Shear-wave splitting and mantle deformation beneath the western Tibetan plateau

Melissa Ann Ray

Follow this and additional works at: http://scholarsmine.mst.edu/masters_theses

Recommended Citation
© 2014
Melissa Ann Ray
All Rights Reserved
ABSTRACT

The Tibetan Plateau has been an enigma to the scientific community since scientists first began to focus their attention on the area. Numerous studies over the decades were conducted to address how the plateau formed, mostly in the central and eastern portions of the Tibetan Plateau. Many questions still remain regarding the western Tibetan Plateau, and this study will add constraints to the mechanisms which regulated the formation of the plateau.

Data was acquired from over 13,000 measurements from 172 stations covering the western region of the plateau encompassing the Qiangtang Terrane, the Lhasa Terrane, and the Himalayan Orogenic Zone. A shear-wave splitting (SWS) method was utilized in order to analyze the seismic anisotropy beneath the plateau.

We present individual measurements here in order to examine spatial variations in splitting time and orientation. After careful analysis, the resulting data set consists of 426 measurements which demonstrate that the study area is characterized by significant anisotropy. All measurements of sufficient quality were used, providing azimuthal coverage surpassing those of the previous study which used station averaged measurements. An E-W orientation is visible in the orogenic zone that rotates to a NE-SW direction north of the Indus-Yalu suture and then rotates to an E-W orientation at approximately 32°N. The Indian plate is subducting the plateau from the south to 33°N, while the Eurasian plate is subducting from the north to 30°N, overlapping between these two points and causing the uplift of the plateau.
ACKNOWLEDGMENTS

I would like to thank Dr. Kelly Liu and Dr. Stephen Gao at Missouri University of Science and Technology for their help and ideas provided in contribution of this study. Without their suggestions and input, this thesis would not have been possible. I would also like to extend gratitude to the Incorporated Research Institutions for Seismology (IRIS) Data Management Center (DMC), from where all the data presented in this study have been requested.

I have further thanks to give to everyone who helped me over the years while working on this study. I would like to thank my friends for taking the time to review my information as well as reading through my work and giving their input.

Special thanks goes out to Cory Reed and Bin Yang, two colleagues at the Missouri University of Science and Technology, who have contributed a significant portion of their spare time to helping me improve the quality of this study: Cory Reed and Bin Yang.
## TABLE OF CONTENTS

<table>
<thead>
<tr>
<th>Section/Layer</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>ABSTRACT</td>
<td>iii</td>
</tr>
<tr>
<td>ACKNOWLEDGMENTS</td>
<td>iv</td>
</tr>
<tr>
<td>LIST OF ILLUSTRATIONS</td>
<td>vii</td>
</tr>
<tr>
<td>SECTION</td>
<td></td>
</tr>
<tr>
<td>1. INTRODUCTION</td>
<td>1</td>
</tr>
<tr>
<td>1.1. GEOLOGICAL BACKGROUND</td>
<td>1</td>
</tr>
<tr>
<td>1.2. OBJECTIVES</td>
<td>6</td>
</tr>
<tr>
<td>2. LITHOSPHERIC MANTLE MODELS</td>
<td>7</td>
</tr>
<tr>
<td>2.1. P-WAVE VELOCITY MODEL</td>
<td>7</td>
</tr>
<tr>
<td>2.2. TOMOGRAPHIC MODEL</td>
<td>8</td>
</tr>
<tr>
<td>2.3. INDEPTH REFLECTION PROFILES</td>
<td>10</td>
</tr>
<tr>
<td>2.4. BOUGUER GRAVITY ANOMALIES</td>
<td>11</td>
</tr>
<tr>
<td>2.5. DOWNWELLING INDIAN LITHOSPHERE</td>
<td>12</td>
</tr>
<tr>
<td>2.6. TELESEISMIC RECEIVER FUNCTIONS</td>
<td>13</td>
</tr>
<tr>
<td>2.7. TELESEISMIC SHEAR-COUPLED P-WAVES</td>
<td>15</td>
</tr>
<tr>
<td>2.8. SEISMIC ANISOTROPY</td>
<td>16</td>
</tr>
<tr>
<td>2.9. SEISMIC POLARIZATION ANISOTROPY</td>
<td>17</td>
</tr>
<tr>
<td>3. DATA AND METHOD</td>
<td>19</td>
</tr>
<tr>
<td>3.1. DATA</td>
<td>19</td>
</tr>
<tr>
<td>3.2. METHOD</td>
<td>21</td>
</tr>
<tr>
<td>3.2.1. Rank A</td>
<td>23</td>
</tr>
</tbody>
</table>
**LIST OF ILLUSTRATIONS**

<table>
<thead>
<tr>
<th>Figure</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.1. The location of the study area and surroundings within the Tibetan Plateau</td>
<td>3</td>
</tr>
<tr>
<td>1.2. Illustration of wave splitting in an anisotropic medium and core refracted seismic phases</td>
<td>5</td>
</tr>
<tr>
<td>2.1. Vertical cross-section showing P-wave velocity model to a depth of 1700 km (Li et al., 2006)</td>
<td>7</td>
</tr>
<tr>
<td>2.2. Cross-section showing P-wave lateral velocities with a tomographic profile (Zhou and Murphy, 2005)</td>
<td>9</td>
</tr>
<tr>
<td>2.3. Cross-section showing resulting interpretation of reflection profiles with geologic cross sections (Hauck et al., 1998)</td>
<td>10</td>
</tr>
<tr>
<td>2.4. Diagram showing interpretation from bouguer gravity anomalies and seismic anisotropy (Chen and Ozalaybey, 1998)</td>
<td>11</td>
</tr>
<tr>
<td>2.5. Cross-section showing downwelling Indian lithosphere (Tilmann et al., 2003)</td>
<td>13</td>
</tr>
<tr>
<td>2.6. Tomographic model from teleseismic receiver functions (Kosarev et al., 1999)</td>
<td>14</td>
</tr>
<tr>
<td>2.7. Lithospheric cross-section showing average Poisson’s ratio (Owens and Zandt, 1997)</td>
<td>15</td>
</tr>
<tr>
<td>2.8. Cross-section of Himalayan-Tibetan collision zone resulting from shear-wave splitting (Sandvol et al., 1997)</td>
<td>17</td>
</tr>
<tr>
<td>2.9. Interpretative cross-section of the Tibetan Plateau resulting from shear-wave splitting (Huang et al., 2000)</td>
<td>18</td>
</tr>
<tr>
<td>3.1. Azimuthal equidistant projection showing event locations</td>
<td>20</td>
</tr>
<tr>
<td>3.2. Flow chart showing procedure</td>
<td>22</td>
</tr>
<tr>
<td>3.3. An example of a quality ‘A’ measurement</td>
<td>24</td>
</tr>
<tr>
<td>3.4. An example of a ‘B’ quality event</td>
<td>25</td>
</tr>
</tbody>
</table>
3.5. An example of a ‘C’ measurement. ................................................................. 26
3.6. An example of a quality ‘N’ event................................................................. 27
3.7. An example of a quality ‘S’ event. ................................................................. 28
3.8. A summary plot from station H1190 .............................................................. 30
4.1. An enhanced view of the study area ............................................................. 32
4.2. PKS measurements which have been selected in this study ......................... 33
4.3. SKKS measurements that are used in this study ........................................... 34
4.4. SKS measurements that have been selected in this study ............................. 35
4.5. Shear-wave measurements in Area 1 ............................................................. 36
4.6. Shear-wave measurements in Area 2 ............................................................. 37
4.7. Shear-wave measurements in Area 3 ............................................................. 38
4.8. Shear-wave measurements in Area 4 ............................................................. 39
4.9. Shear-wave measurements in Area 5 ............................................................. 40
4.10. Shear-wave measurements in Area 6 ............................................................ 41
4.11. Shear-wave measurements in Area 7 ........................................................... 42
4.12. Shear-wave measurements in Area 8 ........................................................... 43
4.13. Shear-wave measurements in Area 9 ........................................................... 44
1. INTRODUCTION

