Relationship of Joint Sets to Folded Diatomite Bedding of the Miguelito Member of the Pismo Formation in Montaña de Oro State Park

A Senior Project

presented to

The Faculty of the College of Agriculture, Food and Environmental Sciences

California Polytechnic State University, San Luis Obispo

In Partial Fulfillment

of the Requirements for the Degree

Bachelor of Science

by

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January, 2014

Abstract

This study was conducted to determine if the orientations of observed joint sets in the late Miocene diatomite bedding of the exposed Miguelito Member in Montaña de Oro State Park relate to the San Andreas wrench fault compressional forces that caused folding of the formation. Strikes and dips of bedding planes and their corresponding first and second generation joint sets were gathered and compiled into a stereonet program for analysis. A cross section of the bedding plane data shows compressional antiform (fold axis oriented ~304/013) and synform (fold axis oriented ~300/001) features. Previous studies indicate post Miocene, tectonic shortening with a stress field oriented σ_1: ~028/002 and 0.2 to 0.23 mm/yr uplift of the San Luis/Pismo structural block. Mode one intensive fractures develop ~90° dips and define a stress field with a maximum stress (σ_1) parallel and a minimum stress (σ_3) perpendicular to resulting joints. The average σ_3 of the finite stress field of the primary joints is ~095/010. The resulting σ_3 of the finite stress field of the secondary joints have a less consistent strike of ~090 to ~180. The data shows that primary joints are syntectonic hydrofractures, created by the same horizontal shortening that caused ductile bedding deformation. The conjugate secondary joint systems are created by a stress field at a more recent time and orientated σ_3 ~135/000. I suggest that the predominant secondary orthogonal joint systems are created by outer arc extension and/or unroofing related to uplift and erosion. Results from this study indicate that brittle and ductile deformation of the Miguelito Member agree with the horizontal northeast to southwest tectonic shortening of the San Luis Obispo/Pismo block. Evidence for a clockwise rotating stress field from the conjugate joint set data may also support the wrench tectonic kinematic model of the California Central Coast.

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Introduction

This project is a field study investigating joint sets in folded diatomite bedding of the coastal Montaña de Oro State Park. Determining orientations of joint sets in the biosiliceous rock can help identify the stress field of tectonic forces that lead to the brittle and ductile deformation of exposed marine bedding along the Montaña de Oro coastline (Keller, 1992). The rhythmically bedded diatomaceous rocks of the Miguelito Member of the Pismo Formation found in Montaña de Oro display primary and secondary systematic joint sets (Image 1 and 2).

A regional stress field of the Montaña de Oro coastline was estimated using two methods. First, strikes and dips of bedding plane orientation were mapped and a maximum compressional force was inferred from the fold orientation data. Second, strikes of primary and secondary joint sets were used to determine the $\sigma 1$ and $\sigma 3$ orientations, which will provide additional information on the direction of regional maximum compressional force. Stress fields determined from both methods were compared to see if there is a positive relationship between the ductile and brittle deformation of diatomite bedding. The estimated stress fields were then compared to the regional stress field determined from previous studies using different and more sophisticated methods. Results from this study may also provide information on the kinematic model for regional crustal shortening of the California Central Coast.

Study Area

The study was conducted in the coastal portion of Montaña de Oro State Park. The park is located 8 km southeast of Morro Bay and 3.2 km southwest of Los Osos, off of Pecho Road (35°15’50.04”N 120°51’43.92”W). Exposed Miguelito Member of the Pismo Formation was examined along a 2.4 km stretch of coastline from the mouth of Hazard Canyon creek south to the northern bluff of Spooner’s Cove (Los Osos, 2013). Portions of analyzed Miguelito Memberare indicated as numbered stations on the Hazard Canyon map (Figure1).

