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Field imaging spectroscopy and inferring a blind thrust earthquake history from secondary faulting: 1944 San Juan Earthquake, Argentina

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Field Imaging Spectroscopy
and
Inferring a Blind Thrust Earthquake History from Secondary Faulting: 1944 San Juan Earthquake, Argentina

A Dissertation submitted in partial satisfaction of the requirements for the degree
Doctor of Philosophy

in

Earth Sciences

by

Daniel Eduardo Ragona

Committee in charge:

Professor Jean-Bernard Minster, Chair
Professor Yuri Fialko
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2007
This Dissertation of Daniel Eduardo Ragona is approved, and it is acceptable in quality and form for publication on microfilm:

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Chair

University of California, San Diego

2007
DEDICATION

To my parents, Beatriz and Salvador, who always taught me with their example to work hard and to follow my dreams.
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Kumar, S., Wesnousky, S. G., Rockwell, T. K., Ragona, D., Thakur, V. C., and G. G. Seitz, (2001), Earthquake recurrence and rupture dynamics of Himalayan Frontal Thrust, India, Science, November 29; 0 10661951-1
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FIELDS OF STUDY

Major Field: Geological Sciences

   Studies in Paleoseismology
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   Studies in Imaging Spectroscopy
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   Studies in Structural Geology and Regional Geology
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Field Imaging Spectroscopy

and

Inferring a Blind Thrust Earthquake History from Secondary Faulting: 1944 San Juan Earthquake, Argentina

by

Daniel Eduardo Ragona

Doctor of Philosophy in Earth Sciences

University of California, San Diego, 2007

Professor J. Bernard Minster, Chair

The studies presented in this dissertation provide new approaches to extract paleo-earthquake information from the geological record. The first chapter describes the development of Field Imaging Spectroscopy, a new methodology for data acquisition and analysis in paleoseismology. The study shows the steps followed from data acquisition, pre-processing, processing and analysis of high spatial and spectral resolution images obtained from cores and a large sample from a fault zone collected at Hog Lake, San Jacinto Fault, Southern California. The study demonstrate that hyperspectral data can be obtained in the field using portable scanners and that high spatial and spectral resolution in the visible to short wave infrared provide a way to enhance subtle or invisible
stratigraphic and structural features. The second chapter focuses on the use of neural networks and naïve Bayesian classifiers to automatically classify hyperspectral image data, providing an objective mapping of the structure of cores, samples and field exposures. The results of this study show that a system integrated by a hyperspectral scanner and pattern recognition algorithms can work as an enhanced eye and an objective classifier to provide the geologist with additional information that facilitates the final description, interpretation and correlation of the geology in paleoseismic exposures and cores. The hyperspectral dataset collected together with a spectral library of the materials observed in the excavation provide a new way to archive paleoseismological data for future analysis. Finally, in chapter 3, an innovative approach to study blind thrust faults is presented. The study of the secondary La Laja fault near San Juan, Argentina shows that the earthquake history recorded in a minor fault provides an indirect way to study the occurrence of large M~7 earthquakes at depth. This investigation also provides the first and perhaps the longest record of the earthquake activity of a blind thrust fault in the world, as well as the most detailed and complete study of past earthquakes in the Argentinean Andes. It also set a good precedent for similar studies in other structures in other regions of the world where the earthquake hazard related to blind thrust faults is largely un-assessed.
INTRODUCTION

In this chapter I am providing a general introduction to the methods and techniques to study past earthquakes. A general discussion regarding why it is important to study paleo-earthquakes and why it is important to develop new methodologies and approaches is briefly discussed.

Earthquake Geology and Paleoseismology

Earthquake Geology, in the broad sense refers to the study of the effects of earthquakes within the earth’s crust by using geological techniques. An important part of earthquake geology is paleoseismology, the study of the timing, location, and size of historic and prehistoric earthquakes (Soloneko, 1973; Wallace, 1981), typically through geological study of past surface ruptures recorded in the recent sediment history along a fault or fold. Current major areas of research in this discipline focus on the understanding of the long-term regularity (e.g. Poissonian, quasi-periodic, clustered) and repeatability (e.g. characteristic slip, variable slip, random) of earthquake ruptures with the ultimate objective of providing insights on the earthquake phenomenon for assessment of the hazard or to validate earthquake physics models.

Why is it important to study past earthquakes?

It is human nature to want to understand and possibly assess what may happen in the future. In the particular case of earthquakes, it translates into the necessity to find ways to assess the probability of occurrence and size of future earthquakes. In the past, assessment of earthquake hazard was mainly based on the historic seismicity and earthquake record of a region (McCalpin, 1996), but that approach was proved not
complete. In some cases, large earthquakes have struck regions with little prior historical seismicity (e.g. 2001 Gujarat; Wesnousky et al., 2001; New Madrid EQ, 1812; Charleston, 1878). In other cases, historical accounts are very general and do not identify the seismic sources, rupture lengths and slip vector, and therefore they are not very useful for assessing the probability of future events. In any case, reliable and systematic historical accounts are only available for very few locations around the planet (e.g. Anatolia Fault Ambraseys and Finkel, 1995) and instrumental seismological records are relatively recent, starting at the end of the nineteenth century. In the specific case of the “New World”, sometimes the average recurrence interval between large earthquakes is longer than the period of historical occupation by the new settlers, and therefore the historical accounts and the past seismological record are not sufficient to identify seismogenic sources and the associated hazard. Furthermore, earthquake hazard assessment based solely on historical events have the tendency to exaggerate the likelihood of earthquake incidence due to recent large earthquakes on faults with long average recurrence times (Lajoie, 1986; Crone et al., 1992; Adams et al., 1991). Knowledge of when, where, how often, and with what magnitude large earthquakes occur is crucial for understanding and characterizing the seismic hazard of a region. Study of the geological features across a fault or preserved in the geological record can provide an important gauge of the rate of fault movement, and thus of earthquake activity. Geological evidence of ground deformation other than faulting (e.g. folding, liquefaction, landslides, etc.) can also help to identify potential earthquake sources, such as blind thrust faults.

Paleoseismic studies provide a longer-term history of the ground rupturing earthquakes ($M_w > 6.5$), which may translate into longer-term probabilities of the
earthquake hazard. Understanding the pattern of occurrence may suggest the future rate of seismic activity [Bolt, 1993]. Paleoseismic studies also can resolve the long-term slip rate of a fault, that is the slip rate averaged over several earthquake cycles. Currently, earthquake geology studies supplement instrumental records of seismicity, InSAR, GPS etc. that monitor the crustal deformation at present time.

**Earthquake Recurrence Models.** One of the outstanding issues in understanding the behavior and physics of earthquakes is the correct modeling of earthquake recurrence, both in space and time. The determination of whether faults behave in a random, quasi-periodic, or clustered recurrence behavior is critical to success in forecasting future seismicity. In the search for patterns in an inherently complex system, earthquake geologists have evolved models of earthquake recurrence that are useful in estimating the likely size and probable occurrence of future seismicity. These models are based on limited observations on recurrent slip at a point along a fault, or variations in recurrence times at multiple paleoseismic sites along individual faults. The presumption that we can model source recurrence as regular progression of repeatable earthquakes began with H. F. Reid’s formulation of the elastic rebound theory (1910). One of the currently more prominent models, the characteristic earthquake model, was originally developed from paleoseismic observations along the Wasatch fault zone (a normal fault) and then applied to the strike-slip San Andreas fault [Schwartz and Coppersmith, 1984]. The uniform earthquake model [Sieh, 1978], also derived from paleoseismic studies, suggested a uniform slip model for individual fault segments, later termed the slip-patch model (Sieh, 1996). However, the repeatability of large ruptures, both in terms of magnitude and distribution of slip, has not been clearly established, and new observations suggest that
some faults and fault systems behave differently than others. Furthermore, paleoseismic observations along the San Andreas fault also suggest a more complex time-history, where the time interval between large earthquakes may be highly irregular.

**Current Methods and Techniques in Paleoseismology**

The methods to collect observations on paleo-earthquakes can be subdivided into two broad categories: surface and sub-surface paleoseismic methods. The first group of methods study the landforms generated by the earthquake activity using geomorphology, mapping, and surveying techniques, including LiDAR. Sub-surface methods or stratigraphic techniques (McCalpin, 1996) focus on the mapping of the stratigraphy and structure of exposures, either natural or more commonly excavations, that recorded ground deformation caused by slip on fault. The stratigraphic techniques in paleoseismology are commonly called “trenching”, in reference to the excavation technique used to expose the paleo-earthquake record. Paleoseismic trenching studies are key to obtain detailed information about, location, type and time of surface ruptures caused by earthquakes. Here we will briefly explain the current methods and techniques used to describe and interpret the stratigraphy and structure exposed at the trench faces; more detailed explanations can be found in McCalpin [1996]. Of course, the first step of the study requires the excavation of a trench perpendicular to the strike of the structure subject to the study. Sometimes complementary trenches parallel to the fault are excavated to identify offset features that can be used to measure slip per event. Once the trenches are excavated, the first step is the careful cleaning and flattening of the excavation walls, by scrapping off material and/or brushing it off until the stratigraphy and structure are well exposed. The next step consists of the construction of a reference
grid usually composed of horizontal and vertical lines of nylon string spaced every 0.5 or 1 m and attached to the trench walls with nails. Once the grid is finish, each panel is photographed to build a photomosaic of the walls. Photologging is quickly becoming the preferred choice of the field geologist because it provides a great base to draw the observed relationships. Commonly, the trench stratigraphy and structure are also logged using gridded paper and tape. The objective of the logging is to draw all the physical features of the trench face at the chosen scale resolution, with little subjective interpretation [Hatheway and Leighton, 1979; McCalpin, 1996]. The most objective representation of a trench exposure is the photomosaic with no interpreted features drawn on it. Hand logging always requires interpretation of the nature and correlation of the contacts. A photomosaic, on the other hand, usually cannot capture all the features that a person can identify in the field (e.g. subtle grain size and color variations, humidity changes, compaction of the sediments, etc), and therefore a combination of both photomosaicing with field observations and interpretations (photologging) is usually preferred. The final trench log is the only archived record of the observed features and interpretation of the excavation (Figure 1).

**Why are new methods and techniques in paleoseismology necessary?**

To achieve a correct description and interpretation of the earthquake history recorded at a paleoseismological site, several critical elements must be present. Some of the most important include:

1- Good resolution of stratigraphy at an appropriate scale to resolve the problem under study.
2- Presence of units with “characteristic features” that permit reliable correlations across faults and between trenches.

3- Experience of the geologist providing the descriptions and interpretations.

4- Excellent (accurate) dateability of faulted horizons (stratigraphic units)

A common problem at many sites has been the inability to recognize “good stratigraphy” with sufficient detail to provide evidence of events. Even worse is the inability to recognize the non-uniqueness of stratigraphy, making correlations across a fault suspect. Furthermore, a common problem is that many sites offer less than ideal conditions for recording past earthquakes. This has led to differences in interpretation, and can result in either an incomplete history or misinterpretation of the earthquake history (McCalpin, 1996; Weldon, McCalpin and Rockwell, 1996). To reduce the impact of these problems, the current methodology in paleoseismology requires many experienced eyes in one trench (trench parties) to discuss the description and reach some agreement on the interpretation. But the problem goes even further than that. Since paleoseismic excavations are a destructive technique, the only information left are the paper logs, descriptions, and the digital photographs of the trench walls. As a result, the original geological data was removed forever and the archived information is strongly dependent upon the experience of the geologists that described the site. Only after more objective archival methods are developed will paleoseismological datasets gain enough reliability to be re-interpreted and re-used for different purposes.

There is a clear need for new approaches to improve our ability to recognize, map and permanently document stratigraphy and structure at paleoseismic sites that will 1) improve the quality of data collection at “average” sites, 2) provide a permanent method
to archive data for future work, and 3) reduce the impact of misinterpretation due to inexperience by making the stratigraphy and structure more “visible”.

**A new method to assist in the description, interpretation and archival of the earthquake record.**

In Chapter 1 of this study, I present a new methodology to acquire, interpret and store stratigraphic and structural information from paleoseismic exposures. The objective of this study was to develop a “Geologist Assistant” system that provides new and objective information of the trench exposures and cores that can be used to improve the description and interpretation of the paleo-earthquake record. The methodology is based on Imaging Spectroscopy, a technique used in air-borne and space borne platforms, and is adapted for first time to the study of geological field exposures, drill cores and lab samples.

Portable hyperspectral visible-near infrared (VNIR) and short wave infrared (SWIR) cameras with high spatial/spectral resolution where used to acquire images of large samples obtained from a paleoseismic excavation. Standard remote sensing pre-processing and processing techniques were applied to the images to obtain useful geological information from features that are invisible or not obvious the human eye, and is not registered in standard digital photography.

In Chapter 2, I focused on the application of pattern recognition algorithms to analyze the hyperspectral datasets and obtain objective lithostratigraphic maps of drill cores and field exposures. The results show that hyperspectral images classified with supervised algorithms can be used to properly map sediments, even those of very similar compositions and grain sizes. Quantitative identification of geological materials can be
An innovative approach to study Blind thrust faults earthquake history.

Blind thrust faults represent an important seismic hazard for many urban areas around the planet. The lack of a primary surface rupture, along with the difficulty in interpreting the geomorphic signal produced by individual earthquakes, make blind thrust faults one of the most challenging types of structures for which to assess seismic hazard. Developing new strategies to study paleo-earthquakes in these scenarios is fundamental. Significant efforts have taken place to understand the geomorphic responses that occur as a consequence of slip and associated folding on a blind thrust fault during an earthquake, but these methods are not precise enough to provide the detailed earthquake history on a particular structure [e.g. Siame et al., 2002, Dolan, et al., 2000].

In chapter 3, I address the issue of the study of blind faults using traditional paleoseismic techniques applied to secondary surface faults. I use the displacement history of the secondary faults as a proxy to resolve the earthquake history of the earthquake-generating blind thrust at depth. The selected study area is an ideal scenario to apply this technique because the link between a large earthquake at depth and secondary faulting at surface was observed in the 1944 San Juan earthquake [Groeber, 1944; Castellanos, 1944; Harrington, 1944]. Other examples of coseismic flexural slip-faulting were observed during the 1980 El Asam, Algeria, earthquake [Philip and Merghraoui, 1983], the 1968 Inangahua, New Zealand earthquake [Lensen and Otway, 1971], the 1987
Superstition Hills earthquake sequence (Klimger and Rockwell, 1989), and the 1994 Sefidabeh earthquake, Iran, [Berberian et al., 2000]. Although the study of secondary faulting to assess the earthquake history of a blind thrust is a promising field, to date, only very few studies of this kind have been performed [Yeats, 1986b; Stein and Yeats, 1989], and as far as my knowledge goes, this study is the first to obtain a successful reconstruction of a long sequence of slip events that can be interpreted to represent the earthquake history of a fault at depth.

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CHAPTER 1

FIELD IMAGING SPECTROSCOPY: A new methodology to assist the description, interpretation and archiving of paleoseismological information from faulted exposures

Abstract

We present a new methodology to acquire, interpret and store stratigraphic and structural information from paleoseismic exposures. For this study we employed portable hyperspectral cameras to acquire field-based visible-near infrared (VNIR) and short wave infrared (SWIR) high spatial/spectral resolution images. We first analyzed four hundred small sediments cores using a hand-held, single-pixel spectrometer (VNIR-SWIR) to determine the feasibility of the method and to assess its potential problems. We then acquired high-spatial resolution (sub-millimeter) spectral data of a large sample (60 x 60 cm) and four cores (7.5 x 60 cm) of faulted sediments from a paleoseismic excavation using portable push-broom AISA hyperspectral scanner. These data, which contain 244 (VNIR) and 245 (SWIR) narrow contiguous spectral bands between 400 and 1000 and 960 to 2403 nanometers (nm), respectively, were processed to obtain the reflectance spectra at each pixel. In this study we are focusing on the analysis of the short wave infrared datasets (SWIR).

The SWIR data were transformed into relative reflectance and geometrically corrected and processed with well-known imaging processing algorithms. Selected spectra were then used to create false-color composite images that best display the faulted stratigraphy. We compared the hyperspectral images to those recorded by a digital camera as well as directly to the field sample and show that the reflectance properties of
the materials in the SWIR region can not only enhance the visualization of the sedimentary layers and other features that are not obvious to the human eye, but can also make visible many detailed features that were not visible in the digital photography. This new data collection and interpretation methodology, herein termed Field Imaging Spectroscopy, makes available, for the first time, a tool to quantitatively analyze paleoseismic and stratigraphic information. In addition, hyperspectral datasets in the visible short-wave infrared spectral range provide a better alternative for data storage. The reflectance spectra at each pixel of the images provide unbiased compositional information that can be processed in a variety of ways to assist with the interpretation of stratigraphy and structure at a site.
1. Introduction

We introduce a new method to assist the description, interpretation and preservation of paleoseismic information through the application of high-resolution field imaging spectroscopy. Paleoseismology concerns the study of the timing and size of past earthquakes, commonly resolved through structural and stratigraphic analysis of deformed sediments at sites of recent sedimentation along a fault [e.g., Sieh, 1978, Weldon et al., 1996; Rockwell et al., 2000]. Such studies are important in understanding the long-term production of large earthquakes along a fault or system of faults, critical elements in seismic hazard studies as well as understanding the underlying physics of the earthquake engine.

The current methodology employed to study the earthquake history of a site typically involves excavating trenches across a fault and documenting the exposed stratigraphy and structure by careful logging, either on paper and/or on photographs [e.g. Weldon et al., 1996]. Stratigraphic units are usually defined by color, mineralogical composition, grain size, lateral continuity, and the presence or absence of pedogenic features. Some of these characteristics are commonly subtle and their identification often requires considerable experience, thereby implying a certain degree of subjectivity in the interpretation of past earthquakes. As the level of confidence on the paleoearthquake history of a site is directly related to the stratigraphic resolution of the site, there is a clear need to develop new methods that objectively document and archive stratigraphic and structural information.

Prior studies in imaging spectroscopy have shown that visible-near infrared (VNIR) and shortwave infrared (SWIR) images, combined with simple but powerful
algorithms, can be used to discern or classify materials of various compositions [e.g. Blom, et al., 1980; Goetz et al., 1985; Goetz et al., 1992a; Clark, et al., 1992; Krause, 1993; Green et al., 1998; Chabrillat et al., 2002; Clark, et al., 2003]. This suggests that spectral imaging techniques can be applied to assist with identification and mapping of stratigraphy and structure in paleoseismic excavations in much the same way as satellite or AVIRIS imagery has been applied to a variety of surface process problems. In this study, we investigated the use of ground-based hyperspectral imaging (hereinafter Field Imaging Spectroscopy) as a new method to assist the collection, interpretation and storage of paleoseismological data from excavations or natural exposures. Here, we show the capability of this technique to enhance or resolve subtle stratigraphy, especially where fine bedding is obscure or indistinguishable with the human eye, and we discuss supervised quantitative tools to assist in the correlation of units across faults. Finally, we show that hyperspectral imagery provides a platform to archive paleoseismic data that allows future analysis, even after the excavations are closed.

2. Background on Imaging Spectroscopy

Imaging spectroscopy is a technique where spectral information from light is acquired and stored at each pixel of an image [Clark, 1999; Mustard and Sunshine, 1999]. If the spectral data correspond to hundreds of closely-spaced narrow bands (high spectral resolution) in such a way that continuous spectra can be reconstructed, the technique is referred as hyperspectral imaging [Clark, 1999]. Imaging spectroscopy has been most commonly used in remote sensing applications (airborne or spaceborne platforms and telescopes) and, when combined with effective algorithms, has been used
to identify and quantify specific mineral assemblages and to create compositional maps of materials [e.g., Clark, 1999; Mustard and Sunshine, 1999; Van Der Meer et al., 2001].

Spectral images contain information on material properties (e.g. reflectance, transmittance, emittance) for the sampled portions of the electromagnetic spectrum (e.g. ultra-violet (UV), VNIR, SWIR, long-wave infrared (LWIR)). For this study, we acquired raw data in the VNIR-SWIR spectral range, and chose to process that data for reflectance. Reflectance is an intrinsic material property and is defined as the ratio between the radiation scattered by a surface to the radiation incident to the surface [Schott, 1997]. The reflectance spectra contain albedo, continuum and absorption features that relate to the material properties of the imaged surface [Clark, 1999; Gaffey, et. al., 1993].

