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A precise time-displacement-length growth history of the Osaka-wan blind thrust: evidence for long-term unstable slip

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A PRECISE TIME-DISPLACEMENT-LENGTH GROWTH HISTORY
OF THE OSAKA-WAN BLIND THRUST: EVIDENCE FOR LONG-TERM UNSTABLE SLIP

by

Pamela Ruth Grothe

B.S., University of Mary Washington, 2006

A thesis submitted to the
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This thesis entitled:
A precise time-displacement-length growth history of the Osaka-wan blind thrust:
evidence for long-term unstable slip
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The final copy of this thesis has been examined by the signatories, and we find that both the content and the form meet acceptable presentation standards of scholarly work in the above mentioned discipline
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A precise time-displacement-length growth history of the Osaka-wan blind thrust: evidence for long term unstable slip

Thesis directed by Associate Professor Karl J. Mueller

The release of seismic moment represented by slip rates on faults is characterized by increasing stability over progressively longer time periods. Yet the transition between patterns of complex moment release at short, paleoseismic timescales and rates of stable slip on faults at longer timescales is largely unknown. We use a record of syntectonic, shallow marine sediments tied directly to the marine eustatic record to map a precise history of uplift across the southern-half of the Osaka-Wan blind thrust fault in central Japan. Results indicate that the blind thrust lengthens rapidly after the onset of slip, and may be weak based on restorations of the upwardly propagating tip of the fault from trishear kinematics. The average rate of slip is more rapid in the middle of the fault, consistent with the distribution of seismic slip in earthquakes and total displacement profiles on other thrust faults. Fine details of the time-displacement length history, however, reveal that uplift rates vary over 60% at scales of 100 ka and 5-10 km along the thrust. In addition, no measurable uplift occurs along much of the fault for a period of 50-100 Ka and may be taken up by a nearby thrust. These results confirm analogue studies of complex fault slip behavior and suggest that the Osaka-Wan thrust may accelerate and decelerate, or even shut off entirely at intermediate timescales.

Inverse trishear modeling undertaken to constrain the geometry of the thrust suggests that the thrust formed as a steeply dipping fault from shallow levels in the crust and propagated upward at rates similar to other basement cored thrusts. Mapping of 14 through-going seismic reflectors tied directly to highstands in the global eustatic record suggests that the southern half
of the fold has undergone a complex growth history. This analysis indicates that the fold: 1) began growing shortly after 1500 ka at rates of 0.19 to 1.13 mm/yr along nearly its entire length; 2) grew laterally outward to its present endpoint almost immediately; 3) shut off for 50 – 100 Ka; and 4) underwent differential uplift that ranged from 0.75 mm/yr in its center to 0.21 mm/yr at its endpoint. Results thus yield a hitherto unavailable high-resolution record of thrust fault and fold growth at short, 100 Ka timescales.

The record of displacement along Osaka-wan suggests that it grew by a mix of scaling laws. The total along-strike displacement profile most closely matches a linear-taper model, yet its early history is consistent with an elliptical-taper slip model of fault scaling. Comparison of possible influences on fold growth suggests that sedimentation rate at the location of each seismic profile in the basin is nearly constant and unlikely to affect transient changes in slip rate, at least to the variation seen in the data. Evidence for reactivation of an older fault is not apparent based on offset of growth strata in comparison to that across the underlying basement-cover contact. However, analysis of fault tip propagation based on trishear kinematics, places the fault tip no deeper than 4 km at its onset, too shallow to have originated as a new fault from deep within the crust. We speculate that a larger sub parallel thrust located in the western part of the basin (the Kariya fault) may have accommodated shortening at the expense of the Osaka-wan thrust at different periods in its history, although we do not as yet have the seismic reflection data required to test this hypothesis.
ACKNOWLEDGEMENTS

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CHAPTER I
INTRODUCTION

1. Overview

Osaka Bay sits in an actively deforming region in southwest Japan (Figure 1.1), located above the subducting Philippine Sea plate slab. A devastating 7.2 magnitude earthquake, the Hyogo-ken Nanbu or Kobe Earthquake, struck the region in 1995, killing over 6,000 people, injuring approximately 40,000 people, and damaging the local infrastructure (Yokokura, 1999). In response to the deadly earthquake, the Japanese government, academic and private organizations conducted seismic reflection surveys to assess future seismic hazards throughout the region and in Osaka Bay. Seismic reflection surveys collected in Osaka Bay subsequently revealed an active, 40 km long, blind thrust fault, named the Osaka-wan fault (Kitada et al., 2001). The availability of high-quality seismic reflection data, along with two deep cores tied to high-precision age dates and the marine eustatic record (Bisawas et al., 1999) forms the basis of this thesis. These data allow the growth of the fault-related fold, and by inference the underlying blind thrust, to be defined in unprecedented detail. The resulting analysis is then compared to studies of other active faults at shorter (paleoseismic) and longer maximum displacement and fault length (Dmax:L scaling) timescales, as well as analogue studies and mechanical models.
Figure 1.1 – Overview map of study region in Japan. Inset map of Osaka Bay.
2. Goals and Tasks

This research has several general goals and methods of analysis. The first part is the collection of a set of measurements that will define how increments of displacement are added through time to build a large fault-related fold – used as a proxy for uplift of the associated Osaka-kan thrust. The second is aimed at determining the inclination of the Osaka-kan thrust and the location of its upwardly propagating fault tip for 12 different times at four locations along its length. This will be done by inverting for the geometry and age of compressive growth strata that continuously buried the fault-related fold as it was being uplifted above the fault. The third will be to compare the results of the study with other thrust faults around the world whose history of slip is known much less precisely than the Osaka-kan thrust. Finally, the results of the time-history analysis and structural modeling will be integrated into a collective model of fault growth and used as the basis to test exiting models based on less well-defined time-displacement histories, the distributions of seismic slip produced during earthquakes, analogue modeling and theoretical physics-based models of fault growth. The goal is to determine whether the Osaka-kan fault grows similarly to other thrusts whose slip history is defined in less detail. But most importantly, this work seeks to redefine the distances and time periods over which rates of displacement stabilize to constant rates, at least with respect of models of fault growth that contain gradients of slip that decrease from their centers to their endpoints. The study is aimed at providing a set of data that will bridge the gap between displacements measured by no more than 5-10 earthquakes, and long term average rates of displacements at timescales of millions of years.

The goals outlined in the previous section were addressed with the following tasks. A three dimensional model of isochronous time-surfaces was created through a portion of the basin
by mapping and correlating a set of continuous, high amplitude reflectors on a grid of seismic reflection profiles. The age of each reflector was then defined by comparing them with synthetic seismograms and sonic logs from two deep continuously cored boreholes that are tied to the grid of seismic profiles. The age of sediment in the cores is already defined by age dating of numerous volcanic ash layers and magnetic reversals (Biswas et al., 1999).

Vertical displacement across 12 reflectors was measured wherever a seismic line crossed the fault-related fold. For this study five lines and two connecting strike lines were used that extend across the southern half of the fold; the northern part of the fold was not mapped because displacement is partitioned across several different strands and greater uncertainty was present due to the smaller displacements on each strand. Slip rates were then determined where each profile crossed the thrust and plotted as a novel 3D time : displacement : length, or TDL, diagram.

