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Comparing Kinematic Models of Orogenic Growth in Taiwan

A Senior Thesis in Geosciences

by

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Abstract
The Taiwan Mountain belt is a consequence of the oblique collision between the Luzon volcanic arc and the Eurasian continental margin. Extensive studies in this region have reached a consensus that the collision began in northernmost Taiwan and has since been propagating south; however, there remains disagreement regarding the kinematic evolution of the mountain belt. Two end member models which predict the growth of the orogenic belt are the doubly vergent wedge model (Fuller et al., 2006) and the underplating model (Simoes et al., 2007). This study presents strain data collected from the eastern Central Range in Taiwan where the predictions of the two models vary the greatest. Field observations show that foliations in the eastern Central Range dip toward northwest toward the topographic divide: an observation that is consistent with a backthrust. Also, strain increases along the mountain belt from west to east. These observations are consistent with the particle trajectory paths predicted by the doubly vergent wedge model. This study also presents strain data consistent with right lateral, along strike shear. This sense of shear is not accounted for in either of the kinematic models. Finally, the results from this analysis show that due to recrystallization, grain center distribution does not record the finite strain history.
**Introduction**

Taiwan is the setting of an active arc-continent collision where the Luzon volcanic arc is colliding with the Eurasian continental margin. The arc is oriented north south while the continental margin is orientated northeast southwest. Due to the obliquity of these plates, the collision has been propagating to the south, and should continue to do so in the future (Suppe, 1981, 1984). Therefore, cross sections of the mountain belt represent different points in time of the collision, where the oldest point in the collisional history can be seen in northernmost Taiwan, and the youngest point can be seen in southern Taiwan (Suppe 1984). This remarkable opportunity to view an active collision in different points in time has led to extensive studies of the structure, metamorphism and kinematic evolution of the Taiwan mountain belt.

Although there is a consensus that Taiwan is a type example of an arc-continent collision, there are different models which explain its structural evolution and kinematics, particularly in the high-grade metamorphic rocks of the Tananao Complex that is exposed on the southeast side of the topographic divide. The doubly vergent wedge model (Fuller et. Al 2006) explains the growth of the orogenic belt from new material accreting onto the western part of Taiwan, then advecting to the east (Figure 1). This leads to the greatest exhumation occurring in the east and an increasing grade of metamorphic rocks from west to east. The model predicts that Taiwan has not only reached topographic steady state, but thermal and exhumational steady state in central Taiwan (Willett et al., 2003, Fuller et al., 2006). The model predicts that there is a narrow zone of underplating that spans 40 km and 50% of the material in the mountain belt accreted from underplating (Fuller et al. 2006). The rocks exhumed in the Central Range are estimated to have been heated to 300 to 350 degrees C. The model predicts that the backstop of the mountain range is a thrust fault and the stratigraphy has normal polarity.
Figure 1 Doubly vergent wedge model which explains the structural and metamorphic view of Taiwan. This figure displays the various geologic provinces of Taiwan and shows a schematic view of the Continental Margin subducting below the Philippine Sea Plate. The arrows represent particle trajectory paths through the mountain belt.
An alternate model of orogenic growth of the Taiwan orogenic belt is explained by a model in which underplating is responsible for ~90% of the accreted material in Taiwan (Figure 2) (Simoes et al. 2007). This model proposes that crustal shortening due to frontal accretion is accommodated by thrust faults on the foothills. Because the crustal thickening is limited, the Longitudinal Valley and Costal Range forms an arcward dipping backstop of the Taiwan mountain belt. The contact between the orogenic wedge and the backstop is predicted to be a normal fault, with corner flow at the point of underplating and exhumation beneath the crustal lid that forms the backstop. Therefore, the growth of the range is due to underplating which occurs primarily under the areas of greatest exhumation in the Hsueshan Range and the Tananao Complex. According to this model, the rocks would reach greater depths than the doubly vergent wedge model, and would be heated to ~550 degrees C. The kinematics of this model predict an overturned sequence of stratigraphy and faulting.

