Thicknesess and Density-Current Velocities of a Low-Aspect Ratio Ignimbrite at the Pululagua Volcanic Complex, Ecuador, Derived from Ground Penetrating Radar

by

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A thesis submitted in partial fulfillment of the requirements for the degree of Master of Science Department of Geology College of Arts and Sciences University of South Florida

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Date of Approval: June 8, 2007

Keywords: Pyroclastic flow, pyroclastic surge, Northern Volcanic Zone, South American Magmatic Arc, caldera

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Acknowledgements

I would like to offer many thanks to each of my committee members, Dr. Chuck Connor, Dr. Sarah Kruse, and Dr. Diana Roman, for guidance and support during my time at USF. Thank you to Paul Silva and Sussane Ettinger for their help during the field session. Thank you to my friends at USF for their time, assistance, and support concerning all aspects (academic and personal) of the master’s process. To my family and friends who are spread throughout the country, thank you for your words of encouragement. It has been a pleasure.
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Thickneses and Density-Current Velocities of a Low-Aspect Ratio Ignimbrite at the Pululagua Volcanic Complex, Ecuador, Derived from Ground Penetrating Radar

John A. Petriello, Jr.

ABSTRACT

The thinning trend of a low-aspect ratio ignimbrite (LARI) in a direction of increasing topographic relief at the Pululagua Volcanic Complex, Ecuador, is established by correlating continuous ground penetrating radar (GPR) profiles and radar reflector behavior with stratigraphic measurements and unit behavior. Minimum density-current and vertical (cross-sectional) velocity analyses of the LARI's parent pyroclastic density-current are performed by analyzing the exchange of kinetic energy for potential energy in an upslope direction. Continuous GPR profiles were acquired in a direction of increasing topographic relief with the intent of identifying the LARI within the GPR record and examining the relationships between the LARI and the underlying paleo-topographical surface. Stratigraphic measurements recorded throughout the field area demonstrate that the LARI thins 7.5 m in an upslope direction (over 480 m distance and 95 m elevation). Stratigraphic measurements enable correlations with GPR profiles, resulting in LARI identification. By utilizing GPR derived paleo-topographical surface elevations, minimum flow velocities of the LARI-producing parent pyroclastic density-current at the base of upslope flow are shown to be at least 25 m/s. Vertical velocity analyses based on the identification of internal GPR reflectors, interpreted as flow streamlines, yield
pyroclastic surge-like cross-sectional velocity profiles of the LARIs parent density-current. Maximum density-current velocities at the base of upslope flow reach 24 m/s and diminish toward the base of the current.
Chapter 1

Introduction

An ignimbrite is a pyroclastic deposit composed predominantly of pumiceous material, emplaced as a hot, sediment-laden flow (Walker et al., 1980; Walker, 1983). Differences between conventional ignimbrites (high-aspect ratio ignimbrites or HARIs) and less well understood low-aspect ratio ignimbrites (LARIs) imply behavioral variations within their parent pyroclastic density-currents. The conventional ignimbrite-forming current is thought to be largely controlled by pre-existing topography, as indicated by relatively thick deposits that tend to pond in topographic depressions (Walker et al., 1980; Walker, 1983; Valentine, 1987; Druitt, 1998). The tendency of LARIs to thinly mantle pre-existing topography, combined with the identification of LARIs in areas of high relief, has led to the deduction that their parent pyroclastic density-currents are minimally influenced by pre-existing topography and are capable of surmounting substantial topographic barriers (Fig. 1) (Walker et al., 1980; Walker, 1983; Valentine, 1987; Druitt, 1998).
Figure 1: High- and low-aspect ratio ignimbrite topographical relations; VP-valley pond, typical of high aspect ratio ignimbrites (HARIs); IVD-ignimbrite veneer deposit, typical of low aspect-ratio ignimbrites (LARIs) (modified from Walker et al., 1980).

Agreement exists about several aspects of LARI formation. LARIs tend to form during eruptions where high discharge rates are maintained for limited periods of time, are often initiated by the collapse of an eruption column, and during transport their parent flows are extremely mobile, potentially reaching velocities of 300 m/s (Druitt, 1998; Valentine, 1987). The transport and emplacement mechanisms of LARI-forming pyroclastic currents are poorly understood. Discrepancies largely revolve around the nature of transport (dominantly turbulent vs. dominantly laminar) and the ability of the flow to surmount topographic obstacles, dependent upon the thickness of the flow (expanded vs. concentrated) (Valentine, 1987; Wilson, 1985; Fisher et al., 1993; Druitt, 1998).

Here I present a case study addressing the nature of LARI-thinning in a direction of increasing topographic relief with corollary velocity analyses based on thinning observations. A pyroclastic flow emplaced during a caldera-forming episode at the Pululagua Volcanic Complex (PVC), Ecuador, (Papale and Rosi, 1993; Andrade, 2002, 2006) is explored via stratigraphic observations and ground-penetrating radar
investigations. The nature of thinning of the pyroclastic flow in a direction of increasing topographic relief is explored by correlating stratigraphic measurements with continuous ground-penetrating radar (GPR) profiles of the deposit. The utilization of GPR allows for mapping in areas where the LARI cannot be directly observed (Davis and Annan, 1988; Russel and Stasiuk, 1997).

GPR reflection profiles of the LARI-covered slope were recorded approximately parallel and normal to the inferred direction of flow. The unique capability of GPR makes it possible to identify reflectors both within the deposit and bounding the deposit, and thus trace these reflectors as the deposit climbs the underlying paleo-topography. Interpretation of these reflectors as both flow contacts and bedding horizons within the flow allows estimation of flow velocity as a function of flow thickness and depth of the bedding horizons within the unit. The majority of velocity analyses were performed using GPR data collected on profiles that climb the topographic slope, roughly parallel to the inferred flow direction.
Chapter 2

Low-Aspect Ratio Ignimbrites

The aspect ratio of a rock unit is defined as $T/D$, where $T$ represents the average thickness, and $D$ represents the diameter of a circle covering the same planimetric area as the unit (Walker, et al., 1980; Walker, 1983; Peterson and Tilling, 2000). The classification of a rock unit using the aspect ratio is a means of quantifying and comparing unit geometry, and in this case is pertinent to ignimbrite deposits. Aspect ratios of ignimbrites have been shown to vary between roughly $10^{-2}$ and $10^{-4}$; values approaching the former are known as high-aspect ratio ignimbrites (HARI), and those approaching the latter are known as low-aspect ratio ignimbrites (LARI) (Walker, 1983). Thus, the aspect ratio is a way of describing flow mobility independent of deposit volume. Using map data from Andrade (2000), the aspect ratio of the pyroclastic flow deposit at the Pululagua Volcanic Complex is calculated to be between $10^{-3}$ and $10^{-4}$, approaching the LARI classification.

Traditionally the term *ignimbrite* has been restricted to the depositional product of a pyroclastic flow, and it is in this sense that it will be used here. The term *pyroclastic flow* is typically used to refer to the highly sediment-concentrated end-member of the pyroclastic density-current spectrum, the dilute end-member being pyroclastic surge. Fundamental differences between the pyroclastic density-current end-members are recognized. Recognition of end-member variations is largely deduced from eyewitness accounts of eruptions and from deposit studies (Anderson and Flett, 1903; Lacroix, 1904;
Fisher, 1993; Druitt, 2002). Pyroclastic flows typically have solids concentrations on the order of tens of volume percent, have a free surface above which the solids concentration sharply diminishes, and transport material through a variety of mechanisms, including particle-particle contact, fluidization support, matrix support, dispersive pressure, and buoyancy (Wilson and Houghton, 2000). Most mass and momentum are carried in the basal current, resulting in higher basal velocities than the overriding cloud (Fig. 2) (Wilson and Houghton, 2000). Pyroclastic surges contain less than 0.1 to 1% volume solids, are density stratified, with higher particle concentrations near the ground surface, and transport material primarily through turbulent suspension (Wilson and Houghton, 2000). Mass and momentum in surges are more evenly distributed, therefore basal concentrations of material are derived from sedimentation from the current, and basal velocities are slower due to ground friction (Fig. 2) (Wilson and Houghton, 2000). Turbulence is not a principle support mechanism in pyroclastic flows, although it may or may not be present (Wilson and Houghton, 2000).