Six of the 12 reflectors were selected for modeling using trishear kinematics based on the simulated annealing algorithm developed by Cardozo et al. (2011). Solutions for trishear parameters such as depth of the fault tip, or the ramp angle (fault dip) were then compared for goodness of fit to the reflectors on the seismic sections. The models were run independently for each reflector on all the seismic lines, as well as bed-by-bed restorations of the entire growth section.
CHAPTER II
A PRECISE TIME-DISPLACEMENT-LENGTH GROWTH HISTORY OF THE
OSAKA-WAN BLIND THRUST, JAPAN: EVIDENCE FOR LONG-TERM UNSTABLE
SLIP

1. Introduction

Models of fault growth yield insight into the release of seismic moment in earthquakes and how displacement accumulates to build structures over long time periods (Bull et al., 2006; Manighetti et al., 2005; Schaugenhauf et al., 2008; Mouslopoulou et al., 2009; 2012). While previous studies have argued that slip rates on faults become constant with time, few opportunities exist to test this in detail (Nicol et al., 1997; Nicol et al., 2005; Mouslopoulou et al., 2009). In one rare case however, the requisite data and geologic conditions are available in an actively deforming region in central Japan. We exploit a fortuitous combination of such conditions in a shallow marine basin, Osaka Bay, to map the three dimensional growth of a large fault-propagation fold, and use this as a proxy for displacement on an underlying blind thrust. For this region, these conditions include finely bedded sediments that cover the fold continuously for at least the last 1200 ka, and are remarkably well dated by volcanic tephra, magnetic reversals and palynology in 900-1600 m-long cores. The geometry of the fold is defined with a grid of high-resolution seismic reflection profiles acquired specifically to image the blind thrust. Deposition in the basin occurred at or near sea level throughout the entire history of uplift along the blind thrust, allowing individual reflectors on the seismic profiles to be correlated with 14 sea level highstands whose ages are precisely known.
The Osaka-wan fault is one of several active, north-trending blind thrusts and fault-propagation folds that accommodate oblique shortening in the Kansai region of Central Japan (Seno, 1977). These folds deform flexural basins filled with Late Quaternary shallow marine and fluvio-deltaic sediments (Itoh et al., 2001) and are marked by forelimbs that become increasingly narrower with depth. Originally termed trishear folds for examples in the Western USA, these structures are associated with blind thrusts that penetrate deeply into the brittle crust. Subsequent studies of trishear folds have illustrated how strata deposited above them can be used to track their progressive development with time (Hardy and Ford, 1997; Allmendinger and Shaw, 2000; Lin et al., 2007).

We undertake detail mapping of growth strata deposited above the trishear fold that accommodates shortening above the Osaka-wan thrust, and define a history of fault slip at intervals of 50-100 ka for the last 1200 ka. While we do not measure displacement directly across the fault, using the overlying fold as a direct proxy for slip is appropriate because these structures have been shown to conserve shortening with depth (i.e. it is similar at different levels). Our mapping is limited to the southern half of the fold to avoid complexity further north where the structure splits into several strands and deforms a thinner sequence of strata whose age is defined in less detail.

2. Methods and Results

Sequence stratigraphic boundaries in the 12 seismic profiles (OD-A, HG-1-1M, GS-8ME, OD-B, HD-3, HD-4, GS-11, GS-7, GS-12, GS-2, GS-6, and GS-NP) used in our mapping are closely correlated with 14 highstands in the global marine eustatic record, yielding a set of continuous reflectors that extend across the entire Osaka Basin (Figure 2.1 and 2.2). The
Figure 2.1 – Geological map of the Osaka Basin with seismic reflection survey lines in the Osaka Bay. Thick black survey lines indicate the five profiles used to measure the vertical offset across the Osaka Bay fault. Survey lines highlighted in yellow are the lines used to correlate age calls from the boreholes to the five survey lines we measure offsets from.
Figure 2.2 – Reflective interpretation for seismic profile GS-8ME. Top panel illustrates our horizon picks across the fold. We measure the vertical displacement from the footwall to the hanging wall. Bottom panel shows the depth-corrected seismic data from which we traced our lines. See Appendix B for interpretations for HG-1-1M, OD-B, HD-3 and HD-4.
correlations in the cores are consistent with tephrachonology and magnetic reversals, marine/nonmarine conditions from faunal assemblages and palynology, lithostratigraphy in the cores, and sonic logs in both of the two boreholes tied to the seismic grid (Itoh et al., 2001; Inoue et al., 2003; Biswas et al., 1999). The history of uplift along the Osaka Bay thrust thus yields a high-resolution record of the timing of uplift at timescales of less than 100 ka with comparable low uncertainty in slip rate along the length of the thrust.

Results of the mapping indicate that slip rates vary markedly during the 1500 ka period over which the Osaka-wan fault has been growing, both in time, and along its length (Figure 2.3). On average, slip rates are higher at the crest of the fold compared to rates near its southern endpoint. The early history of uplift along the fault suggests that it propagated rapidly towards its current endpoint, although data do not permit detailed measurements of its earliest propagation history at the shorter 50-100 ka timescales, available later in its history. Regardless, the fold achieved its current length within at most 300 ka after it was initiated, based on extrapolation of sedimentation rates. Following this and starting at 1200 ka, the fold underwent an average uplift rate of 0.57 mm/yr at its center and only 0.1 mm/yr near its endpoint, a nearly six-fold difference (Table 2.1).

Measurements of cumulative, long term offset over the life of dip slip faults has shown that slip profiles along them are typically triangular in shape, at least for those that have not become linked with other faults as they grew (Manighetti et al., 2005). That is, these faults accrue slip at faster rates in their centers, as observed on average for Osaka-wan. Details of the variation in slip rate at ~50-110 ka time periods during the lifespan of the Osaka-wan fault is considerably more complex however, compared to its long-term average. For instance variation in uplift rates calculated on any of the five transects across the Osaka-wan fault for all of the
Table 2.1 Vertical displacement rates

<table>
<thead>
<tr>
<th>Marine Clay Layer</th>
<th>Age (ka)</th>
<th>HD-4</th>
<th>HD-3</th>
<th>ODB</th>
<th>GS-8</th>
<th>HG-1-1M</th>
<th>Average</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ma12</td>
<td>127</td>
<td>0.28</td>
<td>0.39</td>
<td>0.55</td>
<td>0.63</td>
<td>0.71</td>
<td>0.51</td>
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<tr>
<td>Ma11</td>
<td>242</td>
<td>0.09</td>
<td>0.26</td>
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<td>Ma10</td>
<td>334</td>
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<td>0.49</td>
<td>0.98</td>
<td>0.92</td>
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<tr>
<td>Ma9</td>
<td>427</td>
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<td>0.22</td>
<td>0.38</td>
<td>0.54</td>
<td>0.59</td>
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<td>0.20</td>
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<td>0.70</td>
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<td>621</td>
<td>0.00</td>
<td>0.35</td>
<td>0.23</td>
<td>0.23</td>
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<td>Ma5</td>
<td>712</td>
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<td>0.05</td>
<td>0.16</td>
<td>0.55</td>
<td>0.77</td>
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<tr>
<td>Ma4</td>
<td>787</td>
<td>0.00</td>
<td>0.00</td>
<td>0.07</td>
<td>0.00</td>
<td>0.07</td>
<td>0.03</td>
</tr>
<tr>
<td>Ma3</td>
<td>865</td>
<td>0.26</td>
<td>0.83</td>
<td>0.64</td>
<td>0.64</td>
<td>0.38</td>
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<tr>
<td>Ma2</td>
<td>960</td>
<td>0.05</td>
<td>0.00</td>
<td>0.05</td>
<td>0.11</td>
<td>0.11</td>
<td>0.06</td>
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<tr>
<td>Ma1</td>
<td>1070</td>
<td>0.05</td>
<td>0.36</td>
<td>0.14</td>
<td>0.77</td>
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<td>1120</td>
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<td>0.60</td>
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<td>1.00</td>
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<tr>
<td><strong>Average</strong></td>
<td><strong>0.10</strong></td>
<td><strong>0.35</strong></td>
<td><strong>0.42</strong></td>
<td><strong>0.55</strong></td>
<td><strong>0.59</strong></td>
<td><strong>0.40</strong></td>
<td></td>
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</tbody>
</table>

Units are in mm/yr
Figure 2.3 – 3D plot of time, vertical displacement and length history of the Osaka-wan fault. A) Time slices plotted against distance along fault versus vertical displacement. B) Vertical displacement rate for each profile. C) Time-distance-length, or TDL plot, that combines distance along fault, time, and vertical displacement into a 3D plot. We use color to display uplift rate. White dots are data points; black dots are interpreted data points. Thick white lines connect data points together and illustrate changes in slip rate through time (vertical lines) and along strike (horizontal lines); dashed white lines are interpolated.
periods defined by the depositional record ranges from 0.03 mm/yr to 0.74 mm/yr, (measured respectively for periods of 78 ka and 80 ka). Second order variations in uplift rate suggest however, that the Osaka-wan fault nearly ceased to move over much of its length for two periods of 75 and 95 ka. The two periods of negligible slip are separated by a 78 ka episode of relatively rapid uplift that is higher than the average rate measured over the entire 1200 ka history of uplift. These results imply that the average rate of slip on the Osaka-wan fault is similar to triangular slip profiles on other dip slip faults where displacement is derived from longer-term averages (Manighetti et al., 2005). Yet our data point to previously undocumented second-order behavior that has implications for patterns of fault growth and the distribution of displacement in earthquakes.