1.1. GEOLOGICAL BACKGROUND

The Tibetan Plateau has a long and complex geologic history. It is widely accepted that the plateau formed in response to the collision between the Eurasian and Indian plates initiating approximately 70-50 Mya (Hsu et al., 1995; Sengor and Natal’in, 1996; Yin and Harrison, 2000). The mechanisms causing this collision, on the other hand, are still debated and studied to this day.

Preceding the collision of India and Eurasia, the two plates were separated by the Tethys Ocean. At approximately 140 Mya, a subduction zone formed as a result of the Tethys Ocean being subducted beneath Eurasia (Singh and Kumar, 2009). This northward convergence is ongoing and has caused the formation of several mountain ranges is responsible for the initial formation of the Tibetan Plateau.

The Tibetan Plateau reaches approximately 5 km in elevation and is home to the tallest and most famous mountain range on Earth, the Himalayas. The plateau contains the thickest crust known to exist, varying between 65 km and 75 km, which is twice the global average thickness of 35 km (Fowler, 1990; Twiss and Moores, 1992; Christensen and Mooney, 1995)

There are two terranes present within the study area: the Qiangtang Terrane in the north and the Lhasa Terrane in the south. The Lhasa Terrane is surrounded by the Bangong-Nujiang suture to the north and the Indus-Yalu suture in the south (Figure 1.1). The Qiangtang Terrane is surrounded by the Bangong-Nujiang suture to the south and the
Jinsha suture to the north. Dewey et al. (1988) proposed that the Lhasa Terrane collided with the Qiangtang Terrane in the Late Jurassic period.

This study presents data from western Tibet (26° N-35°N, 83°E-87°E) including the HI-CLIMB array that was deployed from 2002-2005. The data included within this study was acquired from the Incorporated Research Institutions for Seismology (IRIS) Data Management Center (DMC). While many areas within the Tibetan Plateau have been the focus of studies in the past, the western region has not been the target of much exploration (Figure 1.1).

Many studies have sought to determine the origin of uplift within the Tibetan Plateau. In the most common model for Tibetan Plateau deformation, the Indian plate thrusting beneath the plateau at a shallow angle (Sandvol et al., 1997; He et al., 2010) lead to subsequent horizontal shortening within the overriding Eurasian Plate. However, Royden and Burchfiel (2008) also suggested that the thickened crust began to form before the two plates began to collide, having theorized an initial thickening during early-stage subduction of the Tethys Ocean beneath Eurasia.

Another hypothesis suggests that the crustal thickening occurred gradually in response to crustal shortening that has taken place over the last 50 million years due to the continued convergence in the area (Molnar and Tapponnier, 1975; He et al., 2010). One final explanation for the crustal thickness is the possible injection of the Indian crust into the Eurasian crust as the convergence progresses (Zhao and Morgan, 1987). In Section 2, nine varying models for the lithospheric deformation of the Tibetan Plateau will be discussed.
Figure 1.1. The location of the study area and surroundings within the Tibetan Plateau. This study area encompasses a region of three different areas within the Tibetan Plateau, known as the Qiangtang and Lhasa Terranes and the Himalayan Orogenic Zone. The thick black lines denote locations of sutures within the region: IYS is the Indus-Yalu suture, BNS is the Bangong-Nujiang suture, and JRS is the Jinsha suture. The pale red dashed lines denote faults within the area. The blue triangles represent the locations of the seismic stations that were used in this study.
In order to provide additional constraints for the events that have led to lithospheric deformation, this study analyzes the seismic anisotropy of the Tibetan Plateau. Shear-wave splitting is a method commonly employed when studies of mantle anisotropy are conducted. When a shear-wave encounters an anisotropic material, the wave is split into two components that move at different speeds, known as the fast and slow waves (Figure 1.2). The fast wave travels with a velocity quicker than that of the slow wave, arriving at the receiver first. The difference between the arrival times between the fast and slow components has become known in many studies as the splitting time or delay time (δt). The direction in which the fast component is traveling is known as the fast polarization orientation, denoted by phi (φ) (Silver, 1996). The splitting time and polarization direction are the variables upon which this study concentrates because they provide useful information about subsurface geology.

The most common anisotropic material within the mantle is olivine, and is thought to be the cause of the observed mantle-induced anisotropy underlying Tibet. If the mantle is made up predominantly of olivine, we can assume that the mantle in the area is 4% anisotropic (Mainprice and Silver, 1993). Olivine displays lattice preferred orientation (LPO) when undergoing progressive simple shear, which means that the a-axis of the crystals line up parallel to the direction of shear or mantle flow. The fast component of a shear-wave corresponds to this LPO (Zhang and Karato, 1995). By studying the fast orientations of the events within the study area, we can obtain a general view of the mantle flow beneath the Tibetan Plateau.

In the method of shear-wave splitting employed in this study, there are three core refracted P-to-S converted phases involved (Figure 1.2). These phases, collectively
Figure 1.2. Illustration of wave splitting in an anisotropic medium and core refracted seismic phases (Savage, 1999). Three phases originate on one side of the earth, and travel through the core, to be received at a station in the study area (right). The waves encounter an anisotropic medium and split into two known as XKS, are PKS, SKKS, and SKS. The three XKS phases begin at the source of the signal, pass through the core, are converted at the core mantle boundary (CMB), and continue on through the mantle to the receiver. The P stands for P-wave while the S stands for an S-wave. The K denotes each time the wave travels through the outer core, converting to a P-wave in the process.

When the wave encounters a major strength boundary, such as the CMB, it undergoes a phase change (i.e. from P-to-S or S-to-P). When the phase of a seismic wave shifts, it loses the properties it obtained prior to conversion; in this instance, all of the signal which characterizes the Earth from source to the CMB is destroyed. The S-wave is radially polarized when it emerges out of the CMB on the receiver side. This property
thus permits us to examine only receiver-side effects, and consequently assume that all observed seismic anisotropy originates on the receiver side of the ray path.