Figure 2: Pyroclastic density-current cross-sections. Schematic velocity and density cross-section through the dilute end-member (pyroclastic surge) and the concentrated end-member (pyroclastic flow) (modified from Wilson and Houghton, 2000).
Classification of an ignimbrite as HAR or LAR type has implications beyond unit geometry. Unit aspect ratios are influenced, and give clues about, pre-existing topography, initial eruptive conditions, and transport and emplacement mechanisms. Pyroclastic flows producing HARIs are often confined by topographically bounded valleys and plains and the resulting deposit is a relatively thick unit, varying between approximately 10 and 1000 meters (Walker et al., 1980; Dade, 2003). The tendency to pond in topographic depressions, occurrence as a relatively thick deposit, and the presence of a horizontal or gently sloping upper depositional surface are common criteria used to distinguish HARIs from other pyroclastic deposits (Walker et al., 1980). Conversely, pyroclastic flows yielding LARIs appear to be minimally controlled by pre-existing topography, and the resultant deposits are dominated by a thin, landscape mantling veneer deposit (Walker et al., 1980). LARIs have been observed resting on slopes of up to 30 degrees, with an upper surface nearly parallel to the underlying surface (Walker et al., 1980). Thus, HARIs highly alter the pre-existing landscape, essentially erasing evidence of pre-existing topography, and are concentrated in topographic lows, while LARIs tend to mimic the landscape, maintaining pre-existing topography, and have the ability to mantle steep slopes. An implication of LARI slope characteristics is that a LARI-producing flow can literally climb topographic obstacles, a phenomenon that does not occur in a HARI-producing flow. It must be noted that valley-ponding is associated with LARI (Walker et al., 1980; Walker, 1983); however, the majority of the LARI consists of the veneer deposit connecting isolated valley-ponded regions (Fig. 3).
Deviations in LARI characteristics from those of more common ignimbrites (HARIs) are thought to reflect initial eruptive conditions. It is believed that LARIs form during eruptions where high discharge rates are maintained for limited periods of time (Druitt, 1998). As the eruption column ascends into the atmosphere, a dynamic interplay between column velocity, water content, air entrainment, and particle sedimentation determine the fate of the column. If at the point when the velocity of the column approaches zero, the density of the column exceeds that of air, the column will collapse to form laterally flowing density currents (Druitt, 1998). It is typically this phenomenon that induces ignimbrite deposition.

A source of debate within the LARI literature concerns transport mechanisms of the pyroclastic flow after column collapse, largely concerning the state of the flow as it moves across the landscape, either as an expanded flow that is thicker than the topographic obstacles it traverses, or as a dense flow that moves as a ground-hugging
sheet across the landscape. In the expanded flow model, the ability of a flow to traverse topographic obstacles is attributed to large flow thickness relative to the topographic obstacle (Fisher et al., 1993, Valentine, 1987, Druitt, 1998). In the dense flow model, this ability is due to the high momentum of the flow (Wilson, 1985, Druitt, 1998). The ability to image a LARI with high resolution GPR data may help differentiate between these transport mechanisms.
Chapter 3

Pululagua Volcanic Complex

The Pululagua Volcanic Complex (PVC) is located in the Northern Volcanic Zone of the South American magmatic arc (Fig. 4) (Barberi et al., 1998). The caldera is about 15 km north of Quito, Ecuador (Fig. 5). The PVC is defined by an eruptive center (3 x 2 km caldera), syn-caldera deposits, and pre- and post-caldera domes and dome deposits (Fig. 6) (Papale and Rosi, 1993). The volcanic history of the PVC has been broken into four series by Andrade (Andrade 2002, 2006): Series I is represented by old pre-caldera domes and deposits, Series II is represented by young pre-caldera domes and deposits, Series III is represented by syn-caldera deposits, and Series IV is represented by post-caldera domes and deposits. The lowermost portion of Series III deposits (inception of the syn-caldera phase) have previously been studied in detail by Papale and Rosi (1993) and Volentik et al., (2005, 2006).

The syn-caldera phase comprised at least ten eruptive episodes that led to caldera collapse (Papale and Rosi, 1993). Stratigraphy of the Pululagua caldera-forming eruptions has been compiled by Papale and Rosi (1993), in which the entire sequence is divided into lower, middle, and upper units, based on deposit thicknesses and inferred eruption intensities. The LARI studied here is located in the upper portion of the middle eruptive units (near U6 & U7) as defined by Papale and Rosi (1993) (Fig. 7). The identification of additional eruptive units led Andrade (2002) to divide the Series III sequence into four episodes, each delineated by a thin bioturbated ash layer and dated
using carbonized wood. The basal portion of Episode 1 has been dated at 2575±45 yBP, while the lowermost Series IV unit (directly overlying the uppermost Episode 4 ash layer) has been dated at 2240±50 yBP (Andrade, 2002), constraining the duration of the caldera-forming phase. The LARI lies within Episode 4, in which a radiocarbon date at the base has yielded 2460±70 yBP (Andrade, 2006).

Depositional sequences and unit thicknesses within the four syn-caldera episodes vary according to geographic location and proximity to the eruptive center. The low-aspect ratio ignimbrite that is the focus of this study is located in Episode 4 as defined by Andrade (2002, 2006) and the upper portion of the middle eruptive units as defined by Papale and Rosi (1993); therefore it is a product of late-stage caldera forming events. This pink pumice and ash-rich deposit is largely concentrated in the northeast, east, south, and southeastern portions of the caldera. Deposits in the north, northwest, and southwest are generally confined to topographic lows. In the areas of greatest concentration the unit is seen mantling the surface, in cases having been deposited while the flow was traveling uphill. Thicknesses measured in the south vary between 2-9 meters. In contrast, thicknesses in the north and west vary between 7-30 meters (Andrade 2002, 2006). The field area for this study is located to the south of the caldera, largely because this area is much more accessible for geophysical surveys and stratigraphic sections are exposed in quarry walls and erosional gullies.
Figure 4: Map of Western Ecuador. Blue circles- cities; Red triangles-volcanoes. Pululagua is located just north of the equator.
Figure 5: Map of the Pululagua region. Blue circles - cities; Red triangles - volcanoes; Green box - location of the study site.
Figure 6: Geological sketch map of the Pululagua Volcanic Complex; where the red square indicates the location of the stratigraphic column shown in Figure 7 (modified from Papale and Rosi, 1993).
Figure 7: Stratigraphy and nomenclature of products of the Pululagua caldera-forming eruptions, observed NE of the caldera (red box in Fig. 6). U1-U10-eruptive units are separated from each other by erosive unconformities. BF, WA, F2-F7-Plinian and/or Subplinian pumice fallout layers. Numbers on the left-hand side of the column indicate deposit thickness in cm. The LARI is deposited near U6 & U7 in the middle eruptive units. Nomenclature is based on Papale and Rosi (1993). (modified from Papale and Rosi, 1993).
The use of ground-penetrating radar (GPR) in volcanological studies has increased in recent years. This stems from demonstrations of GPR capabilities outside of the volcanological realm. Some early case studies demonstrating the effectiveness of GPR in acquiring detailed shallow subsurface information were presented by Davis and Annan (1988). They showed that GPR is effective to depths of 20 m both for mapping sedimentary stratigraphy and for detecting fracture zones in igneous rock. Their GPR interpretations were confirmed by ground truthing. Numerous other case studies led to the realization that GPR is effective in acquiring detailed subsurface information, particularly in sedimentary environments, and spawned the integration of GPR into studies of volcanic deposits.

Descriptions of GPR contributions to volcanological investigations are reviewed below. At the caldera of Volcan Sollipulli in Chile, a combined radar and gravity survey was used to determine caldera ice thicknesses along 2D profiles and provided a constraint on the buried topography within the ice-filled caldera (Gilbert et al., 1996). Antenna frequencies of 3.5 and 5.8 MHz were utilized along two survey lines, and, based on radar reflections, caldera ice thicknesses of 424 meters were inferred (with an estimated $\pm 10$ m...
accuracy). Reflections from the ice-rock interface were detected in all but the central portion of the caldera.

A GPR survey of Holocene volcanic deposits in western Canada demonstrated that GPR is effective in delineating stratigraphic contacts and has potential to aid in quantifying deposit distributions and thicknesses (Russel and Stasiuk, 1997). GPR transects were run using 100 MHz antennae in an attempt to correlate radar profiles with near-site field exposures. Four volcanic units were studied, a 3-6 meter thick basalt flow, a 3-4 meter thick pumice-rich tephra fallout, a 15 meter thick pyroclastic flow deposit, and a 60 meter thick pumice talus deposit (Russel and Stasiuk, 1997). Direct correlations between unit characteristics and radar response were made by performing GPR surveys overlying observable deposits. These capabilities will be discussed with respect to the basalt lava flow and pumice-rich tephra fallout. In the case of the basalt lava flow, a GPR profile 40 meters in length was carried out along the flow’s upper surface. A poorly indurated, irregular, scoriaceous autobreccia up to 1 meter thick makes up the lowest portion of the flow (Russel and Stasiuk, 1997). Characteristic diffraction events were evident within the radar record at depths equivalent to the stratigraphically measured lava flow base. The diffraction events were interpreted to have been either induced by basal flow irregularities or basal autobreccia. Analysis of the tephra fallout deposit was performed with similar stratigraphic control. As was the case with the lava flow, the GPR survey was performed directly above cross-sectional exposures. Underlying the tephra fallout is a thick layer of colluvium. At near midpoint along the 50 meter traverse, the radar record revealed a strong reflection at 3.6 meters depth, that was nearly equivalent to the stratigraphically-measured basal fall depth. Rapid attenuation below this level in the
GPR profile was interpreted as an artifact of the high electrical conductivity of the underlying colluvium. Overlying the basal reflector, a general absence of coherent reflectors was interpreted to be a result of the overall massive character of the tephra fallout deposit (Russel and Stasiuk, 1997).

Other GPR contributions to physical volcanology include subsurface stratigraphic analyses at the Ubehebe hydrovolcanic field, Death Valley, California. GPR surveys were performed initially with antennae frequencies of 50, 100, and 200 MHz, and in a corollary study with antennae frequencies of 900 MHz (Cagnoli and Russel, 1999; Cagnoli and Ulrych, 2000). The lower frequency antennae permitted evaluation of base surge deposits and alluvial material thicknesses and revealed stratigraphic unconformities between base surge deposits and underlying sandstones (Cagnoli and Russel, 1999). The high-frequency portion of their study provided resolutions that allowed for interpretations of climbing dune forms in the base surge deposit.

