The 1871 Lānaʻi Earthquake in the Hawaiian Islands
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Abstract
The historic Lānaʻi earthquake of 1871 is reappraised based on new science. This 1871 event occurred between Oʻahu and Maui, where currently 80% of the State of Hawaiʻi population resides. I focus on expanding the considered modified Mercalli intensities (MMIs) applied in prior seismic hazard analyses and the application of an earthquake MMI–magnitude, duration–magnitude, and fault-scaling relations. Compared with the MMI–distance trend of the 2019 $M_w 7.1$ Ridgecrest, California, earthquake, the Lānaʻi event appears larger. The 1871 earthquake and other $M ≥ 4.9$ earthquakes (measured instrumentally) trend along the Molokaʻi fracture zone (MFZ), suggesting a tectonic relationship. The MFZ near Hawaiʻi is the boundary between ~85 and ~100 Ma age lithosphere. Consistent with the preponderance of available evidence and new science, I propose a hypothetical, revised $M_w ~7.5$ earthquake model of the 1871 Lānaʻi earthquake associated with the MFZ. This seismic event may credibly be considered as the third largest earthquake statewide in Hawaiʻi’s history and the largest historic earthquake northwest of the Big Island of Hawaiʻi.

Introduction
The Lānaʻi earthquake of 19 February 1871 (Honolulu local time) is the largest earthquake to have occurred in the Hawaiian Islands northwest of the Big Island of Hawaiʻi. This earthquake is discussed in first-hand accounts (Alexander, 1871), reported in Europe by Perry (1875), and listed within the “Sandwich Islands” in global earthquake catalog of Milne (1911). The magnitude of the event was subsequently estimated at magnitude $M ~ 7$ (Soloviev and Go, 1975; Furumoto et al., 1980; Cox, 1985) based on intensity reports, and $M_l ~ 6.8$ (Wyss and Koyanagi, 1992) in comparison with the 1938 Maui earthquake (Fig. 1)—the largest earthquake since the foundation of networks of seismometers at the turn of the century 1899–1900. Furthermore, the Lānaʻi earthquake may have been the third largest earthquake in the state’s history, only exceeded by the 1868 Kaʻu (M~7.9) and 1975 Kalapana ($M_w 7.7$) earthquakes on the Big Island. Nonetheless, the principal focus today upon this 150-year-old temblor is due to its location within the proximity of 80% of Hawaiʻi’s population between Oʻahu and Maui. Furumoto et al. (1990) noted that contrary to conventional wisdom, the earthquakes in the Maui–Oʻahu region are nonvolcanic. Though prevalent within Hawaiʻi’s active volcanos, earthquake swarm activity characteristic of magma migration has not been observed in the region. Rather, earthquake activity distal to the active volcanos is attributed to crustal loading by the dormant volcanos and lithospheric flexure (e.g., McGovern, 2007). In reviewing the seismic hazard indicated by the 1871 Lānaʻi event, its proximity to the Molokaʻi fracture zone (MFZ) (Fig. 1) poses seismological and tectonic implications paralleled by observations of changes in the Hawaiian hotspot track, rate of volcanism, and isotope geochemistry.

This revival of interest in the 1871 earthquake is led by State of Hawaiʻi concerns regarding seismic hazard potential in relation to the ongoing decadal review of U.S. seismic hazard maps. The initial study of the 1871 earthquake (Cox, 1985) was similarly impelled by the formation of a University of Hawaiʻi (UH) Natural Hazards Task Force in the 1980s by the State Office of Civil Defense for studies of the Oʻahu intensities of historic earthquakes (e.g., Cox, 1985, 1986) to investigate the seismic risk zone to which Oʻahu should appropriately be assigned in the building codes of the city and county of Honolulu.

This historical update proceeds from Cox (1985, 1986) and reviews new science augmenting our understanding of the 1871 Lānaʻi earthquake. I focus first on the seismology: intensity–shaking, magnitude–intensity systematics, prediction equations for significant duration of earthquake ground motions, and the MFZ. Based upon this new information, I propose a revised model for the 1871 earthquake which is consistent with the preponderance of evidence.