These two models are end members predicting different structural and metamorphic histories. The critical wedge model predicts significantly less material has been accreted due to underplating. Also, the doubly vergent wedge model states that central Taiwan has reached exhumational steady state while the underplating model suggests that the HR units have not yet reached exhumational steady state. The critical wedge model suggests that the stratigraphic sequence has a normal orientation and the contact with the backstop is a thrust fault while the underplating model suggests that the sequence is overturned and the contact with the backstop is a normal fault. Simoes et al. 2007 predicts that rocks of the Tananao achieved temperatures of 550 degrees C due to very deep burial prior to exhumation. The doubly vergent wedge model predicts shallower paths along largely horizontal trajectories before turning up towards the
Figure 2 Underplating model which explains orogenic growth of Taiwan. The arrows represent particle trajectory paths. This model shows deep particle paths and little deformation within the mountain range.
surface and the rocks reaching temperatures of 300 to 350 degrees C. The Simoes model predicts that the bounding fault is a southeast dipping normal fault, with counter clockwise shearing when looking north. Fuller et al. predicts that the bounding fault is a northwest dipping backthrust with clockwise shear when looking north.

In this study, I present data for the strain magnitude in the Tananao schist that can be used to evaluate the predictions of these models. First, I describe the geology of Taiwan and the location of my study area. Next, I will describe the observations that were made in the thin sections and the strain analyses that I will use. Finally, I will present the strain data and discuss how these findings fit in with the two kinematic models which explain the orogenic growth in Taiwan.

**Geologic Setting**

Taiwan is a mountain range that records the collision between the Asian passive continental margin and the Luzon volcanic arc. The passive margin includes a basement consisting of metamorphic rocks that record an earlier Cretaceous orogeny, rift basins that record the initial opening of the South China Sea, and a capping of drift-related clastics deposited on the shelf and continental slope. The mountain belt has a topographic divide that lies in the Central Range, and the topography is asymmetric, with a wide, gently sloping prowedge that faces northwest, and a narrow, steeper retrowedge that faces southeast.

There are four major geologic provinces of Taiwan which young progressively northwestward and run parallel to the northeast–southwest axis (Figure 3). From east to west, the geologic provinces are the Coastal Range, the Central Range, the Western Foothills, and the
Figure 3 Geologic map of Taiwan that designates the four geologic provinces. The geologic regions on this map run parallel to the northeast southwest striking axis of the island.
Explanation

Geologic Units

- Yellow: Recent Alluvium
- Tan: Pleistocene to recent conglomerates, clastic rocks and terrace gravels or andesite
- Green: Miocene slate, phyllite and sandstone interbeds or andesite
- Blue: Eocene quartzite slate and sandstone
- Orange: Tanana Schist, Gneiss and Marbles
- Red: Andesite and Volcaniclastics
- Gold: Oligocene Sandstone, slate and shale

Geologic Provinces

A Coastal Plain
B Western Foothills
C Central Range
D Coastal Range
Coastal Plain. The Coastal Range is a remnant of the Luzon Island Arc and has played an important role in the growth of the mountain belt (Ho 1988). The rocks here are Neogene in age and consist of marine and volcanic clastics that have lithofacies that are exotic relative to the rest of the island (Ho 1988).

The Central Range consists of an eastern flank that is primarily composed of basement rock and represents the oldest rocks in Taiwan. Although the metamorphism and age of basement granites is Cretaceous, the original age of sediments intruded by the granites is not well constrained. This country rock consists primarily of schists and marbles (Ho 1988) and is referred to as the “Tananao Schist”. The western flank of the Central Range can be divided into the Western Central Range and the Hsüehshan Range. The Western Central Range consists of Eocene slates composed mainly of dark gray phyllite with interbeds of whitish to dark-colored metasandstones, limestone lenses, and Miocene slates composed of dark gray sandstone and disseminated marly nodules (Fisher et al., 2002). The Hsüehshan Range consists of Eocene to Miocene passive-margin shallow-marine sequence of sandstone, quartzite, and argillite metamorphosed at prehnite-pumpellyite to lower-greenschist facies (Fisher et al., 2002).

The Western Foothills province is lies to the west of the Central Ranges and is composed of a imbricate fan that telescopes a sedimentary sequence composed of marine clastic deposits that range in age from Oligocene to Pleistocene (Ho 1988).

The study area that is the focus of this thesis is the metamorphic complex which lies on the eastern flank of the Central Range (Figure 4). The regional dips range from 18 degrees to 89 degrees and generally dip to the northwest (Fisher, 1999). The dips tend to increase from west
Figure 4 The locations of samples collected for this study. The samples were taken from various distances from the backthrust.
Figure 5. Orientation of foliations and lineations within the study region. The foliations generally dip northwest toward the topographic divide and the lineations are orientated along strike.
to east across the study area. The dip of cleavage ranges from 5 degrees to 90 degrees and generally dips to the northwest (Fisher, 1999). The dip of the cleavage also generally increases from west to east. Structural lineations display plunge directions to the northeast and southwest (Fisher, 1999).