1.2. OBJECTIVES

There are many explanations for how the crust has undergone deformation, but additional questions remain concerning the mechanisms controlling this deformation. The lithospheric mantle also undergoes deformation; unlike the crust, however, there is no direct way to observe how the mantle undergoes this deformation. Data must be gathered and applied through a variety of different methods in order to attempt to formulate a hypothesis about the lithospheric structure.

As indicated in the next section, different studies were conducted to analyze different types of data, and have used different methods to interpret the data. There are nine separate lithospheric models that will be discussed in detail subsequently, and shall later be compared to the data to determine which model best fits the new results garnered from this study. In this study, I will use data that have not been available previously to provide independent constraints on the formation mechanism of the western Tibetan Plateau.
2. LITHOSPHERIC MANTLE MODELS

2.1. P-WAVE VELOCITY MODEL

Li et al. (2006) created a P-wave velocity model (Figure 2.1) to image the upper mantle beneath Southeast Asia. Combined datasets from the International Seismological Centre and the Annual Bulletin of Chinese Earthquakes were used in the study. By using a crustal correction, they were able to greatly improve the imaging of structures within the upper mantle.

Figure 2.1. Vertical cross-section showing P-wave velocity model to a depth of 1700 km (Li et al., 2006). The red color represents slow velocities and blue represents fast velocities.

As indicated in Figure 2.1, the Indian slab is subducting beneath southwestern Tibet and the Lhasa Terrane to a depth of at least 400 km, possibly to 660 km. They
suggest that the remaining upper mantle beneath the Tibetan Plateau is of Eurasian origin. Evidence supports a theory that part of the Indian lithosphere became detached and is present at around 400 km below the surface and currently sinking deeper into the lower mantle.

With increased resolution within the upper mantle, several structures are made visible beneath the Tibetan Plateau and SE Asia. A structure was found beneath eastern Tibet at a depth of approximately 200 km. Unlike the previous structure, this structure displayed a low velocity which was explained by hot material channeled within the crust, and attributed to volcanic activity and flow of material within the mantle.

2.2. TOMOGRAPHIC MODEL

Zhou and Murphy (2005) used tomographic data in order to propose their model of Tibet (Figure 2.2). For their interpretation, they analyzed a high resolution tomographic model known as P1200, a velocity model extending to 1200 km depth from the surface. At the time of their analysis, there were few seismological stations available within the plateau. Most of the data for their seismic wave tomography results were obtained from outside Tibet in order to increase the data coverage.

As indicated in Figure 2.2, there are several structures found within the mantle delineated by this particular model. The most visible structure is a high-velocity body present between 16°N and 36°N to an approximate depth of 265 km indicating that the Indian lithosphere is present underneath most of the Tibetan Plateau. There is another possible structure present between the Indian lithosphere and the Tibetan Plateau that is hypothesized to be an asthenospheric layer. The combined isostatic response of this layer,
the Indian lithosphere and the Tibetan crust could explain the elevation of the Tibetan Plateau.

![Figure 2.2. Cross-section showing P-wave lateral velocities within a tomographic profile (Zhou and Murphy, 2005). The vertical exaggeration of the tomographic profile is 20:1. The purple crosses are the locations of focal points for earthquakes. The dashed lines from bottom to top denote elevations of 0, 2, and 4 km.](image)

The resulting model credits the uplift history and low relief of the plateau to two sources: the Indian lithosphere being subducted subhorizontally beneath the Tibetan Plateau, and a thin channel of asthenosphere between the subducted Indian lithosphere and the Tibetan lithosphere that is heating the Indian lithosphere. There are two predictions made in their model: the Indian lithosphere underthrusted beneath Tibet should be equivalent to the crustal shortening undergone in the Himalayan Mountains and is assisting the uplift of the Tibetan Plateau, and in southern Tibet there should be a young geochemical signature present in the mantle originating from partial melting.
2.3. INDEPTH REFLECTION PROFILES

Hauck et al. (1998) used data from the INDEPTH seismic array to determine the location of the Indian continental crust (Figure 2.3). The seismic profiles available through the INDEPTH seismic array allow for viewing of the subsurface below Tibet. They combine the reflections with published geologic cross-sections to create interpretative cross-sections of the Himalayas.

Figure 2.3. Cross-section showing the combined interpretation of reflection profiles with geologic cross-sections (Hauck et al., 1998). The suture zone is the Yarlung-Zangbo suture zone, gb is the Gangdese batholith and MHT is the Main Himalayan Thrust. Also shown in the figure are the Tethyan belt (thb), the South Tibetan Detachment (STD), the Main Central Thrust (MCT), the Kangmar Dome (KD), the Renbu-Zedong Thrust (RZT) and the Greater Himalayan belt (ghb).

The INDEPTH profiles show that a north-dipping decollement underthrusts Tibet to a depth of approximately 45 km to some point beneath the Tethyan belt (thb, Figure 2.3), a sedimentary belt present to the north of the Himalayan belt along the northern Indian continental margin (Burg and Chen, 1984; Searle et al., 1987). The hanging wall
of the decollement became detached from the Indian mantle lithosphere and is present beneath northern Tibet. They found evidence to support that the Indian mantle underplates the southern half of the Tibetan Plateau. They were not, however, able to determine whether the crust and mantle were coupled beneath the plateau.

2.4. BOUGUER GRAVITY ANOMALIES

Chen and Ozalaybey (1998) used Bouguer gravity anomalies in addition to seismic anisotropy to analyze the Indian shield and subsurface geology of the Tibetan Plateau (Figure 2.4). They began by analyzing digital seismic data from stations from the Global Seismic Network and GEOSCOPE in order to determine the anisotropy of the Indian slab beneath the Tibetan Plateau. They discovered the Indian lithosphere is only slightly transversely anisotropic, while most of the Tibetan Plateau is significantly transversely anisotropic. The onset of significant anisotropy beneath the Tibetan Plateau is observed at the northern terminus of the subducted Indian plate.

Figure 2.4. Diagram showing interpretation from bouguer gravity anomalies and seismic anisotropy (Chen and Ozalaybey, 1998). The Eurasian lithospheric mantle is denoted by the horizontal dashed lines; the vertical lines denote the Indian lithospheric mantle and the Indian crust is shaded in gray.
Birefringence (shear-wave splitting) measurements demonstrate delay time increases from 0.1 s to 0.7 s at 30° and higher to 1.6 s at 33°N. Chen and Ozalaybey (1998) found that the Eurasian mantle is present beneath the Tibetan crust to a point just north of 30°N and the Indian mantle continues beyond the termination of the Eurasian slab until approximately 33°N. Between these two points, there is a marked high in the measurements of Bouguer gravity anomalies between the distances of 600 km and 1000 km on the surface, indicating a juxtaposition of the Indian lithosphere and the Eurasian lithosphere. This coincidence could explain the large Bouguer anomalies that have been found in the area.

2.5. DOWNWELLING INDIAN LITHOSPHERE

Tilmann et al. (2003) used data from both INDEPTH II (I2) and INDEPTH III (I3) in order to create a velocity model for the upper mantle of Tibet (Figure 2.5). They used 40 stations from I3 and six from I2 and assumed lateral mantle change between station locations was negligible. 32 measurements from I2 and 36 from I3 were subsequently used for their study. After conducting tomographic inversion, structures between 29°N and 33.5°N within a depth range of 100 to 400 km were resolved with a horizontal resolution of 60 km and a vertical resolution of 100 km.