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Modified Mercalli Intensity

Cox (1986, p. 7) recognized that “Considerable subjective judgment is involved in estimating modified Mercalli intensities (MMIs), and different estimators may come to somewhat different conclusions as to the place-specific intensity of an earthquake even on the basis of the same description of its effects.” Assessments of the intensities reported in the eyewitness account of Alexander (1871) and from newspapers (English and Hawaiian language) from all Hawaiian Islands form the core data source. At the time of the February 1871 earthquake, W. D. Alexander was President of O‘ahu College—now Punahou School—which suffered considerable damage from the earthquake. Educated at Yale (B.A., M.A.), Alexander sent a detailed description of the event within 10 days to J. D. Dana—Editor of the American Journal of Science and Arts, who served as geologist for the 1840 U.S. Exploring Expedition to Hawai‘i and is recognized as an originator of Hawaiian volcanology (Appleman, 1987). Alexander’s observations On the Earthquake at O‘ahu Hawaiian Islands were published by Dana in the journal within months. Two compelling descriptions include:

It was compared by some to the sensation of riding a “bucking mustang”…

The schooner Annie in the channel south of Lanai was terribly shaken and her bulwarks split amidships.

The Cox (1985) intensity assessments were peer reviewed by the UH Task Force—including the Chair of the Department Geology and Geophysics (G&G), Dean of Architecture, Chair of Civil and Environmental Engineering, Director of the Pacific Tsunami Warning Center, two professors of G&G, and a geophysicist within the Hawai‘i Institute for Geophysics—and may be considered as the consensus view of the Hawai‘i seismological community. This distribution of MMI for the 1871 earthquake is plotted in Figure 2. Different assessments from five other studies of 1871 intensities are compared with the detailed study of Cox (1985) in Figure 3. In particular, Wyss and Koyanagi (1992) compared the felt area of the 1871 earthquake with the pattern of intensities associated with the January 1938 Maui earthquake and suggested that the events had a similar location and magnitude (Fig. 2).


The shock of April, 1868, [the great Kā‘u, Mauna Loa earthquake] was very light here, and scarcely noticed by a few, but this one roused up everyone on the island, shook it from vale to peak, and raised and rent its bold, rock ribbed coast. A great portion of the well known bluff, Pali Kaholo, has fallen into the sea, enormous fragments have broken from those towering ocean walls between Manele Bay and Kamaiki Point; masses of the red basalt have been torn from the beetling [e.g., jutting] turrets of Puupehe, the lone sea tower near the southeastern end of the Island; huge

Figure 1. Bathymetric map of the Hawaiian Islands. Island names are in black italics. Thin black lines plot isochrons (Ma) of lithospheric age (Müller et al., 2008), which coalesce along the width of the Molokai’i fracture zone (MFZ). Crossing the MFZ, 85 Ma lithosphere abuts against 100 Ma lithosphere. The proximal location of the 1871 Lāna‘i earthquake (Cox, 1985) is indicated by the solid red (gray) star. The location of Honolulu on O’ahu is designated by the red(gray)-white star. North of Maui the location of the 1938 Maui earthquake (M6.8) is shown by the red(gray)-white circle. The color version of this figure is available only in the electronic edition.
Figure 2. Modified Mercalli intensity (MMI) distribution (white roman numerals) during (a) the 1871 Lāna‘i earthquake (Cox, 1985) and (b) the 1938 Maui earthquake (Wyss and Koyanagi, 1992). Note for the 1938 event, two ships felt intensity V north of the Islands. For the 1871 event, highest intensities (IX and VIII) were experienced on Lāna‘i, East Moloka‘i, and West Maui, whereas for the 1938 earthquake, the highest intensity (VIII) was limited to eastern Maui. Note larger MMI on O‘ahu for the 1871 earthquake, and the more rapid fall-off with distance on Maui and Lāna‘i for the 1938 earthquake. The nominal trend of the MFZ (Fig. 1) is plotted in light blue(gray). See Figure 4 for descriptive MMI values. The color version of this figure is available only in the electronic edition.
boulders have been hurled from the mountain sides, and the ravines are filled with debris of rocks and trees and slides of earth; several great clefts have been opened in different parts of the Island; and it has been shaken and broken as though the mighty elements of the earthquake were surging and upheaving at its very foundations and ready to burst forth with volcanic fury, and convert its lovely valleys once more into flaming, sulfurous crater.

