Seismic Investigation of the Kunlun Fault: Analysis of the INDEPTH IV 2-D Active-Source Seismic Dataset

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SEISMIC INVESTIGATION OF THE KUNLUN FAULT:
ANALYSIS OF THE INDEPTH IV 2-D ACTIVE
SOURCE SEISMIC DATASET

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Master’s Program in Geophysics

THESIS

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Dean of the Graduate School
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By

William Seelig

2017
Dedication

To my wife, Theresa, who inspired me to pursue a career change into the geosciences, and encouraged me to keep chipping away at my goals.
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ANALYSIS OF THE INDEPTH IV 2-D ACTIVE
SOURCE SEISMIC DATASET

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WILLIAM GEORGE SEELIG

THESIS

Presented to the Faculty of the Graduate School of
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in Partial Fulfillment
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ABSTRACT

The Tibetan Plateau has experienced significant crustal thickening and deformation since the continental subduction and collision of the Asian and Indian plates in the Eocene. Deformation of the northern Tibetan Plateau is largely accommodated by strike-slip faulting. The Kunlun Fault is a 1000-km long strike-slip fault near the northern boundary of the Plateau that has experienced five magnitude 7.0 or greater earthquakes in the past 100 years and represents a major rheological boundary. Active-source, 2-D seismic reflection/refraction data, collected as part of project INDEPTH IV (International Deep Profiling of Tibet and the Himalaya, phase IV) in 2007, was used to examine the structure and the dip of the Kunlun fault. The INDEPTH IV data was acquired to better understand the tectonic evolution of the northeastern Tibetan Plateau, such as the far-field deformation associated with the continent-continent collision and the potential subduction of the Asian continent beneath northern Tibet. Seismic reflection common depth point (CDP) stacks were examined to look for reflectivity patterns that may be associated with faulting. A possible reflection from the buried North Kunlun Thrust (NKT) is identified at 18-21 km underneath the East Kunlun Mountains, with an estimated apparent dip of 15°S and thrusting to the north. Minimally-processed shot gathers were also inspected for reflections off near-vertical structures such as faults and information on first-order velocity structure. Shot offset and nearest receiver number to reflection was catalogued to increase confidence of picks. Reflections off the North Kunlun (NKF) and South Kunlun Faults (SKF) were identified and analyzed for apparent dip and subsurface geometry. Fault reflection analysis found that the North Kunlun Fault had an apparent dip of approximately 68°S to an estimated depth of 5 km, while the South Kunlun Fault dipped at approximately 78°N to an estimated 3.5 km depth. Constraints on
apparent dip and geometry of the NKF/SKF and NKT provide information valuable for seismic hazard analysis.
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INTRODUCTION

The Tibetan Plateau, often called the “Roof of the World,” is a geographic feature that averages approximately 5000 meters in elevation. The subduction/collision of the Indian continental lithosphere beneath Asia during the Eocene epoch (approximately 50 Ma) uplifted the Himalaya, Earth’s tallest and most extensive mountain range, as well as the Tibetan Plateau (Leech et al., 2005). Understanding the complex structure of the region has been an ongoing effort for geoscientists around the globe. A refined understanding of tectonism and deformation along the boundary may help constrain processes associated with continent-continent subduction and collision processes as well as the plateau uplift that may apply to other continental convergent zones. Within the Plateau and along its northern boundary lie several strike-slip faults that have accommodated growth to the east and west. (See Figure 1) The crustal strain is thought to be accommodated by crustal thickening within the northern Plateau and by way of the thrust belts of the Tibetan Plateau. East-west extension occurred mainly in the southern Plateau along N-S trending rifts (Figure 1) (Ni and York, 1978; Tapponnier and Molnar, 1978). East-west extension and active east-west trending strike-slip faults have allowed a significant amount of upper crustal material to move eastwards. During the past century alone, the Kunlun Fault, a ~1000-km long active intracontinental strike-slip fault experienced five magnitude 7.0 or greater earthquakes (Wei et al., 2010). Constraining rupture zones of seismicity has been a priority for seismologists and is of great concern to people who live there. In 2007, the International Deep Profiling of Tibet and the Himalaya Phase IV (INDEPTH-IV) reflection/refraction survey was completed, which collected refraction and reflection data along a 270-km profile across the Kunlun suture in the northeastern Plateau. Constraints on fault geometry of the Kunlun Fault
may provide insight into structure of the fault at depth, which would have important implications for future earthquake rupture modeling of the boundary.

Figure 1 - Major faults, terranes and sutures of the Tibetan Plateau. Blue lines represent previous active-source profiles, with INDEPTH IV highlighted in the black rectangular area. NKF – North Kunlun Fault, SKF – South Kunlun Fault, NKT – North Kunlun Thrust, EKM – East Kunlun Mountains. (Modified from Karplus et al., 2011)
**GEOLOGIC BACKGROUND**

The formation of the Tibetan Plateau is best placed in context of larger Indo-Asian tectonism. From the late Paleozoic through the early Mesozoic, the Tethys Ocean existed between the paleocontinents of Gondwana and Laurasia (e.g. Smith and Colchen, 1988). The southerly-lying Gondwana fragments began drifting northward since about 180 Ma, accreting with Laurasia. Eventually the Tethys became a laterally narrow, yet deep trench, until complete closure and suturing of the Tethys Sea during the late Triassic-early Jurassic (Leech et al., 2005). Subduction of the Tethys itself is responsible for much of the initial thickening of the southern Tibetan crust since the Asian southern margin was a continental arc (Royden et al., 2008).