As indicated in this model (Figure 2.5), the observed mantle in the north and south of Tibet have different qualities. In the south, there is cold and strong mantle present coincident with relatively fast seismic velocities. Conversely, characteristically weaker and warmer mantle lithosphere underlies the northern Tibetan Plateau. These two areas are separated at approximately 32°N near the Bangong-Nujiang suture. They suggest that the Indian lithosphere has shortened since the collision, or that the missing
lithosphere is part of the upper mantle in central Tibet. The study also found a dipping structure beneath the Tibetan Plateau present on the receiver function images. This structure is interpreted as subduction of the Eurasian lithosphere in a southward direction, possibly causing a downward flow.

Figure 2.5. Cross-section showing downwelling Indian lithosphere (Tilmann et al., 2003). The Eurasian lithosphere is shown dipping southward and present beneath the Eurasian lithosphere is a convection cell.

2.6. TELESEISMIC RECEIVER FUNCTIONS

Kosarev et al. (1999) utilized 353 teleseismic receiver functions from INDEPTH II and 406 from the 1991 to 1992 Sino-American PASSCAL experiment for their study (Figure 2.6). Their data suggest that there are differences between the crustal and mantle structures of north and south Tibet. This may be caused by high temperatures in the mantle lying under northern Tibet.
There is a conversion boundary present within the mantle called the Zangbo conversion boundary. It dips north and represents a strong mechanical boundary, as it converts P to S waves. Its existence suggests that the Indian crust has been subducted beneath the Eurasian lithosphere and has not been destroyed. The Eurasian lithosphere, on the other hand, is assumed to be destroyed. Various structures are visible beneath the crust. The Moho is present underneath the entire Tibetan Plateau, dipping to the north to a depth of around 80 km. Also visible are the 410 and 660 km discontinuities that dip to the north and parallel one another.

In this model (Figure 2.6), both the Eurasian and Indian mantles are being subducted, but in two entirely different ways. The Indian mantle has detached itself
during subduction, but remains buoyant and is perseveres. The Eurasian lithosphere, meanwhile, is being continuously subducted and destroyed as the descent continues.

2.7. TELESEISMIC SHEAR-COUPLED P-WAVES

Owens and Zandt (1997) performed a crustal study by utilizing teleseismic shear-coupled P-waves gathered by the Sino-American broadband experiment in the Tibetan Plateau that was deployed between 1991 and 1992 (Figure 2.7). The waves used in the study were obtained from a single earthquake event that was recorded at ten different sites and sampled the interior of the Tibetan Plateau, leading Owens and Zandt (1997) to propose a model in which there are lateral variations in crustal structure.

![Figure 2.7. Lithospheric cross-section showing average Poisson’s ratio (Owens and Zandt, 1997). The color of each section is dictated by the Poisson’s ratio. Blue areas denote mantle lithosphere while red areas show locations where the mantle has a lower velocity than the southern plateau.](image-url)
Owens and Zandt (1997) observed a decrease of approximately 20 km in the overall thickness of the crust from the south to north. Due to the variations in crustal thickness and changes in observed Poisson’s ratios, they proposed that the crust is partially molten in the northern Tibetan Plateau. They also suggested that underthrusting extends as far northward as the Bangong-Nujiang suture, possibly accommodated by migrating thrust faults, thus causing the Lhasa Terrane to thicken through underplating. The Indian crust underneath the Lhasa Terrane decreases in thickness to the north by crustal transfer, wherein sheets of lower Indian crust are transported northward along low-angle thrusts.

2.8. SEISMIC ANISOTROPY

Sandvol et al. (1997) used three shear-wave phases collected from the INDEPTH I and II seismic arrays (ScS, SKS, and SKKS) to examine the strength and orientation of seismic anisotropy beneath the Tibetan-Himalayan collisional zone. The ScS phases came from three events within 5° and 20° epicentral distance of the array, while the SKS and SKKS phases were obtained from eight events with epicentral distances between 85-180°. Sandvol et al. (1997) utilized the methods of Silver and Chan (1991) to determine the shear-wave splitting parameters (Figure 2.8).

Events north of the Gandese belt were found to have NE-SW orientations which paralleled adjacent fault zones. The authors used these results to argue for lithospheric-wide coherent deformation. Two stations near the Indus-Tsangpo Suture demonstrated little to no seismic anisotropy in the collision zone, which was explained by a subvertical mantle caused by downwelling of the Indian continental lithosphere. They also found seismic anisotropy to be significant below the Lhasa block.
2.9. SEISMIC POLARIZATION ANISOTROPY

Huang et al. (2000) utilized 141 shear-wave measurements from SKS and SKKS phases obtained from sixteen earthquakes recorded by the INDEPTH III experiment to determine the orientation and magnitude of seismic anisotropy within the study region (Figure 2.9). They were successful in determining that strong anisotropy is present in the Qiangtang and Lhasa Terranes, which are characterized by splitting times between 1 and 2 s with fast orientations of E-W and NE-SW.
A change in shear-wave splitting characteristics occurs at 32°N. North of this observed change, shear-wave splitting measurements become null. The crust beneath the array used within the study is 65 km thick, thus the authors determine that much of the visible splitting in this area can be attributed to the crust. The sudden disappearance of shear-wave splitting at this point is a strong indication of the termination of the underlying Indian lithosphere.

The upper mantle is hot and weak under northern Tibet, and is being compressed from several directions, causing lower-crustal flow to the east. The compression causes melting which causes the crust above to weaken. This makes the Eurasian lithosphere unstable, resulting in gravitational foundering into the mantle. The rigid Indian lithosphere thrusting beneath Tibet causes the warmer and weaker Eurasian mantle to be pushed to the east. This causes the mantle to thicken, gain mass (i.e. eclogitize) and detach.
3. DATA AND METHOD

3.1. DATA

This study uses shear-wave splitting measurements to present relatively new data regarding the formation of the western Tibetan Plateau. The study area encompasses portions of various areas within the Tibetan Plateau, including the Qiangtang Terrane, Lhasa Terrane, Bangong-Nujiang suture (BNS), Indus-Yalu suture (IYS), and the Himalayan Orogenic Zone (Figure 1.1).

The data used for this study were obtained from the IRIS DMC, which archives seismic data from all over the world and makes them available to the public. These seismograms were recorded by two networks: the Himalayan Nepal Tibet Experiment and the Nepal-Himalaya-Tibet Seismic Transect. The first set of stations ran from 2001 through 2003 while the second set of stations recorded data from 2002 through 2005.

13,423 three component seismograms were obtained from 258 events recorded by 172 stations within the Tibetan Plateau (Figure 1.1). These stations have recently become available to the public for analysis, and represent a portion of the plateau that lacks thorough study. The XKS phases originate from many events at various locations around the earth, and were received at stations within the study area. Figure 3.1 is centered on the study area and shows the locations of the events used in this study.