3. Discussion

We see significant variation in slip rate along the half-length of the thrust, both in time and space. This sort of complex behavior is documented in analogue (Schlagenhauf et al., 2008) and mathematical (Kim and Sanderson, 2005) models, but has not been observed in physical data. We compare our data with Mouslopoulou et al. (2009), a recent study that mapped longer term average displacement rates in a population of thrusts in the South Wanganui Basin, New Zealand (Figure 2.4). Our results suggest that displacement rates on the Osaka-wan fault vary by a factor of six and include periods of almost negligible slip.

While a number of possible mechanisms for shutting a fault off at these timescales might be considered, we suspect the simplest possible process may be related to fault interaction (Bergen and Shaw, 2010). We posit whether that episodes of negligible slip on the Osaka-wan fault might be correlated with periods of more rapid slip with the nearby Kariya fault, located on
Figure 2.4 Time verse displacement rates from the five profiles of Osaka-wan fault (plotted in red) compared with a population of ten thrust fault that deform the South Wanganui Basin (SWB), New Zealand (Mouslopoulou et al., 2009; plotted in blue). It is important to note that measurements from the Osaka-wan are from one fault, while the measurements from the SWB are multiple fault segments. We only plot to 1600 Ka for purposes of this study but the SWB data extend to 4400 Ka. Notice the variation in slip from the Osaka-wan fault that is not visible in the SWB. This level of detail allows for more detail growth and fault behavior analysis. White squares are interpolated measurements of displacement.
the western margin of the basin. Testing of such interaction awaits depth processing of a seismic profile that extends across both the Kariya and Osaka-wan faults (Japanese colleagues are currently working to depth-correct just such a profile).

The implications of our work for studies of seismic hazards is perhaps more important, at least for societal reasons. For example, if paleoseismic studies were conducted on a fault that was currently behaving similarly, with a nearly complete shut off in displacement, such studies might underestimate risk should slip rates increase in the future. Conversely, the opposite would be true for a period of faster slip. The crux to this problem lies in obtaining measurements at time periods longer than are available in the best paleoseismic records, but shorter than the periods available from our study.
CHAPTER III
TRISHEAR MODELING OF THE OSAKA-WAN FAULT, OSAKA BAY, JAPAN:
FAULT NUCLEATION AND PROPAGATION

1. Introduction

Active blind thrust faults pose significant seismic hazards, especially where they form in rapidly subsiding sedimentary basins where they are buried continuously throughout the period they are active (Suppe, 1979; King and Brewer, 1983; Stein and King, 1984; King et al., 1988; Stein and Yeats, 1989; Bullard and Lettis, 1993, Taboada et al., 1993; Namson and Davis, 1994; Shaw et al., 2002). In central Japan, the devastating 1995 Mw 6.8 Hyoguken Nanbu, or Kobe earthquake, illuminated the seismic hazard in the Osaka Basin. Although the Kobe Earthquake was largely a strike-slip event, it motivated the seismological community to systematically search for other previously unknown active faults that posed a hazard to the region. As an example, the risk of blind thrusts was not well known before the Kobe earthquake and was subsequently revealed after seismic reflection surveys were collected in Osaka Bay (Figure 3.1; Kitada et al., 2001). One of the blind thrusts discovered in the Bay was the Osaka-wan fault, the focus of this study.

In spite of the previous underestimated risk of active faults in and around Kobe, this region is clearly undergoing active deformation. Oblique subduction of the Philippine Sea Plate drives oblique shortening in the region which is partitioned into an array of sub-parallel strike-slip and thrust faults. The Osaka-wan fault is a 40 km long structure that trends NE-SW and splits into several strands along its northern half (Yokokura et al., 1998). Seismic reflection
Figure 3.1 - Geological map of the Osaka Basin with mapped seismic reflection survey lines in the Osaka Bay. Thick black survey lines indicate the five profiles we used to measure the vertical offset of the folds across the Osaka Bay fault. Survey lines highlighted in yellow are the lines used to correlate age calls from the boreholes to the five survey lines we measure offsets from. Inset map shows Osaka Bay in relation to Japan. Abbreviations are as followed: GS – Geological Survey of Japan; HG – Hyogo Prefecture; KB – city of Kobe; HD – the Hydrographical Department; NP – Power Reactor and Nuclear Fuel Development Corporation; OD – Geo-Research Institute, Osaka; and KIA – Kansai International Airport.
profiles gathered in the wake of Kobe revealed that blind thrusts in the basin accommodated about 2.5 km of vertical offset; more importantly, the data revealed compressive growth strata that extended across the Osaka-wan fault (see Chapter II and Appendix B). Correlation of reflectors on the profiles with cores in a deep borehole (Biswas et al., 1999) suggested that every reflector in the basin, (nearly all extend completely across it) could be tied to a specific sea level highstand. Given the large number of highstands during the Late Quaternary, this offered an opportunity to track the growth of a large thrust fault in unprecedented detail. Most importantly this age control bridges the gap between coseismic and paleoseismic measurements of displacements and much longer, averaged rates of slip on thrusts (Mouslopoulou et al., 2009; Nicol et al., 2005).

In this chapter, we present inverse trishear analysis undertaken to define the geometric evolution of the Osaka-wan fault and to track the propagating fault tip upward in the brittle crust and along the strike of the fault through time. The kinematic data will support the uplift history from the measurements of the growth strata outlined in the previous chapter. Four of the seismic profiles have a full set of reflectors that all extend across the fold (although we only model six of the 14 that are available); the fifth line in the crest of the fold was not modeled with trishear kinematics because the reflectors cannot be traced across the entire fold due to their steep inclination.

2. Geological Setting

Osaka Bay is a Late Quaternary shallow-marine basin formed by flexure in the footwall of the Kariya fault, itself exposed along the eastern edge of Awaji Island (Figure 3.1). The Kariya fault displaces granitic rocks in its hanging wall, rocks that underlie Late Quaternary
sediments deposited in the Osaka Basin to the east. Dextral shear across the Kariya uplift is accommodated by the Nojima fault exposed along the western edge of the uplift on Awaji Island. The Nojima fault extends north and west of Kobe as the Arima-Takatsuki Tectonic Line (ATL), a set of oblique structures exposed along the base of Rokko mountains, which form the northern margin of the Osaka Basin. Other large thrusts in this region of Japan include structures further to the east that deform the Osaka Plain and the Nara and Ikoma basins. These faults and the Osaka-wan and Kariya faults collectively absorb right lateral displacement on the Median Tectonic Line (MTL), which itself accommodates partitioned shear above the subduction interface with the Philippine Sea Plate. While the thickness of the seismogenic crust in this part of Japan lies at 13 kilometers depth (implying a relatively high crustal geothermal gradient), this part of Japan does not contain a well-developed set of arc-related volcanic centers, due to a more shallowly dipping slab here present on Kyushu to the west, and western Honshu to the east.