Cumulatively, these studies show that the utilization of GPR in volcanic terrain can provide an understanding of the subsurface that in some cases is well beyond what is possible via measurements of exposed stratigraphic sections. Implementing this method over broad areas provides a great deal more information than do section measurements alone. Furthermore, these studies show that GPR results nicely correlate with stratigraphic data (i.e., borehole logs, sections) taken in proximity of the GPR traverse. Such direct correlations can yield definitive radar identifications which can then be extrapolated to the entire GPR traverse.
Theory

Introduction

Ground-penetrating radar (GPR) is a near-surface geophysical method that uses high-frequency radio waves as a means of detecting subsurface contrasts in electrical and magnetic properties. The premise behind GPR is that as a radio wave contacts an interface separating materials of varying electrical and magnetic properties, a portion of the wave is reflected and later received by the GPR system. A typical system consists of a signal generator, transmitting and receiving antennae, and a receiver that amplifies, digitizes, and stores the returning signal (Davis and Annan, 1989; Reynolds, 1997). The instrument is able to determine precisely the time difference between wave transmission and arrival. With appropriate velocity constraints, radar travel times can be converted into depth measurements, which indicate the depth to the radar reflector (i.e., the electromagnetic contrast).

Acquisition

GPR acquisition is many ways analogous to seismic reflection methods. GPR systems are often run in reflection profiling mode, with a system consisting of one transmitting antenna and one receiving antenna, with a fixed offset between the antennae. The seismic reflection analog to GPR profiling is the common offset method, the name of which derives from the equal increments in which the seismic source is progressively
offset. The results of GPR profiles are radargrams, showing travel time to radar reflectors (or depth) versus distance from a fixed starting point (Fig. 8). A requirement for travel time to depth conversion is knowledge of radar velocities. Velocities are determined by performing common midpoint soundings (CMPs), which need to be performed close to the time of profile collection, as changes in ground moisture alter radar velocity. Inaccurate depth values will be calculated if the moisture content varies between the time of profile and CMP acquisitions.

![Example GPR reflection profile radargram](image)

**Figure 8**: Example GPR reflection profile radargram. Data from Site 2_Line 3 (see text).

*Common Midpoint Sounding*

Common midpoint soundings (CMPs) generate reflections from common midpoints in the subsurface by moving the transmitter and receiver away from each other such that the midpoint remains fixed (Fig. 9) (Reynolds, 1997).
The seismic analog to a CMP sounding is alternatively referred to as the common depth point method, CMP stack, or CMP gather. Analysis of CMP soundings can also follow techniques developed for seismic surveys. On a CMP radargram of travel-time (t) versus distance (x) (Fig. 10), one can identify the air wave and the direct wave, both with a direct travel path from transmitter to receiver, the former through air and the latter through near-surface materials, which plot as straight lines. Later arrivals are reflected waves which plot as hyperbolas, a result of the increasing time requirements necessary to reach the receiver with progressively larger transmitter-receiver separations. Reflector arrival times are picked, and both arrival times (t) and their relative distances (x) are squared in order to determine velocities. The result is an $x^2-t^2$ function, which translates the hyperbolic reflection into a linear segment. Root-mean-squared velocities and in turn interval velocities can be calculated according to the Dix Method, and two-way travel time-to-depth conversions can then be performed using a constant velocity assumption as derived from CMP analysis. GPR data are typically not migrated.
Wave Propagation

Electrical and magnetic properties of geologic media exert fundamental controls on wave propagation, specifically velocity and attenuation. Velocity and attenuation are dependent on subsurface properties, namely the relative permittivity, conductivity, and magnetic permeability. The physics of radar wave behavior can be very complex; however, in most geological settings simplified relationships (presented below) between electromagnetic properties and wave propagation are valid.
**Velocity**

Radar wave velocity is governed by the relative permittivity and relative magnetic permeability,

\[ v = \frac{c}{\sqrt{\mu_r \varepsilon_r}} \quad (1) \]

where \( v \) - wave velocity (m/s), \( c \) - electromagnetic wave velocity in a vacuum (3 x 10^8 m/s or 0.3 m/ns), \( \mu_r \) - relative magnetic permeability (dimensionless), and \( \varepsilon_r \) - relative permittivity (dimensionless). In most geologic media, magnetic minerals (i.e., iron oxides) are not abundant, therefore \( \mu_r = 1 \), and wave velocity is essentially dependent on \( \varepsilon_r \). Wave velocity is inversely proportional to the relative permittivity; so as \( \varepsilon_r \) increases, wave velocity decreases. In geologic settings, the relative permittivity has a minimum value for air (\( \varepsilon_r = 1 \)) and a maximum value for water (\( \varepsilon_r = 80 \)), therefore the relative permittivity of the media will lie somewhere between 1 and 80. This potential \( \varepsilon_r \) range yields a possible velocity range between 0.3 and 0.033 m/ns. Most dry geologic materials have a relative permittivity between 4 and 8, so it is largely the water content that controls wave velocity (Davis and Annan, 1985). It is a natural corollary that rock porosity influences wave behavior, as porosity controls the amount of space available for water. Determined velocities of the LARI at Pululagua vary between 0.108 m/s and 0.128 m/s. With the assumption that \( \mu_r = 1 \), this indicates that \( \varepsilon_r \) values vary between 5.5 and 7.7.

**Attenuation and Absorption**

Energy losses leading to attenuation occur as radar waves propagate into the ground for several reasons. Inherent to radar waves is attenuation due to the geometrical spreading of energy. As the wave spreads in a spherical manner throughout the
subsurface, a reduction in energy per unit area occurs at a rate of $1/r^2$ ($r$ is the distance traveled). Another means by which energy is lost is scattering. Where the wave meets an object or contact with a dimension similar to or greater than the wavelength, scattering of energy will occur, decreasing the amplitude of the transmitted wave. Finally, the conversion of electromagnetic energy into heat also contributes to overall energy losses, a phenomenon termed absorption. Absorption is a function of material conductivity, relative magnetic permeability, and the relative permittivity (Reynolds, 1997). Wave attenuation is characterized in terms of the skin depth ($\delta$) and its inverse, the attenuation factor ($\alpha=1/\delta$). Skin depth is a general EM term that can be defined as the depth in which the signal decreases in amplitude to 37% or ($1/e$) of the initial value (Reynolds, 1997). In non-magnetic materials, it is the conductivity that primarily controls wave attenuation. A general rule is that as conductivity increases, the attenuation factor increases, leading to smaller skin depth values and lower penetration depths. Skin depths can range from the millimeter scale for clay rich substances (no penetration) to the decameter scale for limestones and granites. Penetration depths in the Pululagua study area are a maximum of 18 m.
Chapter 5

Methods

Data Overview

Stratigraphic, ground penetrating radar (GPR), and complementary GPS data were acquired with the intent of analyzing the relationships between LARI thicknesses and paleo-topography, and to delineate the internal structure of the LARI. All data were acquired southeast of the Pululagua Caldera, 4.8-5.4 km from the caldera’s center (Fig. 11). This area was chosen because the LARI is thin relative to areas in the North and East of the caldera, and the LARI is deposited in areas of increasing topographic relief (Fig. 12), allowing for upslope thinning and subsequent velocity analyses. Thirteen stratigraphic sections were measured throughout the field area. GPR data consists of CMP soundings and profiles acquired at four individual study sites, totaling seven CMP soundings and 21 profiles (Fig. 13). Distances between stratigraphic sections and the nearest GPR profile range from 20 meters to several hundred meters. Topography is generally increasing from north to south (Figs. 14-16).
Figure 11: Pululagua syn-caldera deposit distribution. The caldera rim and the area of study are shown.
Figure 12: Pululagua study area. Stratigraphic labels, GPR Sites, and syn-caldera deposit distributions are displayed.

- GPR Profile
- Stratigraphic Section
- CMP Sounding

Syn-Caldera Deposits: Pyroclastic flows, lapilli falls, tephra fallout deposits, rich in pumice (Andrade, 2002)
Figure 13-A: GPR Sites 1 (above) and 2 (below); where numbers in blue correspond to the associated GPR profile and the red CMP label corresponds to the associated CMP (red triangle).
Figure 13-B: GPR Sites 3 (above) and 4 (below); where numbers in blue correspond to the associated GPR profile and the red CMP label corresponds to the associated CMP (red triangle). The exact location of CMP 2 is unknown due to data loss.
Figure 14: View looking SE toward GPR Sites 1, 2, and 3. The increasing topographic relief low on the flanks of Casitahua Volcano (Fig. 6) is visible in the background. The pink LARI can be seen in the foreground.

Figure 15: View looking NE toward GPR Sites 1 and 2. The photograph was taken from a position near Stratigraphic Section 20202 (Fig. 12). The pink LARI is visible throughout the section.
Figure 16: View looking SE towards GPR Site 3. The photograph was taken from a position near Stratigraphic Section 13101 (Fig. 12).

**Stratigraphic Section Acquisition**

Erosional gullies and quarry road cuts facilitated the measurement of 13 stratigraphic sections throughout the study area. Section locations were chosen with the intent of accurately recording variations in LARI thickness. Clear exposures throughout the study area allowed for accurate measurements. Sections were measured with a standard survey tape.

