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Discovery of a trachyte ignimbrite sequence at Hualālai, Hawaii.

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Discovery of a trachyte ignimbrite sequence at Hualālai, Hawaii.

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Abstract Ignimbrites are common in many intraplate ocean islands but have been missing from the known geological record in Hawaii. During a recent field campaign, the remnants of a trachytic ignimbrite sequence have been discovered at Hualālai volcano, fortuitously preserved from subsequent basaltic lava flow cover. We provide a preliminary description of these deposits, as well as bulk and glass chemical analyses to determine their potential relationship with other nearby trachytes from Pu'u Wa'awa'a (PWW) and Pu'u Anahulu (PA). The results suggest that these ignimbrites are from neither PWW nor PA, but instead may relate to trachytes that are found as maar wallrock blocks some 20 km distant. Therefore, despite being rare overall in Hawaii, the ignimbrites - and more generally trachytes - were probably widespread around Hualālai. Compared to other intraplate ocean islands, the combination of a fast-moving plate, high magma supply and eruption rates underneath Hawaiian volcanoes may explain the scarcity of ignimbrites preserved at the surface. Their presence at Hualālai could reflect unusual conditions of edifice stress during the transition from shield to post-shield volcanism.

Key-words Pyroclastic density currents · ignimbrites · Hawaii · Hualālai volcano · trachyte

Introduction

Ignimbrites (here defined loosely as pyroclastic density current 'PDC' deposits consisting dominantly of a poorly sorted mixture dominated by juvenile pumice and ash, e.g. Branney and Kokelaar 2002) are widespread along arc, back-arc, and continental intraplate regions that erupt evolved magmas (e.g. phonolites, trachytes, rhyolites). Large ignimbrites have also been identified at several oceanic intraplate settings, including at the Canary Islands (Freundt and Schmincke 1995), the Azores (e.g. Duncan et al. 1999), and Cape Verde (Eisele et al. 2015). Along the Canary Islands, this type of volcanic activity has produced many hundreds of km^3 of deposits. Evolved magmas typically erupt in intraplate oceanic islands during post-shield volcanism. Their origin is often attributed to fractional crystallization (±replenishment) of alkalic basalts that produces phonolites or trachytes, and/or mixing of basalts with assimilated sediments or crustal intrusions, which typically yields rhyolites (Freundt and Schmincke 1995; Freundt-Malecha et al. 2001; Hansteen and Troll 2003; Edgar et al. 2007; Sigmarsson et al. 2013).

In Hawaii, exposed volcanic sequences involving evolved magmas are comparatively rare at the surface. Exceptions include the voluminous Pu'u Anahulu-Pu'u Wa'awa'a trachyte flow and cone association at Hualālai, Hawaii (Stearns and Macdonalds 1946), trachyte domes and flows on West Maui (e.g. Pu'u Koae, Mt Eke, Pu'u Launiupoko, Stearns and Macdonald 1942; Velde 1978), and the rhyodacitic Mt. Kuwale flow on Oahu (Van der Zander et al. 2010). To date, however, no ignimbrites have been identified, in contrast with other intraplate sites such as the Canary Islands. Pyroclastic density current deposits recognized at Kilauea are distinct in being basaltic and lithic-rich/juvenile-poor, with an inferred phreatomagmatic origin (McPhie et al. 1990; Swanson et al. 2012). In this brief communication, we describe the first discovery of ignimbrite deposits in Hawaii, at Hualālai volcano. We briefly speculate on the potential for other similar deposits to be buried underneath the recent lava flow cover, and the hazard implications of such eruptions for Hawaii.

Description of deposits

The Pu'u Anahulu (PA) trachyte flow on the north flank of Hualālai is a topographically prominent feature (≤ 260 m from base to top) that has been linked to the nearby trachyte pyroclastic cone of Pu'u Wa'awa'a (PWW; Fig. 1; Stearns and Macdonald 1946; Cousens et al. 2003; Shamberger and Hammer 2006). The Pu'u Anahulu and Pu'u Wa'awa'a trachytes are >100 ka (Clague 1987; Cousens et al. 2003), and by far the oldest subaerial Hualālai rocks exposed (Hualālai's next youngest exposed flows are ~13 ka, Moore et al. 1987).

During recent field work, we identified a previously undescribed tephra sequence on top of the Pu'u Anahulu flow. This sequence was preserved from erosion and weathering at only a few sites (nine locations are described here, cf. Fig. 1), although the base of the deposit still blankets the flatter portions of some of the Pu'u Anahulu flow lobes. The thickest section (preserving the most comprehensive record of the ignimbrite deposits) was trenched about 1.5km from the nearby Pu'u Wa'awa'a trachyte cone (location 1) (Fig. 2a).