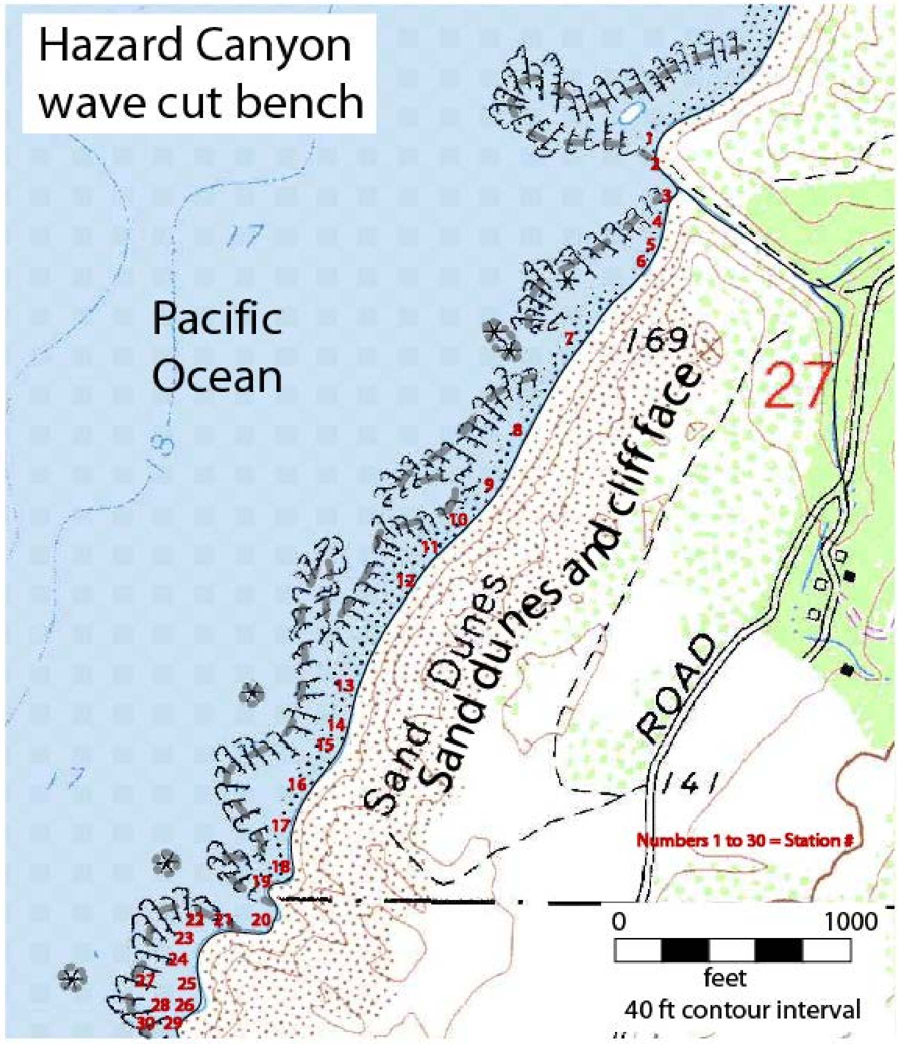

Figure 1. Map of the study area. Numbered Stations are indicated in red on the upper Miocene diatomite bedding of the Miguelito Member. Map template provided by Dr. Scott Johnston (Johnston, 2013).

Age, Stratigraphy and Composition of the Miguelito Member

The Miguelito Member is the basal portion of the Pismo Formation that overlies the older Monterey Shale Formation. Diatoms, deposited in a series of offshore basins along the California margin during the mid-Miocene to early Pliocene epochs, lithified to form the Miguelito Member. The latest Miocene to early Pliocene layers of the Miguelito Member have been eroded away at the coast. The presently exposed layers of coastal Miguelito Member are estimated to be late Miocene (10.4-6.0 Ma) in age and 884 m thick (Keller, 1992).

The Miguelito Member of the Pismo Formation is a rhythmically bedded, organic-rich 2–20cm thick, hemipelagic, biosiliceous shales interlayered with thinner 0.5 to 3 cm mudstone beds. The biosiliceous rocks are primarily diatomite that has undergone varying degrees of diogenesis (Opal-CT to quartz chert). Limestone and carbonaceous shale are found in less frequency within the diatomaceous layers. Siliceous mudstone and orogenic-phosphatic marl traces are found within the mudstone layers. Dolomite concretions, 0.2 to 1.5 m in diameter, are found between layers of diatomite (Keller, 1992).