At all section locations, clear stratigraphic contacts allowed for precise thickness measurements of nearly all visible units. The LARI was visible in its entirety at all stratigraphic section locations. Stratigraphic nomenclature is based on a
month_date_section number format. For example, six sections were taken on January 31, 2006, and are respectively labeled 13101 to 13106.

**GPR Acquisition**

GPR site selections are dictated by several key factors. First, vehicle accessibility is a necessity due to the high quantity of GPR equipment. Fortunately, many regions to the south of the caldera are quarried, providing access via quarry roads and allowing freedom of site selection. Second, the terrain must allow for reasonable GPR acquisition. Surveys cannot be performed in areas of either abundant vegetation or extremely rugged terrain, due to the requirement that both the GPR transmitter and receiver stay coupled with the ground. Therefore, study sites were also chosen according to these constraints, with vegetation consisting of small grasses and sparse shrubs, and topographic gradients remaining somewhat mild. Third, GPR acquisition took place in areas where clear field exposures allowed for stratigraphic control. Several stratigraphic sections were recorded within 30 meters of a GPR profile, allowing for correlations between stratigraphy and radar reflections.

At each of the four GPR sites, site profiles and CMP soundings were acquired within 1-2 hours of each other to ensure that CMP derived velocities would accurately represent those of the profiles. CMP soundings were acquired within meters of GPR profiles, often crossing a profile traverse path.

GPR profile distances and orientations vary between sites, as a function of the terrain (erosional gullies). Profiles that were acquired in an upslope or downslope
direction typically span the largest distances. At Sites 1, 2, and 3, these lines were traversed from the SW to NE. At Site 4 these lines were traversed from N to S.

GPR data were acquired using a Sensors & Software PulseEKKO 100 GPR system. A 400-volt transmitter was used for both CMP and profile acquisitions. Reflection profiles were acquired in bistatic antennae mode with a sampling rate of 800 ps. During profiling mode, the number of stacks for each trace was 16, and the attempted step size for each line was 25 cm or less. Such a step size is desired to avoid spatial aliasing. The number of stacks for each CMP trace was 32. Information regarding profile and CMP variables such as antenna frequencies, antennae separation, time windows, the number of traces per profile/CMP, and CMP step sizes are presented in Tables 1 and 2.
<table>
<thead>
<tr>
<th>Site:Line</th>
<th>Antenna Frequency (MHz)</th>
<th>Antennae Separation (m)</th>
<th>Time Window (nS)</th>
<th>Traces</th>
<th>Profile Distance (m)</th>
<th>Average Trace Spacing (m)</th>
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</thead>
<tbody>
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<td>250</td>
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<td>25</td>
<td>0.08</td>
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Table 1: GPR reflection profile acquisition parameters.
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<th>Site: CMP</th>
<th>Frequency (MHz)</th>
<th>Initial Antennae Separation (m)</th>
<th>Step Size (m)</th>
<th>Time Window</th>
<th>Traces</th>
</tr>
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<td></td>
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<td>1</td>
<td>0.2</td>
<td>400</td>
<td>55</td>
</tr>
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<td>CMP 2</td>
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<td>1</td>
<td>0.2</td>
<td>500</td>
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<tr>
<td>Site 2:</td>
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</tr>
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<td>CMP 1</td>
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<td>64</td>
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<td>Site 3:</td>
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</tr>
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<td>0.2</td>
<td>400</td>
<td>55</td>
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Table 2: CMP Sounding acquisition parameters. The CMP step size refers to the distance in which the transmitter and receiver are progressively offset (i, ii, iii in Fig. 9).

**GPR Processing**

All GPR data were dewowed prior to analysis to remove low frequency components. Automatic gain controls (AGC) were applied to enhance reflector recognition. Several GPR profiles required a reversal to maintain consistency in final presentation. For example, Site 1: Line 2 was originally acquired from NE-SW, however the final format is presented as SW-NE. Tables 3 and 4 are a compilation of profile and CMP processing parameters.
<table>
<thead>
<tr>
<th>Site:Line</th>
<th>Reversal</th>
<th>AGC Window (ns)</th>
<th>AGC Max (ns)</th>
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<td>Line 2</td>
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<td>50</td>
<td>100</td>
</tr>
<tr>
<td>Line 4</td>
<td>R</td>
<td>50</td>
<td>100</td>
</tr>
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<td><strong>Site 2:</strong></td>
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</tr>
<tr>
<td>Line 4</td>
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Table 3: GPR profile processing parameters; where R-profile reversal and (-)-Original acquisition orientation.
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<th>AGC Max. (ns)</th>
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</thead>
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<tr>
<td>Site 3:</td>
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</tr>
<tr>
<td>CMP 1</td>
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</tr>
<tr>
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Table 4: CMP Sounding processing parameters.

**GPS Acquisition**

GPS data were acquired with a Leica GPS system (GS20) to establish locations of stratigraphic sections, CMPs, and GPR profiles. For stratigraphic sections, GPS data were recorded on the present day surface, directly overlying the section. Both UTM coordinates and elevation data were recorded. For CMPs, GPS data were recorded only at the CMP center point. For GPR profiles, GPS data were acquired with the intent of spatially delineating the profile and recording elevation changes along the profile. Both GPR profile and GPS acquisitions were performed along a survey tape; therefore, GPS positions, GPR trace numbers, and relative profile distances as indicated on the survey tape were recorded. The frequency of GPS points along profiles varies from one recording every 8 to 40 meters, where profiles acquired in areas of larger topographic variability often have larger numbers of GPS recordings. Table 5 presents the frequency of GPS recordings with respect to distance and GPR traces.
<table>
<thead>
<tr>
<th>Site:Line</th>
<th>Number of GPS Recordings</th>
<th>Average Distance Increment (m)</th>
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Table 5: GPS measurement frequencies. The number of GPS recordings along GPR profiles, average distance increment (m), average trace increment (GPR traces). For those profiles where only two points were recorded (start and end), the values represent the length of the line and the number of traces per line.
Chapter 6

Results

Study Site

A site map displaying the locations of 13 stratigraphic sections, four GPR sites, and GPR site CMP soundings and profiles is presented in Figure 17. Refer to Figures 13-A and 13-B for individual GPR profile labels. Line A-A’ indicates the location of a fence diagram that will be discussed below.

Stratigraphy

Up to nine individual stratigraphic units are exposed in the field area. From the surface downward, these units consist of a soil unit, and upper surge, an upper tephra fallout, the LARI, a surge package (Surge Package I), an accretionary lapilli unit, a second surge package (Surge Package II), a combination of tephra fallout units, and a paleosol. In some parts of the field area, the upper surge and the upper tephra fallout are reworked. This sequence is visible near its entirety at only select stratigraphic sections (Figs. 18-20), typically in areas of high relief relative to other parts of the study site (Sections 13106, 20104, and 20105).
Figure 17: Study area with stratigraphic section labels, GPR Site labels, and fence diagram (A-A'). Symbols are consistent with Figure 12.
Figure 18: Soil, Upper Surge, Upper Tephra Fallout, and the LARI. The photo was taken in the vicinity of Section 13106.
Figure 19: LARI, Lower Surge Package I, Accretionary Lapilli, and Lower Surge Package II. The photo was taken in the vicinity of Section 13106. Notice the white pen for scale.

Figure 20: Lower Surge Package II, Tephra Fallout Deposits, and Paleosol. The photo was taken in the vicinity of Section 13106.
Select measurements from thirteen stratigraphic sections are presented in chronological order (Table 6). Refer to Appendix A for complete stratigraphic sections. LARI thickness correlations between select stratigraphic sections and the closest GPR profile position are presented in Table 7.

<table>
<thead>
<tr>
<th>Stratigraphic Section</th>
<th>LARI Package Thickness (m)</th>
<th>Depth to Upper LARI (m)</th>
<th>Upper Tephra Fallout Thickness (m)</th>
<th>Upper Surge Thickness (m)</th>
<th>Surface Elevation (msl)</th>
</tr>
</thead>
<tbody>
<tr>
<td>13101</td>
<td>1.40</td>
<td>0.30-1.12</td>
<td>0.12-0.13</td>
<td>0.0-0.81</td>
<td>2726</td>
</tr>
<tr>
<td>13102</td>
<td>3.19</td>
<td>1.48-1.56</td>
<td>0.12-0.13</td>
<td>0.74-0.80</td>
<td>2718</td>
</tr>
<tr>
<td>13103</td>
<td>6.10</td>
<td>1.65</td>
<td>Reworked 0.40</td>
<td>Reworked 0.40</td>
<td>2700</td>
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<tr>
<td>13104</td>
<td>8.54</td>
<td>0.05-1.17</td>
<td>Reworked 0.47</td>
<td>Reworked 0.47</td>
<td>2680</td>
</tr>
<tr>
<td>13105</td>
<td>4.12</td>
<td>2.48</td>
<td>Reworked 1.38</td>
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<td>2685</td>
</tr>
<tr>
<td>13106</td>
<td>1.85</td>
<td>1.06-1.27</td>
<td>0.10-0.14</td>
<td>0.46-0.53</td>
<td>2733</td>
</tr>
<tr>
<td>20101</td>
<td>3.30</td>
<td>2.25-3.25</td>
<td>0.40-0.75</td>
<td>1.10</td>
<td>2712</td>
</tr>
<tr>
<td>20102</td>
<td>3.45</td>
<td>2.7-3.00</td>
<td>0.30</td>
<td>1.20-1.35</td>
<td>2688</td>
</tr>
<tr>
<td>20103</td>
<td>2.68</td>
<td>0.68-0.81</td>
<td>0.17</td>
<td>0.06-0.07</td>
<td>2704</td>
</tr>
<tr>
<td>20104</td>
<td>1.77</td>
<td>0.71-1.13</td>
<td>0.18</td>
<td>0.20-0.40</td>
<td>2794</td>
</tr>
<tr>
<td>20105</td>
<td>0.94</td>
<td>0.66-0.84</td>
<td>0.16-0.19</td>
<td>0.20-0.35</td>
<td>2747</td>
</tr>
<tr>
<td>20201</td>
<td>2.28</td>
<td>0.55-0.60</td>
<td>0.10-0.15</td>
<td>Eroded</td>
<td>2796</td>
</tr>
<tr>
<td>20202</td>
<td>1.13</td>
<td>0.38-0.82</td>
<td>0.12-0.18</td>
<td>0.16-0.30</td>
<td>2775</td>
</tr>
</tbody>
</table>

