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STRAIN HISTORY OF THE TAIWAN OROGENIC BELT, MEASURED FROM
SYNTECTONIC PRESSURE SHADOWS

A Thesis in
Geosciences
by
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Abstract

Incremental strain histories from syntectonic fibers in pyrite pressure shadows in the eastern Central Range of Taiwan indicate a progressive change from down dip to along strike extension during deformation. The change in stretching direction, measured from strain histories, is used to evaluate the kinematics of the orogenic system. The subduction zone beneath the island of Taiwan is influenced by two types of obliquity. First, plate motion vector of the Philippine Sea plate is slightly oblique to the regional strike of the mountain range. There is also a component of obliquity between the Luzon volcanic arc, on the Philippine Sea Plate, and the edge of the Eurasian continental margin. The strain histories quantified from the Slate Belt record the changes in strain along the advection path of the material through the orogenic system. The Taiwan orogenic system is at topographic steady-state, so the particle path of material through the system is determined by the point of accretion of material into the system and the location of the maximum erosive flux of material out of the system. Two different models attempt to explain the advection of material as either a doubly-vergent wedge with shallow lateral advection from the point of accretion, or as a deep-seated corner flow with primarily vertical advection from the point of accretion. A vertical advection path would show no systematic change in strain through the deformation history while a lateral advection path would record changes in strain direction that correspond to strain regimes across the mountain range. Incremental strain histories in cleavage parallel samples show a systematic change from downdip to along strike stretch, corresponding with lineation trends and indicating shallow lateral advection. Incremental strain histories in cleavage perpendicular samples show both clockwise and counter-clockwise rotation of strain, indicating probable influence from both types of obliquity within the deformation system.
# TABLE OF CONTENTS

List of Figures .................................................................v

Acknowledgements .............................................................viii

1 Introduction ........................................................................1

2 Background .........................................................................8
  2.1 Physiographic Provinces ..................................................8
  2.2 Tananao Schist ..............................................................13
  2.3 Slate Belt .........................................................................14
  2.4 Eastern Central Range Mesoscale Structure .......................15
  2.5 Eastern Central Range Microscale Structure ......................16
  2.6 Pressure Shadow Growth ................................................18

3 Field Observations .............................................................20
  3.1 Tananao Schist ..............................................................20
  3.2 Slate Belt .......................................................................22

4 Methods ............................................................................24
  4.1 Strain Analysis ..............................................................24
  4.2 $^{40}$Ar/$^{39}$Ar Dating ......................................................30
  4.3 SEM Mineral Identification ..............................................30

5 Strain Analysis Results ........................................................31
  5.1 Cleavage-Parallel Sections ..............................................31
  5.2 Cleavage-Perpendicular Sections .....................................36

6 Discussion .........................................................................42

7 Conclusions ....................................................................47

References ........................................................................49

Appendix A: Field Data ..........................................................53

Appendix B: MATLAB code ..................................................54

Appendix C: Pressure Shadow Images .....................................58

Appendix D: Plots of Cumulative Incremental Elongation ..........76

Appendix E: Plots of Progressive Finite Stretch .......................78
List of Figures

**Figure 1.** Regional map of the Taiwan subduction system. The Chinese passive margin is subducting beneath the Luzon volcanic arc as the Philippine Sea Plate moves to the northwest. Two types of obliquity affect the deformation of the Taiwan orogen. A. Obliquity between the plate motion vector, moving NW, and the regional trend of the Taiwan mountain range, which is oriented approximately 025°. The resulting obliquity could introduce a component of left lateral shear in between the retro-wedge and prowedge. B. Obliquity that results from the converging geographic features produces a southward propagating collision. The subducting continental margin is oriented approximately 060° and the overriding Luzon Arc is oriented approximately 016° off of north, so the collision began earlier in the north and more recently in the south, as the two features zipper closed.

**Figure 2.** Two models show particle paths through the orogenic system of material accreted from the subducting Eurasian plate. The particlal paths are determined by the region of accretion (red). In model A, based on Fuller et al., 2006, underplating and accretion of continental margin material begins underneath the far western extent of the island and material follows lateral paths (gray) through the internal mountain range and is exhumed as part of the Central Range. In model B, based on Simoes et al., 2007, accretion and underplating only occurs underneath the farthest eastern extent of the island and material follows mostly vertical paths (gray) to the surface. The dashed gray line illustrates the accretion of largely undeformed, stratigraphically young material that makes up the Western Foothills.

**Figure 3.** Stretching lineations measured at road outcrops along the northern Cross-Island highway are shown in map view. The red line on the map shows the trace of the highway. This unpublished data was collected during a previous field season. Stretching lineations in the Hshuehshan Range, on the western side of the topographic divide consistently plunge down-dip. On the eastern side of the divide, in the Central Range, stretching lineations plunge NE and SW, subparallel to cleavage plane strike and the trend of the mountain range.

**Figure 4.** Map of the five major physiographic provinces of Taiwan. The Coastal Plains, Western Foothills, Hshuehshan Range, and Central Range are all derived from continental margin material accreted from the subducting Eurasian plate. The Coastal Range is made up of deformed volcanic arc and seafloor material accreted from the Philippine Sea Plate and Luzon Arc. The Longitudinal Valley, between the Eastern Central Range and the Coastal Range, is the suture zone between the colliding tectonic plates.

**Figure 5.** Map of the geologic formations and major faults across the island of Taiwan. The red squares show regions of sample collection. Greenschist samples were collected in the north along the eastern Central Range (Fig 7) in the blackschist/greenschist unit (PM3) and slate samples were collected in the south (Fig 8) in the Pilushan Slate Formation (Ep).
Figure 6. The map on the left shows cleavage plane orientations along the eastern edge of the Central Range. The map on the right shows stretching lineation orientations along the same expanse. Stretching lineations measured along the eastern edge of the Central Range typically trend along-strike and plunge either NE or SW. Stereoplots show the composite orientations of cleavage planes (S1) and lineations (L1). Lineation trends are similar in the pre-Tertiary metamorphic complex and the Eocene slate belt, indicating that the deformation history is consistent along the Central Range. (Adapted from Fisher et al., 2002).

Figure 7. Locations of greenschist samples collected in the Yuli Belt along the eastern edge of the Central Range. Samples were collected along roadside outcrops on Provincial Highway 14. Orientations shown are cleavage plane strike and dip, measured in the field. In one case there where two samples taken from the same location; average cleavage plane orientation is reported on the map in this case.

Figure 8. Map of collection locations of slate samples along the eastern Central Range in the southern half of the Longitudinal Valley. Samples were collected at roadside outcrops in multiple river drainages. The orientations shown are cleavage plane strike and dip measured at the outcrop. In the second southernmost river drainage, multiple samples were taken at each location. In these cases, the orientation reported on the map is the average of all cleavage plane orientation measurements taken at that site.

Figure 9. Examples of digitized pressure shadows from 4 different cleavage parallel samples (sample number shown in upper right corner). Each pressure shadow is divided into straight increments (bounded by red dots) which are analyzed as successive increments of strain. The yellow dashed line in each image is the external reference frame, in the cleavage parallel sections the reference frame is the strike of the measured cleavage plane. The quartz pressure shadows are antitaxial so the most recent increment of growth is at the edge of the pyrite grain and the earliest increment of growth is at the ends of the pressure shadow. The samples show a curvature in the shape of the pressure shadow, indicating non-coaxial strain histories: the earliest fibers are oriented at a high angle to the final strike and the youngest fibers are oriented at low angles to the final strike.

Figure 10. Plots of cumulative incremental elongation (CIE) for four different cleavage parallel samples (sample number indicated in upper right corner of each plot). Each line is the quantified strain history of one pressure shadow and all pressure shadows in a sample were compiled on one plot. The theta angle is the orientation of elongation for a particular segment relative to the final strike orientation (0). Coaxial strain would be shown as a vertical line with unchanging theta value. Coaxial strain along strike would be a vertical line at 0. All cleavage parallel samples show non-coaxial strain, with theta values of initial strain at high angles to the strike gradually changing to low-angle or along-strike elongation during late deformation.
**Figure 11.** Plots of progressive finite stretch (PFS) for four different cleavage parallel samples (sample number indicated in upper right corner of each plot). Each line is the quantified progressive finite stretch of one pressure shadow and all pressure shadows in a sample were compiled on one plot. The theta angle is the orientation of finite stretch at a particular point in the deformation history relative to the final strike (0). All cleavage parallel sections show PFS histories as straight lines with steep slopes at mid to high angles relative to strike. This indicates that the PFS changes gradually through deformation and the orientation of the finite strain ellipse at the end of deformation is oblique to both the initial and final stretching directions.

.....pg 35

**Figure 12.** Examples of digitized pressure shadows from 4 different cleavage perpendicular samples (sample number shown in upper right corner). Each pressure shadow is divided into straight increments (bounded by red dots) which are analyzed as successive increments of strain. The yellow dashed line in each image is the external reference frame, in the cleavage perpendicular sections the reference frame is the trend of the observed stretching lineation in the cleavage plane. The quartz pressure shadows are antitaxial so the most recent increment of growth is at the edge of the pyrite grain and the earliest increment of growth is at the ends of the pressure shadow. The samples show a curvature in the shape of the pressure shadow, indicating non-coaxial strain histories: the earliest fibers are oriented at a high angle to the final stretching direction and the youngest fibers are oriented at low angles to the final lineations.