The spectral data is stored in the form of a matrix, commonly called a hyperspectral cube, where spatial information is stored in the x and y axes, and a third axis contains the spectral information of each x-y pixel. Naturally, all the information contained in a hyperspectral cube (e.g. 245 bands for AISA Hawk) cannot be represented in a single image. Rather, it is necessary to construct images using combinations of selected bands, band ratios, or alternatively, to show the spectral response of selected pixels. A variety of algorithms also exploit a number of other features like spectral similarity, absorption bands, statistical transformations, supervised and unsupervised classification to produce images and extract qualitative and quantitative information from the data.
3. Spectral Imaging of Geologic Stratigraphy

Previous studies have demonstrated that imaging spectroscopy can successfully be applied to a variety of geological problems, in most cases from remote platforms. In this study, we focus on near range (submeter distances) field or lab applications for earthquake geology studies (paleoseismology). Hyperspectral images should be able to assist in the identification of stratigraphy and structure to resolve the earthquake history of a site. To test this hypothesis, we conducted two sets of experiments on sediments collected from the Hog Lake paleoseismic site [Rockwell et. al, 2003] along the San Jacinto fault in southern California. The first test on the spectra of individual samples was aimed to determine whether soils or sediments with similar visible characteristics have distinctive VNIR-SWIR reflectance spectra.

The second test consisted of the acquisition of high-resolution hyperspectral data of a 60x60 cm slab and four cores of faulted stratigraphy from Hog Lake. The experiment was designed to evaluate whether close range (sub-meter) hyperspectral images of soil and sediments can be obtained in the lab or the field, and to investigate whether these images can facilitate or improve our field observations. Although all the spectral information for both experiments was collected in the lab, the small size of the instruments allow for data acquisition in the field. The sensors can be mounted on an x-z motion device that can directly scan the trench walls or exposures.

Finally, we show that the hyperspectral datasets provide an unbiased method to record geological information of a paleoseismic site that can be archived for immediate or future analysis after the excavations are closed.
3.1. Test 1: Spectra of Individual samples

From the Hog Lake exposures, we collected four hundred samples from well-stratified sediments in a 50 by 50 cm section of a trench wall (20 x 20 samples). In general, the sampled materials are clastic sediments dominated by silt, silty-clay and sand. The samples were air dried for a week and taken to the Jet Propulsion Laboratory where two sets of measurements (sun and artificial light) were obtained with a portable spectrometer ASD FieldSpec® Pro FR (350-2500 nm spectral range). This instrument has a spectral resolution of 3–4 nm in the 350- to 1000-nm region (spectral sampling of 1.4 nm), and 10–12 nm in the 1000 to 2500 nm (spectral sampling of 2 nm) [Analytical Spectral Devices, 2002].

The first set of measurements was acquired at very short range (~ 10 cm) under sunlight and clear sky conditions, and each sample was measured five times. In addition, two hundred white reference (Spectralon®) measurements were collected throughout the experiment under the same conditions.

The second group of measurements was obtained under artificial light (two halogen lamps connected to a stabilized source) in a dark room, and at about the same distance of ~10 cm as the first group. Through the data collection scheme, 20 measurements were also made on the white reference surface. The data obtained were transformed into relative reflectance [e.g., Duggin and Cunia, 1993] and re-sampled to obtain a spectral resolution of 10 nm.

To determine whether similar sediments or soils have distinctive VNIR-SWIR spectral characteristics that can be used for classification, we first assessed the spectral variability of the five measurements of spectra acquired for each sample under sunlight
conditions (Table 1, Figure 1). We then compared the mean between different samples using their spectral angles (see last three lines of Table 1) and their root mean square distances (RMS) [Yuhas et al., 1992, Krause et al., 1993, Mustard and Sunshine, 1999]. While RMS is an indicator of the overall similarity between two spectra, the spectral angle mapper algorithm (SAM) only compares spectral shape without taking into account the intensity. For such cases, this is especially important because while the intensity varies significantly among the five measurements of the same sample, the spectral shape remains constant. These intensity variations, which are likely due to poor spatial control (primarily, the distance from the sample to the probe) during data acquisition, diminished the utility of the RMS comparisons. On the other hand, spectral angle measurements among the five reps of the same sample (see first three lines of Table 1) show variations that are about two orders of magnitude smaller than the angles between different samples. This indicates that the shape of the reflectance spectra can be used to successfully group or separate different materials and/or create a relative stratigraphy.

In addition, we determined the variability on the measurements as a function of wavelength. We first re-normalized the spectra by their maximum value to remove the effect of intensity variations due to a variety of sources. Then we estimated the mean and standard deviation for the five measurements of each sample (Figure 1). The results clearly show that the spectral variability between different samples is much larger than the statistical variations (2σ error bars) of the measurements of the same sample at each band.
Table 1.1. Spectral angles (SAM). SAM 41, 202 and 400 show the spectral angle measured between the reflectance spectra of the first reading against each of the five readings of the same sample. SAM 41 vs 202 and 41 vs 400 compare the spectral angle of the mean spectra of sample 41 with the five readings of samples 202 and 400 respectively. SAM 202 vs 400 show the spectral angle between the mean spectra of sample 202 and each of the five readings of sample 400. Sample 41 (s41) is a fine to medium, light gray sand with abundant biotite, sample 202 (s202) is a light brown silty-clay with fragments of organic material, and sample 400 (s400) is a light greenish-gray silty-clay with scattered patches of secondary calcium carbonate.

<table>
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<tr>
<th></th>
<th>reading 1</th>
<th>reading 2</th>
<th>reading 3</th>
<th>reading 4</th>
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</tr>
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<td>0.007078</td>
<td>0.012307</td>
<td>0.0083417</td>
</tr>
<tr>
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<td>0.018787</td>
<td>0.020978</td>
<td>0.015148</td>
</tr>
<tr>
<td>SAM 400</td>
<td>0</td>
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<td>0.0097755</td>
<td>0.013164</td>
<td>0.017441</td>
</tr>
<tr>
<td>SAM 41 vs 202</td>
<td>0.27624</td>
<td>0.28099</td>
<td>0.2914</td>
<td>0.29141</td>
<td>0.28775</td>
</tr>
<tr>
<td>SAM 41 vs 400</td>
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<td>0.12947</td>
<td>0.1261</td>
<td>0.12521</td>
<td>0.12443</td>
</tr>
<tr>
<td>SAM 202 vs 400</td>
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<td>0.28133</td>
<td>0.28753</td>
<td>0.27281</td>
<td>0.28071</td>
</tr>
</tbody>
</table>

During this first test, we assessed some of the potential limitations of reflectance spectroscopy to separate different sediment classes. The most important factors that affected the spectra in this first test were the poor control in illumination during the natural light experiment, the variability of the sample to probe distance relative to the distance from the white reference to the probe, and the variation in moisture content of the samples. Illumination and relative distance problems were addressed during the artificial light experiment. Moisture variations of the samples introduced a limitation, mainly affecting the ability to perform sample spectra comparisons for correlation or mapping purposes. Water not only produces a reduction of the intensity of the light reflected, it also modifies the spectral shape by introducing deep, wide absorption bands.
around 1400 and 1900 nm. Further, it causes an overall depression of the infrared section of the spectra [Idso et al., 1975, Skidmore et al., 1975, Twomey et al., 1986, Muller and Decamps, 2000, Lobell and Asner, 2002].

**Figure 1.1.** Relative reflectance vs. wavelength of samples s41, s202 and s400. The spectra were normalized by their maximum value. The error bars (plotted every 40 nm for clarity) indicate two standard deviations $2\sigma$ above and below the mean of the five measurements. The measurements were obtained under sunlight illumination and therefore strong atmospheric water absorptions around 1400 and 1900 nm are shown as gaps in the spectra.

### 3.2. Test 2: Hyperspectral Imaging of Large Samples

Recently developed portable hyperspectral imagers (push broom scanners) make it possible to acquire VNIR-SWIR images at high spatial and spectral resolution in the field and lab. These spectral cameras, mounted on an X-Z motion device, can acquire a continuous swath in the same fashion as space-borne or airborne platforms. As the AISA
Hawk or AISA + hyperspectral imagers were not readily available for our use in the US, we transported a portion of the trench wall and several cores to SPECIM headquarters in Finland for image acquisition. It is important to mention that the hyperspectral scanners are portable (16 x 16 x 36 cm) and can be deployed in the field to scan various exposures.

3.2.1. Sediment sampling

We collected a group of samples that are representative of the stratigraphic variability observed at the excavation site. Their size was constrained by portability, since the samples needed to be transported as airline luggage to the lab. We obtained a large, representative sample of faulted sediment from the Hog Lake paleoseismic excavations in a 60 x 60 x 3 cm aluminum box, along with four 60 x 7.5 x 3 cm cores collected in aluminum channels. While the box was intended to represent a portion of the fault zone, the cores were obtained to evaluate the potential for automated stratigraphic correlations. Three of the cores were collected to simulate a continuous 1.8 m core, located approximately 2 m from the fault. The fourth core was obtained 1 m from the opposite side of the fault. Prior to sampling, we carefully flattened and cleaned a one square meter area of the trench wall. The samples were recovered by pressing the aluminum box and channels against the wall and cutting the sediment away from the trench face. All samples were wrapped in plastic, covered with an aluminum top plate, and stored in a wooden container for transport.

3.2.2. Acquisition of Spectral Images

Previous to data acquisition, we cleaned the surface of the samples and set fiduciary marks for future orthorectification and registration of the images. For the 60 x
60 cm sample, we inserted 44 pieces of wooden tooth picks, randomly distributed to cover the total area. We also inserted about 13 tooth pick pieces on each of the four 60 x 7.5 cm core samples. Once all the marks were inserted, we measured the x-y relative location of each of the registration points.

We used the following procedure for all data collection. First, we placed a piece of white reference material (OP.DI.MA.) at the same height as the surface of the sediment and directly within the field of view of the camera. Under these conditions, we set the integration time and acquired 50 frames, each composed of 320 (SWIR) or 512 (VNIR) spatial pixels with 245 spectral bands. Second, we obtained 50 frames of the dark current of the instrument under the same integration time as the measurement of the white reference. Third, each of the 15 portions of the sample was scanned under the same light conditions as the white reference measurements and finally the dark current was measured again with the same settings as the sample.

3.2.2.1. Large Sample Imaging (Box Sample)

The 60 cm x 60 cm sample was set on a mobile platform controlled by a stepper motor. The sensor heads were held in a fixed position orthogonal to the sample. The distance from the foreoptic to the sample surface was approximately 55 cm. The light source was generated by two 500-Watt halogen lamps positioned about 50 cm from the surface on each side of the sample. Two different instruments were used to make the measurements: 1) an AISA Hawk for SWIR range and 2) AISA + for VNIR range.

For the SWIR measurements the sensor was equipped with an 18° field-of-view front objective which, at a 55 cm distance, produces a swath of approximately 17 cm and
a pixel width of 0.057 cm for a total of 320 pixels per line. Integration time was 5 milliseconds (ms). The stepper motor was set at a constant speed, resulting in a 0.04 cm pixel size in the direction of motion (perpendicular to the scanning line).

For the VNIR measurements a 39.7° field-of-view front objective was used with the AISA + instrument, which translates into a swath of ~38.1 cm at a distance of 55 cm. The resultant pixel width is 0.077 cm for a total of 512 pixels along the line. Integration time was 120 ms. The instrument motion velocity was set to yield a 0.05 cm pixel size in the direction of motion.

**3.2.2.2. Cores imaging.**

The four pieces of 60 x 7.5 cm were scanned following the same protocol as the large sample.

The VNIR images of the core were acquired with the AISA+ sensor positioned 40 cm above the sample, and with two 500 Watt lamps arranged on both sides at approximately the same height as the sensor. The integration time used was 150 ms. The swath width was ~27.7 cm, resulting in a pixel size of 0.056 cm. The cores were measured under their normal moisture conditions (slightly less moisture than the trench wall).

The SWIR images of the cores were obtained with an AISA Hawk sensor under exactly the same setup as the large sample. The cores were placed at 55 cm from the spectral camera and the integration time was set at 5 ms. The swath width was 17 cm, resulting in a pixel size of 0.057 cm.
3.2.3. Pre-Processing

A series of standard pre-processing techniques were applied to transform the raw data into geometrically corrected spectroscopic images with reflectance information at each pixel. Since we acquired the data under stabilized artificial light and at a very short distance (~55 cm), we assume that atmospheric effects are constant during the experiment, that illumination is stable and that the instrument maintains a linear response throughout the experiment. Taking these assumptions as valid, the only remaining important radiometric distortion is a result of the instrumentation dark current. As a dark current measurement is made following each sample, this correction is straightforward and simply requires subtraction of the measured constant at each pixel and band. Finally, we transformed the raw values obtained after dark current removal into relative reflectance. For each pixel and band of the image, we perform the ratio between the sample measurements and the white reference, both measured under the same conditions as mentioned in the protocol. Absolute reflectance was obtained by multiplying the relative reflectance by the reflectance of the white reference (OP.DI.MA) to correct for its small absorptions.

Spatial pre-processing is later applied to remove geometric distortions introduced in our image acquisition process. These distortions include panoramic distortion, variations in distance and velocity of the sensor and aspect ratio distortion. Panoramic distortion is produced by a constant angular field of view of the sensor. As a result, the effective pixel size on the ground is larger at the edges of the scan than at nadir. In addition, microtopography of the sample and velocity variations in the “push-broom”,
stepper motor may cause variations in pixel size along the direction of motion. The vertical scale may differ from the horizontal scale because of a faster or slower calculated speed of the motion device. The ideal speed needed to maintain the aspect ratio must be calculated from the integration time and the pixel width. Mismatches in the calculation will produce an aspect ratio distortion. We chose to correct for geometric distortions by imaging registration techniques. Specifically, we used the wooden control points set on the samples to rectify the image.

3.2.4. Data Processing

Although all the SWIR and VNIR images were processed and analyzed, for this study we prefer to be concise by focusing on only three of the SWIR images; one from the large box and two from cores located on opposite sides of the fault. After preprocessing, we created false color composite images and applied standard transformations (e.g., minimum noise fraction, decorrelation stretch) to display broad features like stratigraphic units and structure. These images were compared with detailed hand-drawn logs and high-resolution digital photography of the samples.

3.2.4.1. Large Sample (Box Sample)

We analyzed the image taken of the 60 x 60 cm sample after it was dried for 12 hours with heat lamps. We chose the dried version for our first analysis to minimize the water absorption affects that we had previously observed on the individual sample experiments, and that have been well described in the literature [e.g., Twomey et al., 1986, Lobell and Asner, 2002]. The pre-processed hyperspectral image has 1206 x 1521
pixels (width and height, respectively) and 245 reflectance bands ranging from 996 to 2403 nm (SWIR).

To visualize the information of the spectral image, we constructed a false color composite of the data displaying bands 1169, 1775 and 2368 as red, green and blue, respectively (Figure 2). These bands were chosen because they represent three characteristic parts of the spectra. To further enhance the features on the image, we applied the decorrelation stretch algorithm [Soha and Schwartz, 1978; Gillespie et al., 1986; Rothery, 1987] to the color composite (Figure 2). Finally, to reduce the spectral dimensionality of the dataset, we applied the minimum noise fraction algorithm (MNF) [Green et al, 1988], a statistical transform algorithm that, in contrast to principal component analysis, always produces new components ordered by image quality. From the 245 bands, we selected only ten MNF bands that contain significant geological information and 99.8 percent of the variance of the dataset. The MNF images enhanced many of the features already observable in the infrared color composite and decorrelation stretch image (Figure 2).

We also applied supervised classification using the spectral angle mapper (SAM) algorithm [Yuhas, et al., 1992, Krause et al., 1993] to test the validity of spectral correlations across the fault zone. This algorithm evaluates the angle between a reference vector (spectrum of the material that we wish to find), chosen a priori, against each of all the vectors (spectra of each pixel) of the image. An angle of zero indicates that the vectors (spectra) are identical while larger angles show how different the spectra are. In our evaluation, we first selected the spectra of pixel z188y774 (Figure 3 and Figure 2 c
**Figure 1.2.** a, is a digital photograph of the large sample box (60 x 60 cm) containing a section of a fault zone from the Hog Lake site. Figure 2 b, Detail of a section of figure 2 a. Figure 2 c, is a false color composite of SWIR bands (1169, 1775 and 2368 nm) of the large sample box (compare with figure 2 a). The image has similar spatial resolution as figure 2 a (same number of pixels per square inch). Numbers 1 to 4 and color circles indicate the location of the spectra shown in Figure 3. Figure 2 d. Detail of the SWIR color composite. Notice the detailed stratigraphy in this image and compare with figure 2 b. Figure 2 e, Decorrelation stretch of the SWIR image shown in figure 2 c. Notice the enhancement in colors helps to define the stratigraphic units and the correlation of layers across the fault zone. Letters a to e correspond to stratigraphic units at both sides of the fault. Compare with figure 2 a and 2 c.
for pixel location) as the reference material for unit c (Figure 2 e) and compared it with the remaining pixels of the image. Second, we evaluated the range of angles that best mapped unit C on one side of the fault (angles between 0 and 0.016 radians). Third, we mapped the entire image using the angles obtained in the previous step (Figure 4). Finally we evaluated the strength of the correlation across the fault and determined the best correlation using the area with the higher density of pixels that fall in the preferred range of spectral angles (Figure 4). The preliminary results show that SAM can provide a quantitative tool to assess the strength of correlations between layers in cores and across structural discontinuities, such as faults.

Figure 1.3. Spectra of four different units selected from the large sample box. The location of the spectra is indicated in figure 2 c with numbers 1 through 4 corresponding to the pink, yellow, green and blue circles, respectively. # 1 corresponds to the spectrum from pixel x238y425 (line with circles in this figure). Similarly, line # 2 corresponds to the spectrum at x259y569 (squares), # 3 corresponds to the spectrum at x188y774
(diamonds) and # 4 corresponds to the spectrum at x269y837 (stars). The spectrum of the pixel located at x188 y774 is representative of unit c on figure 2 e. This spectrum was used for the spectral angle mapper (SAM) classification of figure 4.

Figure 1.4. a) Shows a SAM classification using the 245 bands of the SWIR dataset for the large box sample (Figure 2 c). The classification was based on a single pixel (x188, y774) as the reference. The tolerance angle chosen was 0.016 radians. White pixels show the areas of the image with spectral angle less or equal than 0.016 (from a total range expanding from 0 to 0.59 radians, where smaller numbers indicate higher spectral similarity). Black are pixels with spectral angle bigger than 0.016. The letter C indicates the correlated horizons across the fault zone which, are equivalent to horizon c in figure 2 e. Figure 4 b and c show detail areas of the SAM image where we found the highest density of pixels that are similar to the reference spectrum.

3.2.4.2. Core samples.

Although all the acquired core images were processed and analyzed, in this study we only include the results from two SWIR images, corresponding to the Top-R and Top-
L cores. At the time of data acquisition, the cores still preserved most of their original (field) moisture. After pre-processing, each of the images comprised 1486 x 143 pixels (height and width, respectively) with 245 reflectance bands in the spectral range of 960 to 2403 nm. The images were displayed as false color composites using wavelengths 1192, 1682, 2288 nm as red, green and blue, respectively (Figure 5). The images were then processed with the MNF algorithm for dimensionality reduction, and the best MNF transformed bands were selected and displayed as red, green and blue false-color composites (Figure 5).

4. Discussion

We compared the products obtained from processing the short wave infrared hyperspectral datasets against digital photographs and direct visual observations of the previously described samples. Our objective was to assess the advantages and problems of the proposed Field Imaging Spectroscopy technique for paleoseismic studies.

4.1. Display or Enhancement of Subtle or Invisible Features

We compared direct visual observations and high-resolution digital photographs against SWIR images of the sample box and cores (Figures 2 and 5). The results show that the infrared images illuminate many features that are not obvious or visible in the digital photography or from direct observation of the samples. This is particularly clear in certain portions of the sample box (compare figure 2b against 2d) where finely laminated stratigraphy can only be observed in the infrared image. In the core samples,
**Figure 1.5.** (a) Three different images of the Top-L core. DP corresponds to a high resolution digital photograph of the core taken with a 3.2 megapixels camera; FCS is a false color composite image created using three SWIR bands (1192, 1682 and 2288 nm) as red, green and blue; MNF is a false color composite constructed with MNF bands 1, 2 and 3 as red, green and blue, respectively. Figures I to VI are detailed sections of the three images of the core (rectangular black boxes). Notice that the spatial resolution of the digital photograph and the SWIR hyperspectral images are approximately the same. (b) Three images of core Top-R. Abbreviations DP, FCS and MNF are the same as in figure 5 a. Figures I to VI are detailed portions of the three images of the core. In all figures, compare the DP with the FCS and MNF. Notice how much more stratigraphic detail is provided by the SWIR images.
the infrared images enhanced many obscure layers and made obvious a small fault that was barely visible in the digital photos (Figure 5).

4.2. Quantitative Analysis and Comparisons of Units Using Reflectance Spectra: Correlation of Layers Across Faults or Trenches.