The Osaka Basin has subsided rapidly from the Late Plio-Pleistocene (Huzita, 1983) and is infilled with over 3 kilometers of sediment (Itoh et al., 2000, 2001). Subsidence has been proposed by Japanese workers to be driven by either the faulting on the Osaka-wan fault (Yokokura et al., 1998), which likely should only create accommodation space east of the fault, or by differential subsidence of fault-bounded blocks due to its location on the margin of a proposed rhomboidal depression (Itoh et al., 2000, 2001), but with an inference of tectonic pull apart on strike slip faults. As stated previously, we argue that the large Kariya fault, which has a minimum of 1.5 km of offset across it, drives most of the subsidence of the Osaka Bay. Alternatively, Kusomoto et al. (2001) argues that the basin may have formed at the termination of the MTL and ATL if the secondary fault producing the right-lateral motion was reverse and produced displacement larger than 20% of the lateral movement.
The basin is filled with sediments of the Osaka Group – a continuous sequence of Plio-Pleistocene strata comprised of fluvial and lacustrine deposits (e.g. silt, sand and gravel) in the lower part and sequences of alternating marine clay layers and freshwater sediments in the upper section (Ikebe et al., 1970; Itihara, 1993). The basin, which was situated near sea level for at least the last 1.2 million years, has a stratigraphic architecture strongly influenced by marine and non-marine transitions, as recorded in the upper section of the Osaka Group of alternating marine clay and non-marine silt and sand. The age of the marine clay layers corresponds well with the global eustatic record of sea level highstands (Takatsugi and Hyodo, 1995) and hence provide essentially perfect absolute elevation datums (Itoh et al., 2003).

Fifteen marine clay layers were initially identified in the Osaka Group and were designated sequentially as the oldest Ma-1 through the youngest Ma13 (Itihara, 1961; Yoshikawa et al., 1997; the Ma designation is a local system used by Japanese researchers to reference the stratigraphic sequence in the region). Three additional marine clay layers were later identified from cores in the central part of the basin in between Ma12 and Ma10 and were labeled Ma11.1, Ma11.2 and Ma11.3 (Furutani, 1989), totaling 17 marine layers. In addition, more than 50 volcanic ash layers are recognized in the Osaka Group, providing unprecedented age control on the marine clay layers (Biswas et al., 1999). In summary, the correlation of the lithostratigraphy in the boreholes is one-to-one for each reflector in the seismic reflection profiles.

3. Seismic and Well Data

High-resolution seismic reflection surveys were collected in Osaka Bay in the wake of the 1995 Kobe earthquake. The data were collected by multiple agencies, including Geological Survey of Japan (GSJ), University of Tokyo (TK), Hyogo Prefecture (HG), city of Kobe (KB),
Hydrographic Department (HD), the Power Reactor and Nuclear Fuel Development Corporation (NP), and Geo-Research Institute (OD), and combined together to investigate the subsurface structures for a better understanding of the region’s seismic hazard. The marine seismic data were collected and processed using standard techniques (Yokokura et al., 1999).

A 1700-m borehole (HS-K1) at Hgashinada, Kobe City, the longest core in the Osaka Basin, provided the link between the seismic reflection data and lithostratigraphy. The borehole penetrated granite basement below 1545.5 meters, which is overlain with unconsolidated sediments of the Osaka Group (Figure 3.2). Biswas et al. (1999) further refined the depositional history of the Osaka Group for the past 3.2 million years by identifying two short geomagnetic reversal events at 0.69 Ma and 1.6 Ma in addition to the previously mentioned age controls from volcanic tephra.

Kinugasa and Mizuno (1996) first correlated the borehole with seismic reflectors, tying seismic line GS-NP, which crosses the borehole, to the marine clay layers in the core. In addition to the tephrachronology and magnetostratigraphy, the marine clay layers from Ma-1 to Ma12 were further pinpointed in the core by diatom analyses, electrical resistivity, and sulphur content (GSJ, 1996; Biswas et al., 1999). The latest marine clay layer, Ma13, was deposited in the upper 23.27 meters of the core, which was not sampled; no marine clay layers were found below 692 meters (Biswas et al., 1999). The core contained forty-five volcanic ash layers, ten of which were dated directly using tephrachronology (GSJ, 1996; Biswas et al., 1999).

Lithostratigraphy and faunal assemblages defined in the cores were also used to independently identify transitions from fluvio-deltaic to shallow-marine conditions, again consistent with transgressive sequence stratigraphic boundaries that correlate with specific sea level highstands. Ma-1 to Ma4 and Ma9 to Ma13 were defined from detailed
Figure 3.2 – Lithostratigraphy for the 1700 m GS-K1 core marked with the marine layers and ages (modified Biswas et al., 1999).
magnetostratigraphy and tephrochronology; the ages of Ma5 to Ma8 ages were determined by correlating stratigraphy with the oxygen isotope stages based on the climate record from pollen analysis (Itoh et al., 2000, 2001).

4. Trishear kinematic model

Fault-bend folds (Figure 3.3) were first described geometrically by Rich (1934) and then later quantified by Suppe (1983) and further developed into a widely used set of geometrical relationships termed fault-related fold theory. Early fault-propagation fold models of basement cored uplifts similar to Osaka-wan were based purely on kink geometry and had restrictive geometric assumptions that did not match natural examples particularly well (Suppe, 1983; Suppe and Medwedeff, 1990; Suppe et al., 1992). The first descriptions of fault-propagation folds were developed by Erslev (1991), which he termed as “trishear” fold. Erslev’s original simple kinematic model described how slip distribution on a fault radiates from a propagating fault tip in a triangular zone of shear. Erslev’s (1991) trishear model was later quantified into a method used in quantitative structural analysis by Hardy and Ford (1997) to specifically address a suite of potential variables, including propagation to slip ratios, the utility of growth strata in progressive restorations, and analysis of strain across the structure. Allmendinger (1998) further improved the trishear model to allow greater flexibility in the starting parameters, variations in the parameters during analysis, variability in strata thickness and dips, and the ability to model strata during the growth of the structure. Most importantly, Allmendinger (1998) created the first set of easy-to-use computer codes to model trishear folds, which were used to explore the development of many additional natural examples (Champio et al., 2001).
Figure 3.3 – Illustration of a simplified trishear envelope. Growth strata may vary from classical sigmoidal monocline geometry as shown in the upper example. Others have unique convex upward shape, as shown in lower example, which results from sliding of the trishear envelope up the synclinal axial surface.
Trishear kinematic modeling has been applied in many natural fault-propagation folds (Erlsev, 1991; Allmendinger, 1998), including predicting finite strain and brittle fracturing within fault propagation folds (Allmendinger et al., 2004; Cardozo et al., 2005), incorporating growth strata geometries (Hardy and Ford, 1997; Gawthorpe and Hardy, 2002), and applying fault propagation fold theory to seismic hazards (Allmendinger and Shaw, 2000). The key advantage of using trishear algorithms in these studies was their ability to invert fold geometry to determine the geometry of underlying, seismogenic blind thrusts similar to the Osaka-wan fault.