Many previous studies have made use of the SKKS and SKS phases. In this study, both of these phases are presented in addition to the less-commonly used PKS phase. As will be demonstrated later in this study, PKS measurements are sometimes the only evidence of anisotropy within the study area.
The Qiangtang and Lhasa Terranes comprise a bulk of the study area. Of the 172 stations used for this study, all but four are part of the Nepal-Himalaya-Tibet Seismic Transect. Within this grouping, many of the stations are included in the HI-CLIMB seismic array. The HI-CLIMB data is significant, because it provides us with an opportunity to explore the deformation mechanisms of a previously unexplored portion of the Tibetan Plateau and the India-Eurasian collision zone.
3.2. METHOD

The data used in this study was obtained through a series of processing with programs written in FORTRAN. The programs were developed by Professors Stephen Gao and Kelly Liu, currently located at the Missouri University of Science and Technology. Parameters from the program were chosen based on an analysis method similar to that which was presented by Silver and Chan (1991). Within the program there are many subroutines that can be used individually for different tasks, but in this instance work together in a carefully orchestrated fashion to gather and execute the calculations necessary for shear-wave splitting. A breakdown of the procedure can be found in Figure 3.2.

The first step in obtaining the data is sending a BREQ_FAST request to the IRIS DMC system to group all of the required data together. The data requested has a cutoff magnitude of 5.5 and an epicentral range of 85-180 degrees. Once this has been completed, the information is downloaded using ftp and placed in the desired location to await further processing.

Once the data was received from the stations (13,423 XKS measurements) the program mentioned previously commences the search for necessary parameters and calculations for shear-wave splitting within the study area. All of the seismograms are automatically band-pass filtered between a range of 0.04 and 0.5 Hz with a 4-pass 2-pole design. This allows for a better signal-to-noise ratio (S/N), permitting noise reduction to increase the signal visibility (Liu, 2009; Gao and Liu, 2009). In order to keep waveforms of higher quality for further processing, the filters can be manually changed to reprocess the data.
Each event is rotated into a radial and transverse component coordinate system. Any seismograms that have a large amount of noise on the radial component are automatically removed, since the noise hinders signals and makes measurements unusable. The seismograms remaining are applied to calculate the parameters for shear-wave splitting: the orientation of the fast wave (φ) and the time between the arrival times of the fast and slow components of the wave (the delay time or splitting time, denoted δt). Values are computed for the parameters insomuch that, for XKS arrivals which have excellent signal on the radial component, the transverse component demonstrates little or
no energy post-correction (Silver and Chan, 1991). This is achieved through a method known as the minimization of transverse energy, a method for the seismic analysis of core refracted waves (Vecsey et al., 2008).

Arrival times of individual seismograms are calculated by the IASP91 Earth model. Using this model, the calculations focus on a 25 second interval: 5 seconds before the predicted arrival time (a) and 20 seconds after (f) (Liu, 2009). Using the transverse energy minimization method, a grid search is conducted that calculates the interval that best minimizes the energy on the transverse component. If these measurements do not allow for a satisfactory waveform, then these values (a and f) can be changed or the events can be rejected during visual analysis.

After the calculations have been completed, every measurement is checked manually through visual inspections to make sure no mistakes were made (i.e. no quality measurements were rejected or vice versa). Any measurements with large splitting times (usually above 2.5 seconds) are dismissed, since anything larger is rarely visible (Silver, 1996). Standard deviations of the splitting times that were larger or similar to the splitting times were also removed from consideration.

During the automatic and visual inspections the seismograms are monitored and ranked based on their qualities (Liu, 2009). There are five rankings that are given the seismograms: A, B, C, N, and S. An ‘A’ measurement is for outstanding, ‘B’ for acceptable, ‘C’ for unusable, ‘N’ for null, and ‘S’ for special (Liu, 2009).

**3.2.1. Rank A.** In order for a measurement to be granted the ranking of ‘A’, it must show significant energy on the radial component and little energy on the corrected
transverse component (Figure 3.3). In addition, the original fast and slow particle motions must show a circular pattern while the corrected particle motion should demonstrate excellent linear behavior. This measurement must show a clearly defined minimum on the energy contour map (i.e. it must have low values of uncertainty in regards to the calculated measurements for $\varphi$ and $\delta t$). For this study, an ‘A’ ranking was given to an ‘outstanding’ measurement with a standard deviation (STD) for $\varphi$ of less than 10° and a STD for $\delta t$ of less than 0.20 s.

Figure 3.3. An example of a quality ‘A’ measurement. The top two windows show the original and corrected SKS seismograms, the middle two windows show the particle motion patterns, and the bottom window displays the contour map.
3.2.2. **Rank B.** A ranking of ‘B’ has the same requirements as rank ‘A’ but has more uncertainty with regards to the splitting times and fast wave orientation. This ranking is given to ‘good’ measurements that are not of the highest quality, but are still usable for the study (Figure 3.4). The plots have the same requirements as those of an ‘A’ measurement, but have different allowances for the STDs of $\phi$ and $\delta t$: $10^\circ-20^\circ$ and 0.20-0.62 s, respectfully.

![Figure 3.4](image_url)

Figure 3.4. An example of a ‘B’ quality event. Notice how the two signals match after correction. This is a ‘B’ event due to the presence of noise in the signal and the high values for the uncertainty of $\phi$ and $\delta t$. 
3.2.3. **Rank C.** The rank of ‘C’ is given to measurements that are not usable. This ranking is set to a seismogram that shows a large amount of noise on either component, resulting in poorly defined energy minima, or a measurement that does not have the proper motion patterns (i.e. an original linear particle motion pattern, which could indicate a broken instrument component). A measurement that has high degrees of uncertainty (for STD of φ exceeding 22° and/or for STD of δt exceeding 0.62 s) are automatically given the ranking of ‘C’ (Figure 3.5).

Figure 3.5. An example of a ‘C’ measurement. Note how the post-correction seismograms do not match and how the particle motion plot for the corrected component is chaotic rather than the required linear pattern.
3.2.4. **Rank N.** This measurement is a null measurement. There will be no measureable energy on either the original or corrected transverse component of the seismogram (Figure 3.6). Null measurements occur in cases of absent anisotropy, weak energy, or when the phase is arriving from a direction similar to the fast or slow directions (Liu, 2009).

Figure 3.6. An example of a quality ‘N’ event. There is no visible energy on the original or corrected transverse component.
3.2.5. Rank S. This is a special measurement that shows significant energy on the radial component of the seismogram, and has high quality arrivals (Figure 3.7). The energy on the transverse component of a quality ‘S’ measurement cannot be properly reduced.

Figure 3.7. An example of a quality ‘S’ event.
3.3. FINALIZING DATA

For this study, only ‘A’ and ‘B’ measurements are used to show the presence of significant anisotropy within the area of interest. Any event in which $\phi$ has a large uncertainty of 22.5 is checked and normally rejected. The boundaries of the calculation window ‘a’ and ‘f’ can be manually changed in order to minimize the calculated uncertainty of $\phi$ and thus avoid rejection of a good quality event.