The samples were collected from the Tananao Schist (Figure 4). This unit consists of a variety of metamorphic rocks; however, the samples used in this study are greenschists. Greenschists are exposed extensively throughout the metamorphic belt, occurring as thick beds, individual layers, or lenticular bodies interbedded with other metamorphic rocks (Ho 1988). These greenschist appear dark green in color with easily visible foliations. In places, there is a crude preservation of pillows, suggesting that the greenschists of the Tananao schists may have originally been oceanic basalts.

**Methods**

In order to analyze strain, microstructures and grain shape fabrics were analyzed under thin section. Strain was quantified in two ways: measurements of pyrite pressure shadows and analysis of grain center distributions. The techniques of measuring strain using pressure shadows and the center-to-center method are outlined below.

Pyrite observed under the microscope in the samples occurs as both euhedral and subhedral. Euhedral pyrite forms after diagenesis during the course of low grade metamorphism accompanying tectonic deformation (Ramsay and Huber 1983). Pyrite forms crystals that are resistant to deformation and protect the rock matrix on either side from experiencing the full magnitude of the maximum compressive stress. This results in areas of low strain where fissures
form, followed by the infill of fibrous crystalline material (Ellis 1986). Pressure shadows found in the samples 1-9 show growth beginning at the pyrite crystal growing toward a host of different composition. This deformation is known as antitaxial fiber growth where the youngest fibers are those closest to the crystal (Durney and Ramsay, 1973).

The curvature of these fibers record rotation during deformation is defined as either coaxial strain or non-coaxial strain. Coaxial strain produces pressure shadows that form in straight fibers. During coaxial deformation, elongation is defined as \( \varepsilon = \Delta l / l_o \) where \( \Delta l \) equals the length of the fibrous material and \( l_o \) is the radius of the pyrite crystal. Non-coaxial deformation occurs during cases of simple shear. This style of deformation has a rotational component which is used to analyze deformation history. The external rotation rate during deformation, or external vorticity \( (\dot{\omega}_e) \), is determined by the spin, or angular velocity of the stretching axes relative to the material \( (\dot{\omega}_{sp}) \), and the internal velocity \( (\dot{\omega}_i) \) (Allmendinger, Cardozo and Fisher, 2012).

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\dot{\omega}_e = \dot{\omega}_{sp} + \dot{\omega}_i
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In order to analyze each component of angular vorticity, I conduct an analysis of how the magnitude and orientation of stretch vary through time relative to an external reference frame, and an internal reference frame. This analysis is conducted using the MATLAB function fibers from Allmendinger, Cardozo and Fisher (2012) This function uses the cleavage plane as the x-axis as the internal reference frame and calculates incremental strain history based on points selected along the curved fibers. The stretch and angle of rotation is determined for each increment chosen along the fiber.
Pressure shadows also form around porphyroblasts, large crystals which form by metamorphic growth in a more fine-grained matrix (Passchier and Trouw, 1998). Porphyroblasts record tectonic evolution and are used to interpret strain histories based on layering patterns. During formation, the shape-preferred orientation of grain fabric in the surrounded matrix is preserved in the porphyroblast (Zwart, 1962). Therefore, deflection of the orientation of grain fabric within the porphyroblast relative to the surrounding matrix is a result of rotation or simple shearing. Simple shear can also be observed in rotated pressure shadows that form around the porphyroblasts.

The center to center technique analyzes the redistribution of grains in order to create a strain ellipse where the maximum and minimum stretches can be determined. Points which are randomly distributed that undergo deformation remain in random distribution (Frye 1979). Therefore, it is impossible to make strain calculation on a random distribution of points. The center to center technique is based on the idea that grain center distributions in rocks are initially isotropic and that deformation distorts this isotropic distribution. Isotropic distributions arise from the assumption that grains initially have a mean size; therefore, grains cannot be closer together than the sum of the radius of the grain and the grain’s nearest neighbor (Ramsay and Huber 1983). A technique developed by Norman Fry (1979) calculates the strain of a finite point distribution by providing a graphical solution to the center to center method. The technique plots the center of near neighbors relative to a grain center A. This procedure is repeated using a new grain center, plotting near neighbors relative to the same fixed point A. These grains plot at a distance of twice the radius of the grains. Therefore, if all the radii are equal, the plot results in a perfectly packed sample which has experienced no strain. However, the strain of the sample
modifies the distances between nearest neighbors, and principle stress can be identified by creating a strain ellipse which fits the points of near neighbors around center point A.