.....pg 37

**Figure 13.** Plots of cumulative incremental elongation (CIE) for four different cleavage perpendicular samples (sample number indicated in upper right corner of each plot). Each line is the quantified strain history of one pressure shadow and all pressure shadows in a sample were compiled on one plot. The theta angle is the orientation of elongation for a particular segment relative to the final stretching lineation orientation (0). All cleavage perpendicular samples show non-coaxial strain, with theta values of initial strain at high angles to the strike gradually changing to low-angle or along-strike elongation during late deformation. In all samples, stretching lineation was observed to be subparallel to the final strike, so late elongation at low angle to the external reference frame can be interpreted as approximately along-strike elongation.

.....pg 38

**Figure 14.** Plots of progressive finite stretch (PFS) for four different cleavage perpendicular samples (sample number indicated in upper right corner of each plot). Each line is the quantified progressive finite stretch of one pressure shadow and all pressure shadows in a sample were compiled on one plot. The theta angle is the orientation of finite stretch at a particular point in the deformation history relative to the final stretching orientation (0). All cleavage perpendicular sections show PFS histories as straight lines with steep slopes at mid to high angles relative to final stretching lineation. This indicates that the PFS changes gradually through deformation and the orientation of the finite strain ellipse at the end of deformation is oblique to both the initial and final stretching directions.

.....pg 41
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1 Introduction

The island of Taiwan is formed from an ongoing arc-continent collision in which the continental margin of the Eurasian plate is subducting beneath the Luzon volcanic arc on the Philippine Sea Plate (Figure 1). The Philippine Sea Plate and the Luzon Arc are moving in a NW direction. Measured rates range from about 70 mm/y (Seno, 1977) to about 90 mm/y (Suppe, 1981) relative to the Eurasian plate. Two types of obliquity are seen in this collision that could influence the kinematics during orogenesis. First, there is an obliquity between the relative plate velocity vector and the orientation of the axis of the mountain range (Figure 1a). The strike of the Taiwan orogen is 025° and the direction of motion of the Philippine Sea Plate is 305° (Suppe, 1981), which is about 10-15° from orthogonal, with a left-lateral sense of obliquity. This 10-15° obliquity could introduce a left lateral strain component that is not accounted for in orogenic models that assume a perpendicular collision.

There is also a component of obliquity resulting from the orientations of the colliding tectonic elements such as the edge of the continent and the volcanic arc (Figure 1b). The Eurasian passive margin is oriented approximately 060° while the Luzon volcanic arc trends approximately 016° (Suppe, 1981), creating an oblique collision zone where, as the plate subducts, the passive margin and the volcanic arc collide first in the north, with significant mountain building beginning approximately 5Ma (Simoes et al., 2007). As subduction continues, the arc-continent collision propagates southward. From the plate motion vector and estimates for the margin edge and volcanic arc orientation, the southward propagation of the collision occurs at a rate of about 90 mm/y along the strike of the volcanic arc (Suppe, 1981), although estimates based on other methods are typically slower (e.g., 50 mm/y from Willett et al., 2003). In a simple 2-D framework that ignores along-strike deformation, a transect across
Figure 1. Regional map of the Taiwan subduction system. The Chinese passive margin is subducting beneath the Luzon volcanic arc as the Philippine Sea Plate moves to the northwest. Two types of obliquity affect the deformation of the Taiwan orogen. A) Obliquity between the plate motion vector, moving NW, and the regional trend of the Taiwan mountain range, which is oriented approximately 025°. The resulting obliquity could introduce a component of left lateral shear in between the retro-wedge and prowedge. B) Obliquity that results from the converging geographic features produces a southward propagating collision. The subducting continental margin is oriented approximately 060° and the overriding Luzon Arc is oriented approximately 016° off of north, so the collision began earlier in the north and more recently in the south, as the two features zipper closed.
northern Taiwan represents the most mature stage of the collision, and transects moving southward depict progressively earlier time slices in the evolution of the collision. The steady convergence rates allow a relatively fixed time-for-space equivalence within the mountain range; every 50 - 90km along the strike of the mountain range is equivalent to 1 my in time measured from the initiation of continental collision (Suppe, 1981).

The time-space equivalence of the southward propagating collision has also been used to argue for a steady-state orogenic system in Taiwan (Suppe, 1981; Willett and Brandon, 2002; Willett et al., 2003), where the flux of continental material into the range is balanced by erosion and the topography does not vary through time. The elevation of the orogenic divide rises from just below sea level in the subduction zone off the southern tip of Taiwan to a relatively constant elevation in central and northern Taiwan. Along this same length, the width of the orogen gradually increases from south to north, reaching a constant value of approximately 87 km and a mean elevation of 1350m (Suppe, 1981) in central Taiwan. The landscape also changes from southernmost Taiwan towards the more mature mountain range of Central Taiwan, where it is characterized by deeply incised river drainages. Given a topography that is relatively constant through time, the flux of material accreted from the Eurasian continental margin is balanced by the erosional flux off of the mountain range. It is estimated that it takes the system about 1.3my to reach steady-state conditions and longer to reach thermal steady state (Willett and Brandon, 2002). At steady state, material that is accreted from the western edge of the subduction zone moves along systematic particle paths through the fixed mountain belt geometry; structural observations at the surface reflect the sum total of the deformation along that advection path (Clark et al., 1993).
Most of the material making up the mountain ranges of Taiwan is accreted off the Eurasian passive margin as it subducts beneath the Philippine Sea Plate. There are two mechanisms by which material from the continental margin of Asia can be accreted into the orogen: 1) offscraping, where shallow sediments of the foreland basin are imbricated at the deformation front, and 2) underplating, where material that has underthrust beneath the frontal thrust sheets is transferred across the basal decollement. The Western Foothills exposes thrust sheets of Miocene and younger rocks that were offscraped, but much of the Central Range is composed of Eo-Oligocene slates and older basement rocks that bypass the thrust front and are underplated. The path that a particle of rock takes through the orogen depends on the location of the point of entry and the distribution of accretionary and erosive fluxes.

There are two competing models that have attempted to explain the particle paths of material within the Taiwan orogen (Figure 2). In order to explain high temperature measurements based on carbon maturity (Beyssac et al., 2007), Simoes et al. (2007) argue for a model in which crustal material is carried deeply beneath the Philippine Sea plate into areas of high temperature and pressure before return to the surface along paths parallel to an eastward dipping normal fault that bounds the eastern margin of the Central Range of Taiwan. However, there is a Cretaceous tectonothermal event that could have affected the basement rocks, and the carbon maturity observations do not allow for differentiation of the time at which the temperature was high. Their model stresses rapid underplating at the easternmost extent of the subduction zone as the primary method of uplift within the Central Range and allows for little penetrative strain or changes in strain orientation through the orogenic belt (Simoes et al., 2007).

Fuller et al. (2006) explains the orogenic system of Taiwan as a doubly-vergent wedge in which material is deformed as it is advected along shallow paths from west to east through the
Figure 2. Two models show particle paths through the orogenic system of material accreted from the subducting Eurasian plate. The particle paths are determined by the region of accretion (red). In model A, based on Fuller et al., 2006, underplating and accretion of continental margin material begins underneath the far western extent of the island and material follows lateral paths (gray) through the internal mountain range and is exhumed as part of the Central Range. In model B, based on Simoes et al., 2007, accretion and underplating only occurs underneath the farthest eastern extent of the island and material follows mostly vertical paths (gray) to the surface. The dashed gray line illustrates the accretion of largely undeformed, stratigraphically young material that makes up the Western Foothills.
mountain range. The prowedge faces the incoming accretionary flux, and the retrowedge faces the Philippine Sea plate. Higher rates of exhumation and erosion seen in the eastern Central Range suggest that the majority of accreted material moves along a shallow near-horizontal path from the western side of the mountain range but curves upwards towards the surface in the Central Range (Willett and Brandon, 2002). The material from the eastern Central Range also records the longest residence time and deepest burial of any rocks in the Central Range and therefore records the most complete deformation history of the system.

The models proposed by both Simoes et al. (2007) and Fuller et al. (2006) treat Taiwan as a two dimensional contractional system (Figure 2), without consideration given to the potential for out-of-plane displacements. However, both types of previously discussed obliquity of the converging plates introduce a lateral displacement that must be accounted for if the Western Foothills experiences largely contraction orthogonal to the mountain range. There is also previously observed evidence for significant three-dimensional deformation and extension parallel to the strike of the eastern Central Range. Lineations measured across the Central Range show a systematic variation from down-dip trending lineations in the west to along strike trending lineation in the east (Figure 3), an observation not accounted for in two-dimensional models.

In order to determine how extension directions have changed through time, I have analyzed incremental strain indicators in the eastern Central Range. The cumulative strain history measured from syntectonic pressure shadows show when along-strike extension occurs during orogeny and helps to constrain the particle path of material through the system by determining whether the accumulated strain history is more consistent with advection from west to east across Taiwan or with near-vertical exhumation.
Figure 3. Stretching lineations measured at road outcrops along the northern Cross-Island highway are shown in map view. The red line on the map shows the trace of the highway. The black line along the lineations is a smoothed topography profile. This unpublished data was collected during a previous field season. Stretching lineations in the Hshuehshan Range, on the western side of the topographic divide consistently plunge down-dip. On the eastern side of the divide, in the Central Range, stretching lineations plunge NE and SW, subparallel to cleavage plane strike and the trend of the mountain range.
2 Background

2.1 Physiographic Provinces

Taiwan is divided into five distinct physiographic provinces with regional variations in structure, stratigraphy, and lithology: from west to east, the Coastal Plain, the Western Foothills, The Hsuehshan Range, The Central Range, and the Coastal Range (Figure 4). All the rocks of the Taiwan mountain belt are derived from the sedimentary cover or basement of the subducting continental margin. The Longitudinal Valley is the suture zone that separates the Eurasian material in the mountain belt from the Coastal Range, which is formed from material of the Luzon Arc and the Philippine Sea Plate.