The ignimbrite deposits were subdivided into four major eruptive units (EU1-EU4) based on abrupt changes in lithofacies relationships that could be recognized between different outcrops. The grouping into different eruptive units reflect each inferred flow cycle. The Pu'u Anahulu flow underneath the tephra sequence usually consists of holocrystalline (microlites and microphenocrysts) trachyte blocks 10-50 cm in size, enclosed within either (1) a weathered mixture of ash to coarse ash-sized trachyte grains and soil, or (2) a basal pumice-bearing ignimbrite (massive lapilli tuff lithofacies, mLT) containing disrupted lenses of soil, which are interpreted have been remobilized by the ignimbrite (Fig. 2a, Fig. 3c). This ignimbrite (eruptive unit EU1) has a fine ash matrix, and a low abundance of pumice lapilli that reach ~3-4 cm in size at location 1. In addition to soil pods, lenses of fine light gray ash or coarser dark gray ash are abundant near the contact with the blocky surface of the Pu'u Anahulu flow. The presence of remobilized soil at the contact with Pu'u Anahulu blocks suggests that the PDC sequence and Pu'u Anahulu were not produced by the same eruption.

The EU1 ignimbrite is overlain by a cross-stratified unit rich in obsidian and cryptocrystalline trachyte, interbedded with indurated fine ash layers and coarser pumice lapilli beds ('cross-stratified lapilli-ash' xsLT lithofacies, Fig. 2a, Fig. 3b, c, e). This subunit grades into another ignimbrite and together comprise EU2a. EU2b is found at a few locations, and consists of a series of fines-poor diffuse stratified, coarse pumice lapilli beds ('diffuse stratified pumice lapilli-ash' dspLT) that grade into a thinner massive lapilli tuff (mLT) unit (Fig. 3a).

EU3 has a faintly stratified fines-poor coarse ash-rich base (diffuse-stratified lapilli tuff lithofacies dsLT) that is fairly distinctive from other units due to slight changes in color (darker toward the top, Fig. 2a, Fig. 3d, e). At location 1, the top of this unit is dark, highly indurated, and displays small pipe structures that progress into the overlying ignimbrite.

Finally, EU4 has a thin basal subunit composed of coarse pumice ash (normally then reversely graded 'massive coarse pumice ash' mpT) that again transitions into a massive lapilli tuff (mLT) facies. Units EU1, EU2a and EU4 are found in all locations on the PA flows (Fig. 2b). Some locations show low angle imbrication or bed-parallel fabric marked by pumice clasts, typically within the coarser-grained portions of the dsLT and xsLT lithofacies.

Each repeated sequence of a fines-poor, diffuse to cross-stratified unit grading fairly abruptly (usually over <15 cm) into an ignimbrite is interpreted here as a distinct flow unit. Individual flow units aggrade progressively, starting as either granular fluid-based (diffuse-bedded units) or traction-dominated (cross-stratified units) currents that transition into fluid-escape dominated, more dilute current (massive lapilli tuff) (e.g. Branney and Kokelaar 2002; Brown and Branney 2004). The contact between inferred eruptive units is dominantly erosive. Upward increases in induration and pinkish coloration within each main ignimbrite unit could result from partial cementation of the moist tuff as ignimbrites were overridden by the subsequent hot, granular-fluid based PDC currents, or, alternatively, by migration of residual gases after emplacement.

Numerous small pieces of silicified (i.e. composed of pure SiO_2 as verified by Energy-Dispersive Spectrometry) vegetation were found within the EU2 ignimbrite lithofacies. The pieces are generally discontinuous and oriented parallel to PDC stratification, and have an irregular tubular internal structure that suggests they were branches of small trees and brush entrained during PDC emplacement. This interpretation indicates a minimum of a few years between EU1 and EU2. Alternatively, they may be rhizoliths (silicified roots), in which case no inferences about the duration/timing of breaks in activity can be made. A more thorough inspection of the distribution, orientation and state (e.g. fragmented or continuous in the tuff) of this silicified material is required to constrain the time gap between the first two eruptive units.

Nature and origin of pyroclasts

Pyroclasts collected from the different units are almost exclusively trachytic microvesicular pumice, obsidian, and poorly vesicular cryptocrystalline grains (Plate A1 in the Supplementary Material). Crystalline clasts are strongly dominated by flow-aligned alkali feldspar, and are mostly phenocryst-free. A few ash particles of submillimeter non-vesicular microcrystalline basalts were found in thin sections of EU1 and EU2 material, but not in the overlying units.

Glasses within pumice, obsidian and cryptocrystalline clasts were analyzed using the electron microprobe (see Supplementary Material for analytical conditions and corresponding data table) to (1) verify their composition and (2) assess their origin. Only domains that displayed less than about 10% microlites were analyzed to avoid glasses overly modified by syn-eruptive crystallization. The glass analyses were compared to four Hualālai trachyte groups previously analyzed for bulk composition using XRF (Cousens et al. 2003; Shamberger and Hammer 2006): the Pu'u Wa'awa'a pyroclastic cone, the Pu'u Anahulu flow, and the trachytes of Waha Pele (found as lithic blocks co-erupted with recent basalt) and Huehue (extracted from a water well). Hualālai ignimbrite glass analyses were also compared to glass analyses from Pu'u Wa'awa'a pyroclasts (obsidian and pumice with <10% microlites).