**Results**

Strain histories were evaluated from microstructures viewed in thin sections cut parallel and perpendicular to the cleavage and parallel to a lineation defined by fibers and grain shapes. The samples are classified as greenschist facies containing the minerals quartz, actinolite, tremolite, chloritoid, epidote, muscovite, biotite, pyrite, and sphene. The foliation in thin sections is largely defined by the alignment of platy phyllosilicates, but one sample (sample 9) also included porphyroblasts of actinolite with internal grain fabric that was rotated relative to the cleavage in the surrounding matrix. Pyrite inclusions formed pressure shadows of quartz in samples 2 and 4. Sample 9 contained pyrite porphyroblasts, which were bracketed by pressure shadows of biotite. Some of these pressure shadows show a non-coaxial strain history, with clockwise rotation of early formed biotite relative to later increments of biotite growth.

Thin sections that display a sufficient number of quartz grains with well-defined grained boundaries were analyzed using the center-to-center method. Figure 6 show images of thin section of sample 2 viewed both parallel and perpendicular to the cleavage plane (10x magnification). The thin sections cut perpendicular to cleavage show the maximum stretch direction and a strongly foliated surface. Numerous images were used for each sample in order to increase the number of grains evaluated per sample. By using a larger number of grains, the accuracy of the results increases. Figure 7 shows the output of the center-to-center method. In this figure, there is a point around the origin where no grain centers plotted. The anisotropy in the grain center distribution around the origin was best fit by the red ellipse. The long axis of the ellipse represents the maximum principle stretch, (s1) and the short axis of the ellipse represents
Figure 6 Thin sections taken parallel (left) and perpendicular (right) to strike.

Figure 7 Output of the center to center method which shows the plot of grain center distributions. The red ellipse are best fit to show the anisotropy which occurs around the origin.
the minimum principle stretch (s3). The ratio of the stretches of each thin section was calculated and included in Table 1. This table also includes the total stretch for each sample. Strain was calculated on pressure shadows which did not rotate significantly using $\varepsilon = \Delta l / l_o$ (Figure 7). Pressure shadows which rotated clockwise and record non-coaxial strain are shown in Figure 8. The progressive finite strain and cumulative incremental elongation were calculated using the MATLAB function fibers Figure 9. The Cumulative incremental strain history shows variations in the orientation of maximum stretching through time, whereas the Progressive finite strain history shows variations in the magnitude and orientation of the maximum finite stretch, and the last point is the final value for the finite strain. Cumulative incremental strain histories typically show a counterclockwise rotation of the stretching direction through time from an initial orientation of x and a final orientation of y. Progressive finite strain histories depict final strain values of x magnitude and y orientation for the finite strain ellipse. Table 1 shows a summary of the stretch measurements calculated from pressure shadows.
Figure 8 Pressure shadow formed around a pyrite crystal and infilled with quartz.
**Figure 9** Pressure shadow from Sample 9 formed around a pyrite crystal. Biotite has been stretched and rotated clockwise within the pressure shadow displaying non-coaxial strain.
Figure 10 Plots created from Matlab script fibers recording the non-coaxial strain history of rotated pressure shadows. Top shows cumulative incremental elongation vs. the change in stretch direction. Bottom shows changes in orientation and magnitude of the finite strain ellipse.
Figure 11 Porphyroblast of actinolite that has grain fabric deflected relative to the cleavage plane.
Table 1 A summary of the strain data collected from strain ellipses and pressure shadows. Left shows strain ellipses created from the grain center distribution in both cleavage perpendicular (s1/s3) and cleavage parallel sections. Right shows strain collected from pressure shadows using ($\Delta l/l_0$) and the Matlab script fibers.
Discussion

The strain measurements taken from pressure shadows in the metamorphic complex indicate a maximum stretch ranging from 2.87509 to 6.17201. The strain ratios generated from using the center-to-center method indicate a s1/s3 ratio ranging from 1.24004 to 2.08929. The s1/s2 ratios ranged from 1.107 to 1.2216.