The Coastal Plain and the Western Foothills both contain Miocene and Eocene sediments that predate the collision and represent the passive continental margin sequence, overlain by syntectonic sediments shed from the growing orogen and deposited into the subsiding foreland basin (Mouthereau et al., 2000). The Miocene units show a gradual change from thicker deep marine facies in the south (Ho, 1988) to shallow marine and deltaic facies towards the north. Unconformably overlying the Miocene units are Pliocene shallow marine clastic deposits marking the onset of collision. Thick Pleistocene units resulting from an increased rate of sedimentation show a progression from marine to terrestrial deposits, marking a transition from underfilled to an overfilled basin (Flemings and Jordan, 1989).

In the Coastal Plain, these sediments are undeformed and are overlain by a succession of flat-lying Pliocene to Quaternary synorogenic sediments (Teng, 1990). The Pliocene to Quaternary units are composed of synorogenic sediments shed off of the growing thrust sheets of the Western Foothills (Ho, 1988).
Figure 4. Map of the five major physiographic provinces of Taiwan. The Coastal Plains, Western Foot-hills, Hshuehshan Range, and Central Range are all derived from continental margin material accreted from the subducting Eurasian plate. The Coastal Range is made up of deformed volcanic arc and seafloor material accreted from the Philippine Sea Plate and Luzon Arc. The Longitudinal Valley, between the Eastern Central Range and the Coastal Range, is the suture zone between the colliding tectonic plates.
In the Western Foothills, the Miocene to Eocene sediments are deformed into imbricate thrust sheets by three major stages of thrust faulting (Simoes et al., 2007), correlated from local thrusting events. The first tectonic stage begins at the onset of the Taiwan collision (approximately 5 Ma) and the last stage continues to the present (Mouthereau et al., 2000). The basal decollement lies at a depth of approximately 6-8 km (Mouthereau et al., 2000) in the Miocene Chinchui shale, which predates the collision and subsequent syntectonic units, in the frontal two thrusts, but cuts down section into Eocene rocks in the west (Ho, 1988). Thus, the section that is older than Miocene is actively underthrusting the thrust front of the Western Foothills.

The Hsuehshan Range is a structural high between the Western Foothills and the Central Range and is composed of Eocene to Miocene, highly metamorphosed rocks (Clark et al., 1993). The Hsuehshan Range is bounded on the east by the Lishan Fault, which separates it from the Miocene greenschists of the Central Range, and on the west by the Chuchih thrust fault which separates it from the nonmetamorphosed fold thrust belt of the Western Foothills (Clark et al., 1993). Eocene-Oligocene section in the Hsuehshan Range is much thicker than in the Central Range, indicating that the Lishan fault was initially the fault that bounded a rift basin during opening of the South China Sea (Teng et al., 1991). This rift-related normal fault was inverted as a reverse fault during collision (Clark et al., 1993). The Hsuehshan Range is characterized by prehnite-pumpellyite to lower greenschist facies slates and metasandstones (Fisher, et al., 2002) and includes large anticlines, one of which has a folded biotite isograd, indicating that the Hsuehshan Range is more deeply exhumed than the rocks on the east side of the Lishan Fault (Clark et al., 1993). The Hsuehshan Range outcrops in the northern and middle regions of
Taiwan, where the collision has reached steady-state, and tapers towards the younger collision in the south.

The Central Range is composed primarily of three formations: the Tananao schist and two slate units, the Eocene Pilushan Formation and the Miocene Lushan Formation (Figure 5). Both slate formations have similar compositions and are composed mainly of phyllites and argillites, so the age distinction between the two is based largely on fossil records (Ho, 1986). Both slate formations exhibit prehnite-pumpellyite to lower-greenschist metamorphic facies (Chen et al., 1983). The Lushan and Pilushan formations unconformably overlie the Tananao schist, which is the Mesozoic basement of Taiwan (Suppe et al., 1976). The Tananao comprises greenschist facies schist and gneiss units derived from continental margin, mafic seafloor, and granitic intrusions (Ho, 1988).

In the northern part of the Central Range, north of 23.5N, the rock units increase in metamorphic grade from slates of the western Central Range to schists, granites and marbles in the east. The Lushan formation outcrops furthest to the west, followed by the Pilushan Formation, and the Tananao formation outcrops furthest to the east along the mountain front that faces the Longitudinal Valley. Along the eastern edge of the Central Range, there is a systematic variation from older to younger units from north to south from the Cretaceous Tananao schist in the northern 150km of Taiwan to the Eocene Pilushan slate and finally the Mocene Lushan slate. Overall, the easternmost outcrops become gradually younger towards the south, illustrating the time for space equivalence of the evolution of the mountain range in the sense that more mature regions of the mountain range in the north are exhuming more deeply buried rocks.

The Coastal Range is a narrow mountain range running 130km along the eastern length of the island. It is divided into two major units, the volcanic basement material in the
Figure 5. Map of the geologic formations and major faults across the island of Taiwan. The red squares show regions of sample collection. Greenschist samples were collected in the north along the eastern Central Range (Fig 7) in the blackschist/greenschist unit (PM3) and slate samples were collected in the south (Fig 8) in the Pilushan Slate Formation (Ep).
Tuluanshan Formation and a terrigeneous sequence in the Takangkou Formation (Barrier and Angelier, 1986). The Tuluanshan Formation is characterized as andesitic intrusions and lava flows of Miocene age (Ho, 1969). The Takangkou Formation contains a series of Upper Miocene to Pliocene clastic marine units, including andesitic conglomerates, tuffaceous sandstones, and limestones (Barrier and Angelier, 1986). These units illustrate a gradual shift form arc-derived sediments to continent-derived sediments through the collision history and also display a transition up section from sedimentary clasts to metamorphic clasts (Lundberg and Dorsey, 1990). Both the Tuluanshan and the Takangkou are deformed by a series of thrust fault events, forming the current mountain range.

2.2 Tananao Schist

In the eastern Central Range, the Tananao Schist forms the metamorphic basement of the Taiwan orogen and has been dated as late Paleozoic to Mesozoic (Lee and Wang, 1987). It has generally been divided into five different mappable units: black schist, greenschist, metachert, marble, and gneiss (Figure 5). These units are differentiated primarily by metamorphic grade and composition but are difficult to subdivide stratigraphically and so do not necessarily exhibit uniform ages or origin. There are also small amounts of serpentine, some mafic to ultra-mafic rocks, and scattered dikes and quartz veins found throughout the Tananao (Ho, 1988).

Dating of the various units within the Tananao schist gives a range of ages, corresponding roughly to three major tectonic events: a granitic intrusion event (Nanao orogeny ~ 90Ma), the continental rifting and opening of the South China Sea approximately 40Ma, and the ongoing Eurasian plate subduction starting around 10Ma (Ho, 1988). The gneiss in the Tailuko Belt gives the oldest ages and is associated with the Nanao orogeny (Juang and Bellon,
1986). The greenschist in the Yuli Belt shows typically young ages, which correspond to the onset of subduction and modern arc-continent collision (Jahn and Liou, 1977).

The greenschist in the Yuli belt is one of the most abundant lithologies within the Tananao and forms most of the outcrop along the eastern edge of the Central Range. The greenschist rocks are derived primarily from mafic volcanic rocks. Chlorite schist is dominant in the eastern Central Range, with an average thickness of 20-30m for individual layers (Ho, 1988). Crude pillow morphology seen in some greenschist outcrops suggests an oceanic crust protolith (Clark et al., 1992).

2.3 Slate Belt

In the eastern Central Range, the Eocene and Miocene formations of the Slate Belt outcrop along the entire western half of the Central Range and form the highest peaks along the range crest (Figure 5). The slate formations also outcrop along the eastern edge of the Central Range in the southern half of the island, where the Tananao schist tapers into the range. The argillite of the Miocene Lushan Formation and the slightly more metamorphosed phyllite of the Eocene Pilushan Formation are interspersed with occasional sandstone beds (Fisher, et al., 2002) and numerous small quartz veins (Ho, 1988). Lenses of limy to marly material are also present in the Pilushan Formation in the east (Ho, 1988), as well as some thin conglomerate beds (Fisher, et al., 2002).

There are no major structural breaks or lithologic changes within the two slate formations, making lithostratigraphic subdivision uncertain. In addition, the structure of the area is characterized by large-scale isoclinal folds, making repetition of strata and overturned strata common, further complicating stratigraphic determinations (Ho, 1988). The Pilushan and
Lushan formations are largely differentiated based on fossil evidence (Fisher et al., 2002) which can help to date packages of material but is not common enough to give precise stratigraphic breaks.

The Pilushan Formation was deposited during a marine transgression beginning in the early Eocene along the Asian continental margin. Deposition continued through the continental rifting and the opening of the South China Sea and continued through the Miocene with no significant lithologic change or structural break. Teng et al., (1991) suggest that there is a lack of Oligocene in the Slate Belt but a thick sequence in the Hshuehshan Range because during the time of rifting the central Range sat on the flank of a large rift basin bounded by the steeply NW-dipping Lushan Fault. The Oligocene sediments were deposited in the basin to the northwest of the fault and were later exhumed as the Hshuehshan Range, while the region which would become the Slate Belt to the southeast of the fault experienced a period of non-deposition. Both the Eocene and Miocene slates were deformed and metamorphosed during the ongoing collision event.