Each station plot is checked individually for any outlying measurements that does not follow a particular trend. Ideally, the measurements at each station should display a dominant trend in fast polarization orientation. An example of a station plot can be found in Figure 3.8.

When manual checking was completed, the measurements and summary plots were updated to reflect the change in rankings for some of the events. Some measurements did not fit in well with the others, and were reviewed for authenticity a second or third time. Once all of these processes were completed, all of the measurements were visually checked one last time so that all of the events were given their proper ranking. Any events for which $\phi$ varied significantly from the other events within the same station were visually verified. Once all this was completed, analysis and results could be compiled.
Figure 3.8. A summary plot from station H1190. The plots in the top row show azimuthal variations of $\phi$ and the second row displays azimuthal variations of $\delta t$. The map at the bottom left displays the distribution of events for this station and next to that is a rose diagram of the orientations of the fast directions.
4. RESULTS

4.1. GENERAL

13 PKS, 80 SKKS, and 333 SKS A and B parameter between the latitudes of 26°N and 35°N and the longitudes of 83°E to 87°E are measured (Figure 4.1). The combined 426 measurements allow us to create an analysis of the study area. The three phases have been split into three figures: PKS (Figure 4.2), SKKS (Figure 4.3), and SKS (Figure 4.4). The smallest splitting time observed is 0.30 s while the largest is 2.30 s located in the center of the study area above the Indus-Yalu suture. Ninety-five percent of the measurements have a splitting time between 0.5 s and 1.75 s.

The study area has been divided into nine smaller areas based upon the trend of φ to provide higher resolution of events and better enable the visibility of the fast orientations.

4.1.1. Area 1. The first region is the northernmost region of the study area (Figure 4.5). Area 1 is bound by latitudes 33.75° N to 34.5° N and longitudes 83.5° E to 84.5° E. The area is pervaded by an E-W south-dipping fault cutting across the southern extent of the region.

Lying entirely on the Qiangtang Terrane, this area does not demonstrate quantitatively significant seismic anisotropy. The few stations that lie within this area produced seven measurements, most of which were obtained from PKS phases. The measurements are oriented in an E-W direction, with only slight variations in orientation. Area 1 has an average polarization orientation of 82.4 +/- 6.6° and an average splitting time of 0.97 +/- 0.33 s.
Figure 4.1. An enhanced view of the study area. XKS measurements are denoted in different colors: blue for PKS, green for SKKS, and red for SKS. The length of each line is proportional to the duration of $\delta t$ and the orientation of each line corresponds to $\phi$. The key serves as a reference in order to estimate $\delta t$ for each measurement. The locations of the 9 different regions within this study are numbered and marked by blue rectangles.
Figure 4.2. PKS measurements which have been selected in this study. The measurements are marked by solid blue lines.
Figure 4.3. SKKS measurements that are used in this study. Measurements are marked in green solid lines.
Figure 4.4. SKS measurements that have been selected in this study. The measurements are depicted by red lines, which are parallel to the orientation of the fast shear wave. The legend shows a reference for visual interpretation of the splitting times of the measurements.
Figure 4.5. Shear-wave measurements in Area 1. The various colored lines depict different phases: blue for PKS, green for SKKS, and red for SKS. The length of the line corresponds to $\delta t$ and the orientation of the line corresponds to $\varphi$.

**4.1.2. Area 2.** This area lies immediately south of Area 1 (Figure 4.6). It is bound by the latitudes 32.75° N to 33.75° N and longitudes 83.5° E to 84.5° E. Like the first area, Area 2 is also entirely within the Qiangtang Terrane.

The splitting times within Area 2 are diverse and sporadic. There appears to be no predominant orientation of the fast waves in the north, and a mostly NE-SW orientation south of 33.25°. The average polarization orientation is 74.46 ± 11.87°. Splitting times range anywhere from 0.5 s to 1.5 s with an average splitting time of approximately 0.93
Although the measurements are diverse in orientation, there is good azimuthal coverage.

Figure 4.6. Shear-wave measurements in Area 2. The various colored lines depict different phases: blue for PKS, green for SKKS, and red for SKS. The length of the line corresponds to $\delta t$ and the orientation of the line corresponds to $\varphi$. 
4.1.3. **Area 3.** This is the next section in our progression south (Figure 4.7).

Bound by latitudes 31.75° N to 32.75° N longitudes 83.5° E 85° E, this area seems much more anisotropically active. There is a higher density of measurements visible within this section of the study relative to the previous two.

![Figure 4.7. Shear-wave measurements in Area 3.](image)

Figure 4.7. Shear-wave measurements in Area 3. The various colored lines depict different phases: blue for PKS, green for SKKS, and red for SKS. The length of the line corresponds to δt and the orientation of the line corresponds to φ.

This section shows the intersection of the two different terranes within our study area. The Qiangtang Terrane, in the north, and the Lhasa Terrane, in the south, are separated by the Bangong-Nujiang suture at approximately 32.25° N. One fault is visible at 32° N, but does not appear to have any influence on the measurements within the area.
The predominant value of $\phi$ north of the suture rotates from E-W to NE-SW when nearing the suture. The measurements south of the suture are oriented in a NE-SW direction. The splitting times north of the suture range from approximately 1.0 s to 1.5 s, with an average polarization orientation of 58.0 +/- 15.87°. South of the suture, $\delta t$ is smaller, ranging between 0.5 s to 1.0 s with an average of 0.92 +/- 0.27 s.

4.1.4. Area 4. This area (Figure 4.8) is bound by the latitudes 31.5° N to 32° N and longitudes 84.75° E to 85.75° E and is wholly comprised of the Lhasa Terrane, with one visible fault within its borders.

![Image of Area 4](image)

Figure 4.8. Shear-wave measurements in Area 4. The various colored lines depict different phases: blue for PKS, green for SKKS, and red for SKS. The length of the line corresponds to $\delta t$ and the orientation of the line corresponds to $\phi$.

The orientation of the first arrivals are E-W with just a slight change from horizontal towards the south. Splitting times are between 0.75 s to approximately 1.5 s.
The average splitting time is 0.96 +/- 0.27 s and the average fast polarization orientation is 79.5 +/- 9.23°.

4.1.5. Area 5. This area (Figure 4.9), like Area 4, is located entirely within the Lhasa Terrane. It is bounded by latitudes 30.5° N to 31.5° N and longitudes 84° E to 86° E. Several faults pass through this area.

![Figure 4.9. Shear-wave measurements in Area 5.](image)

Measurement density is high for this area, with most of the usable data being SKS in origin, though with a significant SKKS contribution and a small addition from PKS phases. In the north, the fast waves are oriented E-W, and gradually rotate to a NE-SW direction in the southern part of the area. These measurements are N-S in orientation and
thus do not follow the overall trend of $\phi$. The average value of $\phi$ is $66.3 +/− 11.5^\circ$. The splitting times range from 0.4 s to 1.5 s in duration with an average of $0.92 +/− 0.24$ s.