Despite their generally similar major element compositions within the array of eruptives at Hualālai (Fig. 4a), the four main trachyte groups show subtle differences in bulk chemistry (Fig. 4b, c and d). Somewhat surprisingly, the PDC glass compositions are distinct from nearby Pu'u Wa'awa'a or Pu'u Anahulu trachytes, and much more similar to the Waha Pele blocks, found nearly 20 km to the south. At 103 ka, the Waha Pele trachyte is substantially younger than the Pu'u Anahulu flow (114 ka), and probably derives from an effusive eruption as well (Cousens et al. 2003). Therefore, although the Hualālai ignimbrites and the Waha Pele blocks may have originated from the same subsurface magma reservoir, they likely represent different eruptions or, at least, different eruptive phases. We also note a subtle compositional change from EU1 to EU5. The early PDCs have lower MgO and TiO_2 and higher alkali contents compared to the later PDC phases. The later phases are also most similar to the Waha Pele compositions. The magma feeding the Hualālai ignimbrites may have therefore been slightly chemically zoned. In this scenario, effusion of Waha Pele trachytes would have followed the eruption of Hualālai ignimbrites.

Eruption style

With so few outcrops, our record of stratigraphic variations within this ignimbrite sequence is naturally incomplete. Therefore, making inferences about deposit area, thickness and volume, which may help characterize the intensity of the eruption(s) that produced the Hualālai ignimbrites, is not warranted at this point.

Nevertheless, a few observations can be made based on the nature of the deposits and the pyroclast characteristics. The trachyte composition of all analyzed PDC grains and the general lack of basaltic wallrock within the eruptive units suggests that the Hualālai ignimbrite eruptions were dominantly magmatic, with little involvement of external water. These PDCs are therefore different in nature from the other instances of density current deposits found in Hawaii, which are typically generated during phreatomagmatic activity (Swanson et al. 2012). The presence of substantial amounts of non- or poorly-vesicular obsidian and cryptocrystalline material along with the erupted pumice at the base of each PDC unit may be linked with the disruption of a cryptodome or dense conduit plug (i.e. Vulcanian activity). A broad range of relative vesicularities and crystallinities is consistent with a mixture of plug material that was accompanied by subsequent emission of highly vesicular pumice during a more intense eruption phase (e.g. Hoblitt and Harmon 1993; Giachetti et al. 2010). Thorough pyroclast componentry, grain-size and density analyses are required to verify this hypothesis.

Implications for trachyte volcanism at Hualālai and on the Island of Hawaii

Widespread trachytes under Hualālai

The possible cogenetic relationship between the Waha Pele trachyte and the ignimbrites described herein would imply that trachytic PDCs may have covered a large area of Hualālai volcano. Gravity studies by Moore et al. (1987) and Kauahikaua et al. (2000) also support the idea of voluminous trachyte deposits underneath the <13ka basalt cover. These studies showed that Hualālai differs from other nearby volcanoes in lacking clear high gravity anomalies that are typically associated with rift zone intrusives and cumulate bodies. Instead, most of the western and northern regions of Hualālai display low gravity anomalies (cf. Figure 8 in Denlinger and Morgan 2014). Given that Hualālai possesses rift zones and cumulate bodies similar to those of neighboring volcanoes (e.g. Shamberger and Hammer 2006), the low gravity anomalies must represent significant volumes of low density material under the recent basalt. As proposed by

Moore et al. (1987), this low density material may be trachyte. Our finding that trachyte PDCs may have mantled a large area of Hualālai agrees well with gravity observations, and lends further support to the idea of widespread 90-120 ka trachyte under the alkali basalt cap.

The compositional variability of the different Hualālai trachytes could be attributed to (1) chemical zoning in a large magma reservoir, (2) at least four different small trachyte reservoirs scattered underneath Hualālai, or (3) delays between eruptions that would allow trachyte magma to differentiate. The second hypothesis appears the most realistic simply because the chemical differences between the different trachytes are not easily accommodated by either simple fractionation models involving a single differentiating magma (e.g. Cousens et al. 2003), or magma mixing models involving two magma end-members (i.e. the four Pu'u Anahulu, Pu'u Wa'awa'a, Huehue, Waha Pele bulk compositions do not line up on a unique fractional crystallization or mixing trend, Fig. 4).