Collision between the Indian and Asian plates took place between 53 and 58 Ma, based on biostratigraphic and radiometric analysis (Guillot et al., 2003). Leech et al. 2005 dates subduction at 53.3 ± 0.7 Ma, based on tectonic reconstructions and zircon dating, with oceanic subduction occurring at latest by 57 ± 1.0 Ma (Leech et al., 2005). The initial collision resulted in folding of rocks and significant crustal shortening. The extent and mechanism of shortening remains a topic of investigation, but shortening is responsible for the majority of the uplift of the Tibetan Plateau and thickening of the crust to approximately 70 kilometers. However, Cretaceous folding and faulting along the Bangong terrane in central Tibet contributed to some thickening of the crust that predates the Indian collision, as well as a buildup of an Andean-like mountain range along the southern Eurasian plate margin (Royden et al., 2008). Continental subduction is also responsible for the orogeny of the highest mountains on Earth, the Himalaya. The collision between India and Asia transferred compressive stress northward and deformed the Tien Shan and the Kunlun Mountain.
NORTHERN TIBET

The fault systems of Northern Tibet have a complicated history of accretion and deformation. Four distinct zones of accretion bounded by the Kunlun-Qaidam terrane to the south and the China minor plate to the north formed sometime during the Ordovician. Predating the Gondwanan-Laurasian collision at about 50 Ma, the four thrust assemblages began colliding, resulting in back arc volcanism and suturing of the assemblage boundaries (Figure 2). Deformation across northern Tibet (as well as most of the Plateau) is thought to have initiated immediately after Indian-Asian collision in the Eocene. Uplift of northern Tibet is less certain, with estimates ranging from 30 Ma to 15-20 Ma (Yuan et al., 2013). The northern Kunlun Mountains show marine sediments of a foredeep basin predating the Tethys Ocean, and are thought to be of Devonian origin (Yin and Harrison, 2000). The southern end of the INDEPTH IV profile crosses the Songpan-Ganzi flysch complex, a highly folded block of Triassic deep marine basin sediments with a thickness of approximately 10-km. The Kunlun Thrust mapped to the south of the city of Golmud is an implied buried structure that is thought to be associated with ramp stacking at approximately 30 Ma (Mock et al., 1999).
Figure 2 - Models for tectonic evolution of the Kunlun and Qilian Terranes of the North Tibetan Plateau from Early Ordovician to Late Triassic (Modified from Yin & Harrison, 2000)
QAIDAM BASIN

Between the Kunlun fault system and the Qilian Shan on the northern edge of the Plateau lies the Qaidam Basin, which developed as a result of the orogeny of the adjacent mountain complexes in the Paleocene-early Eocene (Yin et al., 2008). The largest basin in the Tibetan Plateau, the Qaidam basin covers an area of 120,000 km² and averages approximately 3 km in elevation, in contrast to the 5 km elevations typical to the rest of the northeastern Plateau (Wang et al., 2006). Ordovician marine deposits are found interspersed with extrusive igneous deposits in many areas of the Basin, and competing models for deposition exist for the presence of these volcanics (Yin and Harrison, 2000). Paleozoic crystalline basement underlies the thick sedimentary basin. The sedimentary fill consists of Eocene-Quaternary sedimentary rocks that thicken toward the center of the basin to nearly 14 km and shallow to ~3 km toward the edges near the Kunlun Shan and Qilian Shan (Yin et al., 2008). Exploration drilling and seismic data show that during much of the Cenozoic, the area of maximum deposition was centrally located in the western area of the basin, indicating that the deeper Qaidam Basin sediments did not originate from the Kunlun and Qilian mountains, as deposits would have thickened toward the respective mountain ranges. The fine-grained sedimentary rocks of the ancient depocenter are hypothesized to have been deposited by a 2000 km-long Kunlun paleoriver in the west of the basin, which provides evidence against a foreland basin origin for the Qaidam Basin (Wang et al., 2006). Modern deposition originates from alluvial fill on the fringes of the Qaidam Basin’s boundaries. (Wang et al., 2006) A north-vergent thrust system with a mid-crustal decollement fault is hypothesized to underlay south-central Qaidam, which formed as a result of movement along the Altyn Tagh strike-slip system on the northern boundary. It may have uplifted the south side of the sedimentary synclinorium observed in the Qaidam Basin (Yin et al., 2008). The
Qilian Shan that lie to the north of the Qaidam Basin is also thought to be linked to accommodation tectonics of the Alytn Tagh. Timing of uplift of the Qilian Shan is uncertain, but is thought to have begun no later than 10 Ma, as a result of decrease in slip rate on the Alytn Tagh and initiation of shortening (Zheng et al., 2010).

**KUNLUN FAULT SYSTEM**

The Kunlun fault system (*Figure 1*) is an active, left-lateral, strike-slip fault that stretches for more than 1000 kilometers roughly from east to west. Fault-zone trapped wave analysis estimates the fault zone at around 300 m across (Wang et al., 2009). The timing of initiation of faulting is debated, but several recent studies (Meyer et al., 1998, Jolivet et al., 2003, Fu & Awata, 2007) suggest faulting began about 10 Ma, based on mapping of rocks with total slip up to ~100 km combined with Quaternary slip rates of ~10-20 mm/yr from GPS (Zhang et al., 2004), field observations (Yin et al., 2008b), and satellite remote sensing (Fu & Awata, 2007). The fault has accommodated a large portion of the northern Tibetan Plateau’s movement eastward relative to the Eurasian Plate. The eastern end of the fault experiences compression thought to be linked to the Longmenshan thrust, as well as the Qinling fault (Chen et al., 1994). In the west, the fault that defines the northern boundary of the Plateau (Yang and Liu, 2002). At the longitude of the INDEPTH IV profile, the Kunlun Fault has two branches (our NKF and SKF, *Figure 4*) with Songpan-Ganzi material between the branches.
SEISMIC INVESTIGATIONS OF NORTHERN TIBET

Numerous seismic studies have been undertaken to better understand the crustal structure and tectonics of the Tibetan Plateau. Given the magnitude of the deformation as a result of continental subduction and collision, the northern Plateau represents an important area to study constraints on uplift, fault slip movement, crustal flow, seismic anisotropy and mantle characteristics.