Tectonic setting

The present tectonic setting and the resulting geologic features of the California Central Coast are shaped primarily by the development of the San Andreas Fault System (SAFS). Mesozoic and Tertiary subduction of the Farallon Plate beneath the North American Plate created an accretionary wedge that built California and much of the continental margin of the western North American Plate. The Franciscan Mélange, found throughout the central coast of California, is the accretionary remnants of the ancient subduction zone. Miocene subduction of the Pacific-Farallon spreading center transformed into a broad zone of right-lateral shear. The San Andreas Fault System developed from this dextral motion in the late Cenozoic. The SAF is the present boundary between the Pacific and North American plates (Clark, 1994).

The San Andreas Fault trends N35W with a 48 mm/yr right-lateral offset (Clark, 1994). The northwest structural grain of the Central California Coastline is shaped by the northwest trending SAFS. The SAF is the master fault of an intricate 800 mile long system of northwest trending faults that accommodate right-lateral shear. Right-lateral offset has been supplemented by relatively smaller strike-slip faults that parallel the SAF. The Hosgri and West Huasna Faults are examples of dextral faults that supplement right-lateral shear of the SAF. The SAFS contains a left stepping restraining bend located northeast of Santa Barbra called, The Big Bend. The Big Bend causes transpression between the North American and Pacific Plate margins. Convergence between these two plates created the uplifted Transverse and Southern Coast Ranges of Santa Barbra county (Clark, 1994).

Northwest of The Big Bend, it is thought that a late Oligocene to early Pliocene wrench regime created a series of west to northwest en echelon reverse, oblique and strike-slip faults. The Edna, Lions Head, San Miguelito, Santa Maria River, Santa Yenez, Los Osos and Wilmer Avenue fault systems are all resulting en echelon faults found northwest of the big bend and are sub-parallel to normal to the SAF (Vittori, 1994).

The en echelon, parallel and sub-parallel faults of the SAFS create fault bound structural blocks. Crustal fault blocks are characterized by a rigid area of crust, uniform in lithology and have undergone relatively little brittle or ductile deformation. The San Luis Obispo/Pismo (SLP) structural block is bound by the Los Osos Valley Fault (LO) to the northwest, the Wilmer Avenue Fault (WA) to the southeast, the Hosgri Fault (HF) to the west and the West Huasna

Fault (WH) to the east (Lettis, 1994). The study area is located on a coastal wave cut bench of a marine terrace on the west side of the San Luis Obispo/Pismo block (Figure 2).