2.4 Eastern Central Range Mesoscale Structure

In the slate belt of the western half of the Central Range, the dominant structures are northwest-vergent isoclinals folds with southeast dipping axial planes and a general strike parallel to the trend of the mountain range. Slaty cleavage along the western length of the range dips moderately southeast (Fisher et al., 2002). Steeply east-dipping crenulation cleavage appears towards the center of the range (Clark et al., 1992).

The cleavage is locally folded into west-vergent folds with fold axes plunging to the northeast (Fisher et al., 2002). Both the schist and slate units are also crosscut by west-dipping,
brittle normal fault zones (Crespi et al., 1996). The slaty cleavage orientation in the eastern Central Range dips southeast south of the Luyeh River drainage but changes to northeast dipping northward along the Longitudinal Valley (Figure 6). Moving into the greenschist in the northern part of the range, the cleavage is transposed by refolding into a northwest dipping orientation (Fisher et al., 2002). This variation along the mountain range could be explained by either the southward propagation of a regional overturned backfold (Clark and Fisher, 1995) or rotation of the rocks along west-dipping normal faults (Crespi et al., 1996). The orientations of fold axes and crenulation axes exhibit a gentle northeast plunge in both the slate and greenschist units (Figure 5), indicating that tectonic events causing the dominant structures affected both the metamorphic basement and the younger overlying sedimentary units and the main schistosity in the phyllites and the overprinting crenulation cleavage both likely occur during the ongoing late-Neogene to recent collision.

2.5 Eastern Central Range Microscale Structure

Across the Central Range from west to east there is a dramatic change in the orientation of a lineation that is regionally ubiquitous in outcrops and defined in thin section by the alignment of elongate chlorite-mica aggregates and fibrous overgrowths. In the western half of the Central Range, this lineation, which I interpret as a stretching lineation, is consistently oriented down-dip relative to the regional cleavage plane orientation. In the eastern half of the Central Range, the stretching lineation plunges gently to the northeast, sub parallel to the structural grain and the overall strike of the mountain range, without any variation in orientation along the range (Figure 3; Fisher et al, 2002). This difference in stretching lineation between the west and east sides of the Central Range indicates a regional variation in the orientation of finite
Figure 6. The map on the left shows cleavage plane orientations along the eastern edge of the Central Range. The map on the right shows stretching lineation orientations along the same expanse. Stretching lineations measured along the eastern edge of the Central Range typically trend along-strike and plunge either NE or SW. Stereoplots show the composite orientations of cleavage planes (S1) and lineations (L1). Lineation trends are similar in the pre-Tertiary metamorphic complex and the Eocene slate belt, indicating that the deformation history is consistent along the Central Range. (Adapted from Fisher et al., 2002)
strain across the orogen. This study was focused on the east side of the Central Range with two objectives: 1) to evaluate the strain and $^{40}$Ar/$^{39}$Ar age of biotites in pressure shadows from basement greenschists in the north in the context of geodynamic models for Taiwan, and 2) to characterize the incremental strain histories recorded by Eocene slates in the south to evaluate whether there is variation through time in the orientation of stretching that would be predicted by an advection path from a site of underplating beneath western Taiwan, where the maximum finite stretch is down dip, to the site of erosional unroofing in eastern Taiwan, where the maximum finite stretch is along strike.

There is no significant variation in lineation trends from north to south along the orogen. Along the eastern edge of the Central Range, the stretching lineation plunges gently northeast (Figure 6). This orientation is consistent within both the greenschist and slate units along the Longitudinal Valley (Fisher et al., 2002). Therefore, while the orientation of maximum stretch changes regionally from west to east, there is no significant variation in maximum extension orientation laterally along the mountain range and the finite maximum stretch direction is the same for all rocks along the eastern edge of the Central Range.

2.6 Pressure Shadow Growth

In the Eocene slates of the Taiwan’s Central Range, quartz fibers grow in pressure shadows around pyrite grains during deformation. The quartz fibers form parallel to the elongation direction at the time of growth (Durney and Ramsay, 1973) and record progressive changes in stretching direction through the deformation history by changes in fiber orientation relative to an external reference frame. Quartz pressure shadows around pyrite grains have been previously demonstrated to be antitaxial (Durney and Ramsay, 1973; Gray and Durney, 1979;
Ramsay and Huber, 1983; Beutner and Diegel, 1985; Ellis, 1986; Fisher, 1990; Fisher and Byrne, 1992; Clark et al., 1993), where the fiber growth occurs at the edge of the pyrite so that the most recent fibers are next to the pyrite and the oldest fibers are found at the ends of the pressure shadows. In addition, the quartz fibers next to the pyrite in these pressure shadows are generally sub-parallel to the stretching lineations within the rock, indicating that these are the most recently formed fibers and the pressure shadows are indeed antitaxial.

The pressure shadows experience passive deformation, which is mostly seen in the tapering of the pressure shadows in cleavage perpendicular sections. In cleavage parallel sections, the pressure shadows are fairly constant in width and all quartz fibers are parallel to each other, indicating that there is no shortening in the cleavage plane perpendicular to the strike. In cleavage perpendicular sections, the quartz fibers asymptotically taper towards the center fiber along the length of the pressure shadow, indicating that there is shortening perpendicular to the cleavage plane.
3 Field Observations

3.1 Tananao Schist

Greenschist samples were taken in the north Central Range in the river drainage along Provincial Highway No. 14 (Figure 7). In this region, cleavage plane orientations strike northeast, between 196° and 230° NE, subparallel to the strike of the orogen. Cleavage planes dip into the mountain range generally at a 30-45° angle with a few extreme outliers (Appendix A). Sample site 3 had cleavage planes with a shallow dip of ~5° and sample site 4 had cleavage planes dipping 77°. Stretching lineations measured at 2 locations are plunging shallowly NE (01°/030° and 26°/080°), which are consistent with previously measured stretching lineations along the eastern Central Range (Fisher et al., 2002). Fold hinge orientations were measured at sample locations 2 and 8. At location 2, the fold hinges plunge shallowly SW subparallel to the strike of the mountain range, with an average plunge and trend of 04°/213°. At location 8, the fold hinge plunges shallowly NE, with an average plunge and trend of 011°/027°.

No clear fabric is seen in the cleavage parallel thin sections. The cleavage perpendicular sections show cleavage traces running horizontal across the section, defined by fine quartz layers. In some cleavage-parallel sections, biotite pressure shadows are found growing around pyrite grains. The basal planes of the biotite in these pressure shadows are perpendicular to the primary stretching direction, indicating crack-seal growth (Clark and Fisher, 1995). Previous measurements of finite strain in the greenschist samples show strain magnitude increases towards the center of the range.
Figure 7. Locations of greenschist samples collected in the Yuli Belt along the eastern edge of the Central Range. Samples were collected along roadside outcrops on Provincial Highway 14. Orientations shown are cleavage plane strike and dip, measured in the field. In one case there were two samples taken from the same location; average cleavage plane orientation is reported on the map in this case.
3.2 Slate Belt

Slate samples were collected at 18 locations (samples 9-27) in the middle and southern parts of the Central Range, in multiple river drainages along the easternmost edge of the range (Figure 8). Orientation of cleavage planes in the slate outcrops show much more variation than the greenschist outcrops but all but 3 of the samples had cleavage plane strike measurements that were approximately 45° sub-parallel to the regional structural strike. Samples 12, 13, and 24 had cleavage planes with strikes oriented almost perpendicular to the mountain range. Cleavage planes in the slate outcrops dip primarily east to southeast, which is consistent with earlier observations (Fisher et al., 2002). Stretching lineations were measured at locations 10 and 19 and were found to plunge shallowly to the NE, consistent with previous measurements (Fisher et al., 2002). Fold hinges measured at locations 10 and 26 plunge shallowly to the NE, with an average plunge and trend of 24°/040°. At location 26, mostly overprinted secondary cleavage could be faintly seen in outcrop, with an average orientation of ~ 295°/45°.

Thin sections were cut from 2 planes within each sample, 1) parallel to the cleavage plane, looking down section, and oriented along strike, and 2) perpendicular to the cleavage plane, looking down dip, and oriented along the trend of the observed stretching lineation. The samples were generally fine grained, with the cleavage perpendicular sections showing cleavage plane fabric trending across the thin section, defined by thin bands of quartz rich material. Pyrite grains around which pressure shadows had formed were found primarily in the quartz-rich layers between cleavage planes.
Figure 8. Map of collection locations of slate samples along the eastern Central Range in the southern half of the Longitudinal Valley. Samples were collected at roadside outcrops in multiple river drainages. The orientations shown are cleavage plane strike and dip measured at the outcrop. In the second southernmost river drainage, multiple samples were taken at each location. In these cases, the orientation reported on the map is the average of all cleavage plane orientation measurements taken at that site.
4 Methods

4.1 Strain Analysis

In order to quantify the progressive change in the direction of maximum stretching through the deformation history of slate samples from the Eastern Central Range, a quantitative analysis of cumulative incremental strain histories was completed. While finite strain methods provide a magnitude and orientation of the maximum stretch that is an integration of the entire history, incremental strain analysis separates a rotational strain history into a series of irrotational strain increments, thus showing changes in the stretching direction through deformation history, measured relative to some external reference frame (i.e., bedding, cleavage or geographic coordinates). Both cumulative incremental elongation (CIE) and progressive finite strain (PFS) were measured on fibers within pressure shadows in each slate sample using the method explained in Allmendinger et al. (2012).