In unpublished notes by Gordan MacDonald in 1973, the Director of the Hawai’i Institute of Geophysics commented on the uncertainty of assigning MMIs “on the basis of descriptions in a century-old newspaper,” noted the tendency of the users to exaggerate the effects of unusual events, and questioned “the possibility of assigning an accurate intensity of at all [sic]” to the 1871 earthquake (Cox, 1985, p. 19). Nonetheless, MacDonald declared regarding the Gazette’s Lāna‘i report: (Cox, 1985, p. 25):

... a single rockfall such as he described on the sea cliffs and valley walls of Lanai would be of little significance.

However, the fall of “a great portion of the well-known bluff, Pali Kaholo” and the extent of the effects on Puu Pehe and the cliffs between Manele Bay and Kamanaike, suggest an intensity of at least VIII, more probably IX, and quite possibly X, even if allowance is made for exaggeration in some of W. M. Go’s descriptions of “ravines filled with debris of rocks and trees and slides of earth;” “Its great clefts...opened up in different parts of the Island”, and other effects.

As observed in Figure 2, the 1938 earthquake may be considered as the lower bound on the magnitude of the 1871 earthquake. Compared with the 1871 earthquake, the 1938 event shows lower intensities on the Islands of Kaua‘i, O‘ahu, Moloka‘i, and Lāna‘i, and greater MMI variance exhibited on Kaua‘i, O‘ahu, Moloka‘i, and Hawai‘i. The magnitude from Gutenberg and Richter (1954) is 6.5. Holman (1982) measured $M_b$ 6.8 and 6.9 from Pasadena and Berkeley seismograms, respectively. Holman (1982) also determined an $M_s$ 6.9 at a period $T = 10$ s, which when corrected to $T = 20$ s (Russell, 2006) yields $M_s$ 6.7 from Berkeley. Combined, the magnitude $M_w \sim 6.8$ for the 1938 event, implying $M_w > 6.8$ for the 1871 Lāna‘i event.

In comparison, Wyss and Koyanagi (1992, p. 60) only report:

Lanai Island VII: Landslides, difficult to stand, stronger than 1868, duration 40 seconds.

The 5 July 2019 $M_s$ 7.1 Ridgecrest, California earthquake provides another basis for interpreting the MMI from the 1871 Lāna‘i earthquake. The U.S. Geological Survey “shakemap” display for the Ridgecrest earthquake is shown in Figure 4, wherein the instrumentally determined intensity (Worden et al., 2012) may be measured as a function of distance from the epicenter. The Ridgecrest MMI values as a function of distance are plotted in Figure 5 for comparison with the intensity-distance data from Cox (1985) for the Lāna‘i earthquake. These data are strong prima facie evidence that the 1871 Lāna‘i earthquake had a magnitude $M_w > 7.1$.

**Intensity Prediction Equations**

Bakun (2006) developed intensity prediction equations (IPEs) relating intensity, distance, and moment magnitude from calibrated earthquakes. Using a training data set of 13 California earthquakes (ranging from 1933 Long Beach to 1999 Hector Mine), and a test data set of five earthquakes $5.9 \leq M_w \leq 7.3$, Bakun (2006) developed a single MMI attenuation model for all of California wherein MMI is a function of $M_w$ and distance in kilometers. Bakun (2006) then successfully applied this relation to 14 “historical” California earthquakes between 1890 and 1927.

Whereas these IPEs are based on California data, they relate to a condition appropriate for California. Nonetheless, similar to ground-motion prediction equations, California relations are applied in other tectonic situations (e.g., Atkinson, 2010). In this spirit, the IPEs distill the relationship of intensity and distance with moment magnitude and may be tested for O‘ahu and Lāna‘i. Applying Honolulu intensities (MMI VI and VII) at a...
distance of ~110 km from Lāna‘i when converted to magnitude yields $M_w$ 7.3 and 8.0, respectively, for the 1871 Lāna‘i earthquake. The proposition that the 1871 earthquake is similar in location and magnitude to the 1938 Maui earthquake (Wyss and Koyanagi, 1992; Klein et al., 2001) may be tested. Using Bakun’s IPEs, the MMI forecast (IV) for Honolulu from a Maui earthquake ($M_s$ 6.8 and 182 km distance) does not match the observed 1871 intensities in Honolulu (VI–VII), thereby prejudicing the claim that the 1871 earthquake had a magnitude and location similar to the 1938 event.