4.1.6. Area 6. This particular area (Figure 4.10) within the study is bound by latitudes $30^\circ$ N to $30.5^\circ$ N and longitudes $85^\circ$ E to $86^\circ$ E. The data within Area 6 originates from SKS and SKKS measurements with a dominant NE-SW orientation. The average fast polarization orientation is $40.3 +/− 7.0^\circ$ with an average splitting time of $1.07 +/− 0.33$ s.

![Figure 4.10. Shear-wave measurements in Area 6. The various colored lines depict different phases: blue for PKS, green for SKKS, and red for SKS. The length of the line corresponds to $\delta t$ and the orientation of the line corresponds to $\phi$.](image)

4.1.7. Area 7. This area (Figure 4.11) marks the terminus of the Lhasa Terrane as far as our data is concerned. This section is bound by latitudes $29^\circ$ N to $30^\circ$ N and longitudes $85^\circ$ E to $86.5^\circ$ E. This area has many faults located throughout, which may be
the cause for what appears to be sporadic results for \( \phi \). The Lhasa Terrane is separated from southern Tibet by the Indus-Yalu suture.

![Figure 4.11. Shear-wave measurements in Area 7. The various colored lines depict different phases: blue for PKS, green for SKKS, and red for SKS. The length of the line corresponds to \( \delta t \) and the orientation of the line corresponds to \( \phi \).](image)

The arrangement of the fast waves is not as dense as in previous areas. There is more azimuthal coverage and fewer apparent clusters of fast waves. Measurements near the Indus-Yalu suture run parallel to the suture. In the north, the SKS measurements are oriented in a NE-SW manner such as were visible in the previous area. There does not seem to be any dominant orientation for the rest of the fast waves. The average
polarization orientation for Area 7 is $42.4 \pm 23.9^\circ$ with an average splitting time of $0.91 \pm 0.36$ s.

**4.1.8. Area 8.** This portion of the study area (Figure 4.12) marks the transition between the Tibetan Plateau and the beginning of the Indian subcontinent. Area 8 is bound by latitudes $27.5^\circ$ N to $29^\circ$ N and longitudes $84^\circ$ E to $86^\circ$ E. A single fault is visible near station XIXI. Boundary markers outline the collision zone between India and The Tibetan Plateau and the location of India.

![Figure 4.12](image)

Figure 4.12. Shear-wave measurements in Area 8. The various colored lines depict different phases: blue for PKS, green for SKKS, and red for SKS. The length of the line corresponds to $\delta t$ and the orientation of the line corresponds to $\phi$. 
A widespread azimuthal coverage is available for this area due to a higher station density, which is in turn due to the continued interest in studying the collision zone. The PKS fast waves are concentrated in the SW corner of the area. Fast waves within the SW corner have an E-W orientation. The measurements in the collision zone follow a mostly E-W pattern, rotating NE-SW when the northern boundary is encountered (i.e. the Main Frontal Thrust). North of the boundary, orientations vary between the E-W and NE-SW patterns established previously. The average polarization orientation is 71.5 ± 14.9° with an average splitting time of 0.84 ± 0.27 s.

4.1.9. Area 9. The final section (Figure 4.13) of the study is the southernmost subset of our data. This area lies at the edge of the India-Tibet collision zone and southern Tibet, though much of the data is present over Nepal. This area is bound by latitudes 26.5° N to 27.5° N and longitudes 84° E to 86.25° E.

Figure 4.13. Shear-wave measurements in Area 9. The various colored lines depict different phases: blue for PKS, green for SKKS, and red for SKS. The length of the line corresponds to δt and the orientation of the line corresponds to φ.
Measurements here are consistent, without much variation in $\phi$. Many stations can be viewed here with the three XKS phases represented. The dominant orientation of the fast waves is E-W. This same orientation continues even across the Main Frontal Thrust (MFT) separating Nepal from Tibet. The average splitting time within this region is $0.98 \pm 0.28$ s with an average orientation of $78.7 \pm 8.1^\circ$. 
5. DISCUSSION

5.1. COMPARISON TO PREVIOUS STUDIES

There have been many studies over the past thirty years that have focused on the Tibetan Plateau. Due to the complexity of the region, the mechanism of the formation of the western Tibetan Plateau is still under debate. Over the previous decades, data has become increasingly available, coinciding with an increase in studies centered on the Tibetan Plateau and its continuing collision with India.

Many different models have been proposed over the years seeking to explain the origin and evolution of the Tibetan Plateau. These models are explored within this study to find the model that best fits the data that has been presented, which in turn includes the HI-CLIMB array.

Chen et al. (2010) used the HI-CLIMB array as well as other networks in order to produce a uniform analysis of the plateau. They used station-averaged measurements in order to decrease the amount of error within the delay time calculations. The present study uses all measurements of sufficient quality rather than average values at each station in order to take advantage of the azimuthal coverage and more accurately examine variations in the polarization orientation.

One of the most common methods for analyzing seismic data within the Tibetan Plateau has been shear-wave splitting. The first known study conducted with shear-wave splitting within the plateau was by Vinnik et al. (1992) which reported an E-W fast orientation from the station SHIO. Gao and Liu (2009) also used a single station, LSA, to conduct a study of the anisotropy within the Lhasa Terrane. They discovered significant
complex anisotropy which differed from previous studies such as McNamara et al. (1994), and subsequently suggested a two-layer anisotropic model in the southern region of Lhasa Terrane.

Nine other models, previously discussed in the second section, use different datasets and methods to propose their interpretations of the Tibetan Plateau. Several of these studies use methods similar to those applied here.

Li et al. (2006) created a model based on P-wave velocities to find various structures in the lithosphere. Their interpretation of the Indian slab subducting beneath the southwest corner of the Tibetan Plateau is consistent with the fast polarization orientations present in the data at the junction of the Indian plate and the Plateau. There is strong anisotropy present in the southern region of the present study area that displays a nearly vertical orientation of N-S which is interpreted as the Indian slab subducting beneath the plateau.

Zhou and Murphy (2005) used a tomographic model to make their interpretation. As with the previous study, they find that the Indian plate is being subducted beneath the Tibetan Plateau, but subhorizontally in this case. Beyond this coincidence, data from the present study does not corroborate any of their findings.

By combining data from INDEPTH I and II seismic arrays with geologic cross-sections, Hauck et al. (1998) were able to make an interpretative model of the events taking place within and below the Tibetan Plateau. They find a decollement beneath the plateau that would demand a complicated fault system beneath the system. The data does not strongly suggest this interpretation, but a decollement could explain the large
variations in fast orientations in the collision zone. Also, the contribution from the lithosphere may not be sufficient to image contributions from shallow-dipping faults.

Chen and Ozalaybey (1998) combined shear-wave splitting with Bouguer gravity anomalies for their analysis. They note increases in anisotropy at 30°N and 33°N which corresponds to the boundaries of the inferred Indian and Eurasian slabs. Between these two points, there is a significant increase in the number of splitting measurements. This supports the assumption that the Indian mantle and the Eurasian mantle both subduct beneath the Tibetan Plateau and overlap between 30°N and 33°N. They also find no significant anisotropy south of 30°N, which is contradictory to the data in the present study.