Why then, did Hualālai erupt uncharacteristically large volumes of trachytes compared to other Hawaiian volcanoes? The unusual timing of trachyte production and eruption, both occurring prior to the post shield stage of Hualālai, may indicate unusual conditions of crustal stress, volcanic load and/or rift-zone organization. Such special conditions may be brought about by accelerated edifice slumping or large-scale collapses (e.g. Denlinger and Morgan 2014). The timing of the North Kona slump on the western submarine side of Hualālai (≥130ka, Moore and Clague 1992), and the Alika landslides – produced by collapse(s) of Mauna Loa (~112-128 ka, McMurtry et al. 1999) – roughly coincide with the onset of trachyte volcanism at Hualālai. Whether these events may have influenced the structure and/or stress conditions of subaerial Hualālai directly remains to be demonstrated. Further higher spatial resolution gravity surveys of the area may help determine whether the subsurface distribution of trachytes is coherent with eruptions controlled by regional volcano tectonics.

Occurrence of ignimbrites in Hawaii

The relative scarcity of ignimbrites in the geological record of Hawaii compared to other locations such as Atlantic ocean islands is probably due to a combination of several factors. Hawaii is the earth's most active hotspot, with a high magma supply rate, underlying a fast-moving plate. Potentially, the high magma supply, even after a volcano enters its post-shield stage, prevents large volumes of magmas from differentiating and reaching trachyte compositions (e.g. Shaw 1985, Clague 1987), favoring instead the formation of large volumes of alkali basalts with subordinate hawaiites, mugearites and benmoreites (Spengler and Garcia 1988; Frey et al. 1990, Sherrod et al. 2007). In contrast, lower supply rates and slower-moving plates at Atlantic hotspots may allow large bodies of magmas to differentiate and erupt as large ignimbrite sheets.

Another consequence of the high magma supply and eruption rates in Hawaii is that volcanoes such as Hualālai can be completely resurfaced by lava flows in a matter of <15 thousand years (Moore et al. 1987). Therefore, exposure of ignimbrites at the surface is also less likely in Hawaii than at other locations where resurfacing rates are substantially slower. As a result, the smaller-volume, thinner Hawaiian ignimbrites may simply be hard to detect.

Hazard implications

The ignimbrites described here are probably of much smaller volume than those that erupted at other ocean islands such as those in the Canaries, which often reach several tens of meters in thickness (e.g. Freundt and Schmincke 1995; Troll and Schmincke 2002; Brown and Branney 2004; Smith and Kokelaar 2013). Nonetheless, the Hualālai ignimbrites were probably voluminous and widespread enough to cause significant regional destruction. This type of event is not likely to occur in the future around Hualālai, because trachyte volcanism appears to have stopped at about ~92 ka. Such eruptions are still nevertheless possible at other Hawaiian volcanoes (e.g. Mauna Loa, Mauna Kea), since trachytes seem to erupt both in between the shield and post-shield volcanic stages (Hualālai), and during the late post-shield stages (Kohala, Island of Hawaii, and West Maui, Island of Maui).

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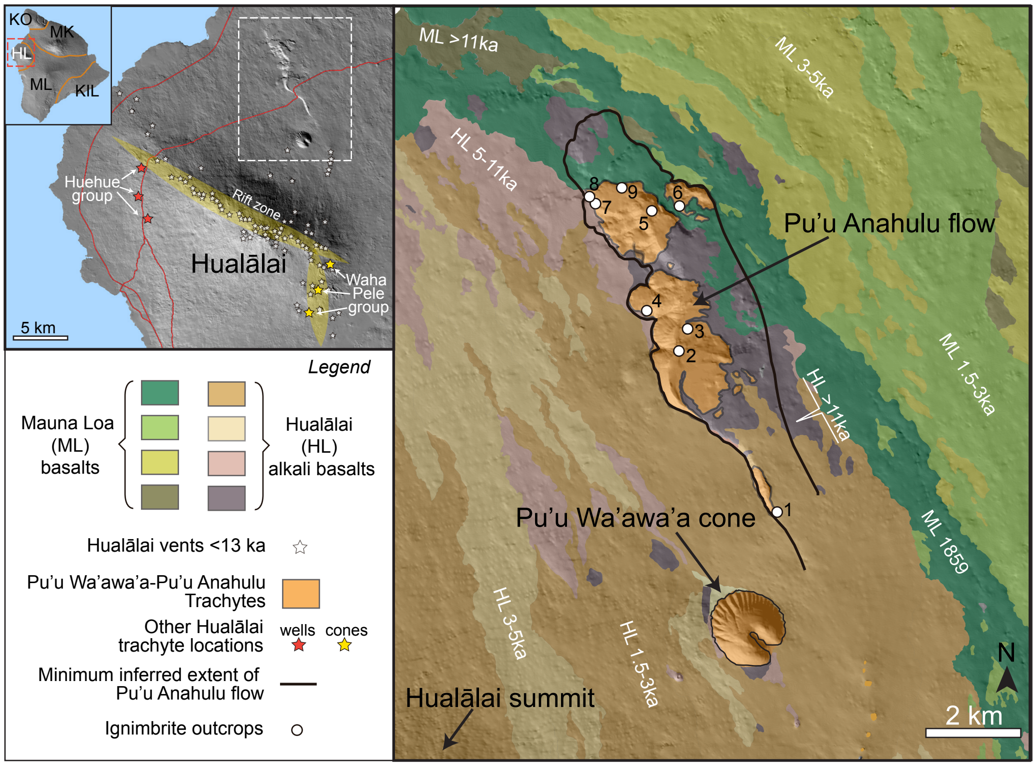
Fig. 1 Geological setting of Hualālai ignimbrites. (Left) Digital elevation model of Hualālai volcano with prominent trachyte exposures (Pu’u Wa’awa’a cone and Pu’u Anahulu flow) on northern flank. Yellow stars show the location of other trachyte blocks found as lithics in more recent basaltic products (’Waha Pele group’), red stars mark the location of wells in which trachyte was recovered (’Huehue group’) (cf. Cousens et al. 2003). (Right) Geological map of the Pu’u Wa’awa’a-Pu’u Anahulu area (modified from Sherrod et al. 2007). Only certain areas of the Pu’u Anahulu trachyte remain uncovered by <13 ka post-shield activity. Numbers refer to main stratigraphic locations described in the text.