Quantitative methods using reflectance spectra can be applied in many ways to assist in the analysis and interpretation of paleoseismic excavations. From identification of a particular material to correlation of equivalent strata across faults or between cores, these quantitative analyses contribute to the elimination of biases in field descriptions. As an example, we evaluated the correlation of layers across a small fault zone that was captured in our box sample (Figure 2 and Figure 4). Although the Hog lake site has excellent, detailed stratigraphy, many of the units exhibit similar physical characteristics as the sediments are derived from a common source area. Correlation of stratigraphy usually requires unique characteristics that can be unequivocally traced across a fault zone, a problem when many units have similar visible characteristics.

We experimented with the hyperspectral datasets to map the reflectance spectra of certain units across faults and between different cores. Using false color composites of the reflectance and minimum noise fraction bands, we selected stratigraphic units that we wanted to test for correlation across the fault (e.g. unit C in figure 2 e and 4 a). We then selected a reflectance spectrum for each unit and applied the spectral angle mapper algorithm to map the spectra across the fault. The spectral mapping matched the stratigraphic mapping obtained from field and sample observations. The spectral correlations showed promising results, even in areas with very similar, repeating stratigraphy.
4.3. Storage of unbiased data for immediate or future analysis.

Paleoseismologic excavations are, by their very nature, a destructive technique. After a site is studied and the trenches are closed, the data that are preserved usually take the form of paper-logs and photomosaics of the trench walls. Photomosaics provide only partial information, and in most cases cannot be used to accurately make interpretations on the earthquake history after the trenches are closed. On the other hand, paper-logs usually have an important interpretative component and therefore have to be used with caution for reinterpretation or reanalysis of the earthquake history. Hyperspectral datasets in the visible short-wave infrared spectral range provide a better alternative for data storage. The reflectance spectra at each pixel of the images provide unbiased compositional information that can be processed in a variety of ways to assist with the interpretation of stratigraphy and structure at a site. Further, the spectral imagery may illuminate subtle features that are a direct consequence of surface ruptures. This tool will assist in the interpretation of the earthquake history not only while the trenches are open, but can also be used for future reinterpretation after the excavations are closed. Our studies indicate that analysis of digital spectral data provide both a more detailed description of the samples and a permanent unbiased dataset, a significant improvement over currently applied practices that utilize photo-logging and hand-logging techniques. Ultimately, this will result in both better and more reproducible results.

4.4. Potential Limitations

By far, the most important potential limitation of the application of this technique is the effects of moisture content of the sediments on the reflectance spectra. In addition to the darkening of the sediments (reduction in reflectance) at all wavelengths, there are
significant absorptions near 1.4 and 1.9 microns when moisture is present. Changes in the reflectance spectrum are wavelength dependant [e.g., Lobell and Asner, 2002] and therefore the shape of the spectra experience important variations as the moisture content increases. These effects have their largest impact on the quantitative correlations or comparisons of materials when the moisture content varies significantly across an exposure or between cores. Some authors [e.g., Muller and Decamps, 2000; Lobell and Asner, 2002] show possible solutions for modeling soil moisture reflectance effects, and they may have to be considered in each particular case. For conditions when the moisture content is similar throughout an exposure (e.g. excavation wall), water absorptions should not affect the correlations because the spectral change is similar along the face. In cases where the moisture content differs from one area to another, direct correlations using the spectra or MNF images will be limited. In our studies, we tested two scenarios. One, a completely dry sample where the moisture content was approximately the same everywhere (Large box sample) and a second case where samples maintained a good percentage of their original moisture (core samples). In both cases we were able to identify stratigraphy and correlate units. The problems appear more obvious when we tried to compare the dry sample with the moist cores. In these cases, the very same stratigraphic units exhibit two different spectra, dry and moist. This type of problem will be common on trench exposures due to many factors (e. g. desiccation of the sediments in areas exposed to sunlight). Approaches to minimize this problem will have to be considered in each case.

Another potential problem with application of this technique relates to the characteristics of each individual trench site and deployment of the hyperspectral
scanners. Some sites may limit the quality of the data that can be collected, especially if the trench faces are not properly prepared (flattened, well-cleaned, etc.). Spectral amplitude will change with changes in illumination angle and distance, and therefore all these characteristics need to be taken into account at the time of data analysis and interpretation. Extremely narrow excavations or the location of trench shoring may make the installation of the scanning equipment difficult, and therefore these issues will have to be considered before planning the excavation. Finally, the extremely large size of the datasets resulting from scanning a trench site may have to be considered at the time of data collection to optimize the balance between quality of information and file size.

4.5. General applications of the methodology

Field Imaging Spectroscopy studies can be extended to many other applications in earth sciences where detailed quantitative analysis is required. Field based scanning of outcrops, cores and mineral alteration zones are just a few potential applications of this technology. In all cases, the most important advantage of the method is the objective description of geologic materials and the potential for numerical analysis of the datasets.

5. Conclusions

Our studies demonstrate that new, portable hyperspectral sensors (AISA Hawk and AISA +) can be used at sub-meter distances for high spatial and spectral resolution (sub-millimeter pixel) imaging in the lab or in the field. Results obtained from processing SWIR hyperspectral images of large samples show that imaging spectroscopy techniques (field imaging spectroscopy) can be successfully applied to assist the description and
interpretation of paleoseismic excavations. Comparisons between digital photographs, direct observation and hyperspectral SWIR images of the samples show that the most important advantages of imaging spectroscopy over current methods in paleoseismology are mainly but not exclusively focused in three main areas: 1) Display or enhancement of subtle or invisible features, 2) Quantitative analysis and comparisons of units using reflectance spectra, including correlation of layers across faults or trenches and between cores and 3) Storage of unbiased data for future analysis.

Work from other authors [e.g., Blom et al., 1980, Goetz et al., 1985, Clark et al., 1992, Gaffey et al., 1993] shows that reflectance spectra can be used to identify many types of geological materials; thus, this technique can be applied to other geological contexts.

We conclude that hyperspectral imaging (Imaging Spectroscopy) of trench exposures offers an exciting new approach that can greatly improve the utility of paleoseismic sites, increase the reproducibility of the results and provide an excellent method for unbiased data archival.

Acknowledgments


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References


CHAPTER 2

Supervised classification of sediments in field exposures and cores using high-resolution hyperspectral imagery and pattern recognition algorithms

Abstract

Our previous investigations have shown that ground-based hyperspectral imaging provides an effective method to study and digitally store stratigraphic and structural data from cores or field exposures. Neural networks and Naïve Bayesian classifiers supply a variety of well-established techniques towards pattern recognition, especially for data examples with high-dimensionality input-outputs. In this article, we present a new methodology for automatic mapping of sedimentary stratigraphy in the lab (drill cores, samples) or the field (outcrops, exposures) using short wave infrared (SWIR) hyperspectral images and these two supervised classification algorithms. High-spatial/spectral resolution data from large sediment samples (drill cores) were collected using a portable hyperspectral scanner with 245 contiguous channels measured across the 960 to 2404 nm spectral range. The data were corrected for geometric and radiometric distortions and pre-processed to obtain reflectance at each pixel of the images. For the supervised classification we built an example set using hundreds of reflectance spectra of the sediments sampled by these cores. The examples were grouped into eight classes corresponding to the most common materials found in the samples. In addition, we generated three other example sets by computing the 2-norm normalization, the first-order derivative and the 5-point averaged derivative of the smoothed reflectance spectra.
for the entire original example set. Each example set was divided into four subsets: training, training test, verification and validation. A multi-layer perceptron (MLP) with variable architecture and a Naïve Bayesian network (NBN) was trained to construct the classification models. We computed the final classification accuracy of our models using the validation sets. The models trained using the original reflectance examples achieved a 98.4 % classification accuracy using the MLP and 92.75 % with the NBN. The 2-norm normalized reflectance training set produced 97 % and 92.7 % classification accuracy for the MLP and NBN, respectively, and the derivatives training sets generated models with 93.8 % and 92.2 % (first order derivative) and 97.6 % and 95.4 % (five points smoothed derivative) classification accuracy for the MLP and NBN, respectively. Each model was applied to classify the images of the cores. We generated MLP and NBN classification images of all the samples and compared them against each other and against a statistical sampling of the real cores for an ultimate qualitative verification of the classification. Both methods exhibit similar classification results for the major stratigraphic units of the drill cores samples. Analysis of the classification divergences between the models may point out problematic areas. In conclusion, the results of this work show that reflectance spectra combined with neural networks or naïve Bayesian classifiers can be used to properly discern and classify sediments of very similar compositions and grain sizes. Quantitative identification of geological materials can be used as a fast and objective method to describe samples, drill cores, trench exposures and outcrops.
1. Introduction

The standard methodology to describe, classify and correlate geologic materials in the field or lab relies on the physical inspection of samples, sometimes with the assistance of conventional analytical techniques (e.g. XRD, microscopy, particle size analysis). This is commonly both time-consuming and inherently subjective [Sieh, 1978; Rockwell et al., 2001; Goldfinger et al., 2003]. Many geological materials share identical visible properties (e.g. fine grained materials, alteration minerals) and therefore cannot be easily mapped using the human eye alone. In these cases, new techniques such as hyperspectral imaging can assist the description and correlation of the geological units and therefore improve the final interpretations. A large number of studies using spectroscopy or imaging spectroscopy, either from air born platforms or from ground based instrumentation, have shown the utility of these techniques to analyze geological materials [e.g. Blom, et al., 1980; Goetz et al., 1985; Green et al., 1988; Goetz et al., 1992a; Clark, et al., 1992; Krause, 1993; Krause, 1996; Taylor, 2000; Chabrillat et al., 2002; Clark, et al., 2003]. Furthermore, recent advancements using state-of-the-art hyperspectral scanners demonstrates that ground-based hyperspectral imaging can provide an effective method to study and digitally store stratigraphic and structural data from cores or field exposures [Ragona et al., 2006].

We present herein a method that combines reflectance spectroscopy and supervised classification algorithms to identify and classify automatically sediments from cores and field exposures with a high degree of accuracy. In our classification strategy, we used both amultilayer perceptron (MLP) [Bishop, 1995] and Naïve Bayesian Networks [Domingos and Pazzani, 1997; Rish, 2001; Hand and Yu, 2001]. The use of
these two methods allows for comparisons that strengthen the validity of the classification scheme. In this article, we specifically focus on the methodology adopted for the construction of the example sets (training, test and verification sets), preprocessing of the data, algorithm training and classification model validation. Finally, we apply the classification models for mapping and correlation of four drill cores from Holocene lacustrine deposits and compare their results with traditional descriptions of the cores.

2. Methodology

The procedure developed for this study consists of eight main steps: 1) image acquisition, 2) reflectance calculation and geometric rectification, 3) construction of the example set, 4) pre-processing of the examples, 5) construction of the classification models, 6) evaluation of the classification models, 7) classification of the drill core images, 8) analysis and comparisons of the classified images.

2.1. Image acquisition

Four cores measuring 60 x 7.5 cm were collected from Holocene lacustrine deposits at the Hog Lake site [Rockwell et al., 2003], and scanned in the lab using a Specim Ltd. short wave infrared (SWIR) hyperspectral scanner (quote a web page, or something). This instrument measures 320 pixels per line and 245 bands (960 to 2403 nm) per pixel as it scans the sample. In addition to the samples, we also collected data from an optical diffuse reference standard (white reference) under the same conditions of illumination and distance used to scan the sediment samples. These white reference
measurements were used to compute the reflectance for each pixel of the images. A more detailed description of the image acquisition can be found in Ragona, et al. (2006).

2.2 Reflectance calculation and Image rectification

The raw data obtained from the scans were radiometrically and geometrically corrected, and then transformed into reflectance estimates through normalization by the white standard measurements. We assume that atmospheric effects are constant during the experiment, that illumination is stable and that the instrument maintains a linear response throughout the experiment (Ragona et al., 2006). The resulting images have a pixel size of ~0.5 mm with 245 reflectance bands between 960 and 2403 nm per pixel. We refer to these images as Core Top (CT), Core Mid (CM), Core Bottom (CB) and Core Left (CL), nomenclature derived from their relative positions in the field (Figure 1).

2.3 Construction of the example set

In this study, an example corresponds to a single reflectance spectrum consisting of 245 spectral bands (or any product derived from their pre-processing) and a class label. The construction of a reliable set of examples is one of the most important steps in the development of an accurate classification model. To build the example set, we first described the stratigraphic layers from the four cores. Next, we collected reflectance spectra examples of each unit from the SWIR hyperspectral images, and re-group these spectra into classes based on spectral similarity evaluated using the root mean squared error (RMS). Finally, we assigned the final spectral classes to the corresponding material classes.
2.3.1 Description of the stratigraphy

We described the composition, grain size, color and secondary features of the most important layers of the observed in cores. These stratigraphic layers correspond to the following five main sediment types: coarse sand, sandy-silt, sandy-silt with carbonate, clayey silt, and clayey silt with carbonate. In addition there are patches of a secondary calcium carbonate and levels with high concentration of carbonized organic material. The sediment classes listed above constitute the principal end members of continuous series of mixes between the different types. Most of the layers are constituted by a dominant sediment type with patches and transitions to mixes of other sediments.

**Figure 2.1.** Relative location of the cores on the wall of a trench excavated on a secondary fault at Hog Lake, San Jacinto Fault, Southern California. Box sample refers to a 60 x 60 cm box containing a fault zone (Ragona et al., 2006). The Core segments Core Left, Core Top, Core Mid and Core Bottom were collected on aluminum U channels as seen on the photography.
2.3.2 Example set construction

From the SWIR hyperspectral images we collected tens to hundreds of spectra from each of the main sediment types identified on the cores. Additionally we collected spectral examples corresponding to fragments of organic material, secondary carbonate and wood (toothpicks set as fiduciary marks). The spectral examples were for the most part collected from the CM image with the exception of examples collected from a coarse sand and sand with carbonate, obtained from the images of CB and CT, respectively. We preferred to obtain the spectral examples mostly from a single core (CM) to make sure that most of the spectra from the images of the other cores were not used on the training, testing and validation sets. This strategy guarantees independence on the core images classification at least for CT, CL and CB.

The spectral examples were grouped into classes numbered from one to eight corresponding to the following materials: (1) sandy-silt, (2) clayey-silt, (3) clayey-silt with carbonate, (4) carbonized organic material, (5) carbonate mix, (6) wood (toothpick), (7) sandy-silt with carbonate, and (8) coarse sand, designations that reflect the predominant material type of each group (Figure 2a). The amount of examples in each group depended on how abundant the material was in the core samples (Table 1).

2.3.3 Training, Testing, Verification and Validation subsets

Four unequal independent data sets were generated by random selection of examples from the master example set. Each subset was subsequently randomized to ensure good mixing of the classes. The subsets were named the training set (TS), the training-test (TTS) set, the verification set (VeS) and the validation set (VaS). The training set is the largest group containing approximately fifty percent of the examples of
the master set. The training-test is the second largest with about twenty percent of the data and the remaining thirty percent was divided between the verification set and the validation set. This last one is put aside and only used at the very end of the process to evaluate the performance of the final model produced by the classification algorithms. The training set is directly used to develop the model, while the training-test set is used to test the performance of the model at each training cycle. The verification set was used to evaluate the model at the final stages of training.

Table 2.1. Number of examples per class, and their corresponding material type. Most of the examples were selected from the hyperspectral image of Core Mid (CM), with exception of Class 7 and 8 obtained from Cores Top (CT) and Bottom (CB), respectively.

<table>
<thead>
<tr>
<th>Class number</th>
<th>Number of examples</th>
<th>Material type</th>
</tr>
</thead>
<tbody>
<tr>
<td>Class 1</td>
<td>1430</td>
<td>Sandy-silt</td>
</tr>
<tr>
<td>Class 2</td>
<td>2530</td>
<td>Clayey-silt</td>
</tr>
<tr>
<td>Class 3</td>
<td>1750</td>
<td>Clayey-silt w/CO3</td>
</tr>
<tr>
<td>Class 4</td>
<td>85</td>
<td>Organic material</td>
</tr>
<tr>
<td>Class 5</td>
<td>332</td>
<td>Carbonate mix</td>
</tr>
<tr>
<td>Class 6</td>
<td>95</td>
<td>Wood-toothpick</td>
</tr>
<tr>
<td>Class 7</td>
<td>316</td>
<td>Sandy-silt w/CO3</td>
</tr>
<tr>
<td>Class 8</td>
<td>300</td>
<td>Coarse Sand</td>
</tr>
</tbody>
</table>

To increase the number of examples from classes 4 and 6 in the TS and TTS, we manufactured new data by adding Gaussian noise with a mean of zero and a small variance (~ 0.001- 0.0001) to each example of these classes [Abu-Mostafa, 1995a, Haykin, 1999]. In this way, we generated about 200 extra synthetic examples for classes 4 and 6 in the TS and approximately 100 examples for each of the TTS and VeS sets. To
further compensate for the class imbalance, we applied both over-sampling and under-sampling methods to the TS and TTS [Japkowicz, 2000]. Our final objective was to obtain 1000 examples per class for the training set and 300 examples per class for the training-test set. We therefore under-sampled classes 1, 2 and 3 and over-sampled the remaining classes. Over-sampling corrections were applied to the output of the model, to adjust for the fact that the classes did not have the same a priori probabilities. The final TS contain 8000 examples (1000 per class) whereas the final TTS have 2400 examples (300 per class). Notice that the verification and validation sets remained unmodified, as no synthetic data over- or under-sampling was applied to them.

2.4 Pre-processing of Examples.

Although the absolute reflectance of the surface of a material is a valid parameter for class separation [Clark, et al 1999], it is also very sensitive to factors other than material properties (e.g. microtopography of the sample, non-lambertian behavior of the materials, distance or geometrical changes between source-sample-receiver). These factors can introduce important variations in the percentage of light reflected by a material, which can lead to errors at the time of classification. It may therefore be a better approach to classify the materials based on their spectral shape (e.g. Spectral Angle Mapper, [Krause, 1998]) rather than to use both spectral shape and absolute reflectance. The original examples from the sets contain 245 input values corresponding to SWIR wavelengths of the reflectance spectra and one output value corresponding to the class number (from one to eight). We applied the following methods to remove the effects of relative changes in the reflectance.
2.4.1 Euclidean or 2-norm normalization

Given a vector \( \mathbf{x} = (x_1, x_2, ..., x_n) \) for \( \mathbf{x} \in \mathbb{R}^n \), the 2-norm normalization is defined as

\[
\mathbf{y} = \frac{\mathbf{x}}{\|\mathbf{x}\|} \quad (1)
\]

Each of the 245 values of the examples in the four sets were normalized using this method (Figure 2b). By applying Euclidean normalization we removed the effects of relative intensity (pixel brightness) leaving the spectral shape as the only distinctive feature of the spectra. Using this data as the input of the pattern recognition algorithms, we can obtain classifications that only use spectral shape to separate the classes. This normalization is frequently used in the remote sensing community in the spectral angle mapper (SAM) classification algorithm [Krause et al., 1998].

2.4.2 Derivative

Previously to apply the derivative, the spectra were smoothed using a five data points moving average. Then, the discrete derivative was computed at each band and every five bands. Given a vector \( \mathbf{x} = (x_1, x_2, ..., x_n) \) for \( \mathbf{x} \in \mathbb{R}^n \), the derivative at each band (\( D_1 \)) (Figure 2c) is defined as

\[
x_n = (x_{n+1} - x_n) \quad (2)
\]

and, the derivative every five bands (\( D_5 \)) (Figure 2d) is written as

\[
x_n = (x_{n+5} - x_n) \quad (3)
\]

For each of the three pre-processing methods, we obtained one new group of TS, TTS, VeS and VaS. In conclusion, we have four groups: 1) Original reflectance example set
Figure 2.2a. Plot of the mean reflectance spectra for the classes used in the classification models. The labels for classes 1 to 8 are shared by all figures. 2b) Plot of the mean 2-norm normalized reflectance for each class. 2c) Plot of the mean smoothed derivative of the reflectance spectra (computed for each band -Derivative One-). 2d) Plot of the mean smoothed derivative of the reflectance spectra (computed every five bands -Derivative Five-).
(RS) with 245 inputs corresponding to SWIR spectra wavelengths with no additional pre-processing, 2) Euclidean norm normalized example set (ENS) with 245 inputs corresponding to 2-norm normalized bands of the reflectance spectra, 3) Derivative at each band example set (DS$_1$) with 244 input bands and 4) Derivative every five bands example set (DS$_5$) with 240 input bands. These four groups were used as the inputs for the different classification models.

2.5 Construction of the Classification Models

Two supervised classifiers, a specific class of Neural Network known as Multilayer Perceptron Network (Bishop, 1995) and a Naïve Bayesian Network (NBN) [Langley et al., 1992] were used to construct classification models for each of the example sets.