Earthquake Duration and Magnitude

Regarding the timing and duration of the 1871 event, Alexander (1871) states:

In regard to the time Flitner’s astronomical clock stopped at 10 11 17 PM Honolulu mean time allowing for the error of the clock. In regard to the duration of the shock Rev G Williamson, Dr J Hutchinson, Judge Hartwell and

--Source: USGS Shakemap

Figure 4. The distribution of MMI is shown for the 2019 $M_w$ 7.1 Ridgecrest earthquake (6 July 2019 03:19:53 UTC, 35.770° N, 117.599° W, 8.0 km depth) derived from the event’s U.S. Geological Survey (USGS) shakemap plot (Worden et al., 2012). Descriptive MMI values are noted in the legend. The linear trend to the southwest plots MMI measured (numerals) along the trend with distance from the epicenter, and plotted in Figure 5 (see Data and Resources). Bold italic numerals are peak velocity in cm/sec. The color version of this figure is available only in the electronic edition.
Figure 5. This MMI plot of the 1871 earthquake is redrafted from the original in Cox (1985), shown in open black circles. Note that Cox’s MMI uncertainties are ±1 MMI unit. The green(gray) vertical lines show the range of intensities observed for the 1938 Maui earthquake on each Hawaiian Island, indicating greater MMI variance. The red(gray) closed circles plotted were derived from Figure 4 for the 2019 $M_w$ 7.1 Ridgecrest, California, earthquake. The comparison of MMI suggests that the 1871 Lāna‘i earthquake was larger than the $M_w$ 7.1 Ridgecrest event. The color version of this figure is available only in the electronic edition.

one or two others who timed it carefully agree within a few seconds in making it 55 seconds. The general opinion here is that it lasted about a minute, and the same was the case at Lahaina and Hilo.

The astronomical clock mentioned participated in the 1874 transit of Venus (Chauvin, 1993). For the 1938 earthquake, no corroborated event durations were available.

To place this 55 s duration estimate in context with standard ground-motion duration measures, I employ the relationships derived by Kempton and Stewart (2006) from a data set of 73 earthquakes, which provides a reasonable amount of data over a magnitude range of $M_w = 5–7.6$ and closest site-source distance range $r = 0–200$ km. One measure of duration is $D_{0.95}$ from equation (13) of Kempton and Stewart (2006), which is the time interval starting from the initial 5% to the last 5% (i.e., 90% of time interval of duration) of integrated energy output, from which the duration may be approximated as (90% of time interval)/0.9. A shear velocity $V_{530}$ site term for basalt measured by Wong et al. (2011) for Hawai‘i is used. The time interval forecast for an $M_w$ 7.3 earthquake on Lāna‘i at $r = 110$ km distance from Honolulu gives a duration of 37 s, which is significantly shorter than the 55 s felt duration. Assuming the maximum $M_w \sim 8.0$ extrapolated from the IEPs of Bakun (2006) projects a duration of 56 s, which approximates the observation reported by Alexander (1871).

On the basis of the Kempton and Stewart (2006) duration–magnitude–distance relation and the 1871 earthquake corroborated-duration estimate (55 s), the earthquake should be considered to have been larger magnitude ($M_w > 7.3$) and/or more distant (>110 km) from Honolulu. However, increasing the source distance from Honolulu, the forecast MMI is reduced even farther away from that observed.

**MFZ**

The locations of the 1938 $M_w$ 6.8 earthquake and $M_I \geq 4.9$ earthquakes since 1940 near Maui and westward are plotted in Figure 6. The approximate trend line of the Hawaiian ridge volcanism from Laysan Atoll to Kaau’i, extending past Maui, crosses the trend line of the MFZ. Measuring magnetic lineations, Malahoff et al. (1966) were able to track the MFZ crossing the Hawaiian ridge within an ~30-kilometer-wide zone, which includes the earthquake epicenters in Figure 6. The earthquake magnitudes and their distances to the fracture-zone trend are listed in Table 1.