The traditional 2D trishear model searches for the best fit model that restores the bedding to a straight line, or datum, based on six parameters: x and y fault tip location, fault dip (ramp angle), fault propagation to fault slip ratio (P/S), apical angle of the triangular zone (trishear zone), and fault slip (Allmendinger, 1998). The initial trishear models used a grid-search approach, an inefficient method that evaluates every model within a broad matrix of parameters to determine the single best-fit restoration of the bedding (Allmendinger, 1998; Cardozo et al., 2011). Restored bedding is evaluated through an objective function ($f_{\text{obj}}$), where the model with the lowest $f_{\text{obj}}$ is the best fit model (Cardozo and Aanonsen, 2009). Cardozo and Aanonsen (2009) developed gradient-based optimization algorithms that have increased the inversion processing speed. Gradient-based optimization requires an initial estimate in which the algorithms traverse the parameter space in search for a $f_{\text{obj}}$ minimum (Cardozo and Aanonsen, 2009; Cardozo et al., 2011). However, the grid-based approach and the gradient-based approach to trishear modeling are affected by local minima, only allowing one unique best-fit trishear model and thereby limiting the possibility for additional best-fit models that may fit the data equally well (Cardozo and Aanonsen, 2009; Cardozo et al., 2011).
Recently, Cardozo et al. (2011) have developed a more robust trishear inverse model using a simulated annealing algorithm. The simulated annealing algorithm is just as efficient as the gradient-based optimization algorithms; however, it is not affected as much by local minima (Cardozo et al., 2011). It searches the parameter space for all possible solutions, providing many unique best-fit models (Cardozo et al., 2011). Simulated annealing is more robust than the optimized trishear inverse model by Cardozo and Aanonsen (2009), and is based on using the analogy of temperature to heat a material and then to lower the temperature to minimize the system energy, as it traverses the parameter space (Cardozo et al., 2011). Cardozo et al. (2011) applied the simulated annealing algorithm in a fault-propagation fold and thrust in west-central Taiwan, an extensional fault-propagation fold in western Sinai, Egypt, and to a clay model of an extensional forced fold by Withjack et al. (1990), illustrating the utility of the method for working with a greater range of solutions rather than a unique model when investigating the controls or variation in parameters that affect the development of fault-propagation folds.

5. Methodology

We perform inverse trishear modeling on a the fault-related fold above the blind Osaka-wan thrust fault to determine the best fit models that restore growth strata, to calculate slip, and to map the location of the blind fault tip at depth with time. To achieve this, our methods required mapping the horizons in the seismic data across the fold, correlating each horizon to the boreholes in the Osaka Bay for age calls, determining a fault dip, and performing the robust trishear simulated annealing algorithm (Cardozo et al., 2011) to restore the growth strata above the Osaka-wan thrust fault.
5.1 Correlations of seismic reflectors

The Geological Survey of Japan and the National Institute of Advanced Industrial Science and Technology provided us with depth-corrected seismic profiles throughout the Osaka Bay. We interpreted the depth-corrected profiles OD-A, HG-1-1M, GS-8ME, OD-B, HD-3, HD-4, GS-7, GS-11, and GS-12 (Figure 3.1). We only focus on the southern-half of the fault, avoiding the northern section where the Osaka-wan fault splits into several smaller branches.

We first mapped parallel and undeformed “layer cake” reflectors in seismic line OD-A (Appendix A), a strike-line located 3-10 kilometers from the base of the forelimb of the Osaka-wan structure (i.e. on its footwall). This profile intersects the four seismic lines that cross the fold used in the trishear modeling (GS-8ME, OD-B, HD-3, and HD-4). We then used seismic line HD-3 to trace the reflectors across the fold to tie into a second strike-line, GS-11, located on the hanging wall of the fault. Correlations across the fold were more robust closer to its southern termination, where displacement was lower (i.e. on HD-3). We then mapped and loop tied the reflectors from profile GS-11, back across the fold using profiles GS-8ME, OD-B, and HD-3. We also correlated GS-11 through two addition intermediate strike lines, GS-7 and GS-12, in order to complete the final loop tie into HD-4. With the reflectors mapped on both sides of the fault, we were then able to correlate reflectors across the crest of the fold where the reflectors were discontinuous across the steep bedding. In total, we were able to correlate 14 marine clay layers throughout the seismic sections, with exception of a few horizons that died out at the edge of the Bay on profile HD-4 (see Chapter II).

We used published data from Inoue at al. (2003) to assign age calls to the reflectors. Inoue et al. (2003) correlated the reflectors of 14 marine clay layers from several boreholes – the deep GS-K1 borehole (also published in Kinugasa and Mizuno, 1996) and shallower
boreholes near the Kansai International Airport (also published in Itoh et al., 2001), with PS logging and VSP records. We assigned ages based on Inoue et al.’s (2003) age-correlated reflectors at the intersection of seismic lines OD-A and OD-B.

5.2 Estimation of fault dip

Inverse trishear models allow us to estimate the best fit ramp angle, trishear angle (TA) and propagation to slip (P/S) ratio to restore beds and to calculate slip; however, these models are more robust with independent data for fault geometry such as might be available from boreholes that directly penetrate the thrust, or direct fault plane reflections. The seismic data do not reveal a clear ramp angle and do not extend far enough to the west to determine it based on the location of a backlimb. To get around this problem, we use the dip of the synclinal axial surface at the base of the fold as a proxy for the dip of the fault (Figure 3.4). The axial surface is clearly imaged in a published two-way travel time seismic profile, TK-1 (Sato et al., 1998). We converted the two-way travel time section to depth based on published stacking velocity functions (Yokokura et al., 1998) and calculated a dip of the axial surface to be about 73°. This high dip is consistent with constraints on fault dip from the nearby Kariya thrust.

5.3 Inverse trishear modeling

We chose six continuous high-amplitude prominent reflectors from four seismic profiles along the southern-half of the Osaka-wan fault, ranging from the oldest growth strata (1200 Ka) to the youngest mapped growth strata (127 Ka), to perform trishear inversions (Figure 3.5). Ideally, pre-growth strata would be more effective for determining the best trishear parameters
Figure 3.4 – Interpreted seismic profile TK-1, from Sato et al. (1998). We traced the bedding across the Osaka-wan fault (yellow) and estimated the dip of the axial surface, assuming it is similar to the dip of the fault. We used the time-depth curve (bottom left corner) to convert the points of the axial surface on the two-way travel time seismic profile to depth in order to calculate actual dip. Other red lines are interpreted faults in the same fault system, from Sato et al. (1998).
for growth strata restoration (e.g. Lin et al., 2007); however, the seismic data do not image pre-growth strata across the fault, precluding this opportunity. Reflectors were traced in a drawing program and digitized as xy points.

We use the simulated annealing algorithm “simulannealbnd” from the MATLAB Global Optimization Toolbox™ to perform inverse trishear modeling (Cardozo et al., 2011). We define a lower and upper limit and a best estimate for ramp angle, TA, P/S, and the x and y fault tip location that are consistent with other better defined trishear folds that are similar to the Osaka-wan. We initially keep the parameters broad and then narrow them as the simulated annealing algorithm tightens the range of values for the parameters that best restore the beds. Our final search parameters were as follows: a ramp angle = 70-75° with a best estimate of 73°; a trishear angle, TA = 40-80° with a best fit value of 60°, and propagation to slip, P/S = 2-3 with a best estimate of 2.5. Fault tip locations were determined independently for each line. A total of 2000 iterations were used in the inversion of each bed (Figure 3.6).

We confirm that, in general, the trishear parameters that best restore the beds are similar from bed to bed and along strike of the fault. We therefore apply the methodology of Cardozo et al. (2011) used to model shallow geometry of the Chelungpu fault in the Taiwanese thrust belt as an example. Without pre-growth beds, the oldest growth strata, bed 1, provides the best opportunity to restore all the growth strata because it has undergone the largest amount of displacement. We use any of the parameters that fit well for bed 1 to invert for the fault slips that best restores all the growth strata.
Figure 3.5 – Tracings of the six interpreted reflectors that were modeled from seismic profiles GS-8ME, OD-B, HD-3 and HD-4. Bed 1 is the oldest mapped growth strata (1200 ka) to bed 6, the youngest mapped growth strata (127 ka). Dashed lines are our interpreted bedrock horizons.
Figure 3.6 – Input bed geometry for a) GS-8ME; b) OD-B; c) HD-3; and d) HD-4. Red box denotes the search area for the fault tip with red circle indicating initial estimate of fault tip.
6. Results

6.1 Trishear inversions bed by bed

The first part of this study defines the best fit parameters for all the beds. Without pre-growth strata to define the trishear parameters, we first perform simulated annealing trishear inversions bed by bed for all four seismic sections in order to determine whether the parameters are consistent among the beds and along the strike of the fault. Figure 3.6 defines the model lines and final search parameters for each section, with the red box marking the search area for the fault tip and the red circle defining the initial fault tip.