Imaging of mantle and lower crust structure is important in understanding dynamic processes on upper crust deformation of Northern Tibetan Plateau and its boundary with the Qaidam Basin. In a 2014 study seismologists analyzed a passive source seismic dataset extending from the eastern Qaidam basin north to the Qilian Shan. Utilizing P-wave and S-wave receiver functions, the researchers were able to interpret the broad structure of the subsurface to a depth of approximately 700 kilometers (Feng et al., 2014). Crustal thickness was found to average 45 to 65 kilometers. Interpretation of a mantle suture was also made, as well as what the researchers interpreted to be the Lithosphere and Asthenosphere Boundary (LAB). The LAB is an area of the Earth with sharp decrease of seismic velocity (often it is also a thermal boundary), typically located between depths of 70-300 km, where the mechanical properties gradually change from the elastic lithosphere to the plastically flowing asthenosphere (Rychert and Shearer, 2009). Another passive-source seismic survey interpreted a diffuse LAB at 90-130 km that dips toward the northeastern Tibetan Plateau from the Asian block but becomes diffuse under the Tibetan lithosphere (Shen et al., 2015). An LAB discontinuity was also interpreted at depths of 160-220 km under southern and northern Tibet using S-P converted seismic waves (Kumar et al., 2006).
A 2006 wide-angle seismic study of north-central Tibet along the Kunlun-Qaidam block to the east of the INDEPTH IV study area found crustal thickness ranging from 65 to 70-km, with portions crossing the Kunlun suture boundary increasing to 80-km to the south (Jiang et al., 2006). North of the Kunlun fault a wide-angle reflection/refraction profile of the Qaidam basin found an 8-km thick sedimentary layer atop a thicker 44-52-km crystalline crust, with thickness increasing at the boundaries of the basin (Zhao et al., 2013). Researchers have suggested a hotter upper mantle beneath northern Tibet which reinforces an argument for crustal partial melting which will be discussed later in this thesis (Unsworth et al., 2004).

Ambient noise tomography studies of northern Tibet have also illuminated velocity changes between associated with faults and topographic changes (Karplus et al., 2013). Low velocity anomalies are found in the middle crust, which the researchers interpret as the possible presence of partial melt. The researchers find that velocity contrasts associated with the sutures between the terrane blocks are not visible below 30 km, which is interpreted to be caused by crustal flow in the lower crust erasing any previous velocity contrasts that existed between the lower crustal roots. Paired with the observation that seismic activity is only observed in the ~20 km of the upper crust (Wei et al., 2010), the study shed much light on the composition and rheology of the crust in Northern Tibet (Karplus et al., 2013).

Detection of seismic anisotropy has also been an important method used to identify mineralogical changes, fractures or lithology boundaries in Tibetan crust. Seismic anisotropy – the variation of velocity with respect to azimuth – within the middle to upper crust serves as a possible indicator of crustal flow beneath the Plateau. Li et al., (2011) found a NE-SW fast seismic direction layer using shear-wave splitting analysis across the northeastern Plateau in the middle to lower crust, and a lower velocity that is interpreted as either deformation from the Indo-Asian collision, or asthenosphere flow. Confirmation of middle to lower crustal ductile
flow could contribute to better understanding of active deformation within the Plateau. In another 2011 study, researchers used passive-source earthquake data from Northeastern Tibet to model seismic anisotropy at middle to upper crust depths (Li et al., 2011).

Previous analysis of the INDEPTH IV reflection and refraction dataset have derived P-wave (Karplus et al., 2011) and S-wave (Mechie et al., 2012) models for the lithosphere beneath northern Tibet. The researchers observed a 20-km change in crustal thickness - from 70 kilometers beneath the Kunlun Mountains to 50 kilometers beneath the Qaidam Basin. The seismologists constructed a tectonic model showing possible the injection of lowermost Tibetan crust under the Qaidam Basin (Karplus et al., 2011). The presence of mid-crustal melt in the Plateau was previously hypothesized from both reflection/ refraction imaging (Nelson et al., 1996) and decreased magnetic signatures recorded by satellites, which may indicate that crustal temperatures exceeding 600°C suggesting widespread crustal melt (Alsdorf and Nelson, 1999).

A 2012 magnetolluric study also supported a crustal flow model into the Qaidam Basin using conductivity anisotropy across the northern region, and suggested that the Kunlun Fault serves as a significant rheological boundary in the Plateau, separating weak Tibetan crust from the cold Kunlun-Qaidam block (Le Pape et al., 2012).

The implied buried North Kunlun Thrust is thought to be a major driver of thickening of the Kunlun Thrust. (Shi et al., 2009) use receiver function analysis to investigate the Kunlun-Qaidam crust, and find evidence of a steeply north-dipping NKT to the north of the East Kunlun Mountains at a depth of 5 to 20 km. Dip of this feature was estimated at N10°-20° (Shi et al., 2009).

The shallow structure and extent of the damage zone of the Kunlun strike-slip fault was investigated by Wang et al. (2009). By analyzing the waveform pattern of fault-trapped waves,
determined that the fault-zone width (300 m) is similar to other major strike-slip faults, including the San Andreas Fault. When examining trapped wave propagation from explosive-sources from surrounding rock across the fault zone, P- and S- wave velocities were found to be attenuated by 7-20 percent, and 30-45 percent, respectively, to a depth of 1-2 km. Researchers interpreted this to indicate high fluid pressure within the fault zone, due to the greater attenuation of $V_s$ phases in contrast with $V_p$ phases (Wang et al., 2009). A high-resolution reflection seismic survey was conducted that crossed the eastern end of the Kunlun Fault-Songpan Ganzi Terrane boundary (at approximately 34°N 105°E, several hundred km to the east of our study area), and found that the North Kunlun Fault terminated in the middle crust at approximately 30-40 km depth along a shared decollement with the South Kunlun Fault. Numerous simple-shear zones associated with duplexing are interpreted within the Songpan-Ganzi and Kunlun blocks, which terminate in the subsurface. The Northern Kunlun fault in this area – referred to as the South Kunlun Fault in this paper – is found to steeply dip to the north at 60-75°.
SEISMICITY

Earthquakes are generally limited to the upper 30 kilometers across northern Tibet, though concentrated to the upper 5-15 kilometers. This constraint on seismicity supports the hypotheses of a weak, hot lower crust under the region and consistent with an asthenosphere upwelling (Wei et al., 2010). Events are mostly concentrated at boundaries of faults but also occur hundreds of kilometers away, indicating continual deformation of north Tibetan crust. Low velocity of Pn and Sn waves through the mantle under this area reinforces this model (Wei et al., 2010).