2.5.1 Multilayer Perceptron Network

This class of network was selected to construct our classification models because it has been broadly tested and used as the basis for a large number of practical applications [e.g. Esposito et al., 2006; Scarpetta et al., 2005, Basu et al., 2004; Del Pezzo et al., 2003]. The multilayer perceptron is a two-layer feed-forward class of neural network [Bishop, 1994; Scarpetta et al., 2005; Esposito et al., 2006] (Figure 3). One hidden layer formed by M processing units with the tanh activation function, and an output layer with $m$ processing units containing the sigmoidal activation function. The output of the hidden units is given by

$$ z_j = \tanh \left( \sum_{k=0}^{n} u_{jk} x_k \right) $$

(4)
where $u_{jk}$ are the weights of the first layer, with $j=1,2, ..., M$ [Bishop, 1994]. In our architectures $M$ was set variable; $k= 0,1, ..., n$, with $n=245$ or $244$ or $240$ depending the input dataset used (RS, ENS, DS$_1$ or DS$_2$). The outputs are obtained by using $z_j$ as the input to a second activation function with a new set of weights, to give

$$y_i = \sigma \left( \sum_{j=0}^{m} v_{ij} z_j \right)$$

(5)

where $v_{ij}$ correspond to the weights in the second layer [Bishop, 1994] that act on the output of each hidden unit $z_j$ to generate the output $y_i$ with $j= 0,1, ..., M$ and $i=1,2, ..., m$.

The sigmoidal activation function $\sigma$ is given by

$$\sigma(a) = \frac{1}{1 + e^{-a}}$$

(6)

which is very convenient for classification problems because it ensures that the network outputs are in the range (0,1)[Bishop, 1994].

The number of hidden units ($M$) used in final model were selected by training different configurations (e.g. 8, 16 and 32 hidden neurons) and retaining the one that generated the best classification accuracy on the TTS, VeS and VaS. For models with equal classification accuracy we kept the architecture with the least number of hidden units. To train the MLP we used sequential back propagation learning (equations 7 and 8) to find the set of weights, which minimize the mean squared error (MSE) function [Bishop, 1994]. The number of training cycles was set to a maximum of 2500 epochs.
Figure 2.3. Multilayer Perceptron Network architecture. $u_{jk}$ are input weights where $j = 1, 2, ..., M$ is the index of the hidden neuron and $M$ is the number of hidden neurons in the perceptron. $k = 0, 1, ..., n$. $n$ correspond to the number of inputs (245, 244 or 240 in our cases); $i = 1, 2, ..., m$ is the number of outputs (8 in our classification models).

with a break condition if the target classification accuracy was reached (an epoch corresponds to a single presentation of all examples in the training set, in our case 8000).

\[
v_{pq}^{\text{new}} = v_{pq}^{\text{old}} + 2\alpha \left[ y_{kp} - P_p(x_k, M, w^{\text{old}}) \right] z_q(x_k, u^{\text{old}}),
\]

for $p = 1, 2, ..., m; q = 0, 1, 2, ..., M$  

(7)

\[
u_{pq}^{\text{new}} = u_{pq}^{\text{old}} + 2\alpha \left[ \sum_{j=1}^{m} \left[ y_{kp} - P_p(x_k, M, w^{\text{old}}) \right] v_{jq}^{\text{old}} \right] \left[ 1 - z_q^2(x_k, u^{\text{old}}) \right] x_{kr},
\]

for $q = 1, 2, ..., m; r = 0, 1, 2, ..., n$

(8)

where, $u$ and $v$ are weights, $\alpha$ is the learning rate set as a very small negative value, $P$ is the perceptron model given the inputs and the architecture of the MLP and $w$ is an initial set of weights.

Four different classification models were obtained after training the MLP using the examples from the RS, ENS, DS$_1$ and DS$_5$ datasets as inputs. To use of the network for classification purposes we needed to transformed the class label (1 to 8) of each example into a 1-of-m scheme [Bishop, 1994]. In this scheme, the class label is an eight-
element vector. Each element of the vector represents the probability that the given example belongs to a particular class (e.g. $[0 \ 1 \ 0 \ 0 \ 0 \ 0 \ 0]$ is Class 2 and $[0 \ 0 \ 0 \ 0 \ 1 \ 0 \ 0]$ is Class 6). Then we created a MLP network with eight outputs $y_k$, one for each class. Under this format the outputs of the neural network represent the Bayesian \textit{a-posteriori} probabilities of an $x$ example belonging to a particular class $C$ [Bishop, 1994; Richard and Lippmann, 1991; Ruck et al., 1990]

$$y_i(x) = P(C \mid x)$$ (9)

The MLP algorithm was trained with different architectures using the TS from each of the four dataset and evaluated with the TTS. Once the targeted classification accuracy was reached, the final model was further tested using the verification and finally the validation sets.

\textbf{2.5.2. Naïve Bayesian Network training}

For this study, we used a naïve Bayesian network (NBN) from the SKIDLkit toolkit written at the San Diego Supercomputer Center (SDSC- CLEOS). These networks are frequently used in many applications because they are simple, and the construction of the classification model from the training data is fast and efficient.

NBNs are a special type of belief networks based on the application of Bayes’ theorem with the assumption of independence between the inputs, reducing a multivariate problem to a group of univariate problems [Alpaydin, 2004, Pennington et al., 2004]. Although independence is generally a poor assumption, naïve Bayesian classifiers can be trained to provide results that compete with more sophisticated algorithms [Rish, 2001]. The objective of the Bayesian classification is to compute the conditional posterior probabilities for each class $P(c_i \mid x)$ where $c_i$ are the classes and $x$ is the input vector (e.g.
reflectance data). Bayes’ formula allows calculation of these probabilities from the prior
probabilities $P(c_i)$ and class-conditional densities $p(x|c_i)$ [Duda et al., 2001]. The
SKIDLkit algorithm construct tables using the training set to estimate the posterior
probability $P(c_i|x)$ of each class. When a new example is presented it is classified, most
commonly, by picking the maximum *a posteriori* probability.

In our study, we trained the Naïve Bayesian network using the four different
example sets that we created. The four probability models obtained from training were
evaluated using the validation sets, following the same methodology as with the neural
networks.

2.6 Evaluation of the classification models: Classification accuracy and confusion
matrices.

The two classification models were evaluated and their performances compared.

2.6.1. Neural Network Model Evaluation

During training, the MSE and the classification accuracy are calculated at the end
of each training cycle by applying the updated set of weights to the TTS. Classification
accuracy, computed as the number of correct classifications over the total examples of the
test training set, only provides a general assessment of the network performance. Once
the target classification accuracy was approached, a more detailed evaluation of the
performance of each of the final models was obtained from confusion matrices [Young,
1993; Bishop, 1995]. A confusion matrix displays the distribution of the correctly
classified and misclassified examples for each class of the TTS. A perfect classification
shows only diagonal entries with zeros off the diagonal. To test the ultimate validity of
the model using examples not included in the construction of the model, we computed the
final classification accuracy and the confusion matrices for the validation sets. These independent tests are the only ones taken into account to report the actual model performance. The results obtained after training the MLP with the four different sets of examples are presented in table 2. Additionally the confusion matrices for the validation sets are shown in figure 4.

2.6.2. Naïve Bayesian Network Model Evaluation

We computed the classification accuracy, as well as the confusion matrices (Figure 5), of the validation sets for each of the four probability models obtained by training a Naïve Bayesian Network. Over all, the classes and classification accuracies for the Naïve Bayesian network models are slightly inferior to those obtained with the

<table>
<thead>
<tr>
<th>Training set</th>
<th>Classification Accuracy</th>
<th>Inputs</th>
<th>Hidden neurons</th>
<th>Outputs</th>
<th>Training cycles</th>
</tr>
</thead>
<tbody>
<tr>
<td>RS</td>
<td>98.4 %</td>
<td>245</td>
<td>8</td>
<td>8</td>
<td>300</td>
</tr>
<tr>
<td>ENS</td>
<td>97 %</td>
<td>245</td>
<td>32</td>
<td>8</td>
<td>1500</td>
</tr>
<tr>
<td>DS&lt;sub&gt;1&lt;/sub&gt;</td>
<td>93.8 %</td>
<td>244</td>
<td>32</td>
<td>8</td>
<td>2500</td>
</tr>
<tr>
<td>DS&lt;sub&gt;5&lt;/sub&gt;</td>
<td>97.6 %</td>
<td>240</td>
<td>32</td>
<td>8</td>
<td>1500</td>
</tr>
</tbody>
</table>
multilayer perceptron. The NBN model, computed using the RS data, obtained 92.5 % classification accuracy while for the ENS, DS1 and DS5 example sets the models achieved accuracies of 92.7 %, 92.2 % and 95.4 %, respectively.

2.6.3. Analysis of results for the MLP and NBN models

The overall accuracy of the classification models and confusion matrices (Table 2, and Figures 4 and 5) show very similar results for both the MLP and NBN methods. The MLP model evaluation on the RS validation set produced a 98.4 % classification accuracy, the highest for all tested models, versus 92.7 % for the same data using the NBN model. Class-by-class analysis of the classifier performance for the RS validation set is presented in the confusion matrix (Figure 4 and 5). For both of the classifiers, the bulk of the inaccuracies are due to misclassifications of class 2 as class 3, and vice versa. The total number of classification errors between classes 2 and 3 is surprisingly low considering the spectral and sedimentological similarity of these two classes (Figure 2 a). Classification of ENS data also shows some problems in distinguishing between classes 2 and 3 for both supervised algorithms. In addition, we also observe misclassification of class 2 as class 7 for MLP and NBN models, and between class 3 and class 7 for the NBN model. Although the relative differences in reflectance between the spectra of class 7 and classes 2 and 3 are important (Figure 2 a), their spectral shapes are quite similar (Figure 2 b). By applying the 2-norm normalization to the dataset, the relative reflectance differences (brightness) are removed and the three classes become more difficult separate. The models that were trained with the DS1 data set show the lowest performance for both classifiers, reaching an over-all classification accuracy of only 93.8 % for MLP and 92.2 % for the NBN. Again, the misclassifications are mainly focused
between classes 2 as 3. In addition, we had some problem distinguishing between classes 2 and 4 with the MLP model, and misclassifications of class 1 as class 2 for both networks (Confusion matrices -Figures 4 and 5-). These problems may be the result of sub-pixel mixing of the selected examples or transitional sediment types between the established classes. Finally, the classification model using the DS5 data produced 97.6 % and 95.4 % accuracies for MLP and NBN models, respectively, with most of the misclassifications occurring between classes 2 and 3. This represents the highest performance for the NBNs.

2.7. Image Classification

Using the best MLP models, and the probability models of the NBN, we classified the images of the four cores. Prior to classification, we applied to the cores the same pre-processing methods used for the training, testing, validation and verification datasets. That is the 2-norm normalization, the derivative at every band and the derivative every five bands of the smoothed spectra. Using the weights obtained from the MLP training and equations 4 and 5, we computed $y_i$ (with $i = 1$ to 8), the class *a posteriori* probabilities for each pixel of the image. Finally, we selected the class of each pixel by picking the maximum *a posteriori* probability (the maximum value of the vector $y_k$). For the NBN, the class type of each pixel of the image was computed using the probability models obtained from training the network and then selecting the maximum *a posteriori probability* $P(c_i|x)$ where $c_i$ are the classes ($i = 1$ to 8) and $x$ is the input from each pixel (e.g. reflectance data). As a result, for each core, we produced four classification images using the MLP and an equal number using the NBN models (Figures 6 and 7).
Figure 2.4. Confusion matrices created by applying the best MLP models (Table 2.2) on the validation sets using each of the four types of pre-processing (RS, ENS, DS1 and DS5). C1 to C8 are the class designations.
Figure 2.5. Confusion matrices created by applying the best Naive Bayesian network models (Table 2.2) on the validation sets using each of the four types of pre-processing datasets (RS, ENS, DS1 and DS5). C1 to C8 are the class designations.
2.7.1. Analysis of the Classified Images

The eight classification images of each core were compared among each other to evaluate their similarities and the divergences in the classifications. We also compared the classification images with the actual samples and with the particle size distributions of the layers for a qualitative assessment of the classification accuracy. To illustrate this analysis, we present the MLP versus the NBN core classification images for the reflectance spectra (RS set) in figure 6. In figure 7, we display a side-by-side comparison of the classification images of each core obtained using the original image (RS), and all the pre-processed sets (ENS, DS₁ and DS₅).

2.7.1.1. Core Top images (CT).

We compared the classification images obtained with the multilayer perceptron for the RS (original reflectance ENS, DS₁ and DS₅ images (Figure 7). We also evaluated the classification results on the RS images obtained with the MLP against the classification of the same images using NBN. When comparing the classification images among each other, we observe that by far, the most common misclassifications are class 1 (sandy-silt) represented as class 7 (sandy-silt with carbonate) and class 3 (clayey-silt with carbonate) as class 2 (clayey-silt) and vice versa (Figure 7 a). Misclassification between classes 1 and 7 is common in the ENS and derivative images because both classes have similar spectral shape but exhibit important differences in their relative reflectance. After pre-processing, the relative reflectance between classes is removed leaving the spectral shape as the only class signature. The DS₁ image is also showing a higher number of pixels classified as class 4 (organic material) instead of class 2. These pixels, in fact, correspond to layers of clayey-silt with high organic material content. When comparing
Figure 2.6. Classification images of the four cores, CT, CM, CB and CL (see Figure 1 for location) obtained from models computed by Multilayer Perceptron (MLP) and Naïve Bayesian Networks (NBN) on the original (un-modified) reflectance spectra images (RS sets). The most common misclassifications are class 2 as class 3 and vice versa.
Figure 2.7. Comparative display of the MLP classification images of the cores, a) CT, b) CM, c) CB and d) CL, obtained using the four different types of pre-processing applied to the spectra of each pixel of the images (RS set = Reflectance Spectra, ENS = 2-norm normalization of the image’s pixels. DS₁ = derivative every band and DS₅ = derivative every five bands of the smoothed spectra). RGB = enhanced digital photography of the core.
between the classification images obtained with the MLP and NBN, we observe that the most common misclassification is between class 3 and class 2. Many pixels of these images classified as class 2 by the MLP model are assigned to class 3 in the NBN images. Although the classes are sedimentologically and spectrally very similar, visual inspection of the core sample indicates that in most cases, the MLP classification was more accurate.

2.7.1.2. Core Mid images (CM)

In general, the four MLP and the four NBN classifications for this core are very consistent and very close to the geological observations. These more accurate classifications were expected, as most of the data used to train the models were obtained from this core. Most of the observations described for CT classifications are also valid here. Comparisons between the images produced by the MLP and NBN classifiers show important disagreement in the classification of classes 2 and 3. Inspection of the core sample show that the MLP provided a better mapping of the distribution of classes 2 and 3 than the NBN model.

2.7.1.3. Core Bottom images (CB)

A comparison with the geological observations indicates that the four types of images produced by each classifier show very good mapping of the main units. As mentioned above for the other cores, classification divergences most commonly occurred between classes 1 and 7 and classes 2 and 3. The DS1 image also shows a higher percentage of pixels classified as class 5 that are assigned to class 2 in the other images. The images generated with the MLP and NBN classifiers (Figure 6) show divergences in classes 2 and 3, as was indicated for other core samples.
2.7.1.4. Core Left images (CL)

The analysis of the images generated by the MLP and NBN model show that most of the classification discrepancies occur where class 1 is incorrectly classified as class 7 in the ENS, DS$_1$, and DS$_5$ images. However, the RS and the DS$_5$ images did an excellent job mapping a small fault located at the bottom of the core (Figure 7 d). Classification differences between the images are also found for pixels of class 2 and class 3 (e.g. Figure 7 d, DS$_5$ Classification.). Finally, the MLP and NBN models commonly differ on the mapping of class 2 and class 3, as seen for other cores.

3. Discussion

Both the Multilayer Perceptron and Naïve Bayesian Network algorithms provided excellent over-all classification accuracies for the validation set, as well as good and consistent mapping of the main lithostratigraphic units observed in the cores. Although there are some divergences in the core image classification results, mainly related to misclassifications of class 1 as class 7 and class 2 as class 3, it is important to note that the sedimentological and spectral differences between these classes are very subtle. These, along with the other misclassifications that we found, can be explained by two main factors: 1) sub-pixel mixing of different materials, that give new spectral types with mixed characteristics; and 2) some geological material classes characterized from these cores do not have hard or well-defined boundaries, but rather, display a gradational series with variations inside of the stratigraphic unit or mixed properties. Classes were primarily selected from the most homogeneous areas of the core, but there are many areas where mixed and transitional materials can be observed. These two factors also explain why
classification accuracy computed on the validation set is much higher than the accuracy of the core image classifications when compared among each other or against the actual sample. The TS, TTS, VeS and VaS sets were selected from the most homogeneous areas of the core, therefore they have relatively small variability inside a given class. Although we made an effort to include examples that represent the spectral and sedimentological variability of each class, transitional types where not included in the example sets. Further, the 0.5 mm pixel size of the images is much larger than the grain size of most of the classes included in this analysis, and therefore, sub-pixel mixing of materials is expected. This was corroborated in several areas of the cores where high density of fine veins and patches of secondary carbonate in silts were mixed in the image as one single material. The spectral characteristics of these areas showed mixed features between class 2 and class 5, which commonly is misclassified as class 3. Another problem found in the image classifications are related to areas with considerable moisture content variations. These areas are commonly found in the borders of cracks in the sample or in the margins of the cores (e.g. Figure 7 d, Orig. Spectra image, at ~ 1000 in the vertical scale, patch of class 8 in class 1). These moisture variation spots were more common in the coarser units, where water drains or evaporates faster than in the finer grained sediments. The most common misclassifications due to moisture variations are class 1 classified as class 8, where the sample had dried out. Another classification problem was found along the cracks of the cores. Most of the cracks are low reflectance pixels due to poor illumination inside the fracture. These pixels, which were usually classified as class 4 (organic material), exhibit low reflectance so the models tended to group all of the low reflectance pixels into the same class. The problem is partially solved when the 2-norm
normalization is performed, but still the pixels in the crack are usually misclassified. Many of these misclassifications may disappear if we define further material property classes (including a class for open fractures). Visual comparisons between images produced by two different classifiers proved useful in the assessment of the accuracy of mapping. These evaluations can be assisted by “difference images” (Figure 8). A difference image is obtained by subtracting two classification images, preferably produced by different algorithms, of the same core. Difference images can help to identify problematic areas. Random misclassifications are usually scattered all over the difference image, but misclassifications that are organized in a pattern may pinpoint problematic areas.

4. Conclusions

In this article, we present a new methodology for automatic mapping of sedimentary stratigraphy in the lab (drill cores, samples) or the field (outcrops, exposures, tunnels) using short wave infrared (SWIR) hyperspectral images, neural networks and naïve Bayesian networks. Ground-based hyperspectral imaging provides near lab quality reflectance spectra at each sub-millimeter pixel of the image that can be used to classify sedimentary units based on subtle spectral differences. This wealth of information, combined with powerful supervised algorithms, provide an objective method to identify and map geological materials at an unprecedented level of detail.

This method was successfully applied to map four core samples of fine-grained sediments at sub-millimetric scale. The use of this technique provided a great assistance
Figure 2.8. Classification images of core CM with the DS$_1$ pre-processing. Left, classification computed with the MLP algorithm. Center, classification obtained with the NBN. Right, Difference Image generated by subtracting the two classification images (MLP – NBN). Zero (light blue) indicates a perfect match between the images, whereas other colors indicate divergences. For instance, the red area at the top of the difference image (-1) corresponds in this case to a difference between the MLP (class 2) and NBN (class 3) classification picks between the two algorithms.
to the geologist description and interpretation of the units. It also provided strong is
needed. Possible applications of this methodology include detail mapping of minerals,
 sediments or hard rocks in drill cores, mine tunnels, outcrops and rock chip “cutting”
samples.