Tilmann et al. (2003) present data from INDEPTH III to create a velocity model to image the mantle. The data in this study can provide some evidence to support the presence of two very different mantles with a distinct boundary at 32°N. At this point in the data, there is a rotation in the polarization orientation from NE-SW to E-W. This change in orientation could mark the termination of the Indian mantle beneath the plateau.

Kosarev et al. (1999) used teleseismic receiver functions to analyze the mantle deformation in Tibet. They suggest that the Eurasian continent is subducting from the north while the Indian subcontinent is subducting from the south. As stated previously, the present study supports these findings.

Owens and Zandt (1998) used data from one event at multiple sites. As a result their coverage is consequently limited, and only samples a few sites within the Tibetan Plateau. They determine that increasing crustal thickness is accommodated through a
series of thrust faults. Thrust faults could be present since many faults are present in the plateau, although the data cannot support or deny these findings.

Sandvol et al. (1997) used shear-wave splitting to determine seismic anisotropy. Unlike their findings, many of the fast orientations in the present study are not parallel to surface features, which does not support the presence of lithospheric wide coherent deformation. Contrary to their findings, significant anisotropy is found within the collision zone. Both their study and the present study found significant anisotropy below the Lhasa Terrane.

The final model we discussed, that of Huang et al. (2000), also utilized shear-wave splitting for their analysis. The data presented were similar to that from the study from this study. Both studies found significant anisotropy in the Qiangtang and Lhasa Terranes. They find a change in splitting parameters at 32°N, which is consistent with the data presented previously. North of this change they do not find any anisotropy, but in the current study a larger dataset is used in order to improve the azimuthal coverage of the study area, displaying significant anisotropy below 32°N.

5.2. HYPOTHESES

The mantle is assumed to be the main source of anisotropy based on Silver and Chan (1988), who state that the mantle is the source of globally observed anisotropy. Many studies have made predictions pertaining to deformation within the Tibetan Plateau. A number of these studies have concluded that vertically coherent deformation and mechanical coupling is the cause of the observed deformation within the Plateau (Flesch et al., 2005; Wang et al., 2008).
In Area 1, around 34°N there is little anisotropy present. Most of the measurements present are PKS phases. The E-W orientation rotates to a NE-SW orientation at the Bangong-Nujiang suture, rotating back to an E-W orientation at 32°N. At 31°N, φ rotates to NE-SW once again. Between 28.5°N and 30°N measurements of anisotropy, with significant δt values, become minimal in quantity. At 28°N there is an increase in anisotropy once again.

It is difficult to compare the results from this study with some of the models discussed earlier, due to the vastly different methods used. This study is most similar to the models proposed by Chen and Ozalaybey (1998), Sandvol et al. (1997), and Huang et al. (2000), since all three use some method of shear-wave splitting. While Chen and Ozalaybey (1998) show increases in splitting parameters at 30°N and 33°N, they find no anisotropy below 30°N, which is partially corroborated by Area 7, where measurements are sparse.

Sandvol et al. (1997) found significant anisotropy beneath the Lhasa Terrane and interpreted their results with a model of coherent deformation. In some areas, φ is parallel to surface traces of faults and sutures. This does not occur often, nor does it affect many of the events in the vicinity. While the present study cannot rule out the presence of vertically coherent deformation, it also cannot provide evidence to support such a claim.

Chen and Ozalaybey (1998) proves to be the model that best fits the data obtained in this study. The splitting measurements are more numerous between 30°N and 33°N, the same points of change in splitting measurements visible to Chen and Ozalaybey (1998). This increase in anisotropic measurements corresponds to the increased Bouguer anomalies presented, and could be explained by an overlapping Eurasian lithosphere and
Indian lithosphere subducted below the western Tibetan Plateau. At approximately 33.5°N, SKKS and SKS phases are mostly absent with PKS being the predominant phase north of the point. This could mark the terminus of the Indian plate below the plateau. The decrease in significant anisotropy at 30°N could mark the end of the Eurasian lithosphere.

Several studies have suggested that the Indian lithosphere is being subducted beneath the Tibetan Plateau from the south while the Eurasian lithosphere is being subducted from the north. Tilmann et al. (2003) noted a separation of two mantle types at 32°N. Kosarev et al. (1999) and Chen and Ozalaybey (1998) both suggest that the Eurasian lithosphere is being subducted beneath the plateau from the north.

There are noted rotations between fast polarization orientations on the Lhasa Terrane that could suggest a two layer model. The different orientations do not overlap often, which suggests that the mantle flow is the source of this change in orientation. Further study is needed with this dataset to determine whether a second layer of anisotropy is present.

Sandvol et al. (1997) found no anisotropy beneath the collision zone. While Area 8 shows that there is not a large quantity, there are still events of significant strength that suggest strong anisotropy. The increase in measurements at 28°N suggests that the lower Himalayas have stronger anisotropy than previously believed.
6. CONCLUSIONS

With the increase in available data and technology, the Tibetan Plateau has been the focus of many studies. We have compared our results and data to those presented in numerous previous studies. There are many competing models that use different data and methods to arrive at different conclusions. Through a combination of our data and those of preceding studies, we create our own interpretation of the events that occurred in the past within the plateau.

There is significant anisotropy beneath the Qiangtang and Lhasa Terranes. Fast polarizations are oriented E-W with rotations to NE-SW in orientation. Significant anisotropy is present south of latitude 33°N with orientations E-W rotating to NE-SW southward. The Himalayan collision zone has some strong anisotropic measurements, but is weakly anisotropic when compared to the rest of the plateau. The southern Himalayan collision zone has strong anisotropy with an E-W orientation. While other studies have found multiple layers of anisotropy, this study cannot support such an interpretation.

Our data agrees most closely with the model suggested by Chen and Ozalaybey (1998). It suggests that Tibetan Plateau is being uplifted by isostatic response resulting from the subduction of Eurasian lithosphere from the north and Indian lithosphere from the south. Between 30°N and 33°N there is an increase in the number of anisotropic measurements explained by the presence of the Indian and Eurasian lithospheric mantle beneath the plateau. The Tibetan Plateau overlies subduction from the north by the Eurasian lithosphere to 30° N and from the south by the Indian lithosphere to 33°N, with the Eurasian mantle sandwiched between the plateau and the Indian mantle.
BIBLIOGRAPHY


VITA

Melissa Ann Ray was born in Denver, Colorado. In May 2006 she received her Associate of Science degree from Northwest Missouri State University at the age of eighteen. That same year, she began school at the Missouri University of Science and Technology, formerly the University of Missouri-Rolla. She graduated with her Bachelor of Science degree in Physics in May 2009. Shortly thereafter, she began the graduate program in geophysics at the Missouri University of Science and Technology. During her first two years in the graduate program, she was awarded a fellowship as a graduate research assistant under Drs. Kelly Liu and Stephen Gao. She graduated with a M.S. in Geophysics in December 2014.

During her time at Missouri S&T, Melissa was a member of the C.L. DAKE Geological Society and the Society of Exploration Geophysicists (SEG). In 2010-2011, she was the vice-president of SEG. In June 2014, Melissa accepted a job offer from Schlumberger, an oilfield services company.