The 1871 earthquake is coincident with several other distinctive geophysical features, established subsequent to Cox (1985). The MFZ has been considered a now-dormant feature (e.g., Anchieta et al., 2011), welding together lithosphere of two ages, where the southern section (100 Ma) is ~15 Ma older than the 85 Ma aged north (e.g., Müller et al., 2008). Tomographic imaging of $P$, $S$, and Rayleigh waves from the Plume-Lithosphere Undersea Melt Experiment (PLUME) array (Wolfe et al., 2009, 2011; Laske et al., 2011) shows the MFZ to be a seismically observable structural feature. Volumetrically, the rate of growth of the Hawaiian ridge volcanic island edifices increased sevenfold in crossing the MFZ (e.g., Bargar and Jackson, 1974; Garcia et al., 2015). The apparent track of the Hawaiian plume bends 20°–30° clockwise southward (Epp, 1984; Wessel and Kroenke, 1997). Abouchami et al. (2005, p. 855) suggest that the coincidence of compositional Pb isotopic transition (Mauna Loa and Mauna Kea) with the bend of the Hawaiian islands chain near Moloka‘i “may be significant.”

**Revised 1871 Earthquake Model: $M_w$ 7.5**

Based upon the evidence presented by (1) MMIs (Cox, 1985; Wyss and Koyanagi, 1992) compared with the 1938 Maui earthquake and 2019 Ridgecrest earthquake, (2) an MMI–magnitude forecast equation (Bakun, 2006), (3) a duration–magnitude forecast equation (Kempton and Stewart, 2006), (4) the seismogenic depth earthquakes observed beneath Maui County by the PLUME array (Anchieta et al., 2011), (5) the abrupt change in elastic material properties manifest at the MFZ between 85 Ma lithosphere adjacent to 100 Ma lithosphere observed by PLUME tomography (Wolfe et al., 2009, 2011; Laske et al., 2011), and (6) the lack of a reported significant tsunami, I have employed the seismic scaling relation...
derived by Strasser et al. (2010) for intraslab lithospheric earthquakes to place limits upon the characteristics of the 1871 fault zone. This model is shown in Table 2 and Figure 7.

The western terminus of the proposed faulting—90 km from Honolulu—produces the strongest shaking in Honolulu. The eastern terminus—150 km from Honolulu—provides for the longer duration of shaking. Faulting predominately in the lithosphere and lower crust is necessary to explain the lack of a reported significant tsunami. Testing the various limits imposed by the observations and scaling relations, a fault with dimensions 73 × 41 km² fits into a seismogenic zone extending to 50 km into the mantle with 1.7 m of average slip—corresponding to an $M_w$ 7.5 earthquake. This model is nonunique, but meets with newly imposed constraints on the earthquake duration, MMI versus magnitude and distance, and MMI observations from the 1938 $M_s$ 6.8 Maui earthquake and 2019 $M_w$ 7.1 Ridgecrest earthquake.

TABLE 1
Earthquakes $M_l \geq 4.9$ within the Footprint of the Moloka‘i Fracture Zone

<table>
<thead>
<tr>
<th>Earthquake Date</th>
<th>Magnitude</th>
<th>Latitude (°)</th>
<th>Longitude (°)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1938/01/23</td>
<td>$M_{GR}$ 6¾ Pasadena</td>
<td>20.920*</td>
<td>−156.362*</td>
</tr>
<tr>
<td>1938/01/23 (relocated)</td>
<td>$M_s$ 6.8 Berkeley</td>
<td>21.020†</td>
<td>−156.090†</td>
</tr>
<tr>
<td>1940/09/02</td>
<td>5.6</td>
<td>21.000*</td>
<td>−155.250*</td>
</tr>
<tr>
<td>1970/10/25</td>
<td>4.9</td>
<td>21.079*</td>
<td>−156.781*</td>
</tr>
<tr>
<td>1976/05/24</td>
<td>4.9</td>
<td>20.995†</td>
<td>−156.362†</td>
</tr>
<tr>
<td>1981/03/05</td>
<td>5.0</td>
<td>21.016†</td>
<td>−156.969†</td>
</tr>
<tr>
<td>1986/04/26</td>
<td>5.0</td>
<td>20.854*</td>
<td>−155.624*</td>
</tr>
</tbody>
</table>