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Integration of core and log data using a neural network as input for reservoir modeling


CHAPTER 3

A Long Rupture Record of La Laja Fault, San Juan, Argentina. Inferring a Blind Thrust Earthquake History from Secondary Faulting

Abstract

Blind thrust faults represent an important seismic hazard for many urban areas around the planet. The lack of a primary surface rupture, along with the difficulty in interpreting the geomorphic signal produced by individual earthquakes, make blind thrust faults one of the most challenging types of structures for which to assess seismic hazard. Significant efforts have taken place to understand the geomorphic responses that occur as a consequence of slip and associated folding on a blind thrust fault during an earthquake, but these methods are not precise enough to provide the detailed earthquake history on a particular structure. In this study, we take an innovative approach to resolve the earthquake history of a blind thrust fault in Argentina. We determined the slip history of an earthquake-related secondary rupture, La Laja fault, and use it as a proxy to characterize the earthquake history of the blind thrust fault at depth. The January 15th, 1944 Ms 7.4 San Juan earthquake, with an epicenter located north of San Juan city, Argentina, caused extensive damage and killed thousands of people in the city of San Juan and surrounding areas. Only two minor small ruptures were recorded after the event. By far, the most prominent of them, La Laja fault, extended for at least 7 km with an attitude of N30°E, 42º E, parallel to the bedding of the Neogene sediments, and a maximum east-side-up vertical uplift of 30 cm. The lack of a major surface rupture that
can be related to such a large earthquake, along with the fact that the total slip and length of La Laja fault are small and parallel to the bedding of the Neogene strata, lead to the interpretation that this structure is a secondary surface rupture linked to the displacement of a major blind thrust at depth. Here, we assume that the compound scarp observed at La Laja was built by repeated events similar to that recorded in 1944 San Juan earthquake. Therefore we interpret that colluvial wedges preserved on the down-thrown side of this secondary fault indirectly record the earthquake history of the blind thrust fault located at depth. To resolve the slip history of La Laja fault, we excavated multiple trenches and described in detail the stratigraphic and structural relationships. We dated 13 samples from the colluvial wedges using optically stimulated luminescence (OSL) techniques, and obtained three radiocarbon ages from sediments post-dating the penultimate event. The detail analysis of the data suggest that La Laja fault colluvial wedges provide a record of nine fault slip events that have occurred over the past ~ 32 ka, resulting in one of the longest records of continental thrust faulting determined anywhere in the World. Based on this, we conclude that the average interval recurrence for the last eight events is 4.1±0.5 ka. This average recurrence is in close agreement with the time determined directly between individual events. These observations argue for fairly quasi-periodic recurrence La Laja surface ruptures, which indirectly suggests a similar behavior of the underlying causative thrust. The slip per event of the blind thrust fault at depth was estimated using the assumption that each event recorded at La Laja fault is always linked to a large earthquake on a blind thrust fault at depth, as observed for the 1944 Ms 7.4 San Juan earthquake. We calculate ~ 2.5 m of slip for the blind thrust fault at depth if the average earthquake is $M_w=7.4$. We also show that the 1944 slip at La Laja is about half of
the average slip per event, suggesting that the average slip on the blind thrust may have been as much as 5 m. Using the average recurrence between events and the 2.5 to 5 m of displacement per event, we obtain a slip rate of 0.6 to 1.2 mm/yr for the blind thrust fault at depth. Independently, we computed a slip rate of 0.8 and 1.3 mm/yr using kink band migration for the Qt3 terrace using Meigs et al.,[in review] methodology. These rates are similar to the rates obtained for other structures in the region [e.g. Siame et al., 2002; Verges et al., 2007]. We conclude that the historical earthquake activity observed between the Precordillera Oriental and the western Sierras Pampeanas, near San Juan city, appears to be occurring at an anomalously high rate when compared to the long average recurrence time of large earthquake. This, in turn, suggests that the cluster of large earthquakes during the past century is not representative of the long term, although it may best indicate the current hazard to the region.
1. Introduction

Blind thrust faults represent an important seismic hazard for many urban areas around the planet. Many large cities have been settled along the fronts of major mountain ranges that are formed by active faults [e.g. Los Angeles in California, San Juan and Mendoza in Argentina, among many others. In many cases, these seismic sources were only identified after destructive earthquakes had occurred (e.g. the 1987 Mw 6.0 Whittier Narrows earthquake and the 1994 Mw 6.7 [Hauksson et al., 1988 and 1995]). In other cases, large blind faulting events have occurred in areas with a poorly established seismic network, and therefore the responsible source faults are still largely unidentified. Even in cases where structures have been located at depth using seismic reflection, seismology and/or borehole studies [Shaw and Suppe, 1994, 1996; Dolan and Pratt, 1997; Shaw and Shearer, 1999; Shaw et al., 2002] or inferred by detailed geomorphic and structural mapping [Rockwell et al., 1984, 1988; Bullard and Lettis, 1993; Molnar et al., 1994; Oskin, et al., 2000; Ishiyama et al. 2004 among others], the detailed earthquake history remains unknown [Dolan, et al., 2000]. Significant efforts have taken place to understand the geomorphic responses that occur as a consequence of slip and associated folding on a blind thrust fault during an earthquake, but these methods are not precise enough to provide the detail earthquake history on a particular structure [e.g. Bullard and Lettis, 1993; Oskin et al., 2000, Siame et al., 2002; Ishiyama et al., 2004]. The lack of a primary surface rupture, along with the difficulty in interpreting the geomorphic signal produced by individual earthquakes, make blind thrust faults one of the most challenging types of structures for which to assess seismic hazard.
The January 15th, 1944 Ms 7.4 San Juan earthquake, with an epicenter located north of San Juan city, Argentina (Figure 1) (31.6°± 0.4° S, 68.5°±0.6 W [Kadinsky-Cade, 1985] heavily damaged the city of San Juan and surrounding areas. The earthquake killed thousands of people, and is generally recognized as the worst natural disaster in the history of Argentina [Castellanos, 1945; Harrington, 1944; Groeber, 1944; INPRES, 1977; INPRES, 2006]. Geological observations immediately following the event only described minor tectonic surface deformation concentrated as two small ruptures. The most prominent of these, described in the literature as La Laja fault, extended for at least 7 km with an attitude of N30ºE, 42º E [Harrington, 1944] and a maximum east-side up vertical displacement of 30 cm [Groeber, 1944; Castellanos, 1944; Harrington, 1944]. The other observed rupture, located a few kilometers to the west of La Laja fault, was much less significant, with only a few centimeters of reverse displacement [Harrington, 1944]. It is important to consider that the local geology was poorly known in 1944, and perhaps these structures were only identified because they cut a road, leaving open the possibility that other similar structures may have moved during the earthquake. However, as Siame et al. [2002] point out, no link has yet been made in the region between historical earthquakes and large fresh Quaternary scarps. The lack of a major surface rupture that can be related to such a large earthquake, along with the fact that the displacement and length of La Laja fault is small and parallel to the bedding of the Neogene strata, lead to the interpretation that this structure is a secondary fault rather than a primary surface rupture [e. g. Castellanos, 1944; Groeber, 1944; Costa et al., 1999; Siame et al, 2002; Meigs, et al. 2007, among others]. Possible explanations for the origin of La Laja fault are bedding plane flexural slip, perhaps induced by bending moment
[Whitney. 1991; Smalley et. al., 1993], or slip along a back thrust related to a basement buttress [Smalley et. al., 1993]. Other authors have preferred to interpret La Laja fault as the main fault rupture, and they considered different options to explain the anomalously small rupture related to such a large earthquake [e.g. Bastias et al., 1985; Perucca and Paredes, 2000, 2002, Alvarado and Beck, 2006].

Based on our field observations as presented in this paper, interpretation of microseismicity [Smalley et al., 1993], and considering the current structural models, we favor the interpretation that the bedding-parallel La Laja fault is a secondary structure, probably resulting from flexural slip folding at the surface that is linked to the displacement of a major blind thrust at depth. The exact mechanism that links the displacement of La Laja fault with the main structure is not well understood, and in this article we are not attempting to elucidate this problem. We assume that the observed deformation resulting from the large 1944 earthquake has occurred in the past in a similar fashion, and that repeated displacement has resulted in the construction of the scarp along the La Laja fault. We neither assume that La Laja fault is the only possible structure that moves at the time of displacement on the blind thrust, nor that La Laja moves every time that the blind thrust is activated. Consequently, we understand that the earthquake record that we studied represents the minimum rupture history for the blind thrust at depth. However, we do assume that La Laja fault only moves as a result of displacement on the blind thrust.

Whichever model and interpretation is correct, it is clear that La Laja fault records, directly or indirectly, the earthquake history of a part of the region east of Sierra de Villicum and west of Sierra de Pie de Palo. The main objective of this study is to
resolve the detailed slip history of La Laja fault utilizing paleoseismic excavations, with the goal of inferring the earthquake history of an important blind thrust at depth. To accomplish our objective, we used traditional paleoseismological techniques and geomorphological and structural descriptions and interpretations. We excavated multiple trenches along a 2 km section of La Laja fault, and described in detail the stratigraphic and structural relationships to obtain an accurate displacement history of the fault. We collected more than 30 sand samples for age estimation using optically stimulated luminescence (OSL) techniques, and three detritic charcoal fragments for radiocarbon dating. We also carefully logged and/or described many of the excavations and surveyed and mapped the structural and geomorphological relationships between the Neogene sediments, the different level of terraces, and faults. Our results provide one of the longest records of continental thrust faulting determined anywhere in the World, and provide a basis for assessing seismic hazard along the pre-Cordillera of Argentina.

2. Geological Setting

La Laja fault is located in southern part of the central Andes, at the eastern limit of Eastern Precordillera (~31.35ºS, ~68.46° W), about 20 km NNE of San Juan city, San Juan, Argentina (Figure 1). At this latitude, the Nazca plate is subducted at a nearly horizontal angle under the South American plate [Baranzangi and Isacks, 1976; Jordan et al., 1983] with a convergence rate of 63 mm/yr. The Andean Orogen at ~ 31º30’S can be divided into four major morpho-structural domains extensively described in the literature [Jordan et al., 1983; Ramos et al., 1986; Mpodozis and Ramos, 1990; von Gosen, 1992]. From west to east they are: the Coastal Cordillera, the High Andes, the Precordillera and
Figure 3.1. a) Geological scheme of the Argentinean Andes between 31°S and 32°S with indication of the main geological provinces and structures. The yellow star indicates the approximated location of the 1944 San Juan earthquake. The focal mechanism for the earthquake is from Alvarado and Beck, [2006]. The red polygons indicate the location of the two main shocks of 1977 Caucete earthquake. The focal mechanisms are from Langer and Hartzell, [1996]. The red box indicates the location of figure b).
b) Satellite image of the La Laja fault area, just north of the San Juan river and the town of Albardón (reproduced with permission of Google). Blue broken line indicates the approximate trace of 1944 La Laja rupture [Harrington, 1944]. Green box indicates the location of figure c.
c) Detail of the studied area. Blue broken line indicates the location of La Laja fault. Yellow solid line is the road to Los Baños de La Laja. This road was cut in 1944 (Figure 9).
the Sierras Pampeanas [Allmendinger et al., 1990]. The most active zone of crustal deformation is located at Eastern Precordillera and west Sierras Pampeanas, as is suggested by active faulting, folding and high level of seismic activity [e.g. Groeber, 1944; Kadinsky-Cade et al., 1985; Uliarte et al, 1987; Smalley et al., 1993; Ramos et al., 1997; Costa et al., 2000; Siame et al, 2002; Meigs et al., in review; Verges et al., 2007]. Both the eastern Precordillera and the Sierras Pampeanas are considered west-vergent structures with basement involved in the deformation [Jordan and Allmendinger, 1986; Figueroa and Ferraris, 1989; Allmendinger et al., 1990; von Gosen, 1992; Zapata and Allmendinger 1996a,b] and show evidence of Quaternary activity. Near La Laja fault, the largest structure of the eastern Precordillera is the Villicum-Pedernal thrust, a mostly blind, ~150 km long, west-vergent structure that deforms Paleozoic and Tertiary sediments and probably involves basement at depth [Allmendinger et al., 1990; Jordan et al., 1993]. Siame et al., [2002] considered this thrust to be an active structure, and perhaps the source of the 1944 San Juan earthquake. This interpretation is not favored by Meigs et al. [in review], which makes the observation that no Quaternary rupture occurred along the western flank of the Sierra de Villicum; they place the location of the 1944 event on a deep, east-vergent ramp beneath the eastern Precordillera.

The Sierra de Pie de Palo, located ~ 25 km to the east of La Laja fault, is a 3162 m high, 80 km long and 40 km wide mountain range mainly formed by crystalline basement and considered part of the western Sierras Pampeanas. No important emergent faults are observed bounding this uplift, and a general understanding of its structure at depth was obtained by analyzing the focal mechanism and surface deformation associated with the two main shocks of the 1977 Ms 7.4 Caucete earthquake [Kadinsky-Cade et al,
1985], and from interpretation of microseismicity. Seismic observations from the 1977 Caucete earthquake, combined with evidence of ~ 1m uplift obtained from leveling data, suggest that this event produced ~ 4 m of slip on a 35° west dipping, 80 km long north-south trending fault with fault tip located at 17 km depth below the surface and a down dip width of ~24 km [Relinger and Kadinsky-Cade, 1985; Kadinsky-Cade et al., 1985]. More recent interpretations of the deep structure beneath the Sierra de Pie de Palo consist of two opposed thrust faults, a lower E-vergent ramp with a fault tip at ~ 18 km depth and a W-vergent fault at shallower depths [Ramos and Vujovich, 2000; Ramos et al., 2002; Verges et al., 2007] (Figure 2 and 3). This model also suggests a large, east-directed blind forethrust ramp beneath the eastern Precordillera and Sierra de Pie de Palo, and a west directed ramp under Sierra de Pie de Palo, as potential seismic sources for 1944 and 1977 events.

![Figure 3.2. Seismicity of the lower and upper crust across 32°S. The deep activity correspond to the interaction Nazca-South America plates. The seismicity < 35 km indicates the region of deformation in the upper crust. From Smalley et al., 1993.](image)

3. East piedmont of Sierra de Villicum and La Laja fault area

La Laja fault is located at the distal edge of the eastern piedmont of the Sierra de Villicum, a dissected pediment developed across deformed Neogene strata that preserves
Figure 3.3. Model cross section of the Sierras Pampeanas, Central and Eastern Precordillera (section A in figure 1) [Verges et al., 2007 compiled from von Gosen, 1992; Ramos et al., 2002; Meigs et al., in press; and seismicity compiled from Smalley et al, 1993 and Ramos et al, 2002].
several episodes of fluvial strath terrace formation. Based on the style of deformation of the Neogene strata, the piedmont was divided into two structural domains [Meigs et al., in review]. A western domain with beds dipping less than 15º to the southeast and with no major faulting or deformation, and an eastern domain characterized by small displacement reverse faults and a southeast-facing monocline. The boundary between domains is marked by a reverse fault affecting the Tertiary sediments and some of the units above the erosional surface of the pediment (Figure 4). A cross section of the eastern domain shows a change in dip in the Neogene units, ranging from 10-15º in the northwest to 35-45º in the southwest [Meigs et al., in review]. East of La Laja Fault, the stratigraphically youngest Mogna formation dips ~ 10º to the southeast.

3.1 Terraces

Four levels of strath terraces capped by 1-3 m of gravel, commonly composed of clasts of limestone and chert, were identified within the piedmont of Sierra de Villicum [Meigs et al., in review; Krugh, 2003; Colombo et al., 2000; Sanchez et al., 1986]. The relative chronology of the terraces was determined by their elevation, along with observations on the differences in their surface morphology and soil development. The oldest terrace remnants, designated as QT1, occupy the highest elevations, while younger terraces (QT2 to QT4) are at progressively lower elevations.

In the western domain, neither the terrace surfaces nor the modern washes are deformed, showing a constant ~3º gradient and a concave up river and terrace profile [Meigs et al., in review, Colombo et al., 2000]. In the eastern domain, faulting and folding affect different levels of terraces, and in some cases the modern wash. The
deformation is produced by small displacement of bedding-parallel reverse faults that generate slight and broad tilting with each slip event (Figure 4). The morphology and preservation of the scarps generated by different faults may suggest a gradual migration of the deformation from west to east, with the older structures to the west and the most recently active faults to the east, with La Laja fault being the youngest (Figure 4 and 5).

### 3.2. South-east facing Monocline (Frontal monocline)

The most pronounced break in slope, along with the most severe terrace deformation and greatest structural relief, is observed along the southeast-facing monocline, which forms the eastern edge of the piedmont [Meigs et al., in review]. The

![Figure 3.4](image.png)
minimum vertical separation across this monocline is much larger than the vertical offset produced by La Laja Fault, thus it is the most important structure affecting the Quaternary deposits in the area (Figures 4, 5 and 6). Meigs et al. [in review] interpreted the formation of this monocline as a consequence of kink band migration, with an active axial surface located somewhere east of the monocline and with passive axial surfaces for each terrace level (Figure 6). Across the monocline, the dips of the terraces change from \(\sim 1-3^\circ\) SE to \(15^\circ-20^\circ\) SE, but the dip of the underlying Neogene beds remains at \(\sim 40^\circ\). Based on the kink band migration model, Meigs et al. [in review] suggested a minimum migration of the passive axial surface of 64 m for terrace \(Q_t_2\) and 35 m for terrace \(Q_t_3\) (figure 6). From our survey data we measured \(\sim 89\) m between the active axial surface and the interpreted passive axial surface of terrace \(Q_t_2\), and between 40 and 55 m for the distance between the active and passive axial surfaces in terrace \(Q_t_3\) (Figure 7). As mentioned above, the monocline concentrates the maximum deformation and structural relief. In the vicinity of the active washes, the bedrock drops more than 10 m to the east across the monocline, as observed in excavations MT and MTJ [Schulz, 2006]. The same situation is observed for older strath terraces (figure 8) [e.g. \(Q_t_2\) and \(Q_t_3\)], which dip 15-20\(^\circ\) SE, forming the frontal monocline structure immediately east of La Laja fault (Figures 6 and 7). Thus, the minimum structural relief of the monocline is about 15 m for the \(Q_t_3\) strath, which is situated \(\sim 5\) m above the level of the modern wash west of the monocline and at least 10 m below the wash surface to the east. Similarly for the \(Q_t_2\) strath, the minimum structural relief is more than 20 m, as the terrace is \(\sim 10\) m above the wash to the west and a minimum of 10 m below the wash at the deepest point of the MT excavation to the east (Figure 7). Further, ground water boreholes and interpretation
Figure 3.5. Satellite image showing location of the trenches and survey points. Green polygons are indicating the location of the trenches across La Laja Fault. Red dots indicate surveyed point.
of electric survey cross sections near Las Lomitas train station, located a few kilometers south of the study area, show that the top of the Neogene erosional surface (strath) is buried by a minimum of 30 m of modern alluvial deposits east of the monocline, and that depth increases farther east [Sanchez et al., 1986; Meigs et al., in review and Verges et al., 2007].

Figure 3.6 Idealized cross section of La Laja fault and the frontal monocline from Meigs et al., [2007]. The different level of terraces from T1 to T5 and their corresponding passive axial surfaces are reconstructed from Krugh, [2003]. The location of the active axial surface and depth of the terraces to the SE of the active axial surface is unconstrained.

3.3. Terrace displacement across La Laja Fault

We focused our study along 1.5 km of the 1944 La Laja rupture, south of the road to Baños de la Laja, where the cumulative fault scarp is well preserved and expressed as an area of relatively higher topographic relief (Figure 5). Structural relationships between La Laja fault and the local terraces provide a first order approach to constrain
Figure 3.7  Survey of the terrace Q3. Total displacement across La Laja Fault is ~10.6m. The actual amount of displacement recorded in the trench T1.
Figure 3.8. (a) Map of the La Laja Fault area and Frontal monoclinal. (b) Photography of the fronta monoclinal and terraces. (c) Detail of the Frontal monoclinal and Neogene beds.
the minimum and the most probable cumulative slip for two time intervals. These intervals are represented by the elapsed time since formation of terraces Qt2 and Qt3, with the total displacement measured for both the terrace straths and their depositional surfaces. The 1944 event generated a scarp across the modern wash surface of ~ 22-35 cm in height (Figures 9 a,b) [Harrington, 1944; Groeber, 1944]. Using a ~40° dipping fault surface, we estimate that fault parallel slip is between 34 and 55 cm. We can use these values to obtain the total post Qt2 and Qt3 displacement, as well as the configuration prior to the 1944 event.

To measure the cumulative fault displacement relative to each of the terraces, we surveyed the strath and surface of Qt2 and Qt3 and projected the data into two cross sections perpendicular to La Laja fault (Figure 7). In all cases, slip was calculated using a ~ 40° dip for the fault and assuming that the displacement was perpendicular to the fault strike (i.e., no component of strike-slip). Post Qt3 terrace displacement was measured as ~10.3±0.5 m of dip slip. This value was obtained by projecting both the hanging wall and footwall Qt3 surfaces into a 40° SE dipping fault plane (Figure 7a). Similarly for the Qt2 terrace surface, we measured a cumulative slip at about 13±1 m if the terrace surface is projected into and across the fault (Figures 7b). For both of these estimates, we assume that our correlation of equivalent surfaces across the fault is correct, as there are no other prospective candidate surfaces.

4. Paleoseismic Excavations at La Laja Fault

To obtain an estimation of the displacement and timing of the slip events at La Laja fault, we excavated 16 exploratory trenches along a 1.5 km segment of the rupture where the
Figure 3.9a. La Laja surface rupture cutting the road to Baños de La Laja. Photography taken a few days after the 1944 San Juan earthquake [Harrington, 1944]. Notice the different shape of the scarp developed on the road (compacted material) and on the unconsolidated gravelly alluvium.