Fig. 2 (a) Stratigraphic column of pyroclastic density current deposits at location 1. Lithofacies nomenclature used follows Branney and Kokelaar (2002), m=massive, LT=lapilli-tuff or lapilli-ash, p=pumice, ds=diffuse-stratified, xs=cross-stratified, lensL=pumice lapilli lens. Lithofacies were grouped into eruptive units EU1-EU4 (see text for explanation). (b) Variations in PDC stratigraphy across the different locations, ordered arbitrarily by distance from the Hualālai summit. Stratigraphy and lithofacies are here represented as simplified patterns, along with information pertaining to lithofacies contact, state of induration and stratification.

Fig. 3 Field photographs of the Hualālai ignimbrite sequence. (a) EU1 ignimbrite and EU2a eruptive unit with a stratified to cross-stratified fine lapilli base interbedded with fine ash beds that transitions into the overlying ignbimrite. The color transition is fairly abrupt but clasts from EU2 base clearly continue into the massive lapilli tuff. (b) Unit EU2b with coarse lapilli-rich and diffuse-stratified basal lithofacies displaying a clear pinch-and-swelling character. Note the abrupt color and grain size transition between the fines-poor pLT base and the underlying EU2a ignimbrite. (c) Faulted/deformed sequence with diffuse-stratified, normally then inverse-graded EU3 base with dark-colored indurated layer and two pipe structures. The dsLT lithofacies grades progressively into a mLT. (d) A slightly more distal location with somewhat diffuse, discontinuous Pu’u Anahulu paleosoil pods within EU1 ignimbrite. (e) Contact of the PDCs with substrate and pinching-swelling behavior. Interaction of the current with small-scale topography (the trachyte blocks from underlying Pu’u Anahulu flow) results in much thinner EU1 and EU2 deposits (marked by two arrows).

Fig. 4 Geochemical characteristics of Hualālai trachytes. (a) Bulk compositions of all Hualālai products (blue symbols and orange field) showing the clear gap in composition between erupted lavas. (b), (c) and (d) Major-element plots of Pu’u Wa’awa’a and Hualālai ignimbrites glasses, compared with bulk analyses of Pu’u Wa’awa’a (PWW), Pu’u Anahulu (PA), Waha Pele (WP) and Huehue (HH) samples (PWW and PA compositions are from an upcoming study, WP and HH from Cousens et al. 2003). Error bars show average standard deviations for both glass and bulk analyses. Gray arrows are differentiation paths for fractional crystallization of different mineral phases typical of the Hualālai trachytes (An=anorthoclase; Ox=oxide; Bt=biotite; Ol=olivine). Note that SiO_2 and MgO are usually lower and the alkalis higher in glasses from PWW pyroclasts (green triangles) when compared with their bulk compositions (blue field). This is because most samples analyzed are not 100% glassy (at least a few microlites are always present). Similar differences are observed between Hualālai ignimbrite glasses (yellow, orange and red circles) and Waha Pele bulk compositions (purple field).