As previously discussed, the thrust faults of the eastern Plateau (e.g. the Longmenshen) accommodate the east-west crustal compression of the Plateau, while the strike-slip faults (e.g. the Kunlun fault) accommodate shearing that is occurring in the northern plateau boundary (Clark et al., 2010) (Turner et al., 2013). The Kunlun Fault in particular has experienced five earthquakes of greater than 7.0 in the past 100 years, including an 8.1 magnitude event in 2001 (Fu & Awata, 2007). The 2001 earthquake was the most powerful event in China in the past fifty years, and had an epicenter near Kusai Lake. (Figure 3) The sparsely populated regions around the earthquake zone prevented any casualties (Zhao et al., 2008). The event propagated from a smaller strike-slip section of the main Kunlun fault and caused co-seismic surface ruptures up to 60 kilometers from the Kunlun fault zone (Liu and Haselwimmer, 2006). The rupture propagated to within 10-20 km of the INDEPTH IV study area (Karplus et al., 2011) and field observations of the rupture area estimated the dip of the North Kunlun fault at approximately 83°S.
Figure 3 - Focal mechanisms of the 2001 Kunlun earthquake. The map shows predominantly strike-slip faulting in middle and southwestern rupture zone, with normal faulting in northwest map area. Yellow extent boxes and numbered circles are study areas from the Liu & Haselwimmer paper. (Modified from Liu & Haselwimmer, 2006)
DATA

Project INDEPTH IV was an interdisciplinary project that collected passive-source earthquake data, seismic refraction and reflection data, and magnetotelluric data in northern Tibet. The seismic refraction and reflection component was acquired during the summer of 2007 along a 270-km north-to-south profile (Figure 4) The instrument array consisted of 655 Reftek RT125 PASSCAL “Texan” dataloggers with 4.5-Hz vertical component geophones spanning the entire 270 km profile for near offset recording at 100 meter spacing, an additional 295 identical instruments spaced at 650 meters for wide-angle coverage along the entire profile, and a Sercel 1000-channel cabled array with 50 meter takeout spacing for higher resolution in the middle section of the profile. Also deployed were 48 three-component short-period and broadband seismometers spaced at 5 to 6 kilometers along the full length of the profile. The Sercel cabled-array and 3-component data were not used in this paper’s analysis. The shot sources consisted of 105 smaller shots (60 to 240-kg charges) spaced at 1 km, and five large-scale shots (1000 to 2000-kg charges) named KS1-KS5 detonated to cover the entire profile (Karplus et al., 2011). For this research, I utilized the Texan vertical component data with 650-m and 100-m spacing exclusively.
Figure 4 - Tectonic map and sutures of the Kunlun fault and surrounding regions, with regional inset. The INDEPTH IV active-source profile is displayed, with corresponding shot and receiver elements. Fault GMT database sourced from Taylor, 2009. 9013, 9028, and KS4 on map are locations of shot gathers in Figures 5, 6, 7, respectively.
METHODS

Initial data processing included merging together the traces recorded by the Texan seismometers into SEG-Y shot gathers. The data were then resampled to a uniform 8 ms (data was recorded at 2 ms, 4 ms, and 8 ms sampling rates depending on the size of the memory cards used). The large shots were numbered 9910, 9920, 9930, 9940, 9950, and 9951. The small shots were numbered 9002-9119. Shot records 9151-9166 were merely noise strips (used to characterize random survey noise) and were omitted from further processing. Processing consisted of three related processes: 1) Initial examination of raw data to inspect major phases and average velocity 2) standard reflection processing sequence to create a common-depth-point stack 3) analysis of fault-related refracted reflections for information on dip angle and general location of NKF and SKF.

RAW SHOT GATHERS

After loading of the SEG-Y files into Landmark’s ProMAX software, I viewed all shots to identify seismic phases and look for any acquisition issues. All shot gathers had an Ormsby bandpass filter at 2-4-8-16 Hz applied. Figure 5 shows a small-shot gather 9013 from the beginning of the INDEPTH line in the southern end overlying Songpan-Ganzi terrane. First-breaks, created by upper crustal refractions ($P_g$) propagate out from the shot source to a distance of slightly over 40 km, with an average velocity of 6 to 6.5 km/s. $P_g$ velocities in the 10-km shot-receiver range are approximately 5 km/s. Velocity increases in this phase are noted at the 20-km offset range, as well as at 35 km. Reflection phases are also seen in the section immediately after the first-arrival energy, identified by their characteristic hyperbolic moveout. Further north in the line, a small shot 9028 (Figure 6) – roughly equidistant between the NKF
and SKF – also shows a $P_g$ refraction first-arrival propagating to over 20 km shot-receiver distance before attenuation, and displaying an average velocity of 6.5 km/s. A slight velocity increase is again seen at 17 km shot-receiver offset. Reflections are also seen in this phase, though are difficult to identify due to high-amplitude surface wave noise. Seismic phases are more distinct propagating to the south than to the north in this section. On the northern end of the line, big shot 9940/KS4 (Figure 7) overlies the Qaidam Basin sediments, and increased noise from the city of Golmud is seen in the data. Near-offset $P_g$ velocities are approximately 2 km/s, increasing to 5.5 km/s past 60 km offset (i.e. at greater depths). Qaidam sediments are a likely cause of decreased velocities in this region.

