodic* seismic induced subsistence is difficult to anticipate or measure over long periods of time. On the basis of InSAR (Synthetic Aperture Radar Interferometry) remote sensing data, Hwang et al (*ibid.*) state that the coastline at Kapoho may be subsiding at a *continuous* rate of between .31 – .67 in/yr. Rates of subsidence at the Property, 11 miles to the northwest of the East Rift Zone, are necessarily much lower as a result of their distance from Kilauea's active rift zone.

The combined effects of land subsidence and rising sea levels suggests an overall (relative) drop in the shoreline elevation relative to sea level of between 0.2 - 0.3 in/yr. The high cliff fronting the Property mitigates the impact of Sea Level Change, a major concern for low-lying coastlines elsewhere in the State. The durability and height of this cliff shows that SLR and land subsidence will not cause significant shoreline transgression in this area, although it will slowly increase the erosive action of storm waves over the next several decades and centuries.

General Coastal Zone Hazards and Risks

Hwang (2005) recommends that all hazards facing coastal areas should be considered when planning for land-use zoning in Hawai'i, and not just erosion. Fletcher *et al.* (2002) portray generalized hazards assessments for long areas of Hawai'i's coastlines, and rate the specific hazards for the area of Puna fronting the Property as shown in Column B of the following Table:

Hazard Type **A**	**Relative Threat (Risk)** **B**	**GCI-determined Relative Threat** **C**
Tsunami	High	Medium
Stream Flooding	Medium-high	Low
High Waves	Medium-high	Medium-High
Storms	High	Medium
Erosion	Medium-low	Medium-Low
Sea Level Change	Medium-high	Low
Volcanic/Seismic	High	Medium
Overall Hazard Assessment	Medium	Medium

Table 3. Natural hazards impacting the coastline fronting the Property (Columns A and B from Fletcher et al., 2002, p.150; Column C from this study).

The values assigned by Fletcher et al (Column B) are highly generalized for long stretches of Puna coastlines. The risk appraisals for the Property that we determined (Column C), differ in some regards from Fletcher et al.'s values (we indicate less risk) because our values are site-specific for the coast fronting the Property. The terms High,. Medium, and Low are subjective, however, and are only intended to convey relative risk as compared to other Hawaiian coastal areas reviewed by Fletcher in his State-wide Atlas.

Volcanic Hazards and Risks

Volcanic hazards are the natural phenomena that could pose a threat to property on or near volcanoes; *Volcanic risk* describes the statistical odds that a particular hazard will impact a particular area.

Volcanic Hazards

The volcanic hazards that could potentially impact the flanks of Kilauea volcano include the following:

a) Lava flow inundation
b) Explosive activity and ash deposition
c) Gas emissions
d) Volcano-related seismic activity

Only the first hazard (lava flow inundation) poses any potentail risk to the Property, and that risk is deemed to be relatively low. The Property is too far from the loci of potential future eruptions (either at the Kilauea summit or along its rift zones) to ever be impacted by significant ash fall. Future gas eruptions at the summit or East Rift Zone could impact the area with Sulphur aerosols during rare wind conditions, but gas levels will be at nuisance levels and of short duration. Major earthquakes will impact the Property in the future, but these will be caused by tectonic forces only indirectly related to Kilauea volcanic activity. Future structures on the Property should be built with strong foundations as mandated by present and future Hawai‘i County building codes.

Volcanic Risk

The Property, although located on young lava flows from Kilauea volcano, is located in an area of relatively low volcanic risk. The Property is located entirely in Lava Hazard Zone 3 (Wright and others, 1992). Zone 3 is the same Lava Hazard Zone as Hilo.

The entire East Rift Zone of Kilauea (ERZ) is located in hazard Zones 1 or 2, because those areas are either within or downslope from potential ERZ eruptive vents. All of the recent 2018 tragic property losses on the lower ERZ were confined to Zones 1 and 2.

The Property is not subject to lava inundation from Kilauea's middle or lower East Rift Zone, as that eruptive zone is located ten miles to the south, and does not present any threat (Figure 11). As has been discussed above, the lavas underlying the Property were emplaced during the brief life of the ‘Ai-la’āu shield, a satellite on the east margin of Kilauea caldera that erupted between about CE 1350 and 1470 (Holcomb, 1987). It would be unprecedented for another eruptive vent to open on this extinct marginal shield in this same area, and the high ground of the shield itself forms a high barrier to prevent any overflows from Kilauea volcano to the east.