Table 6: Stratigraphic section measurements. The measurements are most pertinent to GPR interpretations. GPS surface elevations are also provided.
Stratigraphic Section | GPR Profile | Closest GPR Profile Position (x) (m) | Distance between position x and stratigraphic section (m) | LARI thickness: via section (m) | LARI thickness: via profile (m) | LARI profile variation as % of strat. measurement*
---|---|---|---|---|---|---
13101 | Site 2: Line 1 | 1 | 62 | 1.73 | 1.40 | -19
13101 | Site 3: Line 1 | 105 | 74 | 1.94 | 1.40 | -28
13102 | Site 2: Line 1 | 88 | 20 | 1.35 | 3.19 | +136
13103 | Site 2: Line 1 | 168 | 43 | 1.78 | 6.10 | +242
13103 | Site 2: Line 5 | 31 | 30 | 6.10 | 3.92 | -35
13104 | Site 2: Line 1 | 260 | 38 | 3.65 | 8.54 | +134
13105 | Site 2: Line 1 | 260 | 71 | 3.65 | 4.12 | +13
13106 | Site 1: Line 1 | 0 | 21 | 2.06 | 1.85 | -11
13106 | Site 1: Line 2 | 0 | 31 | 1.59 | 1.85 | +16
20101 | Site 4: Line 1 | 9 | 37 | 1.84 | 3.30 | +79

Table 7: LARI thickness correlations. The correlations are between stratigraphic section measurements and GPR profile measurements at the profile position that is nearest in distance to the stratigraphic section; where - %: profile thickness < stratigraphic measurement; + %: profile thickness > stratigraphic measurement.

**Lithology**

The goal of this study was to acquire GPR and stratigraphic thickness data, with a focus on the low-aspect ratio ignimbrite. With this aim in mind, the inevitable time constraints that arose during the field session prevented the recording of detailed lithologic information at each section. Lithologic observations were noted for only a few stratigraphic sections. Stratigraphic observations predominantly consisted of thickness
measurements. Therefore, lithologic information will be presented for Sections 13101 and 13106. Photographs of the respective stratigraphic sections are presented in Figures 18-20 (Section 13106) and Figure 21 (Section 13101).

Stratigraphic Section 13101

Soil: 0.18 m.

Upper Surge: Eroded, but present within 5 m horizontally (0.81 m thick).

Intercalated pumice layers, lithic rich, occasional pumices up to 11 cm and lithics to 5 cm. Sparse pumice bands ranging from 2-4 cm with intercalated fine-grained bands from 3-5 mm. Top of unit grades into soil. Base of upper surge has a fine-grained white layer that is 0.7 cm thick, with grains less than 1 mm (low porosity).

Upper Tephra Fallout: 0.12-0.13 m. Average pumice between 3-5 cm. Lithics are 20-25% in abundance. Maximum pumice of 13 cm, maximum lithic of 10 cm. Fine-grained uppermost portion (less than 1 cm thick), marking clear contact between Upper Tephra Fall and Upper Surge.

LARI: 1.4 m

Upper 0.70 m: Fine-grained portion of the LARI with laterally pinching pumice bands. Light beige to pink in color. Pumices within bands vary from 4-5 cm. Matrix pumices and lithics from 1-5 mm. Maximum lithic up to 3 cm and maximum pumice up to 2 cm.
Middle 0.60 m: 90% pumice with rare lithics, occasionally up to 21 cm.

Thicker pumice bands than upper portion. Pumices are commonly from 6-9 cm within bands. The unit is finer-grained toward the base.

Basal 0.10 m: Lithic-rich, 60-65% lithics. Maximum lithic up to 9 cm.

Poorly sorted.

Surge Package I: 2.8 m + ?

Upper 1.3 m: Uppermost portion of this 1.3 m surge is very fine-grained, varying from 9-20 cm in thickness, with grains less than 1 mm. The bulk of the lower surge contains rare pumice fragments up to 0.5 cm, and is cross-bedded with grain size in beds uniform. Most beds are 1-2 mm. Occasional pumices up to 3 cm can be found within these beds. The base of this unit is finely laminated with sub-mm to 3 mm pumices and sub-mm to 1 mm lithics.

Lower 1.5 m + ?: Contact between upper and lower portion forms a bench, indicating a change in competency. The upper portion of this unit contains very fine laminations with parallel contacts. The laminations are seen everywhere in outcrop and are 4-22 mm in thickness with sub-mm grains. Lamellae thicknesses increase downward. Below this fine-grained portion, the unit becomes massive, with pumice
fragments up to 1 cm, and a 1-2 mm sandy matrix. The base of this unit is covered by slope debris.

Figure 21: Stratigraphic Section 13101. The Upper Surge is eroded here. The LARI is not pink as is typical throughout the field area.
Stratigraphic Section 13106

Soil: 0.50-0.63 m. Base of soil consists of 50% pumice and lithics.

Upper Surge: 0.46-0.53 m. Cross-bedded.

Upper Tephra Fallout: 0.10-0.14 m. Pumices from 12-20 cm. Lithics to 20 cm.

LARI: 1.85 m

Upper 0.27 m: Fine-grained with less pronounced pumice trains than in lower portions of the unit. Beige in color. Pumices up to 1 cm, lithics up to 5 mm

Middle 1.38 m: Highly oxidized (striking pink) with discontinuous pumice trains up to 20 cm thick and 9 cm long. Middle portion contains 5-10% lithics, with lithics up to 3 cm. Pumices are up to 8 cm.

Basal 0.20 m: Lithic-rich layer. Dominantly dacitic, angular clasts, poorly-sorted, fines-depleted. Lithics are up to 10 cm.

Surge Package I: 1.50 m. Fine-grained, cross-bedded, with lenses from 1-3 mm.

Upslope Thinning

The fence diagram (A-A’) as indicated on Figure 17 is presented below (Fig. 22) with accompanying stratigraphic sections. The associated stratigraphic sections are presented with a legend and depth labels in Figure 23. It is clear that the LARI is thinning as the deposit climbs topography.
Figure 22: Fence Diagram A-A’. The fence (above) displays only the LARI. The associated stratigraphic sections and LARI thicknesses are displayed below the fence. The LARI is the pink unit in both the fence and the stratigraphic sections. Stratigraphic sections are scaled to each other only, not to the fence diagram.
Figure 23: Stratigraphic sections and associated legend relevant to fence diagram A-A'. Numbers on the left side of the sections indicate the depth below ground surface.
**GPR Analysis**

GPR analyses consisted of LARI identification and delineation within profiles, depth determinations to upper and lower LARI-bounding reflectors, LARI thickness calculations, and LARI velocity determinations via CMP soundings in order to convert two-way travel times into depths. GPR data are presented for profiles that allowed for subsequent velocity analyses, the majority of which were acquired in an upslope direction. Remaining GPR data are presented in Appendices B and C.

GPR profiles were analyzed with respect to stratigraphic section measurements and deposit behavior (particularly stratified upper surge behavior) (Fig. 24) to aid in LARI identification and delineations. Interpretations are largely derived from stratigraphic sections located within 30 meters of the closest GPR profile. Reflector geometry and behavior also contributed to interpretations, largely a result of “wavy” reflectors indicative of surge-like features (Fig. 25).