![Figure 5 - Small-shot gather 9013 on south end of line. Black flag is shot location, x-axis is offset in km offset between receiver and source, y-axis is time in milliseconds (not true scale). $P_g$ wave is first-arrival phase from upper crust refractions. Bandpass filter at 2-16 Hz applied to all raw shot gathers. See Figure 4 location marked 9013 for location of shot along INDEPTH IV profile.](image-url)
Figure 6 – Small-shot 9028, roughly between NKF and SKF. Pg phase is crustal refraction. See Figure 4 location marked 9028 for location of shot along INDEPTH IV profile.
Figure 7 - Big-shot 9904 on northern end of line in Qaidam Basin. Pg phase propagates across entire profile. See Figure 4 'KS4' for location of profile.
GEOMETRY

During geometry assignment in ProMAX, source and receiver coordinate information was imported from the TRC (trace) database for use in geometry spreadsheet operations. Due to topographic constraints, permitting and logistical issues, the survey line azimuth was extremely variable, and shot/receiver inline/crossline offset varied to a degree. As a result of the spatial variance of the survey line, a crooked line geometry assignment was used for assigning midpoints. The crooked line geometry feature generates a best-fit processing line (utilizing user-defined parameters) through the survey midpoints, with the processing line serving as the center point of the midpoint boxes, or ‘bins’. An ideal geometry assignment strives to maximize signal-to-noise ratio by capturing all survey midpoints and exploiting maximum survey fold.

Crooked line acquisition also introduces a pseudo-3-D element to a nominally 2-D working space, which must be taken into account when interpreting the seismic section. These issues proved problematic for correct Common Depth Point (CDP) binning assignment, as inconsistent fold and variable spacing (i.e. 650-m wide-angle shots vs. 100-m near offset shots in the central portion) proves challenging for defining a common depth point geometry (Wu, 1996).

Binning collects all traces within user-defined squares or rectangular regions and stacks them together to enhance signal and create an image of the subsurface at that depth point. A rule of thumb for bin space is an ideally square dimension that is half of the nominal shot-receiver spacing in the inline direction, i.e. for our 100-m shot-receiver in the densest section of the array, a 50-m by 50-m bin spacing should give the most optimal results. Experiments with 50-m by 50-m bin spacing and a 269-km maximum offset parameter track proved both computationally
intensive and did not produce a satisfactory signal-to-noise ratio. (Figure 8)

![Figure 8](image.png)

Figure 8—(Left): CDP trial stack with low signal-to-noise from 50-m by 50-m square bin and parameter track set to 269km. CDP stacking function was set to dump all null CDP values, so many midpoints were jettisoned. (Right): Midpoint coverage (white) vs binning locations (magenta). Note binning does not maximize midpoint coverage along the profile.

The inconsistent midpoint distribution and bin overlapping is suspected to have caused an error in common midpoint placement. Attempts at straight-line slalom binning and extremely large crossline bin parameters (in an attempt to capture all midpoints along the survey line) also proved unsuccessful at producing a coherent image. Crooked line track parameterization takes user-defined inputs and attempts to create a best-fit model that plots a processing like through the area of optimal midpoint coverage. A crooked-line parameterization utilizing the Texan receiver coordinates (located in Promax’s SRF database) produced the most satisfactory best-fit line through the midpoint coverage. A 50-m (inline) by 20-km (crossline) bin dimension provided optimal midpoint collection result while preventing smearing of structure in the area of interest (Figure 9).
Figure 9 – (Left) Plot of the parameterization line used for midpoint binning definition, using SRF number (Promax’s native receiver spreadsheet). Black line represents the Texan receiver array, white line is the source array, and green line represents the best-fit parameter line calculated through the midpoints. (Right) INDEPTH profile shown on the left figure, but with survey midpoints and bin dimensions overlaid. Midpoints are the multi-colored area that varies according to offset, while binning dimensions are light-blue semitransparent rectangles. Note midpoints at extreme offsets that were not captured by the bins.
After quality-checking trace fold, the following trace editing was applied to the geometry-corrected data (Figure 10):

1) Noisy traces were deleted – Instrument error, environmental and cultural noise created undesirable noise energy along the entire trace.

2) Air wave mute – energy produced by the explosive blast (~300 m/s velocity) was removed.

3) Top mute was applied to remove the first-break energy. For a small shot-receiver offset, the first break energy travels in a straight line from shot to receiver. For longer offsets, the head-wave refraction is the first energy to reach the receiver. (Sheriff and Geldart, 1995) The high-amplitude nature of first-break refractions can drown out deeper reflection energy and must be removed prior to stacking. (Yilmaz, 2001) The top mute zeroes out all energy before the mute, including pre-first break noise, which improves stacking image quality.

Figure 10 - Left: Original shot gather before trace editing. Center: Noisy traces killed (Red), air wave surgical mute (Green), and first break mutes (Blue). Right: Shot gather after application of mutes.
ELEVATION STATIC CORRECTION

The INDEPTH IV survey line transects extremely rugged and variable terrain, with elevation in the Kunlun pass reaching 4800 m, decreasing to approximately 2600 m in the Qaidam Basin on the northern end of the profile. This variation causes undesirable effects on arrival times which must be corrected prior to CDP stacking using an elevation statics correction. Elevation statics corrections also account for a near-surface weathering layer’s effect on arrivals. (Yilmaz, 2001)

![Diagram of Elevation Statics Correction](image)

*Figure 11 – Principle of elevation statics corrections. N_Datum is the processing datum ProMAX uses to calculate replacement velocity time shifts from the weathering layer to the replacement layer (Vreplacement), which are then pushed down to the user-defined final datum (F_Datum). S_Static, C_Static and R_Static are ProMAX defined trace headers where arrival time corrections are stored for source point, CDP and receiver locations, respectively.*

These corrections require the selection of a final datum to which traces will be shifted, as well as a replacement velocity for the weathering layer. All traces above the final datum are shifted downward in time, while traces that are below the datum have time added to the top of the trace, and are given the defined replacement velocity (*Figure 11*). The highest elevations in the INDEPTH IV profile are approximately 4800 m. A final datum of 4600 m was chosen to
minimize loss of data and velocity detail at the highest elevations. The replacement velocity of 3500 m/s was selected based on a previously constructed velocity model (Karplus et al., 2011). 