A cumulative incremental elongation strain history shows changes in the orientation of stretching as strain accumulates, so the y axis is the cumulative sum of incremental stretches and increases with increasing time; a vertical path is a coaxial extension and a horizontal path is a rigid body rotation. A progressive finite strain history measures the finite elongation versus orientation after each incremental strain accumulation (Tillman and Byrne, 1995). A plot of PFS illustrates the orientation and shape of the finite strain ellipse relative to a fixed reference frame through the history of pressure shadow growth.

In the cleavage parallel sections, pyrite grains, ranging in size from 50µm to 2mm, were evenly distributed throughout the sample, with the exception of small clusters in some of the samples. Approximately 35% of the pyrite grains showed pressure shadow growth, but many were not used because of intergrowth with neighboring pressure shadows or poor fiber definition.
or recrystallization made it impossible to trace a single fiber through the shadow. Of the pyrite
grains with pressure shadows, about 50% are small (<500 µm), with subparallel fibers of a length
less than the diameter of the grain around which they formed, and are oriented approximately
along strike with no change in orientation. These examples were assumed to be incomplete and
representative of only the most recent stretch increments. In cases where the fibers were longer
and showed curved fibers and non-coaxial strain histories, the pyrite center, cleavage (i.e., the
external reference frame), and the points along the fiber were digitized to calculate CIE and PFS.

In cleavage perpendicular sections, pyrite grains, ranging in size 50µm to 2mm, were
generally clustered in lithons between the cleavage selvages. Approximately 60% of the pyrite
grains were hosts to syntectonic fibers in pressure shadows but, because of the clustering of the
grains, many were overlapped and inter-grown. Of those which could be individually identified,
about 40% had pressure shadows which were longer and exhibited some curvature along the
length of the fiber. For these pressure shadows, the pyrite center, cleavage (i.e., the external
reference frame), and the points along the fiber were digitized to calculate CIE and PFS.

Pressure shadows that were analyzed were photographed under plane-polarized light at
4X, 10X, or 20X magnification (to best fit the size of the pyrite grain and pressure shadow). The
images were saved as JPEGs and input into a Matlab code adapted from Allmendinger et al.
(2012) in order to calculate CIE and PFS (Appendix B). The model assumes antitaxial fiber
growth, passive deformation of fibers, and growth parallel to the displacement paths of points
relative to the pyrite center, with noncoaxial strain histories treated as a sequence of small
coaxial stretches.
In cleavage-parallel sections, the fibers do not converge or diverge within each pressure shadow but remain parallel to each other, suggesting no incremental shortening perpendicular to the direction of incremental extension (Allmendinger et al., 2012).

Because the fibers are passive, an inverse method is used in quantifying incremental strain, where the last increment of fiber growth ($n^{F}$) is quantified first and the resulting deformation gradient tensor is used to restore other points along the fiber to their positions prior to that increment. The deformation gradient tensor can be written as

$$
p^m_{X_1} = n^{S_1} p^n X_1
$$

$$
p^m_{X_2} = p^n X_2
$$

where $n$ refers to the increment number and $p$ refers to the defined reference frame. $p^n X_1$ and $p^n X_2$ are measures of the distances from the origin at the center of the grain to the location of initial growth at the edge of the grain, measured parallel to the primary axis $X_1$ and secondary axis $X_2$ respectively, corresponding to the growth of increment $n$. $p^n X_1$ and $p^n X_2$ are measures of the distance from the origin to the location of the far end of increment $n$, measured parallel to the primary axis $X_1$ and secondary axis $X_2$ respectively. $n^{S_1}$ is the maximum incremental stretch for increment $n$.

The deformation gradient tensor for increment $n$ ($n^{F}$) can be written as $n\left(\frac{\partial X}{\partial x}\right)$, where $X$ refers to the point of initial growth at the edge of the grain and $x$ refers to the far end of the fiber increment $n$ and $i$ and $j$ refer to the primary and secondary axes in the defined reference frame.

From this, $n^{F}$ is defined as

$$
p^n F = \begin{bmatrix} n^{S_1} & 0 \\ 0 & 1 \end{bmatrix}
$$

where again, $n^{S_1}$ is the maximum incremental stretch and 1 defines the incremental stretch along the secondary axis $X_2$. 

26
Because fiber growth is parallel to the stretching direction in the cleavage plane, the orientation of stretching for the last increment \( n \) is defined as \( \theta \), the angle between the maximum stretch for that increment and the \( X_1 \) axis:

\[
^n\theta = \tan^{-1}\frac{x_2 - x_2^0}{x_1 - x_1^0}
\]

Once the orientation is defined, the incremental elongation of the first segment can be calculated. First, the initial position vector is projected onto a line parallel to the stretch direction. The projection is defined by \( l_0 \)

\[
l_0 = |X| \cos \theta
\]

and \( \theta \) is defined as the arccosine of the dot product of the unit vectors parallel to \( X \) and \( x - X \). \((x - X)\) is the difference between the end of the fiber and the position of growth on the edge of the grain and defines the length of the increment in question.

\[
\theta = \cos^{-1}\left( \frac{x}{|x|} \cdot \frac{x - x}{|x - x|} \right)
\]

Therefore, the maximum stretch for increment \( n \) is

\[
^nS_1 = \frac{l_0 + |x - X|}{l_0}
\]

The original deformation gradient tensor \( ^{pn}F \) (matrix form) can now be evaluated in the arbitrary reference frame (\( F \)) using tensor transformation matrices (\( R \) and \( R^t \)) by

\[
F = R \cdot ^{pn}F \cdot R^t
\]

The inverse of the tensor can restore the deformed position of the last increment (\(^nX\)) to its initial position before growth (\(^nX^0\)) by

\[
^nX = ^nF^{-1} \cdot ^nX
\]

This inverse deformation gradient tensor is multiplied to all the digitized points along the fiber, eliminating the last increment of strain and restoring all the other points to positions prior to that
increment. This process is repeated for the second to last increment using all the restored positions, and after completing this process for all the fiber segments, the last point within the pressure shadow is restored to a position on the surface of the grain. The result is n values of maximum stretch direction (iθ) and n values of maximum incremental stretch (iS) that correspond to each increment. A plot of iθ versus iS produces a graph of cumulative incremental elongation. The x-axis of the plot is the orientation of incremental elongation relative to the reference frame (i.e. horizontal), whereas the y axis is the cumulative elongation (ΣS).

Using the deformation gradient tensor from each increment, the PFS can be calculated. For each segment n the deformation gradient tensors 1 through n are multiplied:

\[
\begin{align*}
\text{finite } & 1 \mathbf{F} = \mathbf{F} \\
\text{finite } & 2 \mathbf{F} = 2 \mathbf{F} \cdot 1 \mathbf{F} \\
\text{finite } & 3 \mathbf{F} = 3 \mathbf{F} \cdot 2 \mathbf{F} \cdot 1 \mathbf{F} \\
\vdots & \\
\text{finite } & n \mathbf{F} = n \mathbf{F} \cdots 3 \mathbf{F} \cdot 2 \mathbf{F} \cdot 1 \mathbf{F}
\end{align*}
\]

The finite strain is evaluated by determining eigenvectors and eigenvalues associated with the Green deformation tensor:

\[
\mathbf{C} = \mathbf{F} \cdot \mathbf{F}^T
\]

The magnitude of finite stretch and progressive changes in the orientation are determined by calculating a new Green deformation tensor after each strain increment. The orientation of the eigenvector of this tensor gives the orientation of finite stretch and the square root of the eigenvalue gives the magnitude of finite stretch. The magnitude of finite stretch is plotted versus orientation to give a graph of PFS through deformation where change in theta angle for each successive point shows the response in the strain ellipse to changes in incremental strain (Almendinger et al., 2012).
The main difference between strain measurements in cleavage-perpendicular sections is that these planes contain the direction of maximum shortening, perpendicular to the lineation trend and the cleavage planes. In cleavage-perpendicular sections, the fiber growth still follows displacement paths within the matrix but only fiber growth in the center is parallel to the stretching direction. The deformation gradient tensor $p_n F$ for the final increment must take into account the shortening within the plane of the section ($S_3$), perpendicular to the lineation trend, and so is written as

$$p_n F = \begin{bmatrix} S_1 & 0 \\ 0 & S_3 \end{bmatrix}$$

$S_3$ cannot be directly measured from the section it is assumed that $S_1 = 1/S_3$ so that the area change is zero. In cleavage-perpendicular sections, the subscript 1 still refers to the primary axis within the reference frame but the secondary axis is referenced by subscript 3. $X$ and $x$ still refer to the initial and deformed points of each fiber, respectively. The $\theta$ angle of the elongation increments is then calculated by

$$\tan 2^n \theta = \frac{2(n X_1 n x_3 - n X_1 n X_3)}{(n X_1^2 - n X_3^2 - n X_1^2 + n X_3^2)}$$

With the $\theta$ value for the $n$th term determined, the principle strains can be calculated. $p_n F$ in matrix form can then be transformed into the arbitrary external reference frame by tensor transformation matrices $R$ and $R^t$

$$F = R \cdot p_n F \cdot R^t$$

From here, the inverse deformation gradient matrix is used to undeform each increment relative to the next youngest increment using the same process as for cleavage parallel sections to produce the cumulative incremental strain and progressive finite strain.
4.2 $^{40}$Ar/$^{39}$Ar Dating

Biotites were separated by hand from a sample of greenschist from the Tananao schist in Figure 7. Biotite separates were analyzed by step heating to determine the age of the biotite grain by the ratio of released radiogenic $^{40}$Ar. Analysis yielded a saddle-like plateau typical of problems with excess argon in the biotites. A poorly constrained maximum age of 13 Ma was estimated from the results. This is consistent with results of argon dating using laser ablation from biotite pressure shadows from the same rocks in that it is clear that the ages reflect cooling or crystallization during the recent collision and not during Cretaceous metamorphism of the Tananao.