The doubly vergent wedge model predicts horizontal particle paths and deformation within the mountain belt that leads to increasing strain across the central range toward the coastal range. The results from this study are consistent with that prediction. Strain measured from the pressure shadows show spatial variation from west to east. Samples 2 and 4 were collected further east than sample 9. Samples 2 and 4 recorded strain values ranging from 5.47 to 6.17 while pressure shadows from sample 9 recorded strain values ranging from 2.875 to 3.65, showing that strain increases toward the east.

The grain shape fabrics which were analyzed using the center-to-center method also showed spatial variations in s1/s3. Samples 2 and 3 were collected furthest to the east. These samples recorded maximum s1/s3 of 1.96 and 2.08. Sample 4 recorded a maximum s1/s3 of 1.24. Sample 8 was collected furthest to the west and recorded a maximum s1/s3 of 1.525. These samples also show a general trend of increasing strain from west to east.

The samples of the Tananao schist collected have foliations which dip northwest toward the divide of the Central Range. The doubly vergent wedge model predicts a backthrust (Fuller et al., 2006) while the underplating model predicts a normal fault (Fuller et al., 2007). Foliations dipping toward the divide are consistent with a backthrust. Also, it is unlikely that the backstop of the mountain range is a normal fault, given that the dip direction of the foliations is not
consistent with subhorizontal extension or parallelism with a southeast dipping fault but is consistent with strain related to backthrusting on a northwest dipping feature.

The pressure shadows in sample 9 have rotated fibers that indicate a component of simple shear. These pressure shadows are composed of biotite oriented perpendicular to the maximum stretching direction presumably grows by cracking at the pyrite biotite interface. Based on analysis of the variations in orientation of the biotite grain relative to the foliation the pressure shadows have been rotated clockwise and experienced right lateral shearing (since the lineation is subhorizontal). The porphyroblasts in sample 9 are also consistent with right lateral shear. The pressure shadows surrounding the porphyroblasts show clockwise rotation around the inclusion. In addition, the internal grain fabric has been deflected clockwise relative to the surrounding matrix. This is consistent with along strike, right lateral shearing that is not predicted in either model and is also inconsistent with the left lateral obliquity predicted from the obliquity of the Asia-Philippine Plate relative plate motion vector. Fisher (1999) suggests that this reversal in sense of shear could be due to lateral extrusion, which involves extrusion of ductile material parallel to strike, or from the more mature northeastern part of the collision toward the submarine forearc to the south of Taiwan. Lateral extrusion can lead to non-coaxial strain and a reversal in the sense of shear across the extruding mass. This is a potential explanation of why the shearing found in the Tananao shist is inconsistent with the kinematic models. An alternative explanation is given by Yeh (2004) that accounts the reversal in sense of shear to refolding associated with regional structures. In this study, Yeh (2004) also located regions of left lateral shearing, and attributed this variation as due to a position on the opposing fold limbs of areas of right lateral shearing.
The s1/s3 ratios values calculated from the grain center distribution recorded more strain than the maximum stretch strain values calculated from the pressure shadows. The process of foliation development can in some cases weaken grain shape orientation and destroy lithological layering (Means, 1981). Hirth and Tullus (1992) created experiments which observed recrystallization within quartz during deformation through the process of dislocation creep. These observations showed that grain boundary migration can sweep into crystals and act to minimize grain aspect ratios while the deformation acts to increase aspect ratios. These leads to grain center distribution showing lower aspect ratios than the actual stretch ratios. These observations provide an explanation why grain center distribution does not record the finite strain history.

Conclusions

Large scale structural observations as well as microstructure viewed in thin sections created from samples from the eastern central range provide evidence of strain histories in Taiwan. These observations support the predictions of the doubly vergent wedge model as well as record a sense of shear that has not been accounted for in either model. The observations made in this study are summarized:

1. Strain increases across the mountain belt from west to east which is consistent with the particle trajectories predicted by the doubly vergent wedge model
2. Foliations dip northwest toward the topographic divide which provides evidence that the stratigraphic sequence in this region has normal polarity.
3. The study region experienced right lateral shearing which is inconsistent with plate motion observed from GPS.

4. Pressure shadows recorded more strain than grain shape orientation. Therefore, grain shape orientation is successful at determining stress, however, should not be used as a marker for finite strain.
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