*Figure 12* shows the result of the elevation statics correction. Receivers with extreme elevation drops are assumed to have incorrect elevation data in their headers.

**COMMON DEPTH POINT (CDP) STACKING**

Following application of elevation statics, a spiking deconvolution was performed on the data. Deconvolution is one of the most important processing steps to improve seismic image quality, and involves the convolution of the data with an inverse filter – with the desired product being the earth response to the signal (Sheriff and Geldart, 1995). Deconvolution is a powerful tool used to attenuate multiple reflections and aim to produce a zero-phase wavelet, i.e. a wavelet symmetrical about its axes. (Yilmaz, 2001)
Deconvolution operation requires the construction of a defined top and bottom time gate to process the inverse filter. The top time gate is normally set just below the high-amplitude refraction energy to avoid ‘ringing’ effects following the refraction horizon, though it can sometimes be set to include the entirety of the dataset. The bottom time gate can be placed at the bottom of the section, or at an area where the deepest reflections are expected to be found - or simply below the deepest section that the processor is interested in. This preference largely depends on processing objectives and acquisition details (Yilmaz, 2001).

For INDEPTH IV, a top time gate was defined just below the refractions, and set at approximately 20 seconds in the section, to include theorized reflections from the LAB. Parameter testing was then conducted to determine the optimal operator length over which to apply the deconvolution (Figure 13). Operator lengths of 80 ms, 120 ms, and 240 ms were tested. The 240 ms operator length produced smearing along the depth closest to the muted first break energy, and 80 ms produced noise ‘spikes’ following reflectors. A value of 120 ms was determined as the optimal operator length.
After an initial deconvolution was tested with the 120 ms operator, a spectral analysis was then conducted to examine the effects of the operator in the frequency content domain, as well as allow the design of a bandpass filter to be tested. Spectral analysis indicated the desired ‘whitening’ of the frequency domain was achieved, which indicates lateral continuity of the desired frequency range at increased offset. This whitening is prevalent in the deconvolved shot gathers, which show strong and more laterally continuous reflection energy in the section. Some high frequency noise was present at offsets of ~40 km (Figure 14).
The deconvolution process in ProMAX allows a bandpass filter to be run after completion of the deconvolution operation, so a shot gather was inspected before and after application of a 2-4-8-16 Hz bandpass filter to determine its effectiveness (Figure 15). Spectral analysis indicated that high frequency ringing artifacts were introduced following the deconvolution operation (Figure 16), and the bandpass filter successfully attenuated most of the ringing, though it was not completely eliminated (Figure 17). Other filters (0-20 Hz) were tested, but gave poor results.
Figure 15 – Left: Original shot gather 9002 with deconvolution applied. Right: Deconvolution with 2-4-8-16 Hz bandpass filter applied.

Figure 16 – Spectral analysis of shot gather 9002 after application of deconvolution, with high frequency wavetrain seen on waveform analysis plot (top right-hand corner). Left panel is the shot gather, top middle is zoomed in area of blue rectangle, bottom middle is frequency content. Top right displays power spectra, bottom right displays phase spectra.
After application of the deconvolution filter, a CDP stack was produced to quality-check the data before Velocity Analysis (Figure 18). Application of the elevation statics correction produced sub-optimal results (Figure 19). Surface waves contaminated much of the data and made any identification of structure of fault surfaces impossible. Supergathers (groups of CDPs stacked together to increase lateral signal across interfaces) were created in an attempt at running a Velocity Analysis on the data, but the poor quality of the CDP stack prevented any meaningful information from being derived from a Velocity Analysis.

I examined CDP stacks produced with a variety of different options including displaying CDP subsections of the crooked line profile, various time axis ranges, and midpoint parameterizations to attempt better imaging resolution. A CDP stack was generated using only the 100-m spaced Texan receivers in the central portion of the profile, which eliminated the far-
offset midpoints that were suspected of causing geometry issues. Coherent noise (surface noise) was still prevalent in the section, but Automatic Gain Control (AGC) was able to mitigate some of the coherent noise and strengthen reflections from later-arriving events in the subsurface.

Interpretation of this near-offset CDP stack is found in the *Results* section later in this paper.

*Top: Figure 18 –* CDP stack at 50-m by 50-m bin spacing and processing (first break muting, trace kill, deconvolution with 2-16 Hz bandpass filter). Surface waves dominate the section, and elevation statics correction has not sufficiently adjusted for elevation change across profile. **Bottom: Figure 19 -** CDP Stack (same processing parameters, with elevation statics applied).
Conventional seismic acquisition is designed to capture attribute contrasts between horizontal, generally isotropic layers in the subsurface. However, impedance contrasts across vertical fault plane interfaces can allow reflected energy to be detected at the surface, much like conventional horizontal layer contrast reflectivity in traditional seismic acquisition (e.g., Hole et al., 1996). First arrival refracted energy can intersect a fault plane, reflecting energy back to receivers at approximately 90 degrees with respect to the dip of the first break arrivals – effectively a zero moveout. Identification of these zero-moveout reflections is done before stacking, as NMO correction will destroy these signatures. Steep-dip imaging can produce information on geometry and fault dip (Hole et al., 1996). Figure 20 - Top Panel shows a synthetic seismogram that displays how fault dip information can be obtained from seismic records (Hole et al., 1996). Figure 20 - Bottom Panel shows a cross-section of the INDEPTH IV survey showing a ray trace illustration of how a refraction head wave reflects off a steeply dipping reflector – in this case, the North Kunlun Fault.
Top: Figure 20 Synthetic Seismogram for the San Andreas fault. Shown are possible horizontal fault reflection angles (0 degrees) and vertical fault reflections at 60, 90, and 120 degrees, respectively. ‘A’ is a modeling artifact produced during the calculation (modified from Hole et al., 1996). Bottom (20): A model raypath for a head wave that is reflected back from North Kunlun Fault and recorded on an adjacent receiver. Section is for illustrative purposes and is not to scale.