Results of simulated annealing solutions for each bed in the four seismic sections are shown in Appendix C as the distribution of the parameters for models with low objective function plots, evolution of the search, and a cross section showing the best fit model and input geometry. In general, we find that the same trishear angle, P/S ratio, and ramp angle work well for each bed in each profile. We therefore only show results of the simulated annealing inversions for the trishear parameters that best restore bed 1 for each seismic profile.

6.2 Best fit models

In figure 3.7, we show the results of the simulated optimization for the trishear parameters. The paths of optimization are shown for four of the parameters of the inversion: ramp angle, P/S, TA, and fault slip. This figure illustrates the evolution of the search from the initial estimate (circles) to the final iteration (triangles). During the evolution, there are several cycles of temperature reduction and increase, allowing the algorithm to identify local minima (fobj < 0.7). These are the trishear models that can replicate the growth bedding data, as plotted as distribution plots in figure 3.8. The ramp angle of these possible models is high (between 70
Figure 3.7 – Evolution of simulated annealing optimization for the trishear parameters that best restore bed 1 for seismic profiles GS-8ME, OD-B, HD-3, and HD-4. In each plot, the circle represents the initial estimate and the triangle the final iteration.
and 75°). Values for P/S are tightly constrained, with possible values ranging between 2 and 3 with the most local minima around 2.1 and 2.8. The range of TA is broader, with values ranging between 40 and 80°. Fault slip is quite variable among the lines, as expected from vertical displacement measured across the fold, and range from 1 km near the center of the fold to 0.2 km near the edge of the fold.

Any of the models with an $f_{\text{obj}} < 0.7$, as illustrated in figure 3.8, fit all the growth strata well (bed 1 through bed 6). We use these models (about 2200) to invert for fault slips that best restore the growth strata, summarized in Figure 3.9. A total of 316 fault slip models fit the growth strata for GS-8ME, 156 fault slip models for OD-B, 233 fault slip models for HD-3, and 171 fault slip models for HD-4. Slip in seismic profile GS-8ME ranges from 0.70 to 0.95 km for bed 1, 0.62 to 0.75 km for bed 2, 0.50 to 0.62 km for bed 3, 0.39 to 0.49 km for bed 4, 0.21 to 0.30 km for bed 5 and 0.10 to 0.18 km for bed 6. Slip in seismic profile OD-B ranges from 0.52 to 0.68 km for bed 1, 0.42 to 0.50 km for bed 2, 0.40 to 0.49 km for bed 3, 0.32 to 0.39 km for bed 4, 0.19 to 0.21 km for bed 5 and 0.05 to 0.09 km for bed 6. Slip in seismic profile HD-3 ranges from 0.12 km to 0.39 km for bed 1, 0.12 to 0.23 km for bed 2, 0.10 to 0.20 km for bed 3, 0.08 to 0.17 km for bed 4 and bed 5, and 0.02 to 0.06 km for bed 6. Slip in seismic profile HD-4 ranges from 0.15 to 0.36 km for bed 1, 0.14 to 0.21 km for bed 2, 0.10 to 0.19 km for bed 3, 0.08 to 0.12 km for bed 4 and 5, and 0.02 to 0.06 km for bed 6. A noticeable feature is that variation in fault slip converges on the younger beds with less folding.

In figure 3.10, we plot the depth of the fault tip (y) versus the strata for each seismic profile. The y-axis scale is from the input models where (0,0) was arbitrarily assigned. In this case, 0 km equates to a depth of 3 km, or the bottom of the seismic profile. The plots are created
Figure 3.8 – Distribution plots of bed 1 for seismic lines GS-8ME, 0D-B, HD-3, and HD-4. Plots are combined with models from an objective function of 0.7 and less. The total number of models that fit bed 1 for each profile is as follows: GS-8ME – 603; OD-B – 340; HD-3 – 751; and HD-4 – 508.
Figure 3.9 – Fault slip that fits well with the growth strata from bed 1 for a) GS-8ME; b) OD-B; c) HD-3; d) HD-4.
using the best fit models from bed 1, as in figure 3.9. We find an average spread of about 1 km depth for a possible fault tip. Seismic profile GS-8ME ranges from a fault tip depth of approximately 2.8 to 4 km for bed 1, 2.7 to 3.7 km for bed 2, 2.4 to 3.4 km for bed 3, 2.2 to 3.1 km for bed 4, 1.8 to 2.7 km for bed 5 and 1.6 to 2.4 for bed 6. Seismic profile OD-B ranges from a fault tip depth of approximately 3.0 to 3.8 km for bed 1, 2.7 to 3.4 km for bed 2, 2.6 to 3.3 km for bed 3, 2.4 to 3.1 km for bed 4, 2.0 to 2.7 km for bed 5 and 1.7 to 2.5 km for bed 6. Seismic profile HD-3 ranges from a fault tip depth of approximately 1.5 to 2.8 km for bed 1, 1.5 to 2.7 km for bed 2, 1.4 to 2.6 km for bed 3, 1.4 to 2.4 km for bed 4, 1.4 to 2.4 km for bed 5 and 1.3 to 2.3 km for bed 6. Seismic profile HD-4 fault tip depth ranges from approximately 1.4 to 2.7 km for bed 1, 1.4 to 2.6 km for bed 2, 1.3 to 2.5 km for bed 3, 1.2 to 2.3 km for bed 4, 1.2 to 2.3 km for bed 5 and 1.1 to 2.2 km for bed 6.

7. Discussion

Our results illustrate well that there is no one best fit model, but that there are many models that are able to restore the beds to a good approximation, similar to that found by Cardozo et al. (2011). We find that models with a fault dip between 70 - 75°, a trishear angle between 40 - 50°, and a P/S between 2 and 3 will restore the beds to undeformed geometry prior to folding. The inverse trishear analysis also supports the fault as having a steep ramp angle, as suggested in Chapter II. This is fortuitous for the study that defined the time:displacement:length in the previous chapter because the vertical displacements we measure must thus be nearly the same (~96%) as the actual fault slip.

Slip rate values have less variation from the trishear results, than vertical displacement rates seen in Chapter II. We expect this because rates are averaged over a longer time period,
Figure 3.10 – Initial fault tip depth (y) versus growth strata for a) GS-8ME; b) OD-B; c) HD-3; and d) HD-4. For reference, 0 km is a subsurface depth of 3 km.
using only 6 beds. Future work will present trishear results for all 14 beds, allowing for a better comparison of variation between the two methods. Slip is generally higher from the trishear results as it incorporates a 70 - 75° degree fault dip. Regardless, the slip measurements we make using vertical uplift as a proxy for fault slip yield results in unprecedented detail, although the trishear analysis mentioned above will allow us to assess error in the TDL plots more effectively.

More importantly, these results map the location of the fault tip for each stratum on each profile, providing a record of fault propagation in vertical and horizontal directions. We map the depth of the fault tip for each of the six growth strata on the four profiles along strike (Figure 3.11). Ideally, we will fill this in with all 14 growth strata horizons to correlate with the TDL work, but this will be done at a later date. In Figure 3.11, we plot the range of the fault tip depth (y) from the best possible models presented from stratum 1, the reflectors of the basement rock and the 6 strata layers (bottom) with sedimentation rate (top). The range of the possible depth for the fault tips is plotted as a dashed line (for the deepest possible fault tip) and a solid line (for the shallowest possible fault tip). The dotted lines represent each stratum, color coordinated with the fault tip depth. The thick black line represents the depth of the bedrock.