Figure 1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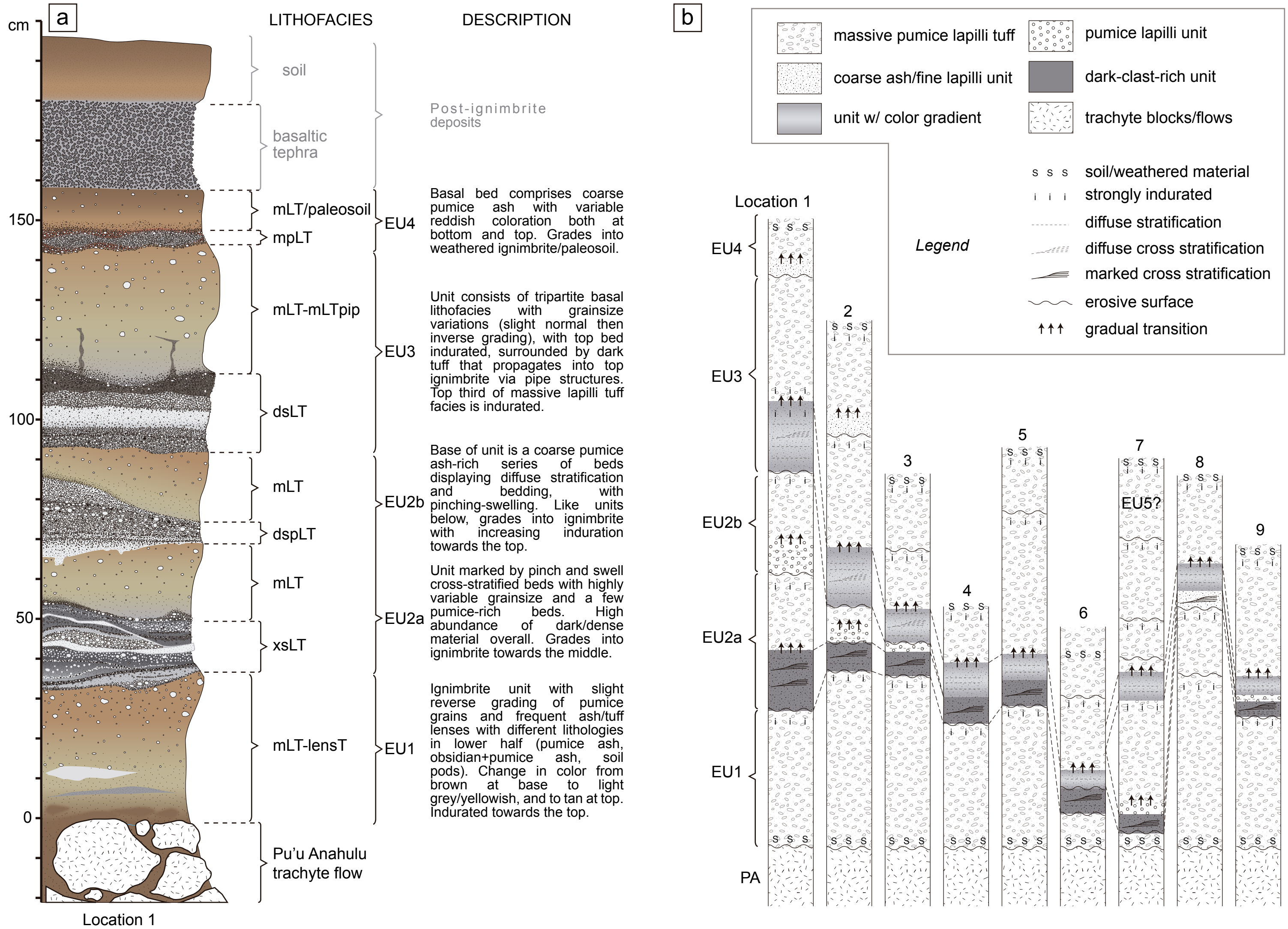
Mauna Loa (ML) basalts
Hualālai (HL) alkali basalts
Hualālai vents <13 ka
Pu'u Wa'awa'a-Pu'u Anahulu Trachytes
Other Hualālai trachyte locations
wells
cones
Minimum inferred extent of Pu'u Anahulu flow
Ignimbrite outcrops
ML >11ka
ML 3-5ka
HL 5-11ka
Pu'u Anahulu flow
ML 1.5-3ka
HL >11ka
Pu'u Wa'awa'a cone
ML 1859
HL 3-5ka
HL 1.5-3ka
Hualālai summit
N
2 km