![Stratified Upper Surge](image)

**Figure 24:** The stratified nature of the Upper Surge. The Upper Surge is about 0.5 m thick in the center of the photo. The LARI is the pink unit below.
Upper and lower LARI-bounding reflectors were identified within the GPR record (e.g. Fig. 25). Reflector interpretations were then extended to profiles lacking stratigraphic control. This capability was a function of the intersecting profile traverse paths, which exist at all sites, and allowed for profile to profile comparisons. A user-controlled MATLAB function was implemented to trace the LARI-bounding reflectors (Appendix D). This was a visual process which required user interpretation and numerous point selections along an individual delineation. A MATLAB assigned interpolation combined with the user selected points resulted in output of two-way travel times as a
function of UTM coordinates, the latter of which was translated into distance along the profile, yielding radargrams with highlighted LARI-bounding reflector delineations (Figs. 26-35). Depth values for the upper and lower LARI-bounding reflector delineations were derived from a relationship between two-way travel time, LARI velocity (via CMPs), and transmitter and receiver antenna spacing, using the equation

\[ d = \sqrt{\frac{t^2v^2 - a^2}{2}} \]  

(2)

where, \( d \)- depth (m), \( t \)- 2-way travel time (ns), \( v \)- LARI velocity (m/ns), and \( a \)- antenna spacing (m). The identification of upper and lower LARI-bounding reflectors allowed for LARI delineations in the majority of GPR profiles. The upper-LARI contact was not associated with a distinctive GPR reflection. The nearest bright GPR return is interpreted to be stratigraphically above the LARI, therefore the upper LARI-bounding reflector does not represent the LARI's upper surface, and instead represents the contact between the Upper Tephra Fallout and the Upper Surge. This interpretation derives from reflector behavior that is indicative of pyroclastic surge bedforms (Fig. 25). The lower LARI-bounding reflector is interpreted as the contact between the LARI and the underlying unit (Surge Package I), largely derived from stratigraphic correlations. The implication is that the delineations are not entirely representative of the LARI, a function of the upper interface. To account for the discrepancy arising from the difficulty of delineating the upper-LARI interface, a GPR site thickness is assumed for the Upper Tephra Fallout (based on stratigraphic measurements) (Table 8). The site-assumed Upper Tephra Fallout thickness was then deducted from upper LARI-bounding reflector depths to determine an estimated depth to the upper-LARI contact. This approach is believed to
be valid because the Upper Tephra Fallout maintains relatively consistent thicknesses
over the survey area. The corrected upper-delineation depth values and the original
lower-delineation depth values were used to create Elevation vs. Distance curves for each
of the profiles by topographically correcting the depth values relative to GPS derived
elevation values (Figures 26-35). LARI thicknesses along each GPR profile were
calculated by taking the difference between corrected upper-delineation depth values and
the uncorrected lower-delineation depth values, yielding Thickness vs. Distance curves
with a superimposed thickness trend line (Figures 26-35). GPR profiles without LARI-
bounding reflector delineations are presented in Appendix F.

<table>
<thead>
<tr>
<th>GPR Site</th>
<th>Upper Tephra Fallout Deduction (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Site 1</td>
<td>0.13</td>
</tr>
<tr>
<td>Site 2</td>
<td>0.13</td>
</tr>
<tr>
<td>Site 3</td>
<td>0.13</td>
</tr>
<tr>
<td>Site 4</td>
<td>0.30</td>
</tr>
</tbody>
</table>

Table 8: GPR Site thickness deductions. Upper Tephra Fall thickness deductions used to correct
upper LARI-bounding reflector depth values.
Figure 26: Site 1: Line 1 GPR profile with LARI delineation (top), topographically corrected LARI (middle), and thickness vs. distance curve with trend line (bottom).
Figure 27: Site 1: Line 2 GPR profile with LARI delineation (top), topographically corrected LARI (middle), and thickness vs. distance curve with trend line (bottom).
Figure 28: Site 2: Line 1 GPR profile with LARI delineation (top), topographically corrected LARI (middle), and thickness vs. distance curve with trend line (bottom).
Figure 29: Site 2: Line 2 GPR profile with LARI delineation (top), topographically corrected LARI (middle), and thickness vs. distance curve with trend line (bottom).
Figure 30: Site 2: Line 4 GPR profile with LARI delineation (top), topographically corrected LARI (middle), and thickness vs. distance curve with trend line (bottom).
Figure 31: Site 2: Line 5 GPR profile with LARI delineation (top), topographically corrected LARI (middle), and thickness vs. distance curve with trend line (bottom).
Figure 32: Site 3: Line 1 GPR profile with LARI delineation (top), topographically corrected LARI (middle), and thickness vs. distance curve with trend line (bottom).
Figure 33: Site 4: Line 1 GPR profile with LARI delineation (top), topographically corrected LARI (middle), and thickness vs. distance curve with trend line (bottom).
Figure 34: Site 4: Line 2 GPR profile with LARI delineation (top), topographically corrected LARI (middle), and thickness vs. distance curve with trend line (bottom).
Figure 35: Site 4: Line 4 GPR profile with LARI delineation (top), topographically corrected LARI (middle), and thickness vs. distance curve with trend line (bottom).
CMP Soundings

CMP soundings were used to constrain GPR site LARI velocities, allow for final travel-time to depth conversions, and determine LARI thicknesses (as described above). Velocity analyses were run after the LARI-bounding reflectors were identified within GPR profiles; this was necessary because without first delineating the LARI-bounding reflectors, reflectors in the CMP radargrams are stratigraphically meaningless. The CMPs were compared to the nearest position on the nearest GPR profile, which allowed for identification of the LARI-bounding reflectors within associated CMPs. The LARI-bounding reflectors were used to obtain velocities using the Dix Method. This process resulted in two interval velocities per CMP. The first interval velocity represents a velocity for units above the upper LARI-bounding reflector, while the second interval velocity ideally represents the velocity of the LARI at the time of that particular CMP sounding (Table 9). In cases where more than one CMP were performed per GPR site, the interval velocities representing the LARI were averaged, yielding a site-averaged LARI velocity. CMPs with reflector delineations are presented in Appendix E.
<table>
<thead>
<tr>
<th>Site: CMP</th>
<th>$V_{Interval}$ (m/ns)</th>
<th>Interval Thickness (m)</th>
<th>Site Averaged LARI Velocity (m/ns)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Site1:</td>
<td></td>
<td></td>
<td>0.123</td>
</tr>
<tr>
<td>CMP1</td>
<td>0.141</td>
<td>2.26</td>
<td></td>
</tr>
<tr>
<td></td>
<td><strong>0.123</strong></td>
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<td></td>
</tr>
<tr>
<td>CMP2</td>
<td>0.121</td>
<td>1.31</td>
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</tr>
<tr>
<td></td>
<td><strong>0.122</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Site2:</td>
<td></td>
<td></td>
<td>0.128</td>
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<tr>
<td>CMP1</td>
<td>0.116</td>
<td>1.48</td>
<td></td>
</tr>
<tr>
<td></td>
<td><strong>0.128</strong></td>
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<td></td>
</tr>
<tr>
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<td></td>
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<td>0.108</td>
</tr>
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<td>CMP1</td>
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<td>2.86</td>
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<td><strong>0.108</strong></td>
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<td>Site4:</td>
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<tr>
<td>CMP1</td>
<td>0.117</td>
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<tr>
<td></td>
<td><strong>0.116</strong></td>
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<td></td>
</tr>
<tr>
<td>CMP2</td>
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<td><strong>0.111</strong></td>
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<td>CMP3</td>
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<tr>
<td></td>
<td><strong>0.103</strong></td>
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<td></td>
</tr>
</tbody>
</table>

Table 9: CMP velocities. The bolded $V_{Interval}$ velocities represent individual CMP derived LARI velocities, while the bolded Site Averaged LARI Velocities represent the velocities used in final time-depth conversions for each of the four GPR sites.

**Velocity Analyses**

Bulk density-current and vertical (cross-sectional) velocity analyses are performed to examine upslope LARI parent density-current flow using a simplified energy-based theoretical analysis, modeled after a turbidity current (Muck and Underwood, 1990). Muck and Underwood (1990) examined upslope flow of unconfined turbidity currents onto a bathymetric high by analyzing the exchange of kinetic energy for potential energy and frictional heat. The turbidity current begins with a mass flow down a landward trench slope and ends with the turbidity current passing through a break...
in slope and ascending upslope, the latter stage which is analyzed with respect to energy losses.

![Upslope Turbidity Current Flow schematic](image)

$\Delta y = \rho \cdot U^2 \cdot (1 - E_{loss}) / \Delta \rho \cdot 2g$

**C1**: Center of current gravity at base of barrier (m)
**C2**: Center of current gravity at peak of upslope flow (m)
$\Delta y$: C2-C1 (m); vertical change in center of gravity
$U$: Turbidity current velocity at C1 (m/s)
$\rho$: Current density (kg/m$^3$)
$\Delta \rho$: Density contrast between current and ambient fluid (kg/m$^3$)
$g$: Force of gravity (m/s$^2$)
$E_{loss}$: Fraction of kinetic energy lost as heat during upslope flow (%)

Figure 36: Upslope turbidity current flow schematic. The kinetic energy equation and variables are displayed in the figure. (modified from Muck and Underwood, 1990).

**Bulk Density-Current Velocity**

The upslope flow analysis developed by Muck and Underwood (1990) is extended to the LARI to obtain 10 bulk flow velocities of the LARI-producing pyroclastic density-current (Fig. 37). Parameter values are listed in the caption, and were held constant throughout the analysis.
\[ U = \sqrt{\Delta E \cdot \Delta \rho \cdot 2g / \rho \cdot (1 - E_{\text{loss}})} \]

**U**: Minimum bulk density-current velocity required at E1 to reach E2 (m/s)
**\( \Delta E \)**: E2-E1; Change in paleo-topographical surface elevation from base to peak of upslope flow (m)
**E1**: Pre-LARI surface elevation at base of barrier (m)
**E2**: Pre-LARI surface elevation at peak of upslope flow (m)
**\( \Delta \rho \)**: Density contrast between LARI-producing pyroclastic density-current and air: 999.04 kg/m³
**\( \rho \)**: Density of LARI-producing current: 1000 kg/m³
**g**: Force of gravity: 9.8 m/s²
**\( E_{\text{loss}} \)**: Fraction of kinetic energy lost as heat during upslope flow: 10%

Figure 37: Bulk density-current velocity schematic. The associated kinetic energy equation, variable descriptions, and parameter values are also displayed.