Figure 3.9b. La Laja fault exposed in trench T3. The surface deformation of 1944 was well preserved in this small wash (Figure 5 for location of this trench). A vertical displacement of about 20 cm was measured at this location.
scarps and relationships between the fault and terraces are better preserved (Figure 5). Based on preservation of the earthquake history, and other conditions, we fully logged and interpreted trenches T1, T2, T3, T4 and T11 (Figure 5). In this paper we present detail logs and interpretations only from trenches where age determinations were made, either using radiocarbon ($^{14}$C) dating or optical stimulated luminescence (OSL) techniques. Trenches T1 and T4 (Figure 5) are the only two trenches with dated strata at this time, and therefore the only two that we completed step-by-step slip reconstructions to illuminate the discrete slip history. The trench T2 log and interpretation is also presented because it exposes the 1944 deformation at an excellent level of detail that allows a precise measurement of slip for that event.

4.1. Description of Trench 1.

Trench T1 was excavated on the Qt$_3$ terrace, ~5 m above the level of the modern wash, approximately perpendicular to La Laja Fault (Figures 5, 10 and 11). The trench was located on a small interfluve, and only the south wall of the excavation preserved the entire section of colluvial wedge stratigraphy. Consequently, only this wall was logged in detail and its sediments dated using OSL techniques.

4.1.1. Stratigraphy

The exposed stratigraphy was primarily divided into three major units. 1) the Neogene beds of Las Tapias Formation, 2) the Qt$_3$ deposits, and 3) the colluvial wedge stratigraphy associated with fault movement. The colluvial wedge stratigraphy was further subdivided into colluvial wedges CW1 to CW9, to describe the displacement history of La Laja Fault.
Figure 3.10. (a) Photolog and (b) Log of trench T1.
Figure 3.10. (c) Detail of trench T1 log
The hanging-wall of the thrust fault was composed primarily of the Neogene Las Tapias Formation (Figure 10). This unit comprises light brown and gray, medium to fine sand with some silty and clayey strata. The bedding is parallel to the main La Laja fault surface, which at the bottom of the trench, have an attitude of N40ºE, 38-42º. Higher in the section, the beds gradually decrease their dip, rolling over to a minimum of ~ 15º (Figure 10). At the top of the well-bedded Tertiary section, there is a 40 to 60 cm zone of weathering, interpreted as a C soil horizon and designated on the logs as unit Nc. Some of the major stratigraphic contacts are still preserved across the friable sediments of this zone. Capping the weathered Tertiary, unit Cs is a reddish soil formed on colluvial sand and gravel. At the surface, an accumulation of limestone clasts, unit A, forms the slope pavement.

The footwall deposits were subdivided into ten stratigraphic units, all of them truncated by La Laja fault. The oldest corresponds to the terrace deposits of Qt3 (Figure 10), a 1.5 m-thick, clast-supported gravel with some coarse sand intercalations. This deposit overlies the Qt3 strath, with an angular unconformity of ~38º developed across the tilted Neogene beds. The base of the Qt3 deposit was not exposed in the trench, although a few meters to the west of trench T1, the terrace deposits and the underlying strath are exposed along the margins of the wash and exhibit a slope of ~ 1.5º to the SE (Figure 7). Above the Qt3 terrace surface, there is a wedge-shaped deposit formed by reddish, fine to medium sand with some gravel that is interpreted as the cumulative colluvial wedge of La Laja Fault. Using clear stratigraphic contacts, we subdivided this clastic wedge into nine units from CW9 at the base to CW1 at the top. Each of these units are interpreted as an individual colluvial wedge associated with fault scarp.
formation and diffusion of mass off of the steepened slope [Nelson, 1992b; Carver and McCalpin, 1996; Hanks, 2000] (Figures 12). Units CW9 to CW6 share similar characteristics, with a triangular gravel deposit at their base and against the fault surface overlain by a wedge-shaped, fine to medium sand deposit with few pebbles (Figure 15). Each of these wedge-shaped units has a gypsiferous soil developed in them, with most of the gypsum concentrated near the upper part of the wedge, and each wedge is capped at the surface by a line of gravels that cover the sandy deposits. We interpret this sequence of deposits as three stages of colluvial wedge formation, beginning with a coarse deposit as the first stage of colluvial wedge formation occurring during or immediately after fault displacement as a consequence of collapse of the fault tip or bull-dozing of colluvial sediment in front of the fault tip. This is followed by gradual accumulation of sandy colluvium related to gradual scarp diffusion from upslope, and finally followed by soil development during periods of relative slope stability. The capping gravels are considered the pavement developed on the slope (Figure 12).

Above unit CW6, the deposits are generally coarser and the wedges are not as clearly defined as for the lower units, in part because they are formed by coarser sediments and they are overthrust by low angle splays of the main fault (Figure 16). Unit CW5 is a matrix-supported coarse gravel formed by sub-rounded limestone clasts within a reddish sand matrix. A weak gypsiferous soil caps part of this deposit, although the main part of the soil was apparently removed by a later thrust event. Similarly, CW4 is a matrix-supported fine gravel with intercalations of clast-supported pebbles. The gravels of unit CW4 are in general finer than those of unit CW5, and the contact between these two units is based primarily on textural differences. We interpret CW4 as another wedge
developed by motion on the fault, resulting in the bulldozing of the previously deposited sediments towards the west. Although this is our preferred interpretation, it is also possible that CW4 and CW5 are a single wedge that has been dis-membered by sub-horizontal thrust displacement, although this interpretation requires an exceptionally large event to account for the observed slip.

Unit CW3 is a reddish sand with scattered limestone clasts overprinted by soil development. Its base is apparently an erosional contact developed over a secondary thrust splay and the CW4 deposits. To the west, it becomes sandier and is undistinguishable from the CW4 distal sand deposits. Unit CW2 is a 35-40 cm thick, poorly stratified, matrix-supported gravel composed of coarse, sub-angular limestone pebbles and cobbles within a brownish sandy matrix. A weak brown soil is observed in the top 15 cm of the CW2 deposit, although the presence of gypsum and secondary clay appears to be very minor. Finally, unit CW1 is a poorly-sorted, wedge-shaped gravel composed of pebbles and cobbles located immediately below the main fault plane. A several centimeters-thick layer of limestone clasts cover the slope of the cumulative colluvial wedges, as well as the hanging wall deposits.

4.1.2. Structure.

La Laja fault is exposed in trench T1 as a 10-15 cm thick shear zone parallel to the stratification of the Neogene beds, with two minor splays near the top of the section. The main fault surface, designated as fault Th1, is concave down, dipping 38° to 42° towards the southeast near the base of the trench, and rolling to shallower dips (~ 15°-25°) up section (Figure 10). The upper fault splay, designated as Th2, is a thrust at the base of a 0.8 m long and 15 cm thick slab of the Tertiary section, with a 12° dip to the southeast
Figure 3.11 a. Excavation of trench 1 across scarp on surface Qt₃. View towards SSE. In the background, excavation of trench MT and the frontal monoclinal (tilted terrace Qt₂).

Figure 3.11 b. Detail of the trench T1, south wall. The Qt₃ gravels are at the bottom of the trench; above, the red composite colluvial wedge. La Laja fault overthrust both deposits as it clearly observed in this exposure.
Figure 3.12. (a) Scheme showing the formation of colluvial wedge from a two events scarp [from Carver and McCalpin, 1996]. Notice the formation of a coarser base followed by finer sediments and formation of soil on the slope as it reach a quasi-equilibrium. All the elements were found in trenches 1 and 4, La Laja fault.
(b) Idealized sequence of stages in the evolution of a 45° dipping reverse fault from Carver and McCalpin, 1996. Notice that only a small percentage of the total slip is preserved after erosion (stage H) therefore the amount measured in a trench exposure is always a minimum.
(c) Types of thrust fault scarps produced along the Spitak fault during the 1988 M$_s$ 6.9 Spitak, Armenia, earthquake. From Carver and McCalpin, [1996] from the original work of Philip et al. [1992]. At La Laja fault we observed types B, C, E and F preserved from the 1944 earthquake.
Figure 3.13. Photomosaic of the lower section of trench T1 (south wall). Annotations show the main features of colluvial wedges, CW9 to CW6. Red dotted line indicates the location of the different branches of La Laja fault. Th1 is the main fault; Th2 and Th3 are secondary splays. N = Neogene strata. Qt3 = top of the gravel deposits of terrace Qt3.
Figure 3.14. Photography of the upper section of trench T1. Sketched interpretation of the faults and associated colluvial wedges. CW1 to CW5 = colluvial wedges 1 to 5. Th1 to Th3 are thrust faults (La Laja fault). Nc = whethered Neogene beds.
(Figure 10). Fault splay Th3, immediately below Th2, is a sub-horizontal thrust that bounds another ~ 1.2 m long and 20 cm thick tabular sheet of Tertiary sand. A minor secondary normal slip fault affects units Qt3 through thrust sheet Th2 (Figure 10), with increasing vertical separation down section. A small fracture affects units Qt3 through CW7, but does not obviously displace any of these units. Sand-filled cracks are observed near the upper boundary of units CW8, CW7, CW6 and CW3, and are probably related to earthquake activity.

4.2. Description of Trench 2

Trench T2, located immediately below and south of trench T1 along the northern edge of the active wash, has an orientation of N55°W and is about 4.5 m in length (Figures 5 and 15).

4.2.1. Stratigraphy

The base of the trench exposed weathered Neogene sediments overlain in angular unconformity by fluvial gravels. The basal gravels are, in turn, overlain by fine to medium laminated sand, which we believe to be sourced from the Neogene sand strata exposed in the side of the wash wall immediately below trench T1. These deposits are broadly folded and faulted. The top of the laminated sand is truncated by an erosional unconformity that apparently post-dates the deformation. The section is capped by undeformed coarse to medium sand.

4.2.2. Structure

In Trench T2 the main fault plane of La Laja Fault displaces the top erosional surface of the Neogene beds at an angle of ~ 41°. In the sandy alluvial section, the fault branches out in at least four faults, each with a fraction of the total displacement. The
Figure 3.15. (a) Photomosaic of trench T2 located across La Laja fault on the modern wash surface. (b) Detail of the fault zone with indication of the 1944 displacement indicated by the green and blue contacts.
hanging-wall of the fault is broadly folded and exhibits distributed dip-slip faulting with
drifts in the upper section of the laminated sand that die out down section.

4.3. Description of Trench 4

Trench T4 was excavated across a low scarp developed on an abandoned
floodplain of a small wash, located ~ 240 m south of the point where La Laja Fault
intersects the road (Figure 5), and about 200 m south of trench T1.

4.3.1. Stratigraphy

The sediments exposed in this trench were divided into 23 units, with the oldest
being the Neogene strata, unit N, exposed in both the hanging wall and footwall blocks of
the fault (Figure 16). The strata of unit N, composed of sand, silt, and to a lesser degree
clay, are tilted 40-42° towards S50°E. As was observed in all other exposures and
evacuations, La Laja Fault is parallel to the bedding of unit N. A conspicuous angular
unconformity separates the Neogene sediments from the Quaternary wash and colluvial
deposits. This unconformity is observed on both sides of the fault, with a minimum fault
parallel separation of ~ 2 m. Above the unconformity, sand and gravel deposits of fluvial
and colluvial origin are found on both sides of the fault, with units U12 to U5 and CW1
and CW2 constrained to the foot-wall and units H3 to H1 and CW1’ and CW2’ only
described on the hanging-wall. Units Su5 to U1 can be correlated across the fault with a
high level of confidence based on their sedimentological characteristics.

On the footwall of the fault, the angular unconformity (strath) at the top of unit N
slopes at about 4° to the southeast. Above this unconformity, units U12 to U10 are
approximately parallel to the strath. Unit U12 is a 10 cm-thick, fine to medium sand
deposit that pinches out or is truncated 1.5 m to the east of the fault. Unit U11 is a 10 to
20 cm thick, clast supported gravel composed of sub-rounded pebbles that coarsen near the fault, and unit U10 is a 10 cm thick, medium sand that maintains fairly constant thickness, where preserved. Overlying these strata, unit U9 defines a wedge-shaped gravel that thickens towards the fault, with a gently west-sloping top contact and a base contact that is parallel to U10. To the east, units U9, U10, and U11, along with the underlying Neogene section of unit N, are cut by an erosive channel deposit, designated as unit U9b, that is composed of a clast-supported gravel.

Unit U8 is 10-15 cm thick, medium sand that overlies unit U9 and U9b, and unit U7 is a 5 cm thick, weakly bedded, fine gravel. Unit U8 is generally sub-horizontal with a slight slope to the west near the lower branch of La Laja fault, although it pinches out both towards and away from the fault, suggesting that it filled a depression along the downthrown side of the fault. In contrast, unit U7 extends the length of the trench. We interpret the sediments from unit U12 to U7 as fluvial wash and overbank deposits with perhaps a colluvial wedge contribution for U9.

Units CW1a and CW1b are stratigraphically above or laterally equivalent to U7. Both units are wedge-shaped, poorly-sorted gravel deposits composed mostly of limestone clasts. CW1a is clast supported with sub-rounded cobbles and pebbles whereas CW1b contains mostly sub-angular pebbles with a higher proportion of sandy matrix. Both deposits are interpreted as part of a single colluvial wedge related to degradation of a fault scarp. On the hanging-wall, CW1a’ and CW1b’ are considered the correlative parts of these wedges.

Overlying the inferred colluvial wedge and older deposits, units U6 and U5 compose a 60 cm-thick package of poorly stratified, pinkish-grey sand that pinches out
towards the fault scarp. They were subdivided into two units because each has a distinct soil profile developed in them, with a B soil horizon near their tops. The soil of unit U6, designated as SU6, is a 10 cm-thick, pink, laterally continuous zone of gypsum and minor clay accumulation. The soil developed on unit U5, designated as SU5, is a 20 cm-thick, laterally continuous, pink horizon enriched with gypsum and minor clay, and contains scattered fragments of charcoal. Both soils are also observed five meters to the north in trench T3. The sand deposits of units U6 and U5 are interpreted as multi-episodic overbank deposition from local flooding of the wash that ponded against the La Laja fault scarp.

A wavy unconformity separates the top of the SU5 soil from unit U4, which is an accumulation of poorly-sorted gravel. Units U3 and U2 are laterally continuous, gravelly sand deposits with pockets of embedded gravel interpreted as channel alluvium. Capping the entire section is unit U1, a gravel with a sandy matrix. Units U4 to U1 are also found on the hanging-wall of the fault.

In addition to the footwall strata, the hanging wall is overlain by three gravel units, H1, H2 and H3, that exhibit a strong red coloration that is likely the result of soil development. The age or correlation of these poorly-sorted fluvial gravels is not clear, although we interpret that the strong reddish soil correlates with the Su5 soil capping unit U5 in the footwall. The strong soil is not laterally continuous across the fault and therefore we conclude that the H1 to H3 deposits are older than the U4 gravels.

4.3.2. Structure

Trench T4 exposes La Laja fault as three discrete fault branches, F1, F2 and F3, with a fourth suspected low angle fault (F4) at the base of the stratigraphic sequence.
Figure 3.16. Photomosaic and log of the south wall, trench T4. Location of the trench is indicated on figure 5.
Figure 3.17. Detail photography of the south wall of trench T4. Faults and stratigraphic contacts are delineated. U12 to U5 are Quaternary deposits of fluvial and colluvial origin.
(Figure 10). Fault F1 is a ~ 35º southeast dipping surface that offsets units Cw1 to U1, and thus it is considered the fault branch that slipped as a consequence of the 1944 San Juan Earthquake. Fault F2, dipping ~ 53º to the SE, cuts Cw1a-a’ and is covered by unit Cw1b’. Fault F3 is a low angle reverse fault dipping ~ 26º to the SE that cuts units U12 to U9 and is apparently overlain by unit U5. F4 is a suspected minor fault branching from F3 that produces a small displacement of units U12 to the base of U9.

5. Age of the Deposits.

A total of 13 sand samples from Trench 1, units CW1 to CW9, were dated using the optical stimulated luminescence technique (OSL) applied on quartz grains. For this study, the medium to fine sand samples collected for OSL dating were obtained at night in total darkness, placed in sealed cylinders and later shipped to Lewis Owen at the Department of Geology, University of Cincinnati, Ohio for dating. Location of the samples from Trench 1 is indicated in Figure 10, and a detailed summary of the dating results on quartz grains extracted from the samples is shown in Table 1. In addition, three radiocarbon dates from detritic charcoal fragments collected from trench T4 were used to constrain the age of the top of unit U5 (Figure 11 and Table 2).

OSL dating technique provides an indirect quantitative determination of the time since a sample of sand or silt was last exposed to sunlight [Huntley et al., 1985; Smith et al, 1990:]. OSL can supply accurate absolute ages in the range of decades to over a hundred thousand years for deposits where the light-sensitive signal in all grains was fully removed by exposure to sunlight during erosion, transportation and deposition. However, if the signal from some of the grains is not totally reset (partial bleaching), it can result in overestimation of the burial age of the sample [Wallinga, 2002].
5.1. Trench T1 OSL Chronology

In this study we assume that the best age of a stratigraphic unit where we dated more than one OSL sample is represented by the youngest date obtained for that unit. This accounts for the likelihood that the older date represents a partially bleached sample. In most cases, the dates generally become progressively older with depth, as expected. The exceptions are a couple samples that apparently have residual age signal, and these results were omitted from the final age analysis.

The middle section of unit CW2 was dated at 2.1±0.3 ka using quartz grains collected from sample T1-S12 (Figure 10). Two samples from unit CW3, T1-S11 and T1-S13, were dated (Table 1). The estimated age of sample T1-S11 is 7.6±0.7 ka whereas sample T1-S13 yielded an age of 8.7±0.9 ka. As the samples are from the same stratigraphic unit, our preferred age for unit CW3 is ~7.6±0.7 ka.

No OSL samples were collected from units CW4 and CW5, and therefore their age can only be constrained by the dates recovered from units CW3 and CW6. The top section of CW6 was also dated, with sample T1-S09 yielding a date of 19.0±1.3 ka (Table 1). Sample T1-S10, recovered from a medium-fine sand, was obtained 80 cm to the west of the previous sample and ~ 10 cm from the top surface of the unit CW6. Its burial age is estimated by OSL at 23.9±1.7 ka (Table 1). As mentioned before, we assume that the best age of unit CW6 is represented by the youngest OSL date, therefore we take the age of CW6 as ~19.0±1.3 ka.
Table 3.1. Summary of OSL dating results from quartz extracted from sediment matrices: sample locations, radioisotope concentrations, moisture contents, total dose-rates, D_E estimates and optical ages

<table>
<thead>
<tr>
<th>Sample #</th>
<th>Particle size (μm)</th>
<th>a.s.l (m)</th>
<th>Depth (cm)</th>
<th>U^a</th>
<th>Th^a</th>
<th>K^a</th>
<th>Rb^a</th>
<th>Cosmic^b</th>
<th>Dose-rate^c</th>
<th>N^a</th>
<th>Mean D_E^f</th>
<th>Age (ka)</th>
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</thead>
<tbody>
<tr>
<td>T1-S01</td>
<td>90-125</td>
<td>630</td>
<td>520</td>
<td>3.21</td>
<td>7.49</td>
<td>1.65</td>
<td>73.1</td>
<td>0.20±0.01</td>
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<td>31.4±2.4</td>
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<tr>
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<td>520</td>
<td>2.37</td>
<td>6.17</td>
<td>1.47</td>
<td>62.9</td>
<td>0.20±0.01</td>
<td>2.50±0.15</td>
<td>29(23)</td>
<td>111.9±16.9</td>
<td>44.8±3.0</td>
</tr>
<tr>
<td>T1-S03</td>
<td>90-125</td>
<td>630</td>
<td>480</td>
<td>2.90</td>
<td>6.52</td>
<td>1.49</td>
<td>66.2</td>
<td>0.20±0.01</td>
<td>2.66±0.16</td>
<td>42.1±2.8</td>
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<td>630</td>
<td>420</td>
<td>2.85</td>
<td>8.53</td>
<td>2.03</td>
<td>82</td>
<td>0.20±0.01</td>
<td>3.28±0.20</td>
<td>23(22)</td>
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<td>6.04</td>
<td>1.35</td>
<td>64.8</td>
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<td>2.62±0.15</td>
<td>26(22)</td>
<td>92.8±13.7</td>
<td>35.4±2.4</td>
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<td>1.5</td>
<td>68.7</td>
<td>0.21±0.01</td>
<td>2.61±0.16</td>
<td>28(22)</td>
<td>105.6±20.0</td>
<td>40.5±2.9</td>
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<td>340</td>
<td>2.61</td>
<td>7.16</td>
<td>1.61</td>
<td>71.6</td>
<td>0.21±0.01</td>
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<td>111.0±19.8</td>
<td>40.2±2.8</td>
</tr>
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<td>T1-S09</td>
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<td>630</td>
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<td>3.49</td>
<td>9.29</td>
<td>2.07</td>
<td>92.6</td>
<td>0.20±0.02</td>
<td>3.51±0.21</td>
<td>24(18)</td>
<td>82.2±19.2</td>
<td>24.5±1.8</td>
</tr>
<tr>
<td>T1-S10</td>
<td>90-125</td>
<td>630</td>
<td>340</td>
<td>3.21</td>
<td>9.98</td>
<td>2.24</td>
<td>97.3</td>
<td>0.20±0.02</td>
<td>3.65±0.23</td>
<td>22(16)</td>
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<tr>
<td>T1-S11</td>
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<td>9.05</td>
<td>2.1</td>
<td>91.6</td>
<td>0.21±0.02</td>
<td>3.69±0.22</td>
<td>17(14)</td>
<td>69.9±9.0</td>
<td>19.0±1.3</td>
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<tr>
<td>T1-S12</td>
<td>90-125</td>
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<td>280</td>
<td>5.7</td>
<td>9.59</td>
<td>1.95</td>
<td>92</td>
<td>0.21±0.02</td>
<td>3.95±0.23</td>
<td>14(13)</td>
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<td>23.9±1.7</td>
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<tr>
<td>T1-S13</td>
<td>90-125</td>
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<td>0.23±0.02</td>
<td>3.80±0.22</td>
<td>17(16)</td>
<td>33.2±10.3</td>
<td>8.7±0.9</td>
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</table>

^aElemental concentrations from NAA of whole sediment measured at USGS, Denver. Uncertainty taken as ±10%. ^bEstimated contribution to dose-rate from cosmic rays calculated according to Prescott and Hutton (1994). Uncertainty taken as ±10%. ^cEstimated fractional water content from whole sediment (Aitken, 1998). Uncertainty taken as ±15%. ^dTotal dose-rate from beta, gamma and cosmic components. Beta attenuation factors for U, Th and K compositions incorporating grain size factors from Mejdahl (1979). Beta attenuation factor for Rb arbitrarily taken as 0.75 (cf. Adamiec and Aitken, 1998). Factors utilized to convert elemental concentrations to beta and gamma dose-rates from Adamiæc and Aitken (1998) and beta and gamma components attenuated for moisture content. ^eNumber of aliquots measured. The number in parenthesis refers to the number of aliquots used to calculate the D_E. ^fMean equivalent dose (D_E) determined from replicated single-aliquot regenerative-dose (SAR; Murray and Wintle, 2000) runs. Errors are 1-sigma standard errors (i.e. σ_n/√n) incorporating error from beta source estimated at about ±5%. 