Figure 2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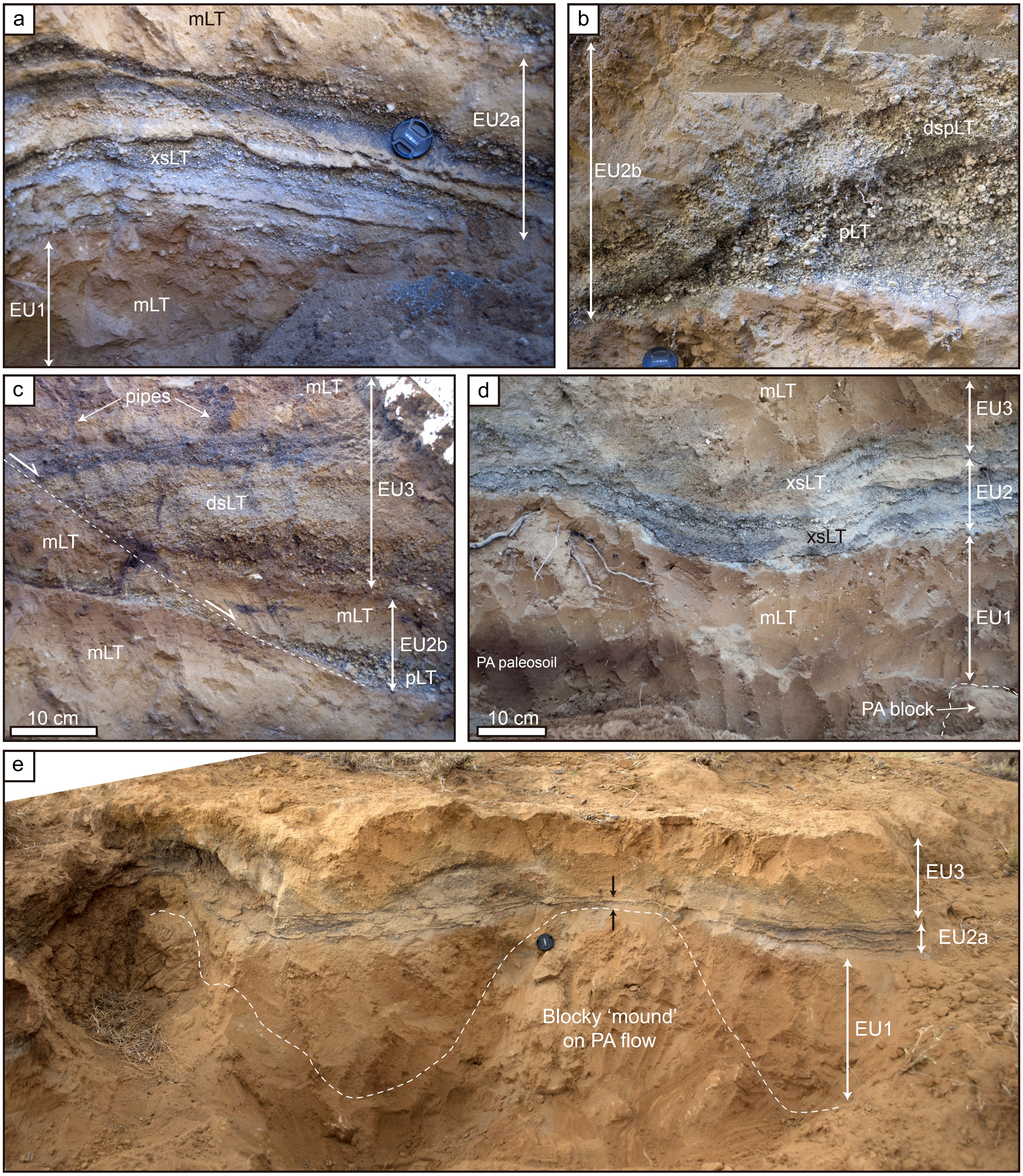
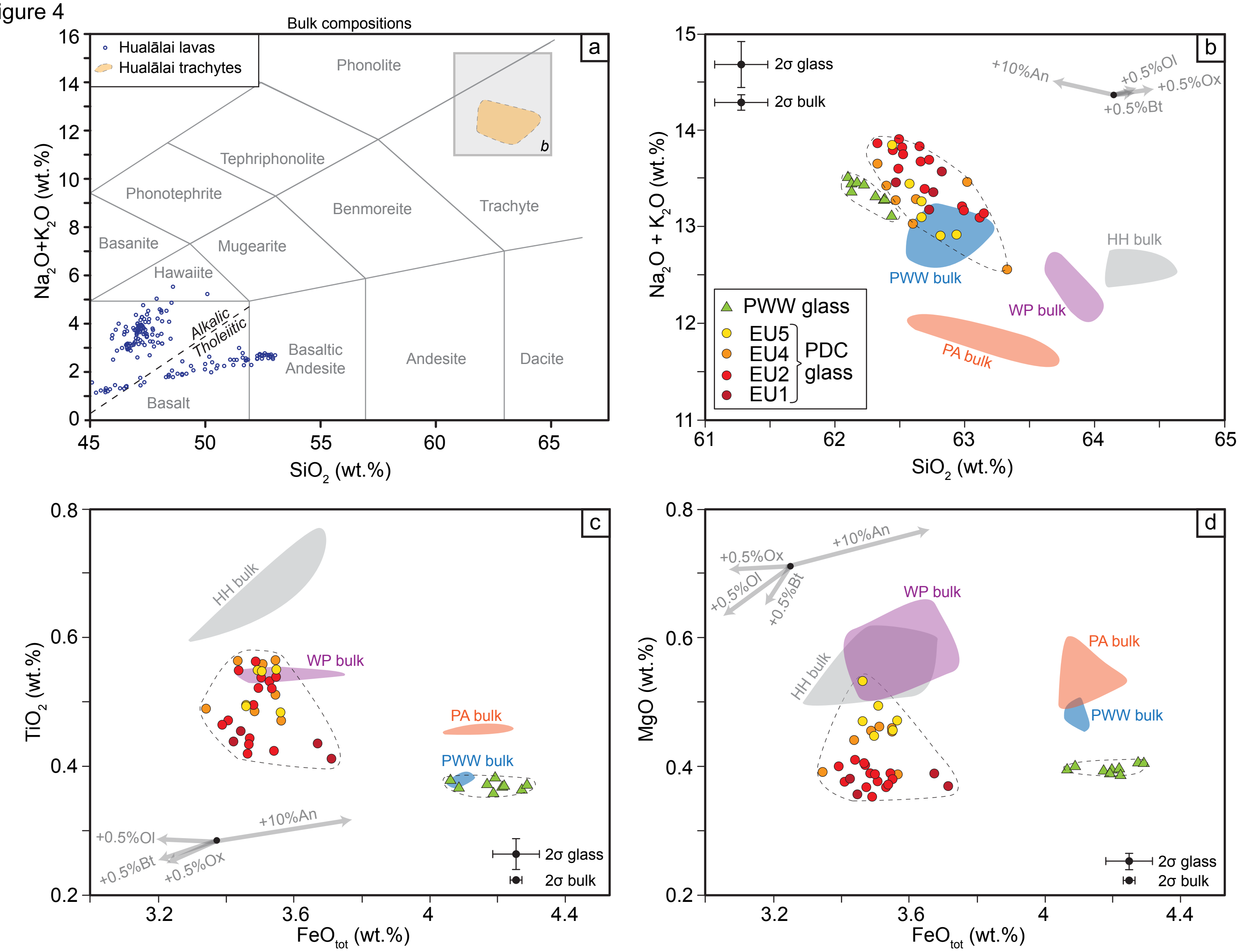
LITHOFACIES
DESCRIPTION
soil
basaltic tephra
Post-ignimbrite deposits
mLT/paleosoil
mpLT
EU4
Basal bed comprises coarse pumice ash with variable reddish coloration both at bottom and top. Grades into weathered ignimbrite/paleosoil.
mLT-mLTpip
dsLT
EU3
Unit consists of tripartite basal lithofacies with grainsize variations (slight normal then inverse grading), with top bed indurated, surrounded by dark tuff that propagates into top ignimbrite via pipe structures. Top third of massive lapilli tuff facies is indurated.
mLT
dspLT
EU2b
Base of unit is a coarse pumice ash-rich series of beds displaying diffuse stratification and bedding, with pinching-swelling. Like units below, grades into ignimbrite with increasing induration towards the top.
mLT
xsLT
EU2a
Unit marked by pinch and swell cross-stratified beds with highly variable grainsize and a few pumice-rich beds. High abundance of dark/dense material overall. Grades into ignimbrite towards the middle.
mLT-lensT
EU1