$M_{GR}$ (Gutenberg and Richter, 1954).
†Holman (1982).
Summary

I have reviewed the recent scientific advances that enhance our understanding of the nature and cause of the 1871 Lāna‘i earthquake and its implication for the potential seismic hazard faced by 80% of the state’s population. The event occurred at the nexus of the MFZ with the Hawaiian volcanic ridge, and in proximity with the 1938 $M_s$ 6.8 earthquake and five $M \geq 4.9$ that trend with the MFZ beneath the volcanos. In comparison with the $M_w$ 7.1 Ridgecrest, California, earthquake of 2019, the Lāna‘i earthquake exhibited greater MMIs with distance. Eyewitness corroborated estimates of the duration (55 s) of earthquake shaking are compared with duration–magnitude relations (Kempton and Stewart, 2006) based on 73 earthquakes. A duration of 38 s—modeled for a Lāna‘i earthquake of $M_w \sim 7.5$—is much shorter than the 55 s of strong shaking observed (Alexander, 1871). Invoking the IPE of Bakun (2006), the observed MMI (VI–VII) is consistent with an $M_w \sim 7.5$ fault spanning a distance range of 90–150 km from Honolulu (Fig. 7) along the locus of the MFZ. The lack of a clearly observed, significant tsunami is evidence for lower crust and mantle faulting. Taking into account scaling relations for intraslab earthquakes (Strasser et al., 2010), a hypothetical, revised earthquake source (Table 2) for the 1871 Lāna‘i earthquake—which accords with the seismological observations—is

![Figure 7. Map of the Hawaiian Islands from Maui to Honolulu. The cyan and yellow trends lines are the same as in Figure 6. MMI measured (roman numerals) for the 1871 earthquake (Cox, 1985) are from Figure 2. The bold-dashed white 1871 fault is nominally located within the mantle and lower crust beneath the volcanos, extending between west (W) and east (E). See Table 2 for details. Note that the actual location of the MFZ trend is hypothetical within a zone ~30 km wide, but may be considered within the range shown in Figure 1. The color version of this figure is available only in the electronic edition.](https://pubs.geoscienceworld.org/ssa/srl/article-pdf/doi/10.1785/0220200220/5143319/srl-2020220.1.pdf)

<table>
<thead>
<tr>
<th>Distance to Honolulu</th>
<th>MMI Forecast</th>
<th>MMI Observed</th>
<th>Duration Forecast</th>
<th>Duration Observed</th>
</tr>
</thead>
<tbody>
<tr>
<td>Eastern end, 150 km</td>
<td>VI</td>
<td>VI–VII</td>
<td>50 s</td>
<td>55 s</td>
</tr>
<tr>
<td>Western end, 90 km</td>
<td>VII</td>
<td>VI–VII</td>
<td>40 s</td>
<td>55 s</td>
</tr>
<tr>
<td><strong>Source Scaling</strong></td>
<td><strong>Length</strong></td>
<td><strong>Width</strong></td>
<td><strong>Area</strong></td>
<td><strong>Slip</strong></td>
</tr>
<tr>
<td>Intraslab earthquake</td>
<td>73 km</td>
<td>41 km</td>
<td>3000 km$^2$</td>
<td>1.7 m</td>
</tr>
</tbody>
</table>

an $M_w$ 7.5 lower crustal and lithospheric earthquake along the MFZ beneath Lāna‘i and West Maui with $\sim$1.7 m of fault slip. This seismic event may credibly be considered as the third largest earthquake statewide in Hawai‘i’s history and the largest historic earthquake northwest of the Big Island of Hawai‘i.

**Data and Resources**

The shakemap for the 2019 Ridgecrest earthquake was downloaded from the U.S. Geological Survey (USGS) (https://earthquake.usgs.gov/earthquakes/eventpage/ci38457511/executive, last accessed October 2019). All other data are published in the open literature, and downloadable via GoogleScholar.

**Acknowledgments**

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