Table 3.2. Radiocarbon ($^{14}$C) dates from the Center for Accelerator Mass Spectrometry Lawrence Livermore national Laboratory. 1) d13C values are the assumed values according to Stuiver and Polach (Radiocarbon, v. 19, p.355, 1977) when given without decimal places. Values measured for the material itself are given with a single decimal place. 2) The quoted age is in radiocarbon years using the Libby half life of 5568 years and following the conventions of Stuiver and Polach (ibid.). 3) Radiocarbon concentration is given as fraction Modern, D14C, and conventional radiocarbon age. 4) Sample preparation backgrounds have been subtracted, based on measurements of samples of 14C-free coal. Backgrounds were scaled relative to sample size.

<table>
<thead>
<tr>
<th>CAMS #</th>
<th>Sample Name</th>
<th>δ$^{13}$C</th>
<th>Fraction Modern</th>
<th>$\pm$</th>
<th>D$^{14}$C</th>
<th>$\pm$</th>
<th>$^{14}$C age</th>
<th>$\pm$</th>
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</thead>
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<tr>
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<td>14C-1-blue nail</td>
<td>-25</td>
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<td>0.0030</td>
<td>-297.0</td>
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<td>35</td>
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<tr>
<td>124334</td>
<td>14C-2</td>
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<td>0.0032</td>
<td>-306.2</td>
<td>3.2</td>
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<td>40</td>
</tr>
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<td>124336</td>
<td>Sample 1-Tr4-pinche-south wall</td>
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<td>0.694</td>
<td>0.0052</td>
<td>-306.0</td>
<td>5.2</td>
<td>2930</td>
<td>70</td>
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</table>

Two sand samples from the top section of CW7, samples T$_1$-S07 and T$_1$-S08, yielded ages of 24.5±1.8 ka and 22.3±1.8 ka, respectively (Table 1). We therefore assume that the age for unit CW7 is best taken as 22.3±1.8 ka. For unit CW8, sample T$_1$-S04 yielded an age of 35.4±2.4 ka., whereas samples T$_1$-S05 and T$_1$-S06 yielded ages of 40.5±2.9 ka and 40.2±2.8 ka from the same strata. From these dates, the best age is about 35 ka, but an additional three samples from unit CW9, located stratigraphically below unit CW8, were dated and two of these yielded younger ages, indicating that these oldest strata have a significant partial-bleach signal. For samples T$_1$-S01, T$_1$-S02, and T$_1$-S03 from unit CW9, the OSL ages are 31.4±2.4 ka, 44.8±3.0 ka and 30.8±2.1 ka, respectively, indicating that this and all overlying strata are no older than about 31 ka. Based on these dates, we consider that unit CW9 is ~30.8±2.1 ka. As the best date for unit CW9 is
significantly younger than any of those obtained for unit CW8, the age of unit CW8 is only constrained by the age of the overlying and underlying units to between 22.3±1.8 ka (age of unit CW7) and 30.8±2.1 ka (age of unit CW9).

5.2. Trench 4 Radiocarbon ages

Three samples of detritic charcoal, collected from the top of unit 5 in trench T4 (Figure 11), were dated using the CAMS facility at Lawrence Livermore National Laboratory. The radiocarbon ages were calibrated using Calib 4.3 to provide dendrochronologically corrected ages in years B.P. The charcoal ages represent a maximum age for the sediment because we are dating the growth age of the dead wood, which occurred prior to the deposition of the sediments of unit U5.

6. Slip History of La Laja Fault

Interpretation of the paleo-surface ruptures on La Laja Fault is based on the geometry and character of the deposits, their relationship with primary and secondary faults, the presence of other secondary structures (folds, fissures, etc), and a model of the colluvial wedge development process [e.g Hanks, et al, 1987; Nelson, 1992; Carver et al., 1996; Rubin et al., 1998 more here] (Figure 12). In the excavations at La Laja fault, we generally identified three stages of colluvial wedge formation. These are: 1) a coarse clastic, triangular-shaped gravel deposit located immediately below or near the tip of the fault plane; 2) a sandy, wedge-shaped accumulation of colluvium that thins away from the fault; and 3) a capping soil that indicates a substantial period of time between events during which equilibrium of slope processes were generally established.

Fault slip events are described in chronological order from most recent (E1), corresponding to the 1944 rupture, to oldest (E9). In all cases, we measured slip
approximately perpendicular to the strike of the fault. Kinematic indicators ( striation on the fault plane) and 3-D trenching of offset features show that 1944 slip occurred approximately orthogonal to the fault as nearly pure dip slip (Figure 17). We interpret that preservation of the displacement history after event E9, along with the associated colluvial wedges CW9 to CW1, occurred after terrace Qt3 was abandoned, perhaps by fluvial incision. This abandonment prevented fluvial erosion of the colluvial wedges and favored their preservation and the recording of fault displacement.

6.1. Event E1

The youngest event corresponds to La Laja Fault surface rupture identified after the 1944 M\textsubscript{s}=7.4 San Juan earthquake. In the area of our excavations, the scarps along the rupture measured about 30 cm in height, consistent with 45-50 cm of dip slip on a 40-45\textdegree
dipping fault (Groeber, 1944; Harrington, 1944). Evidence for this event is found in all trenches, and described in detail for trenches T1, T2 and T4. In trench T1, slip occurred on the main fault surface (Th1), truncated unit CW2 and ruptured the surface at an average angle of ~ 22\textdegree. Two distinctive stratigraphic contacts were used as markers to measure the minimum fault displacement during this event. One is the top surface of unit Nc in the hanging-wall, and its equivalent surface in the footwall, located at the top of the block of sediments bound by thrust fault Th2 (Figures 10 and 18 a, b). The other marker is a weak brown soil developed across units CW2 (footwall) and Cs (hanging wall). This soil was folded and offset by fault Th1 during the 1944 event (E1). Retro-deformation of the hanging-wall block of the fault to reconstruct both contacts requires an estimated fault parallel slip of 40-60 cm (Figures 18 a, b). Additional evidence of deformation related to
Figure 3.18. Schematic reconstruction of the nine events interpreted on trench exposure T1. For each event we measured a minimum displacement. Important erosion occurred on the hanging wall therefore the actual displacement for each event is unknown. Based on the total terrace Qt3 we estimate the actual displacement is approximately twice the minimum displacement measured on the trench T1.

(a) Log of the trench T1 south wall. The western section of the log was not included in this figure since it contains no key information of the earthquake history of this site

(b) Schematic interpretation of the Pre-1944 fault geometry. Estimated displacement in the 1944 event ~ 60±10 cm. The displacement occurred on Th1 cutting a weak soil developed on the colluvial wedge CW2.

(c) Interpretation of the geometry after event 2 (E2). The slip occurred on thrust 2 (Th2), producing a minimum displacement is of ~ 49±3 cm.

(d) Schematic reconstruction of the geometric relationships before to event E2. CW3 is the colluvial wedge developed after E3.

(e) Reconstructed geometry following the E3 event. The displacement occurred on thrust 3 (Th3) and it cut the colluvial wedge CW4. The thrust motion is subhorizontal and the total displacement is not well constrained. Th3 previously moved in event E4 and the combined minimum displacement of E3 and E4 is 1.2±20 cm. The hanging wall shows evidence of post E3 erosion as well post E4 erosion. It is not clear whether more events could be missing. Colluvial wedges CW4 and CW5 are not as well developed as the previous ones (e.g., CW6). In this reconstruction we estimated the E3 displacement to be ~ 60 cm by matching the base of CW-4 deposit with the hanging wall top surface.

(f) CW4 is a gravel deposit that is interpreted to post-date the displacement of Th3 during event 4. It was bulldozed during event E3.

(g) Event 4 (E4) occurred on fault Th3 as it did in the previous event. The estimated displacement is about 65 cm, although there is not strong constraint to determine E3 and E4 independently. E4 subhorizontal displacement pushed forward the sediments of CW5 forward (bulldozing) generating part of the CW4. The finer sediments of CW4 are interpreted as post- E4 motion.

(h) Pre-E4 event. CW5 was deformed by low angle thrust (Th3). The bulldozed material generated part of the coarse section of CW4.

(i) Post E5. The event 5 produced a displacement of ~ 50cm deforming the wedge CW6. Secondary faulting and cracking is affecting CW6 interpreted as a consequence of the E5 deformation.

(j) Pre-E5 event. The fault tip and hanging wall nose are covered by the CW6 deposits, a colluvial wedge developed as a consequence of the E6 event. CW6 is formed by coarser lower part that is interpreted as synchronous with the E6 motion and a finer upper section developed to establish the slope profile equilibrium.

(k) Post E6. The event 6 produced a displacement of ~ 75 cm. A syntectonic wedge, secondary cracking and a small secondary thrust affecting CW7 are considered part of this event.

(l) Pre-E7. The colluvial wedge CW7 developed as consequence of E7 cover the fault tip.

(m) Post E7. The event 7 produced a displacement of ~ 64 cm. E7 cut CW8 and form a colluvial wedge at the base of CW7 deposit.
Figure 3.18 (continue)

(n) Pre-E7 event. The fault tip and hanging wall nose are covered by the Cw8 deposits, composed of a coarser section near the fault, and a finer grain sand above.

(o) Post-E8. The event 8 produced a displacement of ~ 62 cm. The CW9 was cut by the fault and a colluvial wedge was developed by bulldozing and later by progressive accumulation of fine sand. The top of the CW9 shows evidence of erosion with incision of a small channel previous or during E8. Numerous secondary faults and cracks are developed on CW9 perhaps as a consequence of event E8.

(p) Pre-E8 event. The fault tip and hanging wall nose are covered by the Cw9 deposits, formed by a coarser section near the fault, interpreted as bulldozed material during motion of the hanging wall in E9.

(q) Post -E9. The event 9 produced a minimum displacement of ~62 cm. The event generates a colluvial wedge CW9 composed of a coarser gravelly base interpreted as bulldozed material during the E9 hanging wall motion and a fine sand section gradually deposited after the event. E9 deformed the terrace deposit but it is unknown how many previous events occurred while the terrace was the active surface of the wash.

(r) Pre-E9 event. We assumed that the top of the hanging wall was about the same level than the top of the Qt3 terrace deposits in the footwall.
Figure 3.18 continued
Figure 3.18 continued
Figure 3.18 continued
Figure 3.18 continued
this event is observed at the ground surface, where a vertical scarp of 25-30 cm was surveyed along the south side of trench T1 (detail on Figure 7). Also, normal dip slip on fault NF1 produced two to four centimeters of displacement at the base the Th2 thrust sheet, and we infer an equivalent amount of deformation on unit CW2 (Figure 10).

In trench T2, fine-layered sediments and well-defined stratigraphic contacts facilitated the precise measurement of the fault parallel reverse displacement and the scarp height generated at the surface during event E1. At the bottom of the excavation, the planar erosional surface developed on the Neogene beds, unit N, is offset by a 40º southeast dipping La Laja Fault surface. The total slip, measured parallel to the fault on the south trench face, is approximately 50 cm (Figure 15). 3-D trenching of a filled burrow cut by the last event show no lateral component of displacement, which indicates that the E1 slip vector was parallel to the dip of the fault (Figure 17). Consequently, we consider the 50 cm reverse displacement to be the actual 1944 La Laja fault total slip at this location. After 61 years of erosion and sediment accumulation, the current relic scarp is less than 10 cm high. The 1944 ground surface was partially eroded and then buried by coarse sand, leaving only a 15-20 cm vertical scarp. The strath surface at the bottom of the trench shows 32 cm of vertical uplift (Figure 15). These measurements closely match some of the observations reported immediately after the 1944 earthquake. These observations suggest that the additional 30 cm post-seismic creep inferred by Groeber [1944], based on Castellanos [1945] report, perhaps never occurred.

Evidence of event E1 in trench T4 is found in the upper section of the trench where fault branch F1 offsets and folds units U5 through U1 (Figure 11). The minimum E1 slip at this location, measured along the fault on the trench face, was obtained from
displacements of two stratigraphic boundaries, the top of unit CW1a and the upper boundary of soil SU5 (Figure 19 a, b). From the first, we measured ~ 45 cm of dip displacement, whereas for the second we only measured ~35 cm. Folding and back-thrusting observed in the upper units of trench T4 accommodate part of the slip and explains the smaller displacement measured for the SU5 contact.

In conclusion, the slip measured for event E1 in trenches T1, T2 and T4 is consistent with the field observations that followed the 1944 San Juan earthquake [Groeber, 1944; Harrington, 1944; Castellanos, 1944]. We estimate that dip slip in 1944 was about 45-60 cm, with our best determination taken from trench T2 where we measured 50 cm of dip slip.

6.2. Event E2

Evidence for event E2 was observed in trenches T1 and T4. In trench T1, fault Th2 truncates unit CW3 at an angle of 18-20° and is in turn overlain by unit CW2. Thus, we interpret the observed displacement on fault Th2 slip as resulting from the penultimate event. The minimum fault displacement is measured using the erosional surface at the top of the Tertiary block bound by faults Th2 and Th3 as a kinematic marker (Figure 10 and 18 c, d). We interpret that this surface was continuous before E2, and as a consequence of this event it was offset at least ~ 50 cm (Figure 18 c, d). There is evidence of hanging-wall erosion, as expected, and therefore the slip that we measured is considered a minimum. Formation of colluvial wedge CW2 is interpreted as a direct consequence of fault scarp degradation following E2 event.

In trench T4, unit Cw1a is interpreted as a colluvial wedge formed as a consequence of slip on fault F2, during or immediately after event E2. Fault F2 and unit
Cw1a are overlain by unit Cw1b, formed during the later stages of colluvial wedge development. Subsequent overbank deposition of units U6 and U5 buried the scarp. The minimum displacement of fault F2 during event E2 is measured as ~ 60 cm based on the correlation of the top of unit N in the hanging-wall block with the small triangular fragment of unit N located below Cw1a in the footwall (Figure 19 b to d). The measured offset is consider to be close to the actual E2 displacement because we see no evidence of erosion of unit N in the hanging-wall resulting from this displacement, suggesting that this contact was already buried at the time of the rupture.

Although there is no stratigraphic correlation between trenches T1 and T4, we consider the penultimate event (E2) to be the same in both trenches. Further support of this correlation is provided by the OSL and radiocarbon dating.

In trench 1, the OSL age estimation from units CW3 and CW2, together with the stratigraphic and structural relations, provide a reasonable constraint for the timing of event E2. The middle section of unit CW2 yielded an OSL date of 2.1±0.3 ka, which must postdate the actual age of the displacement because some time is required for the formation of the wedge itself. The age of the underlying colluvial wedge (CW3), which is attributed to event E3, provides an absolute maximum age for the timing of event E2, and two OSL samples from CW3 yielded dates of 7.6±0.7 ka and 8.7±0.9 ka (Table 1). Independently, three detrital charcoal samples collected from unit SU5, which buries the clastic portion of the event E2 colluvial wedge in trench T4, further constrain the age of event E2 (Table 4). All of the samples dated to around 3-3.2 ka (calibrated dates Table 2), which also provides a minimum age for event E2. Considering that accumulation of the overbank deposits of unit U6 occurred before the E2 scarp was fully degraded, it is
reasonable to conclude that the sediments of this unit were laid down relatively soon after this event. Soil SU6 represents some additional period of surface exposure time during which oxidation of the upper part of this unit occurred. Based on the weakness of this soil and comparison to others soils from T1 for which we have some age control, we estimate that there is less than 2000 years of surface exposure represented in the development of this soil. The ~ 3-3.2 ka radiocarbon dates from charcoal recovered from unit U5, must postdate U6 by the time represented by formation of the soil SU6. Thus, event E2 is likely at least several hundred to a thousand years older than the age of the radiocarbon dates. Based on these ages and observations, we place the age of event E2 at about 4±1 ka (Figure 20).

Considering that the apparent age of the colluvial wedge of event E2, as dated by OSL, is 1-2 ka younger than the best estimated probable age for this event, we will account for this factor in our best estimates on the ages of the older events, dated by OSL on the finer section of their respective colluvial wedges. Thus, to estimate the age of an event based on the OSL dates of the upper parts of the respective colluvial wedges, we will add 2±2 ka to the youngest OSL age obtained from the middle-upper section of colluvial wedge that postdates the event (Table 1 and Figure 20). In this way, we account for the time of colluvial wedge formation and expand the uncertainty range, which also hopefully accounts for the added uncertainty in partial bleaching of the OSL signal.

6.3. Events E3, E4 and E5

Events E3, E4, and E5 are analyzed together because there are not sufficient age and stratigraphic constraints to resolve each individual event. In Trench 1, events E3 and E4 occurred along thrust fault Th3. Stratigraphically, these events are considered as
Figure 3.19. Reconstruction of trench 2 (T2) earthquake related displacements. a) Post-1944 - Present event 1 62 years after the earthquake ~ 45 ± 5 cm displacement. Displacement measured on the fault plane for the offset of the top Su5 is only 35 cm ± 5 cm. Correlation of the top units across the main fault is challenging due to the lateral variation of the deposits. U1 is probably post 1944. All references are the same as in Figure 16. b) Immediately previous to Event 1 (E1), year 1944 C.E.
Figure 3.19 continued

(c) Post Event 2 some time after accumulation of sediments of units U6-U5 behind scarp generated during and after E2. A soil developed on units H1 U5 (Su5) representing a time of stability around ~ 3.2 ka (dated using $^{14}$C method on charcoal).

(d) We interpreted that Cw1a-Cw1b was formed as a consequence of motion on Fault 2 (F2). This reconstruction model estimates ~ 55 cm displacement on fault 1 (F2).
Figure 3.19 continued

(e) Post-E3-Pre-E2 stage. Fault 2 (F2) moved 55 cm during E2 event. The motion of this fault generated the Cw1, Cw1' probably due to bulldozing and collapse of gravels during the displacement. This interpretation assumes no motion of fault 3 during E2. It is possible some small readjustment on F4. Evidence from field logging and photography shows that the fault 1 tip is located near U5 and therefore it is interpreted as inactive during E2 motion.