Basal and upslope peak elevation values of the pre-LARI depositional surface are used as a supplement to center of current gravities as indicated by Muck and Underwood (1990) (Fig. 36). This elevation supplement maintains dimensional continuity. It is assumed that the basal LARI contact, as delineated in the GPR profiles, represents the surface of the land during pyroclastic density-current ascent and LARI deposition. This assumption is valid unless there is evidence of erosion. Basal LARI-contact delineations yield two-way travel time and depth equivalents along the profile (as described above).
By linearly interpolating between GPS derived surface elevations and later deducting the calculated basal LARI depths, elevation values along the basal contact are calculated. Bulk velocity analysis is not performed for all GPR profiles because the LARI does not in all cases flow upslope, and not all GPR profiles were acquired near parallel to the direction of inferred flow. The calculated velocity is interpreted as the minimum velocity required at the approach of upslope flow for the LARI-producing pyroclastic density-current to reach its maximum observed elevation (as determined via GPR and GPS).
Figure 38: Bulk density-current velocities. Velocities of the LARI producing pyroclastic density-current are a function of paleo-topographical elevation change. Box colors indicate the GPR site and associated numbers indicate the GPR profile.
Vertical (cross-sectional) Velocity

Site 3: Profile 1 is analyzed to determine vertical velocity profiles at chosen positions along the flow. This analysis is performed with the assumption that internal GPR reflectors, which start at the base of the deposit and ultimately impinge on the basal LARI-contact, are equivalent to internal streamlines. Fluid-dynamically, a streamline is defined as a continuous line that has the property that its tangent at each point coincides with the direction of the fluid velocity at that point (Furbish, 1997), or simply the path a parcel follows in a given fluid. This analysis is based on the premise that the LARI-producing density-current is density stratified. Valentine (1987) addressed the interaction of an internally stratified pyroclastic surge with topography, where in a stratified flow, it is stated that there will be a level (streamline) above which all fluid has sufficient energy to top an obstacle and below which all fluid is either stopped (blocked) or simply moves around the obstacle with no upward motion. Valentine (1987) referred to this level as a critical level or a dividing streamline (Fig. 50).

Figure 39: Dividing streamline schematic. Blocking in a density-stratified pyroclastic current occurs below the dividing streamline as it encounters a hill. Below the streamline material cannot flow over the obstacle due to a lack of kinetic energy (modified from Valentine, 1987).
Two internal streamlines (GPR reflectors) were delineated with a user-controlled Matlab function. The Matlab output of two-way travel times was converted into depths, and these depths were deducted from GPS derived surface elevation values to determine streamline elevations along the profile. The third streamline is taken to be the LARI's upper surface, as evident in the GPR profile. If only one streamline is present (Fig. 51), the change in elevation of the streamline is equivalent to the minimum velocity for the streamline parcel to travel from the base to the peak of upslope streamline elevation. At the upslope peak of the streamline (SE1b in fig. 51), the velocity is taken to be zero, as the parcel no longer has kinetic energy and is deposited. In the Site 3: Line 1 analysis, three streamlines are analyzed, and elevation derived velocities are calculated in segments (Fig. 52).
\[ U = \sqrt{\Delta SE1 \cdot \Delta \rho \cdot 2g / \rho \cdot (1 - E_{loss})} \]

U: Minimum velocity of density-current at the base of the streamline required to reach the peak of the streamline (m/s)
SE1a: Streamline elevation at base of upslope flow (m)
SE1b: Peak streamline elevation within flow (m)
\( \Delta SE1 \): SE1b-SE1a; Change in streamline elevation from base to peak of upslope flow (m)
\( \rho \): Density of LARI-producing current: 1000 kg/m³
\( \Delta \rho \): Density contrast between LARI-producing pyroclastic density-current and air: 999.04 kg/m³
\( g \): Force of gravity: 9.8 m/s²
\( E_{loss} \): Fraction of kinetic energy lost as heat during upslope flow: 10%

Figure 40: Vertical velocity profile schematic with associated kinetic energy equation, variable descriptions, and parameter values.
Figure 41: Site 3: Line 1 streamline delineations and velocity profiles. This GPR profile is topographically corrected between 97 and 197 meters distance (x), where black lines- LARI contacts, S1-streamline 1, S2-streamline 2, S3-streamline 3 (upper contact) (above). The vertical blue lines indicate chosen positions for vertical velocity analysis, and associated numbers indicate the corresponding x-value. Velocity profiles at the corresponding x-position are shown below, where black squares- streamline position within flow.
Chapter 7

Discussion

Pyroclastic density-current end-members are largely differentiated by sediment concentration and flow regime. Pyroclastic flows are highly sediment-concentrated, traveling in a predominantly laminar flow state, while pyroclastic surges are dilute, traveling in a predominantly turbulent flow state (Wilson and Houghton, 2000). Eyewitness accounts of historical eruptions and pyroclastic deposit studies have led to the understanding and classification of density-current end-members.

Eyewitness accounts at Mt. Pelee, Martinique, Mt. Unzen, Japan, and Soufriere Hills, Montserrat, have elucidated the behavior of pyroclastic density-currents during transport. Early accounts of pyroclastic density-current transport were summarized by Fisher and Heiken (1982): Flows at Mt. Pelee reportedly traveled along topographic depressions at great velocities in a highly-concentrated state (Lacroix, 1904), while surges flowed in a less concentrated, expanded, and turbulent state, irrespective of topography (Anderson and Flett, 1903; and Lacroix, 1904). Later eyewitness accounts at Mt. Unzen (Fisher, 1995) and Soufriere Hills (Druitt et al., 2002) elaborate on similar density-current behaviors.

Pyroclastic deposit studies have contributed to the understanding of density-current transport. Field observations and grain-size analyses of Quaternary ignimbrites from Italy and the Azores revealed that about 90% of any single ignimbrite is relatively homogeneous (massive), fine-grained, and poorly sorted (Sparks et al., 1973; Sparks,
Unlike flow deposits, pyroclastic surge deposits tend to show cross-bedding, wavy or planar laminations, and/or dune-like structures, lack fine particles, and are better sorted (Sparks et al., 1973; Sparks, 1976; Fisher, 1979; Fisher and Schmincke, 1984). The combination of eyewitness accounts and pyroclastic deposit studies led to the characterization of density-currents with respect to particle concentration and flow regime, and provided the framework for schematic cross-sectional density and velocity profiles (Fig. 2).

The vertical velocity gradient analysis (Figs. 52-55) quantitatively shows that a LARI parent density-current has a surge-like vertical velocity profile (Fig. 2). This interpretation depends on the assumption that internal GPR reflectors are equivalent to flow streamlines. The streamline GPR reflectors (Fig. 52) are clearly traced until the position of impingement on the paleo-topographical surface (basal-LARI contact). Relationships between the streamlines and both the underlying paleo-surface and the LARI highly resemble the dividing streamline schematic presented by Valentine (1987) (Fig. 50).

The bulk flow velocity analyses provide the minimum velocity of the LARI producing density-current at the base of upslope flow, while the lateral velocity analysis details subsequent losses in current velocity as the flow ascends upslope. This interpretation depends on two assumptions, first, that the basal LARI contact represents the paleo-topographical surface, and second, that the thickness of the LARI is equivalent to the thickness of the LARI producing density-current. According to the bulk and lateral velocity models, as flow thickness expands, minimum velocities increase; therefore, bulk flow velocity and lateral velocity values represent absolute minimums, as the observed
LARI thickness can only be equivalent to the minimum thickness of the parent density-current, a function of mass balance.

Stratigraphic measurements reveal that the LARI thins upslope. The majority of LARI delineations within GPR profiles show a similar thinning trend. Exceptions to the upslope thinning trend may be a result of partial LARI erosion by the Upper Surge deposit or incomplete GPR delineations, a function of the upper LARI-bounding reflector being skewed by air and/or direct wave arrivals.

LARI identification within GPR profiles is a function of reflector behavior and stratigraphic correlations; with respect to the former, “wavy” reflectors are seen overlying the upper-LARI contact (Fig. 25), followed by a transition into less pronounced reflectors. These “wavy” reflectors are indicative of surge-like bedforms, and often abruptly transition downward into an area of contrasting reflector behavior, interpreted as the LARI (readily apparent in figs. 28 and 29). These shallow reflector behaviors nicely correlate with the stratigraphic sequence. Basal-LARI contact interpretations were guided by stratigraphic measurements.
Chapter 8

Conclusions

- The LARI is identified in GPR profiles via reflector behavior and stratigraphic measurements.

- The maximum variation in LARI thickness in a direction of increasing topographic relief is 7.8 m, while the maximum elevation change is 34.6 m.

- Minimum LARI-parent pyroclastic density-current velocities at the base of upslope flow (based off kinetic energy loss as the flow ascends upslope) were at least 25 m/s.

- Vertical velocity analyses for Site 3: Line 1 indicate a surge-like velocity profile for the parent pyroclastic density-current, with current velocities decreasing downward through the flow. At the base of upslope flow, the maximum current velocity is 24 m/s, while at the peak of upslope flow, the maximum current velocity is 2.4 m/s.
• The LARI-producing density-current likely has cross-sectional density and velocity characteristics similar to that of a pyroclastic flow, with a dividing streamline separating an overriding current from the basal current.