4.3 SEM Mineral Identification

Greenschist thin sections were analyzed using a Scanning Electron Microscope (SEM) to describe mineral assemblages and in an attempt to identify trace indicator minerals that could help further constrain the range of metamorphic conditions that the rock experienced. Greenschist samples for analysis were prepared as thin sections, microprobe polished, and left uncoated. Backscatter analysis under 120KeV was used to image thin sections and identify minerals by element ratios.

Backscatter element analysis of thin sections identified an array of elements typically found in greenschist grade metamorphic rocks as well as some less common minerals. Quartz, chlorite, chloritoid, sphene, pyrite, and others were found in noticeable abundance in these samples. However, no obvious aluminosilicates of any crystal habit nor any garnets, zoned or otherwise, were found. The findings confirm that the sample is a fairly typical greenschist grade rock, with no noticeable index elements that could help constrain the conditions further.
5 Strain Analysis Results

Strain histories from samples are depicted as Cumulative Incremental Elongation (CIE) histories and Progressive Finite Strain (PFS) histories. In these plots, each line shows the data from a single pressure shadow. Each plot is a compilation of all pressure shadows from a single sample. In samples for which more than one cleavage-parallel or cleavage-perpendicular thin section was cut, the pressure shadows from the two thin sections were combined onto the same plot. Most samples contained between 3 and 10 measurable pressure shadows, with a few samples containing 20-30 pressure shadows.

5.1 Cleavage-Parallel Sections

Of the eighteen samples from which cleavage-parallel thin sections were cut, curved pressure shadows were found in fifteen of them (Appendix C, Figure 9). In the other three samples, either no pressure shadows were found at all or only straight pressure shadows with horizontal fibers showing no curvature. In samples 10, 12, and 24, the CIE is slightly non-coaxial but the total change in $\theta$ for any one pressure shadow is never more than 15° and there is no consistent trend in the direction of rotation within the sample (Appendix D, Figure 10). In the other twelve samples (14-16, 18-23, and 25-27), the $\theta$ angle changes from a higher angle in the first increments of fiber growth to a lower angle in late increments of fiber growth. Over all of the samples, the $\theta$ angle of the first increment of fiber growth ranges between 10° and 85° in either the negative or positive direction but within a single sample the $\theta$ angle of the first increment of strain generally ranges 40° or less. For example, in sample 16, the initial strain increments for every pressure shadow fall between 60° and 80°. In sample 14, the initial strain increments for every pressure shadow fall between -10° and -50°.
Figure 9. Examples of digitized pressure shadows from 4 different cleavage parallel samples (sample number shown in upper right corner). Each pressure shadow is divided into straight increments (bounded by red dots) which are analyzed as successive increments of strain. The yellow dashed line in each image is the external reference frame, in the cleavage parallel sections the reference frame is the strike of the measured cleavage plane. The quartz pressure shadows are anti-taxial so the most recent increment of growth is at the edge of the pyrite grain and the earliest increment of growth is at the ends of the pressure shadow. The samples show a curvature in the shape of the pressure shadow, indicating non-coaxial strain histories: the earliest fibers are oriented at a high angle to the final strike and the youngest fibers are oriented at low angles to the final strike.
Figure 10. Plots of cumulative incremental elongation (CIE) for four different cleavage parallel samples (sample number indicated in upper right corner of each plot). Each line is the quantified strain history of one pressure shadow and all pressure shadows in a sample were compiled on one plot. The theta angle is the orientation of elongation for a particular segment relative to the final strike orientation (0). Coaxial strain would be shown as a vertical line with unchanging theta value. Coaxial strain along strike would be a vertical line at 0. All cleavage parallel samples show non-coaxial strain, with theta values of initial strain at high angles to the strike gradually changing to low-angle or along-strike elongation during late deformation.
The theta values of maximum extension orientation for the final increments of strain generally display a smaller range than the initial increments within each sample. Within the twelve samples showing significant non-coaxial strain, the final increment of strain for nearly every pressure shadow has a theta angle of less than 30°, either positive or negative. Within a single sample, the final increments of strain typically are within 15° of each other. Exceptions include samples 14, where the final strain increments range from -20° to 5° (Figure 10), and sample 27, where the final increments have a range of ~40°, from -20° to 20°.

The twelve samples that record significant non-coaxial strain in cleavage parallel sections show a consistent trend in the change of incremental strain orientation through the deformation history from a high angle to horizontal in early increments to a low angle to horizontal in recent increments. The cleavage-parallel sections were cut into chips with the long edge parallel to strike so that the horizontal (0° on the CIE plot) is the strike of the cleavage plane. Therefore, all non-coaxial samples show a consistent shift from down-dip to along strike elongation through the deformation history. The rotation direction of the strain increments, either from a negative or a positive \( \theta \), is consistent within each of these twelve samples. Samples 14-15, 18-19, 21- 23, and 26-27 show a rotation in incremental strain from negative \( \theta \) towards zero while samples 16, 20, and 25 show a rotation in incremental strain from positive \( \theta \) towards zero. However there is no clear trend separating samples showing negative rotation and samples showing positive rotation, neither regionally nor structurally.

PFS histories were also quantified from the cleavage-parallel sections that which contained pressure shadows. Plots of orientation of PFS were compiled for each sample to show the evolution of the finite strain ellipse for each pressure shadow. The PFS histories for the cleavage-parallel pressure shadows are steep lines with little to no curvature (Figure 11). Some
Figure 11. Plots of progressive finite stretch (PFS) for four different cleavage parallel samples (sample number indicated in upper right corner of each plot). Each line is the quantified progressive finite stretch of one pressure shadow and all pressure shadows in a sample were compiled on one plot. The theta angle is the orientation of finite stretch at a particular point in the deformation history relative to the final strike (0). All cleavage parallel sections show PFS histories as straight lines with steep slopes at mid to high angles relative to strike. This indicates that the PFS changes gradually through deformation and the orientation of the finite strain ellipse at the end of deformation is oblique to both the initial and final stretching directions.
have slightly positive slopes but most are essentially vertical. Across all of the samples, the PFS orientations, which are representative of the finite strain ellipse for each pressure shadow, can range between -60° and 60°, relative to the strike (0° value on the plots). Within individual samples, theta values of the PFS histories are clustered within ~50° of each other in each plot. The maximum finite stretch recorded by each sample is typically 3-5 times the pyrite grain diameter, with a few shadows as high as 10 and one, in sample 1, showing finite strain of magnitude 15.6.

5.2 Cleavage-Perpendicular Sections

Thin sections oriented perpendicular to cleavage and along stretching lineation were cut from the same eighteen samples. Pressure shadows showing curvature were found in 11 of the samples (samples 9, 11-12, 14-18, 21, and 24-25) (Appendix C; Figure 12). Cleavage-perpendicular thin sections from the other seven samples contained either no pressure shadows or only straight pressure shadows showing no curvature. All plots of CIE for these eleven samples, except for one, show changing θ degrees as the strain accumulates, indicating non-coaxial strain (Appendix D). Sample 16 only contained one measurable pressure shadow which showed mostly coaxial strain, with a change in θ values of maybe 5-10°.

In eight of the samples (11-12, 15, 17-18, 21, and 24-25), the θ angle changes from a higher angle in the first increments of fiber growth to a lower angle in late increments of fiber growth (Figure 13). Within each sample, the θ angle of the first increment of fiber falls within a 40° range. Similar to the cleavage-parallel sections, the initial increment of elongation for all pressure shadows are consistently all negative or all positive theta values within a single sample.
Figure 12. Examples of digitized pressure shadows from 4 different cleavage perpendicular samples (sample number shown in upper right corner). Each pressure shadow is divided into straight increments (bounded by red dots) which are analyzed as successive increments of strain. The yellow dashed line in each image is the external reference frame, in the cleavage perpendicular sections the reference frame is the trend of the observed stretching lineation in the cleavage plane. The quartz pressure shadows are anti-taxial so the most recent increment of growth is at the edge of the pyrite grain and the earliest increment of growth is at the ends of the pressure shadow. The samples show a curvature in the shape of the pressure shadow, indicating non-coaxial strain histories: the earliest fibers are oriented at a high angle to the final stretching direction and the youngest fibers are oriented at low angles to the final lineations.
Figure 13. Plots of cumulative incremental elongation (CIE) for four different cleavage perpendicular samples (sample number indicated in upper right corner of each plot). Each line is the quantified strain history of one pressure shadow and all pressure shadows in a sample were compiled on one plot. The theta angle is the orientation of elongation for a particular segment relative to the final stretching lineation orientation (0). All cleavage perpendicular samples show non-coaxial strain, with theta values of initial strain at high angles to the strike gradually changing to low-angle or along-strike elongation during late deformation. In all samples, stretching lineation was observed to be subparallel to the final strike, so late elongation at low angle to the external reference frame can be interpreted as approximately along-strike elongation.
In these eight samples, the $\theta$ values show a systematic shift from higher angles (generally around 40°) to lower angles through the deformation history. The $\theta$ angles of the final increments of strain show lower theta values and fall within a range of 20-40° within each sample. Within the eight samples showing significant non-coaxial strain, the final increment of strain for nearly every pressure shadow has a $\theta$ angle between -20° and 20°. In some samples, the final increments of strain converge to a smaller range. For example, the final strain increments for all pressure shadows in sample 15 are within a 20° range.