(f) Pre-E3 stage. Event E4 occurred on fault 3 and produced an offset of ~80 cm. Our interpretation assumes that the U12, U11 and U10 were deposited before the event E3. Event 3 (E3) generated part of the U9 unit and created a topographic high that was latter filled (in part) by U8. It is possible that another secondary fault F4 had some displacement at the same time of E3.
having occurred after the formation of unit CW5 and prior to deposition of unit CW3. Fault Th3 truncates colluvial wedges CW4 and CW5, with a cumulative minimum displacement of $1.2 \pm 0.2$ m for both events combined (Figure 18 e to h). We interpret the observed displacement in the Th3 fault thrust as likely the result of two separated fault slip events. The younger of the two interpreted events, event E3, partially bulldozed and over-thrust the previously accumulated colluvial wedge CW4, thereby generating a steeper slope that led to the formation of colluvial wedge CW3. The earlier event, E4, partially bulldozed colluvial wedge CW5 and formed the scarp that is related to the formation of colluvial wedge CW4 (Figure 18 e to h).

Event E5 is represented by displacement of the tip of the Tertiary hanging-wall block of the fault from the wedge-shaped gravelly base of unit CW6 up to the base of unit CW5. The minimum slip during this event is estimated at 50 cm, although the exact location of the tip of the fault before and after the event is unknown (Figure 18 i-j). Consequently, the actual displacement could be considerably larger, so we take the 50 cm as a minimum value. Event E5 generated a scarp that produced the CW5 colluvial wedge, which was partially erased by bulldozing during later fault displacements. Narrow, wedge-shaped cracks penetrating the top surface of unit CW6, along with seven centimeters of normal displacement on fault NF1, are interpreted to have resulted from the event E5 rupture. The actual relationship between La Laja thrust and the several footwall normal faults is unclear but probably relates to co-seismic folding of the footwall block or compaction of the footwall sediments.

In Trench T4, in addition to events E1 and E2, we find evidence for a relatively large displacement on fault F3 that can be interpreted as one single event E3 with ~ 80
cm of slip. The displacement for this event is measured from the top of unit N, in the footwall, to the top of the triangular section of unit N, located on the hanging-wall of fault F3 (Figure 19 e). The fault cuts units U12 up through the base of unit U9, and is buried by the upper section of unit U9, interpreted as a colluvial wedge, and by a unit U8, a sandy deposit that pinches out against the fault scarp produced by event E3.

The ages of events E3, E4, and E5 are poorly constrained by OSL dates on samples recovered from units CW3 and CW6 in trench T1. As mentioned before, the OSL estimated ages for two samples taken from the upper-middle section of the CW3 wedge are 7.6±0.7 ka and 8.7±0.9 ka, which provides the minimum age of 7.6±0.7 ka for event E3 (Table 1). Using the relationship between the age of the wedge and the likely age of the event determined for event E2 as discussed above, we add 2±2 ka to the younger OSL age to arrive at a best estimate of 9.6±2.7 ka for the age of event E3 (Figure 20).

Events E4 and E5 are only broadly constrained by the OSL dates of the colluvial wedge developed after event E6, CW6. Two samples from the top portion of the CW6 wedge provided dates of 19.0±1.3 ka and 23.9±1.7 ka (Table 2), which argue that both events E4 and E5 occurred after about 19 ka. The absolute youngest age that they could have occurred is 7.6±0.7 ka, the age of CW3, but that also includes the occurrence of event E3. We assume that there was some time between the occurrence of E3 and E4, and between E5 and E6 based on the development of soils on the distal colluvial wedge deposits, so their likely ages of occurrence probably fall between about 9.6 and 19 ka and are likely spaced out to account for the soil formation (Figure 20).
6.4. Event E6

In trench T1, stratigraphic evidence supported by reconstructions (Figure 18 k, l) suggests slip on fault Th1 during event E6. To estimate the total displacement, we followed the previously described colluvial wedge formation model. The scheme (Figure 12) assumes a collapse of the nose during or immediately after displacement, therein generating a triangular-shaped gravel deposit that indicates the probable location of the fault tip. We infer that during event E6, the tip of the hanging-wall moved from the gravelly base of unit CW7, interpreted as the location of the pre-event E6 fault tip, to the gravel base in unit CW6, considered as the post-E6 fault tip location. This implies a minimum dip slip of 75 cm as measured parallel to the dip of the fault surface, with additional slip possible from erosion of the hanging wall. Intense cracking and faulting of the top surface of unit CW7, interpreted as the ground surface at the time of event E6, was probably developed as a consequence of ground shaking during event E6. Subsequent erosion of the scarp and down slope accumulation of colluvial sediments built up the rest of the CW6 colluvial wedge. As mentioned above, the age of the upper section of unit CW6 is determined by the youngest OSL date from this unit, 19.0±1.3 ka. The youngest OSL age for unit CW7, which pre-dates event E6, is 22.3±1.8 ka, which provides a maximum age for event E6. Using the criteria developed for the age relationship between event and colluvial wedge age, we add 2±2 ka to the CW6 OSL date to yield our best estimate of 21±3.3 ka for the age of event E6 (Figure 20).

6.5. Event E7.

We interpret event E7 as the displacement on fault Th1 that truncates unit CW8 and generated a scarp related to the formation of colluvial wedge CW7. We estimate a
minimum of ~ 65 cm slip for this event based on the distance along the fault between the wedge-shaped gravels at the base of unit CW8 and similar deposits at the base of unit CW7 (Figure 18 m-n). It is a minimum because we do not have a constraint on the amount of material eroded from the fault tip after the event.

The youngest OSL sample taken from the sand at the top section of CW7 dated to 22.3±1.8 ka, and using the same criteria as for other events, we add 2±2 ka to arrive at our best estimated age for event E7 as 24.3±3.8 ka (Figure 20).

6.6. Event E8

We interpret the basal gravel of unit CW8, the formation of the CW8 itself, and the truncation of colluvial wedge CW9 as the main evidence for the occurrence of event E8. Using the same fault slip-colluvial wedge development model as before, we estimated a minimum of ~ 62 cm of fault parallel slip on fault Th1 (Figure 18 o-p). Again, we have no estimate of maximum displacement for this event because the prior and subsequent events all occurred on the same fault surface and we have no constraint as to the amount of erosion from the hanging wall.

Three sand samples from the top of the CW8 unit were dated using OSL techniques, and three more were dated from unit CW9 (Figure 9). As was discussed in the Age of the Deposits section, there is clearly a significant issue with inheritance or partial bleaching for several of these samples. In that CW8 must be younger than CW9, and whereas the youngest of the six dates is on a sample recovered from CW9, we take this date of 30.8±2.1 ka as the maximum age of event E8. Thus, event E8 is poorly constrained to have occurred between about 24 ka (our best estimate for event E7) and
about 31 ka (Figure 20). Soil development on units CW8 CW9, however, indicates that substantial time is present between these events.

6.7. Event E9

Event E9 is the earliest slip event recognized in trench T1. Neogene strata (unit N) were thrust over T3 terrace gravel, resulting in the generation of a fault scarp and an associated colluvial deposit. Although there is no constraint on the location of the tip of the fault prior to event E9, we can assume that minimum slip is represented by reconstruction of the strath across the top of the Neogene in the hanging-wall to approximately the same elevation as the top of the unit Qt3 in the footwall. Reconstruction of the actual strath would require considerably more slip, as discussed below. Using the reconstructions (Figure 18 q, r), we resolved a minimum of 62 cm slip for this event. Collapse of the fault tip, along with post-displacement sedimentation of sand and gravel, formed the CW9 colluvial wedge. As with later events, we interpret that the best age for this colluvial wedge is constrained by the youngest OSL date (30.8±2.1 ka: Table 1), and by adding 2±2 ka, to obtain a date of 32.8±4.1 ka for event E9 (Figure 20).

6.8. Pre-E9 events

In trench T1, our studies focused on the fault slip history after the abandonment of terrace Qt3. Although, it is not clear whether individual fault displacements were preserved during the formation of this terrace, the thickness of the terrace deposits appears to increase in the footwall towards the fault, as determined in a deep exploratory pit. This pit is not represented in the logs because it was unsafe to enter, but the terrace gravel exceeds 1.5 m in thickness below the fault. In general, the thickness of the gravel
away from the fault, as exposed along the margins of the terrace, is about a meter. These observations suggest that at least one event (E10?) may have occurred during terrace formation and prior to terrace abandonment.

6.9 Estimation of average slip per event

In the above analysis of the trench exposures, we estimate the minimum amount of dip displacement for each event. It is a minimum because we cannot account for erosion of the hanging wall, and the simple production of a colluvial wedge demands that such erosion has occurred. Consequently, some or most events may be substantially larger than we infer from our direct observations of slip. Another estimate of the average slip per event can be determined from taking the total displacement of the terrace surface and dividing by the number of observed events. Ideally, we would include displacement of the strath itself, but we do not have complete information for that calculation. Therefore, we used the total offset measured for the Qt3 surface, 10.3±0.5 m, and assume that the slip occurred as consequence of the nine events recorded in the colluvial wedges of La Laja fault exposed in trench T1. Using this method, the average La Laja fault slip per event is ~ 114 cm, which is more than twice the displacement measured for the 1944 event. Although it is possible that our earthquake record is incomplete, we prefer to interpret that the 1944 displacement is actually smaller than the average. This interpretation is supported by the fact that the minimum displacement measured for individual events is usually larger than 50 cm, with some of them having minimums
Figure 3.20. Plot of the estimated ages versus cumulative slip on La Laja fault for the nine events interpreted from trenches T1 and T4. The bars indicate the errors in age and slip per event.
These values are, of course, minimums that do not account for erosion of the hanging wall.

7. Discussion of Results

Analysis of the trench logs obtained from the paleoseismic excavations, along with the terrace geomorphology and the dates presented in this study, provide a detailed slip history of La Laja fault for the past ~32 ka. As mentioned earlier, we consider that La Laja fault is a secondary structure, probably a flexural slip fault, linked to the displacement of a major blind thrust at depth. We also interpret that previous slip of La Laja fault was linked to large earthquakes on the blind thrust in a similar way as observed in 1944. If these assumptions are correct, our study provides important constrains on earthquake recurrence and the slip rate for the underlying blind thrust fault. It also supplies indirect evidence about the relative size of previous earthquakes based on the average slip per event at La Laja fault compared with the 1944 parameters. Finally, we make inferences on the pattern of earthquake occurrence for the San Juan area and suggest that the past century of large earthquakes is not representative of the long term but may best indicate the current hazard.

7.1. Earthquake recurrence

Based on our interpretations, a minimum of nine slip events on La Laja fault (E1 to E9) postdate the formation of terrace Qt3. The best OSL ages of the oldest colluvial wedge CW9 indicate that at least eight events, E1 to E8, occurred after 30.8±2.1 ka, with the age of event E9 interpreted to be 32.8±4.1 ka. Based on this interpretation, we calculate that the average recurrence time for the last eight events is 4.1±0.5 ka. Individual dates of colluvial wedges provide additional information to constrain the ages
of the events. The penultimate event (E2) was independently dated in trenches T1 and T4 using OSL and radiocarbon methods. The calibrated charcoal dates indicate that the very minimum age for this event is around 3 ka. Our best estimated age for event E2 is 4±1 ka, which matches very well the calculated average recurrence time. The age of event E3 is dated to 9.6±2.7 ka; thus, the time elapsed between events E3 and E2 is 5.6±1.7 ka, which is longer than the average but within its error limits. Perhaps the addition of 2±2 ka to the best age of the colluvial wedge CW3 is an overestimation of the time between the event E3 and the CW3 colluvial wedge formation, but this could also represent variability in the recurrence time. Using the youngest OSL dates of units CW3 and CW6, we constrained the age of the events E3, E4 and E5 to between 9.6±2.7 ka and 21±3.3 ka, resulting in an average event recurrence for these three events of 3.8±2 ka, again very similar to the long-term average recurrence. Finally, the time span between events E7 and E6 was estimated to be ~3.3±0.5 ka, slightly below the average. These observations argue for fairly quasi-periodic recurrence La Laja surface ruptures, which in turn argues for similar behavior of the underlying causative thrust. However, as most of these events are relatively poorly constrained in their ages, more dating needs to be completed to reduce the errors and provide better individual time spans between events to confirm this result.

7.2. Fault slip rate

To estimate the minimum slip rate on the causative blind thrust, we combine the average recurrence time of 4.1±0.5 ka with the average displacement required to have produced the Ms=7.4 1944 earthquake. This is a minimum because most of the La Laja events appear to have been larger that 1944, which we address below to develop our best estimated rate.
To calculate average displacement for 1944-type events, we used the empirical regressions of Wells and Coppersmith [1994] assuming that the surface wave magnitude $M_s$ is approximately equal to the moment magnitude $M_w$. From the regressions, we computed a subsurface rupture length of about 74 km and a rupture area of 1830 km$^2$ for the 1944 event. We then applied the moment magnitude ($M_w$) equation [Hanks and Kanamori, 1979] to calculate our estimate of the seismic moment for this event of about $1.4 \times 10^{27}$ dyne·cm. With this estimate for moment, and using the equation for moment magnitude ($M_0=\mu As$, where $\mu$ is the shear modulus of $\sim 3.1 \times 10^{11}$ dyne/cm$^2$ and $A$ is the area of the fault rupture at 1830 km$^2$) [Aki 1966; Hanks and Kanamori, 1979], we obtained an average slip ($s$) of about 2.5 m on the blind thrust. The rupture area and rupture length of the earthquake source fault obtained from the empirical relationships was compared with lengths and widths of the geological structures mapped at the surface and inferred at depth with microseismicity. A fault rupture area of $\sim 1800$ km$^2$ with rupture length of $\sim 70$ km and down dip width of $\sim 26$ km matches well with the dimensions of a potential northwest dipping reverse fault identified with microseismicity by Smalley et al. [1993], and this estimate is supported by the current structural models of the region [Verges et al., 2007 and Meigs et al., in review]. Siame et al. [2002] also computed possible rupture areas for five different possible segments of the Villicum-Pedernal fault. They estimated a 65 km rupture length and a $1950\pm 440$ km$^2$ fault area for the Villicum-Las Tapias segment, which is considered a good match for the 1944 San Juan earthquake. Using the inferred average displacement of 2.5 m and the average recurrence rate of about 4.1 ka, we calculate the minimum slip rate of about 0.6 mm/yr.
Additionally we computed the fault slip rate assuming that the displacement for the average blind thrust earthquake was twice as large as the 1944 displacement. This last estimation is based on the observation that the average displacement of La Laja fault is \( \sim 103 \) cm based on the total separation of the Qt\(_3\) surface, and that this displacement has occurred in nine events. This average slip is nearly twice the displacement measured for the 1944 event, which is estimated at about \( \sim 50 \) cm. Although a relationship between magnitude of a blind fault earthquake and displacement on a secondary, flexural slip fault is not well established, we infer that the 1944 San Juan earthquake was smaller than the average event recorded in our trench exposures. Thus, using the higher value of average slip at La Laja, we estimate that the average displacement on the blind thrust was close to 5 m per event, and using this value yields a slip rate of about 1.2 mm/yr for the causative blind thrust.

Independent of the slip history at La Laja fault, we recalculated the slip rate using the kink band migration method used by Meigs et al. [in review]. The minimum axial surface migration for terrace Qt\(_3\) is between 35 m [Meigs et al., in review] and 50 m (our survey results), and the age of the Qt\(_3\) terrace is estimated from our OSL dating of CW9 as older than 30.8 ka and maybe as old as \( \sim 40 \) ka if we consider that 2.3 m of slip occurred previous to event E9. Based on this new age estimate for the Qt\(_3\) terrace, we recalculate the slip rate to be between 0.8 and 1.3 mm/yr, which agrees well with our estimate from the trenching results. Our estimates also agree well with those of Siame et al. [2002], who obtained a rate of 0.8±0.5 mm/yr for Las Tapias fault, located approximately 16 km SW of La Laja fault. However, the link between these two structures is not established.
The Global Positioning System (GPS)-derived velocity field across the Andes at the latitude of La Laja fault suggests that ~4.5 mm/yr of continuous creep is accumulating between the Precordillera and the Sierra Pampeanas, with most of the deformation accommodated within a narrow deformational zone in the vicinity of our study area [Brooks et al., 2003]. Their model supports the notion that the interior of the Andes is not currently accommodating significant permanent strains, which is also corroborated by field observations that show only very minor active deformation across the Andes [Costa et al., 1994], with most of the active faulting and microseismicity observed to the east of the Precordilleran front. Brooks et al. [2003] also suggest that the model has a small but systematic velocity overprediction near the deformation boundary. If we assume that the GPS convergent rate is valid, it implies that the ~1mm/yr slip rate of the blind thrust fault that we resolved accounts for an important share of the entire deformation, perhaps with the Pie de Palo structure taking an additional substantial part of the strain.

### 7.3. Evidence For Earthquake Clustering

The earthquake activity observed between the Precordillera Oriental and the western Sierras Pampeanas, near San Juan city, appears to be occurring at an anomalously high rate when compared to the long average recurrence time of large earthquakes, as shown in our study. There have been four major earthquakes (1894, 1944, 1952 and 1977) in the past century [Alvarado and Beck, 2006], which if representative of the long term, would suggest a moment rate of about $6 \times 10^{25}$ dyne-cm/yr (approximately four times the 1944 moment; 1894 and 1977 were probably a little larger, 1952 was a bit smaller). Assuming the width of the locked zone of about 80 km
requires a strain accumulation rate of about 30 mm/yr, or an order of magnitude higher than the observed rate from geodesy or geology. This, in turn, suggests that the historical occurrence of earthquakes for the San Juan area is not representative of the long term, but rather, argues for clustering of moment release in the blind thrust system. We speculate that the occurrence of a large event such as 1894 caused stress loading of adjacent structures, thereby resulting in a cascading cluster of large events. The idea of stress loading and triggering is further supported by the observation that there was probably some slip on the blind thrust fault beneath Sierra Pie de Palo in 1944, which later in 1977 produced the ~4 m of coseismic slip in the Ms=7.4 Caucete earthquake [Kadinsky-Cade et al., 1985; Relinger and Kadinsky-Cade, 1985]. This has important implications for seismic hazard in the region because it is not known whether the cluster is finished or whether we can expect more large earthquake activity in the future. In all probability, we are not so lucky as to be at the very end of such a cluster.

8. Conclusions

Detail analysis and interpretation of La Laja fault trench exposures and results from OSL and radiocarbon dating provides a record of nine fault slip events for the last ~32 ka. Based on this, we concluded that the average slip recurrence time for the last eight intervals is 4.1±0.5 ka. This average recurrence is in close agreement with the time determined between individual events. These observations argue for fairly quasi-periodic recurrence La Laja surface ruptures, which indirectly suggest similar behavior of the underlying causative thrust.

We also determined an average slip per event of ~114 cm for La Laja fault, which if correct, implies that the 1944 rupture was about half the size of most events. The slip
per event on the causative fault was calculated based on the assumption that the slip at La Laja fault is always linked to large earthquakes on a blind thrust fault at depth, as observed for the 1944 Ms 7.4 San Juan earthquake. We calculate ~ 2.5 m of slip for the blind thrust fault at depth if the average earthquake is $M_w=7.4$. As the average displacement at La Laja is nearly twice that observed for 1944, we estimated that the average displacement on the blind thrust at depth may have been close to 5 m.

Using the average recurrence time and the 2.5 to 5 m of displacement per event, we obtained a slip rate of 0.6 to 1.2 mm/yr for the blind thrust fault at depth. Independently, we computed a slip rate of 0.8 and 1.3 mm/yr using the observed kink band migration for the Qt3 terrace and applying the Meigs et al. [in review] methodology. These rates are similar to those obtained for other structures in the region [e.g. Siame et al., 2002; Verges et al., 2007].

Finally, we conclude that the historical earthquake activity observed between the Precordillera Oriental and the western Sierras Pampeanas, near San Juan city, appears to be occurring at an anomalously high rate when compared to the long average recurrence time of large earthquakes. This, in turn, suggests that the past century cluster of large earthquakes is not representative of the long term but may best indicate the current hazard.

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CONCLUSIONS

The three studies presented in this dissertation provide new approaches to extract paleo-earthquake information from the geological record. The first two chapters regarding Imaging spectroscopy and automated classification of stratigraphy demonstrate that a system integrated by a hyperspectral scanner and pattern recognition algorithms can work as an enhanced eye and an objective classifier to provide the geologist with additional information that facilitates the description, interpretation and correlation of the paleoseismic exposures. The hyperspectral dataset collected together with a spectral library of the materials observed in the excavation provide a new way to archive paleoseismological data for future analysis.

The innovative earthquake history study of La Laja fault, San Juan, Argentina, presented in chapter 3 provides the first and perhaps the longest record of the earthquake activity of a blind thrust fault in the world, as well as the most detailed and complete study of past earthquakes in the Argentinean Andes. It also set a good precedent for similar studies in other structures in other regions of the world where the earthquake hazard related to blind thrust faults is largely un-assessed.