Raw bandpass-filtered (at 2-4-8-16 Hz) shot gathers were visually inspected for vertical reflections. Shot gathers were viewed using a constant offset spacing to preserve aspect ratio and image true fault dip with respect to first arrivals. Interpreted fault reflections were catalogued by source shot number, receiver that the reflection was recorded on, and source-receiver offset. A
scatter graph of absolute offset vs. receiver number was produced, which served two purposes: 1) Identify the maximum estimated source-receiver offset where fault reflections traveled, and 2) Increase confidence of fault reflection interpretation of the North Kunlun Fault by displaying frequency of reflections on specific receivers. The area of the survey line between receivers 6350 and 6450 (a length of approximately 10 km, as the receivers in this area were spaced at 100-m) contained the greatest number of interpreted fault reflections. The CDP stack previously generated in reflection processing was then examined to determine CDP numbers that were in the same geographic location as Texan receivers 6350-6450. CDPs 1730 to 1800 fell within this range and were examined for evidence of a strong vertical reflector at the location of the North Kunlun Fault.
RESULTS AND DISCUSSION

Figure 21 displays the maximum trace fold of the INDEPTH IV profile, with the highest fold in the middle of the line inside the dense 100-m Texan coverage. For the geometry assignment, a compromise had to be made between collecting as many midpoints as possible, while balancing the need to avoid imposing a false geology due to cross-dip variation along profile. A larger bin dimension normally corresponds to greater signal-to-noise ratio and greater trace fold in each bin (Yilmaz, 2001) and would have been preferable for INDEPTH, but the primary goal of fault imaging of the North Kunlun Fault/South Kunlun Fault needed to be taken into account as well. While bin size values of 325-m (inline) by 1000-m (crossline) produced reasonably well-placed midpoint assignments, the receiver spacing within the targeting areas of the NKF (North Kunlun Fault) and SKF (South Kunlun Fault) was 100 meters, so a 50-m (inline) by 20-km bin (crossline) bin space was used. This bin spacing allowed for a better resolution in the desired target areas of the NKF/SKF, and collected as many traces as possible in the crossline direction to increase signal/noise ratio, while preventing smearing of geologic structures of interest.

Additionally, a parameter track utilizing the unique surface locations of the Texan receivers was able to produce the straightest possible line through the densest fold coverage of the survey, while preserving the geology and signal-to-noise ratio of the data. CDP fold across INDEPTH IV after the previously detailed parameters is displayed in Figure 22.
Figure 21 - Fold diagram based on 1 km x 1 km bin dimensions. Notice the very sparse coverage on the ends of the survey and very high fold in the region near the NKF and SKF (Courtesy of Dan Hollis, Green Mountain Geophysics)
Application of elevation statics produced poor results during trial CDP stacking with somewhat jagged smoothing from CDP to CDP in some areas (Figure 18). Trial stacks using faster replacement velocities (4800 m/s) and longer CDP smoothing factors did not improve the image. Conservative first break muting and air wave editing improved resolution in later times in the section, but CDP stacking prior to Velocity Analysis did not produce sufficient resolution and image quality to interpret fault locations or geometries. Velocity Analysis was attempted to produce stacking velocities, but was abandoned due to poor quality of the reflection processing. Coherent noise from surface waves dominated the CDP stacks, which are an issue exacerbated by bends in crooked-line geometries (Wu, 1996). Stacking separate straight-line sections is a possible method to mitigate the issue of midpoint assignment with variable geometries. Another possibility might be collapsing shot and receiver coordinates onto a straight line before importing into Promax, at the expense of causing issues with crossdip geometry information. Additionally,
the use of more robust surface wave filtering, such as frequency-wave number ($f$-$k$) domain filters, might be able to more robustly remove the surface noise that dominates the CDP stacks.

A CDP stack using only the 100-meter spaced receivers in the central portion of the profile was subsequently generated, which allowed interpretation of a reflection dipping approximately 15° South from the North Kunlun Thrust underlying the Kunlun Suture to be identified at 6 to 7 seconds at depth in the section (Figure 23 and 24). Dip was estimated using trigonometric calculation. Assuming an average crustal velocity of 6 km/s, this would correspond to a depth of roughly 18-21 km for an NKT that underlies the East Kunlun Mountains. Apparent dip direction and subsurface location of the reflector rule out an NKF or SKF interpretation of the feature.

![Figure 23](image_url)

*Figure 23 – CDP stack of the 100m spaced Texas receivers in the central profile. Automatic Gain Control and 2-16 Hz Bandpass filter applied. CDPs binned at 50m spacing across x-axis. Y-axis is two-way travel-time in milliseconds.*
Fault reflection imaging was aimed at identifying possible fault reflections on multiple receivers to increase confidence in picking real (i.e. not noise-related events) reflection locations along the profile. The North Kunlun Fault is approximately 112 kilometers north (as the crow flies) from the south end of the line, and is closest to receiver 6465. The South Kunlun Fault is located approximately 81 kilometers north from the south end of the line, closest to Receiver 6152. The interval between receivers 6350 and 6450 – representing a distance of 10-km, most frequently saw interpreted fault reflections. No fault reflections with a source-receiver offset greater than 80-km were documented, and the majority fell within a range of 20-km (Figure 25). Receivers within the range 6371 to 6386 – a length of 1500 meters – displayed 14 fault reflection picks. This represents a distance from the mapped location of the North Kunlun Fault of approximately 4 km. Receivers 6150 to 6200 – in the vicinity of the South Kunlun Fault, also displayed 14 fault reflection picks, spread over a length of 5 km (Figure 25).
Location of the NKF is interpreted by examining receiver channel concentration of fault reflections, and referencing with the mapped surface location of the NKF. Apparent slope of the North Kunlun Fault is approximately 65°S, displaying a similar slope to the first arrival energy, but rotated at a right angle relative to the first arrivals’ slope. Dip was estimates using trigonometric calculation of dip angle by assuming a horizontal reflector boundary and solving for the fault reflection angle with respect to the first-arrival slope. Wang et al., 2009 found that the NKF dipped at 85° toward the south, using fault-zone trapped wave analysis. Calculated dip of 65°S in contrast to 81°-85°S calculated in others studies (Liu and Haselwimmer, 2006) (Wang et al., 2009) might be due to source-receiver azimuth of my observed fault reflections and the effect on apparent dip. The reflection from the fault is difficult to image past 1000 ms (roughly 5 km at an average velocity of 5 km/s), but does not appear to change slope deeper in the section. More robust surface noise filtering is required to determine if the dip of the fault changes at depth. The width of the reflector boundary is quite thin, considering that the estimated fault zone