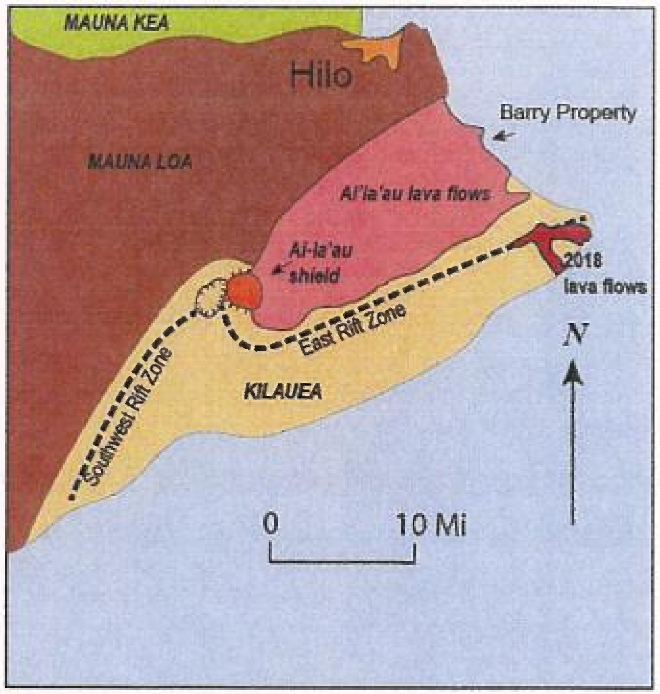

Figure 11. Relationship of the Property to Hawai'i volcanoes, to Kilauea's East Rift Zone, and to the destructive lava flows of 2018.

The risk of lava flow inundation is generally expressed in statistical terms – i.e. "*What are the odds that my Property could be buried by a future lava flow over certain future periods of time?*" This depends on determining a "recurrence interval" for previous lava flows in the area. Although the 'Ai-la'āu eruption probably involved near-continuous eruptive activity for 100 years or so, numerous individual separate lava flows were erupted, much like those that occurred during the 1983-2018 Kilauea eruptions on the middle ERZ. Only two of these 'Ai-la'āu flows have been identified beneath the Property, with estimated ages of about 1350 and 1470 CE, or about 669 and 549 years before the present date (2019). Assuming those ages are more or less correct, that shows two eruptions affecting the Property in 668 years, for a recurrence interval of one eruption every 334 years. If one then makes the assumption that past eruptions were, and future eruptions will be distributed randomly (stochastically) in time, then a simple Poisson Analysis could be used for statistical probabilities of future eruptions. The statistical probability (P) that a lava flow will occur over certain time periods in the future is derived from the following formula (discussed in Lockwood and Hazlett, 2010, pp.427-429):

$$P = 100\,(1 - e^{-t/T})$$

where t = probability evaluation window (yrs), and T = event recurrence interval (yrs). From this formula, the following probabilities that an eruption will occur in a particular time period can be derived (Table 4).

Future time interval (yrs.)	10	50	100	250	500	1000
Probability (%)	3%	14%	26%	53%	78%	95%

Table 4. Poisson probabilities that the Property could be impacted by a lava flow in future times.

The probabilities calculated in Table 4 are, however, far too high because they assume that the past history of lava flow inundation (2 flows in 668 years) will be typical of the future. In fact, this is not true, because deterministic (non-random) factors are involved; the ʻAi-laʻāu eruptions were geologically unique and eruptions are not likely to occur again in that area upslope of the Property for a very long time – likely thousands of years. Therefore, the statistical values given in Table 4 are the statistically highest possible probabilities of future lava flows impacting the Property, but in non-quantifiable fact, actual probabilities are much lower. With the passage of time, the "recurrence interval" for flows at the Property can only increase (assuming Pele doesn't figure out a way to visit) and the statistical probabilities for lava inundation will only decrease.

Summary

Our determination of natural hazards and risks facing the Property, as summarized in Table 3 – Column "C", is low to medium in comparison to other areas of the State, and less than the hazards estimated by Fletcher *et al.* (2002). We consider the Property to be suitable for residential development, in accordance with setback requirements to be determined by the Hawaiʻi County Planning Department.

The shoreline and sea cliff in front of the Property were mapped in order to assess the erodibility of underlying rocks and the dynamic nature of geologic and marine processes that contribute to erosion. The pahoehoe flow that defines the edge of the sea cliff is susceptible to slight, long-term erosion by storm or tsunami waves, and evidence of such erosion is documented by field photography. Historical aerial photos dating back to 1954 were compared to 2017 Google imagery in an attempt to establish an erosion rate for the area, and a rate of about 3.0 inches/year is suggested. A value of 2.2 inches/year was obtained from less precise estimates of lava flow age and distance to the original coastal lava entry point. Such rates are very low as compared to low-lying coastal areas on older islands where global Sea Level Rise and the vulnerability of sandy beaches can create serious long-term shoreline migration problems.