In samples 9 and 14, the initial segments of incremental strain for all the thin sections have negative $\theta$ values between 5° and 40° (Figure 13). As incremental strain accumulates the $\theta$ values of incremental strain segments show counterclockwise rotation towards a positive $\theta$, $\sim$35° then turn and show clockwise rotation back towards negative $\theta$ values during the later part of deformation. The final strain increments have theta between -20° and 5°.

The eight samples that record significant non-coaxial strain in cleavage-perpendicular sections show consistent variations in incremental extension orientation through the deformation history. In most samples, the histories begin with $\theta$ at a high angle to horizontal in early increments to a low angle to horizontal in recent increments or, as in samples 9 and 14, show two rotation directions in succession within the same pressure shadow. The cleavage-perpendicular sections were cut along the primary stretching lineation, which is sub-parallel to the strike, so that the horizontal (0° on the CIE plot) indicates the cleavage and lineation as a reference frame. The sense of rotation of the incremental extension direction, either counterclockwise or clockwise, is consistent within each of these eight samples but varies between samples (Figure 13). Samples 11-12, 15, 17, and 21 show a rotation in incremental stretch from negative theta towards zero while samples 18, 24, and 25 show a rotation in incremental extension direction.
from positive θ towards zero. Like the cleavage parallel sections, there is no clear regional division between samples showing negative rotation and samples showing positive rotation.

Plots of PFS histories from the cleavage-perpendicular sections containing non-coaxial pressure shadows show steep finite stretch curves (Figure 14). Across all samples the orientation of the finite strain ellipses range from -60° to 60° but, similar to the cleavage parallel sections, cluster within about 40° of each other within each sample. The maximum finite stretch recorded within the cleavage perpendicular sections is typically 3-6, with a few samples with finite strain below 3 and a couple individual shadows that record finite strain of magnitude 11 or 12.
Figure 14. Plots of progressive finite stretch (PFS) for four different cleavage perpendicular samples (sample number indicated in upper right corner of each plot). Each line is the quantified progressive finite stretch of one pressure shadow and all pressure shadows in a sample were compiled on one plot. The theta angle is the orientation of finite stretch at a particular point in the deformation history relative to the final stretching orientation (0). All cleavage perpendicular sections show PFS histories as straight lines with steep slopes at mid to high angles relative to final stretching lineation. This indicates that the PFS changes gradually through deformation and the orientation of the finite strain ellipse at the end of deformation is oblique to both the initial and final stretching directions.
6 Discussion

In all slate samples from the eastern Central Range of Taiwan, pressure shadows depict non-coaxial strain in both cleavage-parallel and cleavage-perpendicular sections. Possible explanations for non-coaxial strain histories include: rigid rotation of the rock through a single fixed stretching axis, a change in stretching direction relative to the rocks, or internal rotation related to simple shear. Because the strain is non-coaxial in three dimensions, no single section is capable of representing the entire history, and rotations in cleavage-parallel sections can have a different explanation than cleavage-perpendicular sections, so these data sets are evaluated separately.

In cleavage-parallel sections, rigid rotation of the rock would not be able to produce the observed up to 90° rotation of the incremental extension direction from more downdip to along strike without the unlikely possibility of large regional rotations about an axis perpendicular to the mountain range. Any rigid body rotation of the rocks in this system would be more likely to be about regional fold axes, which are near-parallel to the strike of structural fabrics along the mountain range. The explanation that best explains the non-coaxial strain histories observed in the samples is a rotation of the stretching directions through the rocks from down dip to along strike. If this kinematic framework were fixed relative to the geometry of the orogenic system, this rotation could be accomplished by advection through the orogen. Regional strain partitioning within the orogen could produce two different regions within the system, one to the west in which contraction and thrusting produces down-dip extension and a region to the east dominated by along-strike extension. If all of the material in the system moved west to east through the two fixed strain regimes all the rocks would record the same systematic shift in incremental strain orientation from early deformation to late deformation.
The temporal variation in strain from down-dip to along-strike through the deformation history is matched by a spatial change in lineation trends from west to east across the Central Range (Figure 3). In the western side of the Central Range, stretching lineations are oriented down-dip. In the eastern side of the Central Range, stretching lineations are subparallel to strike and plunge gently northeast. The fact that the temporal variation in stretching axes for samples in the eastern Central Range correlates with this spatial change across the Central Range is consistent with the interpretation of variations in stretching axes in strain histories as due to advection through regions of varying stretching directions.

The particle paths suggested by the change in incremental extension orientation indicate an advection of material from west to east through the orogen, a result that is generally consistent with the predicted particle paths in the Fuller et al. (2006) doubly-vergent wedge model (Figure 2). The main difference in particle paths between the Fuller et al. (2006) and Simoes et al. (2007) models lies in the location where material is initially underplated and incorporated into the orogeny. The doubly-vergent wedge model suggests that underplating occurs beneath the orogen west of the divide, and the flux of material into the range, combined with erosion off the top of the range, leads to movement of this accreted material to the eastern side of the range (Fuller et al., 2006), with lateral advection of material along shallow paths through the orogen and to the surface in the eastern Central Range. The Simoes et al. (2007) deep corner flow model assumes that underplating occurs beneath the eastern side of the orogen and that material follows vertical paths to the surface beneath a normal fault (Figure 2). The change in incremental strain through time measured from the pressure shadows, matching the change in lineation trends from west to east across the mountain range, suggest that the material follows lateral particle paths similar to those suggested by the doubly-vergent wedge model (Fuller et al.,
The Simoes et al. (2007) model also argues that all the shortening of the range can be accounted for by slip at the thrust front so there is no ductile strain during mountain building, a conjecture clearly at odds with the strain measurements of this study. Therefore, the strain history seen in these samples matches more closely with the Fuller et al. (2006) geodynamic model. However, while this model explains the lateral advection of material through the orogen and allows for variations in strain partitioning between the retro-wedge and pro-wedge, it is a two-dimensional model and does not explain the lateral component of stretch related to along-strike extension in the eastern half of the Central Range.

The lateral stretching in the interior of the mountain range can be explained within a three-dimensional orogenic system as a result of the obliquity of collision. Both forms of obliquity that are present in this system—the southward propagation of the collision from the obliquity of colliding features or the lateral shearing of material from the obliquity of plate motion vectors (Figure 1)—have the potential to introduce lateral stretching in the eastern half of the mountain range. Oblique collision has the potential to cause lateral extrusion in the ductile interior of the thickened, rapidly eroding mountain range, while oblique convergence can be partitioned into orthogonal contraction and along-strike simple shear.

The test of these different possibilities lies in the evaluation of the strain histories in cleavage-perpendicular sections. Given that these sections are cut parallel to a sub-horizontal lineation and perpendicular to a moderately to steeply dipping cleavage, the strain histories are depicted approximately in plan view. All pressure shadows show non-coaxial histories, which can be interpreted as due to vertical axis rotations or internal rotation related to simple shear.

The two types of obliquity that are present in this system would result in very different particle paths in three dimensions, paths that reflect the kinematics and the accretionary and
erosive fluxes. The southward propagating collision could result in southward extrusion of a ductile core, perhaps down the topographic gradient to the south. Extruding material would be subjected to both right-lateral and left-lateral simple shear along the edges of extruding packets of material. The oblique plate motion vector would result in left-lateral simple shear through the entire retrowedge.

The pressure shadows that were analyzed showed both clockwise- and counterclockwise rotation of the incremental extension direction, indicating that along-strike extension was not a result of only plate motion obliquity. The sense of rotation of the incremental extension direction is consistent within each sample but samples taken from outcrops within a kilometer of each other often showed opposite senses of rotation, suggesting that the region could be subjected to a general shear, where deformation is partitioned into small scale zones of right and left lateral shear. Most likely, both southward propagation and plate motion obliquity contribute to the development of lateral extension within the retrowedge.

There were pressure shadows found in cleavage-parallel sections that did not show non-coaxial strain but instead recorded only along strike elongation. It is likely that the entire pressure shadow recorded some non-coaxial strain but the curvature of the shadow was out of the plane of the thin section. The pressure shadows contain fibers that curve in both cleavage-parallel and cleavage-perpendicular sections so the fibers closest the pyrite are the most likely to be represented within the section. However, the pressure shadows showing coaxial strain were found in samples intermingled with the non-coaxial pressure shadows which we quantified, so the most likely explanation is that all of the samples underwent non-coaxial strain but some sections cut through the center of the pyrite and contained more complete histories. The
observation that the lineation is parallel to the latest increments of strain indicates that the lineation tracks the incremental stretching axis and is not a record of the finite strain.

The possibility of cutting off part of a three-dimensional pressure shadow by making a two-dimensional section is a difficult problem to avoid. The plots of cumulative incremental strain history for each sample show variations of 10-25° in the orientation of the first strain increments for pressure shadows within the sample. The variation that is seen could be explained if the first increments of fiber growth, the outer tips of the pressure shadows, were oriented slightly out of the plane of the thin section and were cut off.
7 Conclusions

Incremental strain analysis of pressure shadows show that the rocks in the eastern Central Range experience along-strike extension during the last stages of deformation. This is consistent with previously observed stretching lineations which trend NE along the strike of the orogen. Along-strike extension sub-parallel to the Central Range indicates that the Taiwan orogen is a complex, three-dimensional deformation system, encompassing significant lateral strain out the plane of the typical deformation models that focus on a cross-section across the mountain range.