We first observe that the depth of the fault tip is relatively shallow, only 4 km in the subsurface at its deepest point. This suggests that the fault is reactivated rather than a new fault originating from the base of the seismogenic crust, as might be expected from structures with more rapid propagation or higher P:S than estimated for Osaka-wan, or higher amounts of slip for P:S similar to the values for Osaka-wan. This is consistent with the results in Chapter II, where the fault propagates outwards instantaneously (at least within the resolution of the data) before growing with higher rates of uplift in the center later in its history. This type of fault
Figure 3.11 – Depth of fault tip ranges plotted against distance along fault, based on the best fit models from bed 1. On the bottom plot, dashed lines are the deepest possible fault tip locations; solid lines are the shallowest possible fault tip depths. The dotted lines are the depths of the reflectors in the footwall. Thick black line is the depth of the bedrock. The top plot illustrates changes in sedimentation rate between the time of each stratum being deposited.
reactivation behavior has been previously documented by Nicol et al. (2005) and Walsh et al. (2002) and used as the model for scaling of reactivated faults in general.

We are interested in assessing what properties might the propagation of the fault tip. One possible influence is the strength of the material through which the fault tip is propagating. In Figure 3.11, the two outer profiles (HD-4 and HD-3) support a location for the fault tip either in the basement rock or completely above the basement rock for its entire history. For the two inner profiles (OD-B and GS-8ME), the fault tip either remained in the basement rock or potentially moved into the sediment above between 587 and 334 Ka. We would expect that the fault tip will propagate faster through basement rock, and more slowly through overlying sediment, which has been shown to absorb shear more effectively by bedding-parallel slip (Roering et al., 1997). Without additional information that would decrease uncertainty in the trishear results, such as direct knowledge of fault dip, it is not possible to test whether rock strength can be correlated with small changes in P:S as estimated from our study.

The range of the original depth of the fault tip as defined by our study does suggest, however, that the current center of the Osaka-wan fault probably does not correspond with the crest, or middle of the preexisting structure, assuming that the shallower depths of the fault tip for the older structure correspond to larger displacement on it. This is illustrated where shallower starting depths for the fault tip are shown from our analysis to lie closer to the southernmost endpoint of the Osaka-wan structure.

Another possible factor that might impact fault tip propagation is sedimentation. In Figure 3.11, we plot the sedimentation rate along strike of the fault for each time interval between the strata (i.e. the line for 1200 Ka represents the rate between 1200 and 1070 ka; the line for 127 ka represents the rate between 127 Ka and present). Sedimentation rate is high early
on in the faulting history (1200 Ka to 1070 Ka) and more recently (127 Ka to present). The rate was lowest between 865 and 334 Ka. There was no change in rate for about 500 Ka, until about 334 when the rate increased. We do not see a clear pattern to conclude that changes in sedimentation rate affect the propagation of the fault tip. More likely, sedimentation is fairly constant through time and the variation in slip rate is associated with other processes or boundary conditions.

Plots of sedimentation rate (measured on the footwall) compared to uplift rate for points along the faults (i.e. the locations of the seismic profile) do correlate well with uplift rate at those locations, as one might expect (Figure 3.12). We interpret this as simply reflecting more rapid deposition on the downthrown side of the fault, a process common to any structure that produces topographic or bathymetric relief. In essence, these plots simply show additional detail illustrated by the larger scale stratigraphic structure across the fold.

In summary, the Osaka Basin started to form from flexure in the footwall of the Kariya fault no later than about 3000 Ka. Faulting began as early as ca. 1500 ka. By 1200 ka, the earliest age constraint, the fault tip is no deeper than 4 km. These results thus support evidence for a space-time pattern of fold growth where a reactivated fault grew rapidly towards its endpoint and then builds slip more rapidly in its center. Our results clearly do not support growth of the Osaka-wan fault from deep levels of the crust that correspond with the depth of the brittle-to-ductile transition.
Figure 3.12 – Sedimentation rates versus displacement rates for profile A) HG-1-1M; B) GS-8ME; C) OD-B; D) HD-3; E) HD-4; and F) each profile plotted together on the same scale for comparison.
8. Conclusion and Future Work

We performed simulated annealing optimization trishear analysis on a fault-related fold from the Osaka-wan blind thrust fault using six strata that extend across the fold. The simulated annealing trishear optimization allows us to define a range of best fit models that restore the growth strata. The results suggest a fault with a steep ramp angle (70-70°), high trishear angle (40-80°), and a P/S of 2-3, all consistent with faults of this nature. We find slip just under 1 km near the center of the fold.

We also modeled the depth of the fault tip using analysis of trishear parameters and find that the fault tip is shallow in the crust, suggesting a reactivated fault. At this point, our results do not allow us to test whether other factors (such as fault strength, sedimentation rate, interaction among other nearby faults) influence the propagation of the fault tip.

To further expand the work presented in this thesis, we will perform bed by bed restorations, searching for P/S, trishear angle and fault slip, while using a fixed fault tip and fault dip that have already been constrained by existing results. This will allow us to attempt to make more meaningful comparisons between the P/S, trishear angle, and fault slip along with other parameters such as sedimentation rate. We will do this for all 14 beds, starting with the sections with greater folding. It would also be interesting to test whether P/S changes through time, as this will affect the depth of the fault tip. With regard to the TDL measurements, having tighter constraints on fault dip would also help us to refine values for actual fault slip (while we measure uplift directly, slip also depends on fault dip). The key here is to decrease uncertainty in the differences in slip rate with time we measure along the entire structure, adding credence to the results presented earlier in the thesis.
CHAPTER IV

CONCLUSION

In an effort to better understand the seismic hazard in the greater Osaka region in the wake of the Kobe earthquake, government agencies in Japan collected marine seismic surveys, revealing the 40 km long Osaka-wan blind thrust fault. These data, coupled with detailed stratigraphy of precisely known ages defined in deep boreholes, offer an unprecedented opportunity to map the 3D pattern of growth of a fault-related fold from a blind thrust fault. Results of our work bridge the gap between measurements taken at shorter paleoseismic and long term average slip rates.

Our results confirm analogue studies that suggest variation in slip rate on faults may be more common that previously suggested from studies in which slip is averaged over long periods. In addition, our work suggests that measurements of higher displacement in the center of dip slip faults also occur at the intermediate (~50 ka) timescales and at the distances (5-10 km) we measured. This has important implications for scaling of faults, where such triangular slip profiles suggest that the surface area of actively growing faults achieve a maximum value quickly (perhaps even more so for a reactivated example like Osaka-wan). Total moment release must remain the same whether or not a fault grows laterally at slower rates, because total displacement on a fault is directly correlated with the magnitude and frequency of earthquake occurrence (e.g. Characteristic vs. Gutenberg Richter behavior). Yet knowing how slip is likely to vary along strike, for a given earthquake of a certain size with a corresponding recurrence interval, is useful for engineering studies that seek to mitigate seismic risk. For example, the risk
perceived to exist to critical infrastructure might be underestimated if it were located closer to the center of a fault like Osaka-wan because displacement would be higher in these areas. This assumes that the proximity to an earthquake source matters, which has been shown to be the case, especially in regions where seismic waves are attenuated rapidly across sedimentary basins.

Our results suggest that long-term stability of the rate of slip does not appear to ever fully occur on the Osaka-wan fault, a major thrust fault capable of generating large earthquakes. While answers to why slip rate changes along the Osaka-wan thrust await additional modeling and measurements of the uplift history on the nearby Kariya thrust, the results are profound. Firstly, our results imply that assumptions for the seismic hazards posed by thrusts that have records of past earthquakes for say, the last few tens of thousands of years may be inappropriate. For example, if paleoseismic studies were conducted on a thrust that showed similar systemic variation in slip rate for a period when slip was slower might underestimate risk. Conversely the opposite would be true for a period of faster slip. The crux of this problem lies in measuring even finer details of change in slip rate along a major fault, such that they might be compared with long paleoseismic records. The challenge is thus to measure and understand rates of change at ever smaller distances and shorter time periods until these approach records from paleoseismic studies, acquisition of which are notoriously difficult and can consume a lifetime of work.