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*Figure 25 – Fault reflection picks observed at specific receiver channel numbers versus source-receiver offset.*
of the NKF is 300 m (Wang et al., 2009). See Figure 26 for interpreted fault reflection off the North Kunlun Fault.

Figure 26 - Shot Gather 9028, with blue arrow indicating interpreted fault reflection from NKF, and red line displaying intersection with first break arrivals. X-axis is in kilometers, Y-axis is time in milliseconds. Red line is at a shot-receiver offset of 12km at receiver 6395.
In the South, the interpreted fault reflections from the South Kunlun Fault were less numerous, and reflection segments much shorter before being attenuated at depth (*Figure 27*). Fault dip was estimated at approximately 78°N to at least 700 milliseconds (approximately 3.5 km based on an average 5 km/s velocity) though this was difficult to accurately determine due to the lower velocity contrast across the SKF and contamination by surface wave energy, which is common in sub-vertical fault imaging (Hole et al., 1996). Dip was estimated by trigonometric calculation of angles assuming a flat refractor layer. Reflection segments were not vertically continuous enough to determine the presence of a change in dip at crustal depths to meet a common decollement interface linked to the NKF. The vertical reflections were observed in other areas along the profile, which could represent unmapped faults, rose structures associated with bends in the NKF and SKF, or reflections off different sections of the variable NKF/SKF fault zone interfaces.
Figure 27 – Shot gather of Shot 9023 with blue arrow indicating interpreted fault reflection from SKF, and red line displaying intersection with first break arrivals. X-axis is in kilometers, Y-axis is time in milliseconds. Red line is at a shot-receiver offset of 7.5km at receiver 6180. Note change in apparent angle of reflection vs the interpreted fault reflection from the NKF.
CONCLUSIONS

A CDP stack using the Texan near-vertical receivers allowed mitigation of some of the effects of midpoint scattering and geometry issues associated with the crooked-line geometry. A strong reflection is seen in the stack near the CDP range 1060-1160 at a two-way travel time depth of 6-7 seconds. At an estimated depth of 18-21 km and underneath the East Kunlun Mountains, I interpret this reflection to be from the buried North Kunlun Thrust. The dip is estimated at 15° South, which indicates that main movement is thrusting to the north. Location of the thrust directly north of the North Kunlun Fault indicates that the North Kunlun Thrust extends at least as far south as the NKF. What is unclear from the data is if the NKT continues at depth to the south, or shares a common decollement with the NKF/SKF.

My inability to produce a reflection stack of satisfactory resolution was largely due to complications with midpoint binning and the difficulties associated with ‘mountain-front processing’, i.e. surveys with severe topographic variation along the profile, uneven trace fold and complex geology. Future processing could attempt mitigation of these issues by processing the crooked line along three (or more) straight line segments to minimize midpoint scatter and uneven offset or application of post-stack migration techniques. 2-D refraction velocity inversion modeling with my first arrival picks may also shed light on velocity changes and contrasts associated with the Songpan-Ganzi and Kunlun-Qaidam terranes, the North Kunlun and South Kunlun Faults, the Kunlun Thrust, and other regional structures. Further reflection processing may also illuminate the general Moho structure at depth, as well as perhaps more detailed structure of the buried Kunlun Thrust System. Fault reflection imaging of the NKF and SKF provided information on estimated apparent dip angle and location of faults at depth, as well as constraints on limits of fault reflections at far offsets. A near-vertical NKF and slightly north-
dipping SKF agree with a geometry model of crustal-scale faults that terminate in the upper crust along a common decollement. Vertical fault imaging remains a useful technique for identifying reflectivity contrasts across fault zones, as well as identifying possible unexposed subsurface faults and synclinal structures associated with strike-slip faults like the Kunlun Fault System. Numerous vertical reflections were found outside of the general locations of the NKF and SKF, which could imply small, buried normal faults that accommodate some of the fault stress associated with the main faults, similar to the buried simple-shear zones interpreted in (Wang et al., 2011). These reflectors could also indicate the velocity contrasts in different sections of the NKF and SKF fault zones, as fault zones are inherently variable reflectors (Sheriff and Geldart, 1995). Future work could also investigate possible fault asperities of the NKF and SKF that may indicate locked sections of the fault, which would have broad implications for future seismicity in the region.
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CURRICULUM VITAE

William Seelig was born in Arlington, Texas, and grew up in El Paso, Texas. He completed his Bachelor’s degree at the UTEP in 2009 and began working in human resources for several years. In 2013, he began taking courses toward a degree in the geosciences. He joined the UTEP Geological Sciences graduate program in 2015 to pursue a Master’s Degree in Geophysics, and worked as a Research Assistant under the direction of Dr. Marianne Karplus on the INDEPTH IV survey. During his studies, he served as President of the UTEP chapter of the Society of Exploration Geophysicists and was a recipient of the Permian Basin Area Foundation Scholarship Award. While completing his M.S., he accepted a concurrent position with the U.S. Geological Survey in Menlo Park, and plans to continue his career as a permanent employee with the USGS.

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