Ignimbrite unit with slight reverse grading of pumice grains and frequent ash/tuff lenses with different lithologies in lower half (pumice ash, obsidian+pumice ash, soil pods). Change in color from brown at base to light grey/yellowish, and to tan at top. Indurated towards the top.
Pu'u Anahulu trachyte flow
Location 1
b
massive pumice lapilli tuff
pumice lapilli unit
coarse ash/fine lapilli unit
dark-clast-rich unit
unit w/ color gradient
trachyte blocks/flows
Legend
soil/weathered material
strongly indurated
diffuse stratification
diffuse cross stratification
marked cross stratification
erosive surface
gradual transition
Location 1
2
3
4
5
6
7
8
9
EU5?
EU4
EU3
EU2b
EU2a
EU1
PA

Figure 3



a
mLT
EU2a
xsLT
EU1
mLT
b
EU2b
dspLT
pLT
c
pipes
mLT
EU3
dsLT
mLT
mLT
EU2b
mLT
pLT
10 cm
d
mLT
EU3
xsLT
EU2
xsLT
mLT
EU1
PA paleosoil
PA block
10 cm
e
EU3
EU2a
Blocky 'mound' on PA flow
EU1

Figure 4



Bulk compositions
Hualālai lavas
Hualālai trachytes
a
Phonolite
Tephriphonolite
Phonotephrite
Benmoreite
Trachyte
Basanite
Mugearite
Hawaiite
Alkalic
Tholeiitic
Basaltic Andesite
Andesite
Dacite
Basalt
b
Na_2O+K_2O (wt.%)
SiO_2 (wt.%)
2σ glass
2σ bulk
+10%An
+0.5%Ol
+0.5%Ox
+0.5%Bt
HH bulk
PWW bulk
WP bulk
PA bulk
PWW glass
EU5
EU4
EU2
EU1
PDC glass
$Na_2O + K_2O$ (wt.%)
c
TiO_2 (wt.%)
FeO_{tot} (wt.%)
d
MgO (wt.%)