While analogue studies of normal faults that become linked and simplified with time show variations in slip rate similar to Osaka-wan (Schlagenhauf et al., 2008), there is little mechanical analysis of why this might occur. Are there systemic aspects of the accumulation of strain on isolated faults that produce variation in slip rates that are not related to interactions between multiple faults? If this behavior exists, what might drive it, such as stress transfer over greater distances or time periods than usually ascribed in studies that suggest earthquake
triggering occurs? Regardless of these questions, Osaka-wan grows in ways that suggest that slip rates do not stabilize at timescales that are shorter than one might expect. The question is why.
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APPENDIX A

OD-A STRIKE LINE

Figure A.1 – Seismic profile OD-A. OD-A was a key profile in correlating published age calls to our data and tying together the reflectors in the footwall of the fault from profiles HG-1-1M, GS-8ME, OD-B, HD-3 and HD-4. Dashed colored lines are our interpretations for each marine reflector. Dashed vertical black lines mark the crossing of the five key profiles used in this study.
APPENDIX B

TIME-DISTANCE-LENGTH RESEARCH:
BED INTERPRETATIONS AND OFFSET MEASUREMENTS

This section presents our interpretive reflectors and our measurements behind the time-distance-length plot as described in Chapter II. First, we illustrate our interpretation of the 14 reflectors from each seismic line, as done for GS-8ME in Figure 2.2: HG-1-1M (Figure B.1), OD-B (Figure B.2), HD-3 (Figure B.3), and HD-4 (Figure B.4). In Table B.1, we define our measurements from the footwall and hanging wall for each reflector and calculate the vertical offset. Reflectors in HD-4 with a value of null were not traceable; the offset measurement was interpolated from the offset measurements above and below the missing reflector.
Figure B.1 – Reflector interpretation for seismic profile HG-1-1M. Top panel illustrates our horizon picks across the fold. We measure the vertical displacement from the footwall to the hanging wall. Bottom panel shows the depth-corrected seismic data from which we traced our lines from.
Figure B.2 – Reflector interpretation for seismic profile OD-B. Top panel illustrates our horizon picks across the fold. We measure the vertical displacement from the footwall to the hanging wall. Bottom panel shows the depth-corrected seismic data from which we traced our lines from.
Figure B.3 – Reflector interpretation for seismic profile HD-3. Top panel illustrates our horizon picks across the fold. We measure the vertical displacement from the footwall to the hanging wall. Bottom panel shows the depth-corrected seismic data from which we traced our lines from.
Figure B.4 – Reflector interpretation for seismic profile HD-4. Top panel illustrates our horizon picks across the fold. We measure the vertical displacement from the footwall to the hanging wall. Bottom panel shows the depth-corrected seismic data from which we traced our lines from.
Table B.1 – Measurements of the depth of the footwall and hanging wall and the vertical displacements

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All measurements in meters

*offsets interpreted
Figures C.1 – C.4 are distribution plots of parameters of models with low objective function. We chose a maximum objective function of 0.7. Figure C.1 includes plots of bed 1 through bed 6 for seismic line GS-8ME. In general, we find the following parameters that fit well for all beds: ramp angle between 70 and 73°; P/S of 2.1 to 2.4 and 2.7; and TA of 40-50°. Slip varies from 1 and 0 km. Figure C.2 includes plots of bed 1 through bed 6 for seismic line OD-B. In general, we find the following parameters that fit well for all beds: ramp angle between 70 and 73°; P/S of 2.1 and 2.7; and TA between 40 and 50° and 75 and 85°. Slip varies from 0.9 and 0 km (outliers not included as they are not consistent with other profiles). Figure C.3 includes plots of bed 1 through bed 6 for seismic line HD-3. In general, we find the following parameters that fit well for all beds: ramp angle between 70 and 75°; P/S of 2.0 and 3.0; and TA of 40-80°. Slip varies from 0.5 and 0 km. Figure C.4 includes plots of bed 1 through bed 6 for seismic line HD-4. In general, we find the following parameters that fit well for all beds: ramp angle between 70 and 75°; P/S of 2.0 and 3.0; and TA of 40-80°. Slip varies from 0.4 and 0 km.

Figures C.5 – C.8 are plots that illustrate the evolution of the search from the initial estimate (open circle) to the final iteration (open triangle). Models with a lower objective function than 0.7, or the “possible” models, are synthesized in the distribution plots (Figures C.1 – C.4). A total of 2000 iterations were used in the inversion of each bed. Lastly, we plot cross-sections showing the best fit models and input geometry for each bed, in Figures C.9 – C.12.
Figure C.1 – Distribution plots for seismic profile GS-8ME. We picked an objective function of 0.7. The total number of models that fit for each bed is as follows: bed 1 – 603; bed 2 – 444; bed 3 – 446; bed 4 – 414; bed 5 – 883; bed 6 – 1083.
Figure C.2 – Distribution plots for seismic profile OD-B. We picked an objective function of 0.7. The total number of models that fit for each bed is as follows: bed 1 – 340; bed 2 – 654; bed 3 – 462; bed 4 – 268; bed 5 – 980; bed 6 – 1147.
Figure C.3 – Distribution plots for seismic profile HD-3. We picked an objective function of 0.7. The total number of models that fit for each bed is as follows: bed 1 – 751; bed 2 – 575; bed 3 – 851; bed 4 – 943; bed 5 – 1415; bed 6 – 1103.
Figure C.4 – Distribution plots for seismic profile HD-4. We picked an objective function of 0.7. The total number of models that fit for each bed is as follows: bed 1 – 508; bed 2 – 733; bed 3 – 814; bed 4 – 1151; bed 5 – 1404; bed 6 – 962.
Figure C.5 – Evolution of simulated annealing optimizations for the trishear parameters that best restore bed 1 through bed 6 on seismic profile GS-8ME. In each plot, the circle represents the initial estimate, and the triangle the final iteration. Black dots indicate models with $f_{obj}$ less than 0.5.
Figure C.6 – Evolution of simulated annealing optimizations for the trishear parameters that best restore bed 1 through bed 6 on seismic profile OD-B. In each plot, the circle represents the initial estimate, and the triangle the final iteration. Black dots indicate models with $f_{obj}$ less than 0.5.
Figure C.7 – Evolution of simulated annealing optimizations for the trishear parameters that best restore bed 1 through bed 6 on seismic profile HD-3. In each plot, the circle represents the initial estimate, and the triangle the final iteration. Black dots indicate models with $f_{\text{obj}}$ less than 0.5.
Figure C.8 – Evolution of simulated annealing optimizations for the trishear parameters that best restore bed 1 through bed 6 on seismic profile HD-4. In each plot, the circle represents the initial estimate, and the triangle the final iteration. Black dots indicate models with $f_{\text{obj}}$ less than 0.5.
Figure C.9 - Cross-sections showing the best fit models and input geometry for seismic profile GS-8ME a) bed 1, b) bed 2, c) bed 3, d) bed 4, e) bed 5, and f) bed 6. Red lines are input geometry and blue lines are best fit models. Initial and final fault tip locations plotted with red circles.
Figure C.10 - Cross-sections showing the best fit models and input geometry for seismic profile OD-B for a) bed 1, b) bed 2, c) bed 3, d) bed 4, e) bed 5, and f) bed 6. Red lines are input geometry and blue lines are best fit models. Initial and final fault tip locations plotted with red circles.
Figure C.11 - Cross-sections showing the best fit models and input geometry for seismic profile HD-3 for a) bed 1, b) bed 2, c) bed 3, d) bed 4, e) bed 5, and f) bed 6. Red lines are input geometry and blue lines are best fit models. Initial and final fault tip locations plotted with red circles.
Figure C.12 - Cross-sections showing the best fit models and input geometry for seismic profile HD-4 for a) bed 1, b) bed 2, c) bed 3, d) bed 4, e) bed 5, and f) bed 6. Red lines are input geometry and blue lines are best fit models. Initial and final fault tip locations plotted with red circles.