The slight erosion that does occur on this rocky coastline appears to be episodic, related to infrequent storm wave activity. Future inland migration of the shoreline will be impacted predominantly by such unpredictable and episodic storms, and could be accelerated by unforeseeable sudden subsistence due to seismic and tectonic events that are impacting shorelines closer to Kilauea's East Rift Zone. Over the very long term (centuries) coastal erosion and shoreline migration everywhere will be accelerated by global warming and rising sea levels.

The Property lies within Hawaiʻi island Lava Flow Hazard Zone 3 as determined by Wright and others (1992) – the same Hazard Zone as Hilo. The only volcanic hazard that could threaten this Property in the future is the potential for future lava flows from Kilauea volcano to inundate this area of the Puna coast. This risk of lava flow inundation is extremely low as compared to most areas of Kilauea, based not only on statistically calculated probabilities (Table 4), but also by the fact that this area is not threatened by future lava flows from Kilauea's active East Rift Zone. This part of the Puna coastline could only be threatened by Kilauea summit overflows, which are most unlikely given the high eastern walls of the summit caldera. The fact that Kilauea's summit magma chamber drained so completely in 2018, and is not likely to refill and overflow in any direction for a substantial period of time, gives further reason to disregard the potential for lava flow inundation.

References Cited

Anderson, T.R., C.H. Fletcher, M.M Barbee, L.N. Frazer, and B.M. Romine. 2015, Doubling of coastal erosion under rising sea level by mid-century in Hawai'i: Natural Hazards v. 78 (1):75

Clague, D. A., Hagrstrum, J.T., Champion, D. E., and Beeson, M. H. 1999, Kilauea summit overflows – their ages and distribution in the Puna District, Hawaii: Bull. Of Volcanology, v.61, n. 2, pp 363-381.

Fletcher, C. H., Boyd, R., Neal, W. J., and Tice, V., 2010, Living on the Shores of Hawaii – Natural Hazards, the Environment, and our Communities: University of Hawaii Press, 371 pp.

Fletcher, C. H. , Grossman, E. E, Richmond, B. M. and Gibbs, A. E., 2002, Atlas of Natural Hazards in the Hawaiian Coastal Zone: U.S. Geological Survey, Geologic Investigations Series Map I-2761, scale 1:50,000.

Holcomb, R. T., 1987, Eruptive History and long-term behavior of Kilauea Volcano: pp. 261-350 in Decker, R. W., Wright, T. L,, and Stauffer, P. H., 1987, Volcanism in Hawaii, Vol. I: U. S. Geological Survey Prof. Paper 1350, 839 pp.

Hwang, D. J., 2005, Hawaii Coastal Zone Mitigation Handbook: Hawaii Coastal Zone Management Program, DBED, State of Hawaii, 216 pp.

Hwang, D. J., 2007, Coastal Subsidence at Kapoho, Puna, Island and State of Hawaii: Private report for Hawaii County Planning Department, 82 pp.

Lockwood, J. P. and Hazlett, R.T., 2010, VOLCANOES – Global Perspectives: Wiley-Blackwell Publishers, Oxford, 641 pp.

Mattox, T. N. and Mangan, M.T., 1997, Littoral hydrovolcanic explosions – a case study of lava-seawater interaction at Kilauea volcano: Journal of Volcanology and Geothermal Research, v. 75, n. 1, pp. 1-17.

Moore, J. G., 1970, Relationship between subsidence and volcanic load, Hawaii: Bulletin of Volcanology, V. 34, pp. 562-576.

Moore, J. G. and Fornari, D. J., 1984, Drowned reefs as indicators of the rate of subsidence of the Island of Hawaii: Journal of Geology, v. 92, p. 752-759.

Moore, R. B. and Trusdell, F. A., 1991,Geologic Map of the Lower East Rift Zone of Kilauea Volcano, Hawaii: U. S. Geological Survey Misc. Investigations Series, Map I-2225, Scale:1:24,000.

Swanson, D. A., Rose, T. R., Fiske, R. S., and McGeehin, J. P., 2012, Keanakāko'i Tephra produced by 300 years of explosive eruptions following collapse of Kīlauea's caldera in about 1500 CE: Journal Of Volcanology and Geothermal Research, v. 215-216, No. 2, pp. 8-25.

Wolfe, E. W. and Morris, Jean, 1996, Geologic Map of the Island of Hawaii: U.S. Geological Survey Map I-2524-A; 1:100,000.

Wright,T. L., Chun, J.Y.F., Esposo, Joan, Heliker, C., Hodge, J., Lockwood, J. P., and Vogt, S. M., 1992, Map showing Lava-flow Hazard Zones, Island of Hawaii: U.S. Geological Survey, Misc. Field Studies Map MF-2193, 1:250,000.