![Diagram of LARI-producing density current with cross-sectional profiles](image1.png)

Figure 42: LARI-producing density current with cross-sectional profiles

• Below the dividing streamline, the bulk of the flow is density-stratified, resulting in internal flow streamlines. Below the internal streamline, particles are deposited due to kinetic energy losses. Multiple internal streamlines represent multiple depositional regimes.

![Diagram of basal LARI-producing density current with cross-sectional profiles](image2.png)

Figure 43: Basal LARI-producing density-current with cross-sectional profiles.
Chapter 9

Recommendations

Concerning future aspects of the study, I would like to recommend detailed analyses of internal structure within the LARI, with the aim of relating deposit characteristics to radar reflections. This will be very helpful in the vicinity of the Site 3_Line 1 profile in which the vertical velocity analysis is based. Similarly, with other GPR profiles, internal radar characteristics need to be correlated with stratigraphic exposures. The Site 2_Line 1 profile will be most useful as it is directly adjacent to the erosional gully where Stratigraphic Sections 13101 to 13105 were acquired. Preferably, detailed measurements of deposit structures will be made, with a concentration on variations in grain size/density (pumice trains, micaceous alignments, etc.) and the depth to these variations below the upper-LARI contact.

It will also be of use to acquire stratigraphic measurements in the SSW portion of the study area, with the aim of characterizing the upslope extent of the LARI. An understanding of deposit variations between the upslope and downslope portions of the study area will elaborate on topographically induced behavioral variations of the density-current.
References


Gilbert, J.S.; Stasiuk, M.V.; Lane, S.J.; Adam, C.R.; Murphy, M.D.; Sparks, R.S.J.; and J.A. Naranjo. 1996, Non-explosive, constructional evolution of the ice-filled caldera at Volcan Sollipulli, Chile. *Bulletin of Volcanology.* v. 58, pp. 67-83.


Appendices
Appendix A: Stratigraphic Sections and Legend

A-1: Stratigraphic Section 13101 and stratigraphic legend.
A-2: Stratigraphic Sections 13102 (left) and 13103 (right)
A-3: Stratigraphic Sections 13104 (left) and 13105 (right)
A-4: Stratigraphic Sections 13106 (left) and 20101 (right)
Appendix A (Continued)

A-5: Stratigraphic Sections 20102 (left) and 20103 (right)
Appendix A (Continued)

A-6: Stratigraphic Sections 20104 (left) and 20105 (right)
A-7: Stratigraphic Sections 20201 (left) and 20202 (right).
Appendix B: LARI Delineations with Thickness vs. Distance Curves

B-1: Site 1_Line 3 LARI delineation and thickness vs. distance curve with thickness trend line.
B-2: Site 1 Line 4 LARI delineation and thickness vs. distance curve with thickness trend line.
Appendix B (Continued)

B-3: Site 2 Line 6 LARI delineation and thickness vs. distance curve with thickness trend line.
B-4: Site 2 Line 7 LARI delineation and thickness vs. distance curve with thickness trend line.
Appendix B (Continued)

B-5: Site 4 Line 3 LARI delineation and thickness vs. distance curve with thickness trend line.
B-6: Site 4_Line 5 LARI delineation and thickness vs. distance curve with thickness trend line.
Appendix B (Continued)

B-7: Site 4 Line 6 LARI delineation and thickness vs. distance curve with thickness trend line.
Appendix B (Continued)

B-8: Site 4_Line 7 LARI delineation and thickness vs. distance curve with thickness trend line.
Appendix B (Continued)

B-9: Site 4_Line 8 LARI delineation and thickness vs. distance curve with thickness trend line.
Appendix C: Topographically Corrected LARI

C-1: Site 1_Line 3 depth corrected LARI. From left to right, NW to SE

C-2: Site 1_Line 4 depth corrected LARI. From left to right, NW to SE
Appendix C (Continued)

C-3: Site 2_Line 6 depth corrected LARI. From left to right, NW to SE

C-4: Site 2_Line 7 depth corrected LARI. From left to right, NW to SE
Appendix C (Continued)

C-5: Site 4_Line 3 depth corrected LARI. From left to right, W to E

C-6: Site 4_Line 5 depth corrected LARI. From left to right, NW to SE
Appendix C (Continued)

C-7: Site 4_Line 6 depth corrected LARI. From left to right, W to E

C-8: Site 4_Line 7 depth corrected LARI. From left to right, NW to SE
C-9: Site 4 Line 8 depth corrected LARI. From left to right, W to E
Appendix D: LARI-Bounding Reflector Matlab Code

function LayerPicksSimpleUTM
% reads in a single .mat format file
% no gains applied
% lets user pick arrival times of reflections
% writes out reflection arrival times
% this version allows no timeshifting or trend removal
% this version only saves picks at positions between first and last pick
% S Kruse Oct 06

% adds in UTM positions of points along line
% assumes format of worksheet is (no header)
% column 1 trace, column 2 cum distance,
% column 3 easting, column 4 northing
% S Kruse Nov 06

clear all; close all;

%***********INPUT SECTION STARTS
HERE****************************************

filein = 'PUS2L2Mg.mat'
fileUTM = 'PUS2L2M_UTM.xls'
sheetUTM= 'traceUTM'; % name of worksheet in file UTM
fileoutstem = 'PUS2L2M_Lower2Ign';
irev = 1; %set to 1 if line is reversed

%The suffix LP indicates layer pick to avoid confusion in the future

%SET maximum time to show on screen for making time picks in ns
tshow = 550; %ns, if greater than total time in record, has no effect

%***********INPUT SECTION ENDS
HERE****************************************

%build output file name
tfile=[fileoutstem 'times.txt'] % output times

%read in data
load(filein,'A','x','t');
[nt nx] = size(A);

%Pick returns and compute velocities
[x,layert] = LayerTimePickSimple(tshow,filein);
%layert
%interpolate UTM coordinates of points along lines
U=xlsread(fileUTM, sheetUTM);
[nobs ncol] = size(U)
for i=1:nx
    iobsright = 1;
    while (U(iobsright,2) <= x(i) && iobsright < nobs)
        iobsright = iobsright + 1;
    end
    iobsleft = iobsright - 1;
    E(i) = U(iobsleft,3) + (U(iobsright,3)-U(iobsleft,3))... 
        *((x(i)-U(iobsleft,2))/(U(iobsright,2)-U(iobsleft,2)))
    N(i) = U(iobsleft,4) + (U(iobsright,4)-U(iobsleft,4))... 
        *((x(i)-U(iobsleft,2))/(U(iobsright,2)-U(iobsleft,2)))
end
size(E)

if (irev == 1)
    E = fliplr(E);
    N = fliplr(N);
end

%write out layer times
TimeOutUTM(x,layert,E,N,tfile);
Appendix E: CMP LARI-Bounding Reflector Delineations

E-1: Site 1_CMP 1 LARI-bounding reflector delineations

E-2: Site 1_CMP 2 LARI-bounding reflector delineations
Appendix E (Continued)

E-3: Site 2_CMP 1 LARI-bounding reflector delineations

Site 3: CMP 1

E-4: Site 3_CMP 1 LARI-bounding reflector delineations
Appendix E (Continued)

E-5: Site 4_CMP 1 LARI-bounding reflector delineations

E-6: Site 4_CMP 2 LARI-bounding reflector delineations
E-7: Site 4_CMP 3 LARI-bounding reflector delineations
Appendix F: GPR Profiles

F-1: Site 1 Line 1 GPR profile

F-2: Site 1 Line 2 GPR profile
Appendix F (Continued)

Site 1 Line 3 NW to SE

F-3: Site 1 Line 3 GPR profile

Site 1 Line 4 NW to SE

F-4: Site 1 Line 4 GPR profile
Appendix F (Continued)

F-5: Site 2 Line 1 GPR profile

F-6: Site 2 Line 2 GPR profile
Appendix F (Continued)

Site 2 Line 3 NW to SE

F-7: Site 2(Line 3 GPR profile

Site 2 Line 4 SW to NE

F-8: Site 2(Line 4 GPR profile
Appendix F (Continued)

Site 2 Line 5 NW to SE

depth (m)  vel=0.128m/μs

0  5  10  15  20  25  30

F-9: Site 2 Line 5 GPR profile

Site 2 Line 6 NW to SE

depth (m)  vel=0.128m/μs

0  10  20  30  40  50

F-10: Site 2 Line 6 GPR profile
Appendix F (Continued)

Site 2 Line 7 NW to SE

F-11: Site 2 Line 7 GPR profile

Site 3 Line 1 SW to NE

F-12: Site 3 Line 1 GPR profile
Appendix F (Continued)

F-13: Site 3 Line 2 GPR profile

F-14: Site 4 Line 1 GPR profile
Appendix F (Continued)

Site 4 Line 2 NW to SE

F-15: Site 4_Line 2 GPR profile

Site 4 Line 3 W to E

F-16: Site 4_Line 3 GPR profile
Appendix F (Continued)

Site 4 Line 4 W to E

F-17: Site 4_Line 4 GPR profile

Site 4 Line 5 NW to SE

F-18: Site 4_Line 5 GPR profile
Appendix F (Continued)

F-19: Site 4_Line 6 GPR profile

F-20: Site 4_Line 7 GPR profile
Appendix F (Continued)

Site 4 Line 8 W to E

F-21: Site 4 Line 8 GPR profile