Cleavage parallel sections show a systematic change from down-dip to along-strike extension in pressure shadows in all sections. The change in elongation direction during the deformation history matches the change from down-dip to along-strike trends of stretching lineations measured across the Central Range. The compatibility of the spatial variation and temporal evolution of the elongation direction supports particle paths that advect material laterally from west to east through two different strain regimes within the orogenic system. Cleavage perpendicular sections show both clockwise and counterclockwise rotation of strain in different samples, which is consistent with internal rotation related to simple shear between cleavage planes, perhaps related to extrusion due to obliquity between the colliding bodies and a general shear regime that is restricted to the eastern side of the orogen.

Finally, stretching lineation is shown to record only the most recent increments of strain instead of the finite strain. The finite strain ellipses of all samples are oblique to the stretching lineations, as a result of the variations in strain orientations throughout deformation. The lineations are subparallel to the regional structural strike and to the youngest fibers in the pressure shadows, suggesting that stretching lineation tracks the incremental extension direction
and not the finite extension direction; existing fabrics can easily be overprinted during changes in the direction of maximum incremental stretch.
References


Jahn, B. M., A. Y. Glikson, J. J. Peucat, and A. H. Hickman, 1981. Rare Earth Geochemistry and isotopic data of archean silicic volcanic and granitoids from the Pilbara Block, western


Appendix A: Field Data

**GREENSCHIST SAMPLES**

<table>
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<tr>
<th>Sample #</th>
<th>latitude (N)</th>
<th>longitude (E)</th>
<th>Cleavage plane (strike/dip)</th>
<th>Lineation (plunge/trend)</th>
<th>Fold hinge (plunge/trend)</th>
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**SLATE BELT SAMPLES**

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Appendix B: MATLAB code

Function Fibers.m

function [cie,pfs] = Fibers(imageName,kk)

% Fibers determine the incremental and finite strain history of a fiber in
% a pressure shadow

% USE: [cie,pfs] = Fibers(imageName,kk)

% image: A character corresponding to the image filename, including
% extension (eg. = 'fileName.jpg')
% kk = An integer that indicates whether the fiber is on a cleavage
% parallel (kk = 0), or cleavage perpendicular (kk = 1) section
% cie = cumulative incremental elongation: column 1 = Incremental theta,
% column 2 = cumulative incremental maximum elongation
% pfs = progressive finite strain history: column 1 = Finite theta,
% column 2 = maximum stretch magnitude

% NOTE: Output theta angles are in radians

% Read and display image
IMG=imread(imageName);
imagesc(IMG);

% Prompt the user to define a reference plane. If the current reference
% plane is not satisfactory, the user can re-select the input points
a='n';
while a=='n'
    clf; % Clear figure
    imagesc(IMG); % Display image
    hold on;
    disp('Select two points along the reference plane, from left to right. ');
    [refpx, refpy] = ginput(2);
    refpx = round (refpx); % Rounds input x points to nearest integer
    refpy = round (refpy); % Rounds input y points to nearest integer
    plot(refpx,refpy,'--y','LineWidth',1.5);
    a=input('Would you like to keep the current reference plane? (y/n)','s');
end

% Prompt the user to select the origin and fiber points from the image
% display. The origin is defined at the center of the porphyroclast.
% The fiber points are selected sequentially along a single fiber path.
% If the current fiber path is not satisfactory, the user can re-select the
% input points
a='n';
while a=='n'
    clf; % Clear figure
    imagesc(IMG); % Display image
hold on;
plot(refpx,refpy, '--y', 'LineWidth',1.5)
disp ('Select the origin point, center of porphyroclast.');
[xo, yo] = ginput(1); %Select center of grain as the origin
xo=round(xo); yo=round(yo); %Rounds positions to nearest integer value
plot (xo,yo,'ok','MarkerFaceColor','k', 'MarkerSize',8) %Plots origin

%Digitize points along fiber
disp ('Digitize points along the fiber');
disp ('Left mouse button picks points');
disp ('Right mouse button picks last point');
x = []; y = []; n = 0; but = 1;
while but == 1
    n = n + 1;
    xi = round(xi); %Rounds point coords to nearest integer
    yi = round(yi);
    plot (xi,yi,'-or','LineWidth',1.5); %Plots point
    x(n) = xi; y(n) = yi; %Add point to fiber path
end
a=input('Would you like to keep the current fiber path? (y/n) ', 's');
end
hold off;

%Start calculation
%Switch y values from screen coordinates with (0,0) at the upper left
corner to cartesian coordinates, with (0,0) at the lower left corner
nrow=size(IMG,1); %Number of rows in image
yo=nrow-yo;
y=nrow-y;
refpy = nrow-refpy;

%Set origin of coordinate system at center of pyrite sphere
x=x-xo;
y=y-yo;

%Rotate all points into a reference frame parallel to X1
phi=atan((refpy(2)-refpy(1))/(refpx(2)-refpx(1)));
Rot=[cos(phi) sin(phi);-sin(phi) cos(phi)];
vec=[x;y];
ewvec=Rot*vec;
x=newvec(1,:);
y=newvec(2,:);

%Initialize some variables
cie = zeros(n-1,2);
rotmat = zeros(2,2,n-1);
finmat = zeros(2,2,n-1);
elong = zeros(1,n-1);
C = zeros(2,2,n-1);
pfs = zeros(n-1,2);
%Incremental, inverse modeling of pressure shadow (Backwards)  
for i=1:n-1  

%If cleavage parallel section  
if kk == 0  
cie(n-i,1)=atan((y(2)-y(1))/(x(2)-x(1)));  
end  

%If cleavage perpendicular section  
elseif kk == 1  
cie(n-i,1)=(atan((2*(x(2)*y(2)-x(1)*y(1)))/ (x(2)^2-y(2)^2-x(1)^2+y(1)^2))/2;  
end  

Beta=[cos(cie(n-i,1)) sin(cie(n-i,1));-sin(cie (n-i,1))...  
cos(cie(n-i,1))];  

%If cleavage parallel face  
if kk == 0  
h=[x(1);y(1)];  
H=[x(2);y(2)];  
v0=H-h;  
v1=h/norm(h);  
v2=v0/norm(v0);  
Alpha=acos(dot(v1,v2));  
initlength=norm(h)*cos(Alpha);  
st1inc=(norm(v0)+initlength)/initlength;  
posmat=[st1inc 0;0 1];  
end  

%If cleavage perpendicular section  
elseif kk == 1  
Bigx1=Beta*[x(1);y(1)];  
Bigx2=Beta*[x(2);y(2)];  
st1inc=(Bigx2(1)/Bigx1(1));  
st3inc=(Bigx2(2)/Bigx1(2));  
posmat=[st1inc 0;0 st3inc];  
end  

rotmat(:,:,n-i)=Beta*posmat*Beta;  
elong(n-i)=st1inc-1;  
for j=1:n-i  
newposition = rotmat(:,:,n-i)[x(j+1); y(j+1)];  
x(j)=newposition(1);  
y(j)=newposition(2);  
end  

%Plot cummulative incremental maximum elongation  
figure;  
cie(:,2)=cumsum(elong); %Cummulative, incremental, maximum elongation  
plot(cie(:,1)*180/pi,cie(:,2),'o');  
xlabel('Theta incremental deg');
ylabel('Cumulative incremental elongation')
axis([-90 90 0 max(cie(:,2))+0.5]);

%Compute progressive finite strain (Forward)
finmat(:,:,1)=rotmat(:,:,1);
for i=2:n-1
    finmat(:,:,i)=rotmat(:,:,i)*finmat(:,:,i-1);
end

%Determine Cauchy deformation tensor
for i=1:n-1
    C(:,:,i)=finmat(:,:,i)'*finmat(:,:,i);
end

%Stretch magnitude and orientation: Maximum eigenvalue and their
%corresponding eigenvectors of Cauchy's tensor. Use Matlab function eig
[V,D]=eig(C(:,:,i));
pfs(i,2)=sqrt(D(2,2));
pfs(i,1)=atan(V(2,2)/V(1,2));
end

%Plot Progressive finite strain
figure
plot(pfs(:,1)*180/pi, pfs(:,2), 'o');
xlabel('Theta finite deg');
ylabel('Progressive Finite Strain');
axis([-90 90 1 max(pfs(:,2))+0.5]);
end
Appendix C: Pressure Shadow Images

**Cleavage Parallel Sections** (‘sample#_shadow’)

- Sample10_a
  - 10_b
  - 10_c
  - 10_d

- Sample12_a
  - 12_b
  - 12_c

- Sample14_a
  - 14_b
  - 14_c
Cleavage Perpendicular Sections (‘sample#_shadow’)

Sample9_a  Sample10_a

Sample11_a  11_b  11_c

Sample12_a  12_b  12_c

12_d  12_e  12_f

12_g
Appendix D: Plots of Cumulative Incremental Elongation

Cleavage Parallel Sections

Sample 10

Sample 12

Sample 14

Sample 15

Sample 16

Sample 18

Sample 19

Sample 20

Sample 21

Sample 22

Sample 23

Sample 24

Sample 25

Sample 26

Sample 27
Cleavage Perpendicular Sections
Appendix E: Plots of Progressive Finite Stretch

Cleavage Parallel Sections

Sample 10

Sample 10

Sample 10

Sample 10

Sample 10

Sample 10
Cleavage Perpendicular Sections

Sample 9

Sample 10

Sample 11

Sample 12

Sample 14

Sample 15

Sample 16

Sample 17

Sample 18