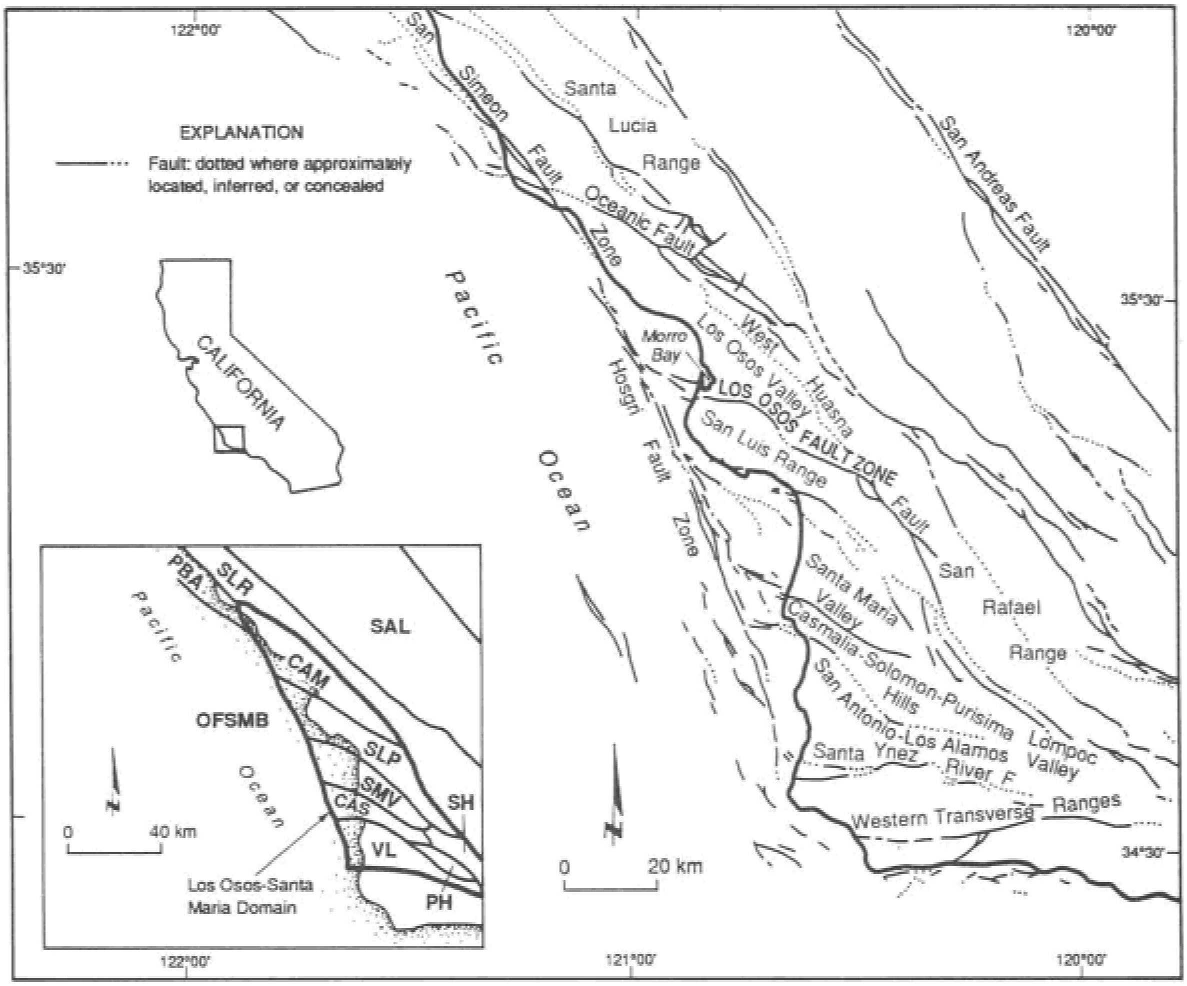

Figure 2. Map of structural blocks and faults in the Central Coast of California provided by Lettis and Hall. The study area is located in the northwestern portion of the San Luis/Pismo block. SAL= Salinian block; SLR= Santa Lucia Range block; PBA= Piedras Blancas anticlinorium; CAM= Cambria block; SLP= San Luis Obispo/Pismo block; OFSMB= Offshore Santa Maria Basin block; SMV= Santa Maria Valley block; CAS= Casmalia block; VL= Vandenberg/Lompoc block; PH= Purisima Hills block; SH= Solomon Hills block (Lettis, 1994).

The Los Osos fault zone is a west-northwest trending reverse fault. It makes up the northwest boarder of the SLP block. The Los Osos fault is a discontinuous en echelon zone that extends from the northwest trending dextral Hosgri fault in Estero Bay and intersects the dextral West Huasna fault south of San Luis Obispo. The Wilmer Avenue reverse fault makes up the southeastern border of the SLP block. Like the Los Osos fault, the Wilmer Avenue fault is a northwest trending discontinuous en echelon zone that extends from the Hosgri fault in the northwest to the West Huasna fault in the southeast (Lettis, 1994).

In the late Oligocen to late Miocene the San Luis Obispo/Pismo structural block underwent a transtensive phase. Subsidence of the structural block and formation of the Pismo and Huasna marine basins occurred. Later, The SLP block transitioned into a transpressive phase in the late Miocene to early Pliocene. Contractional tectonic forces resulted in brittle and ductile deformation of the SLP crust (Vittori, 1994).

33 kilometers of faults normal and sub-parallel to the San Andreas fault zone, accommodating post-Miocene transpression, created the southern coast ranges. Since the late Pliocene, the deformation of this area has been from northeast to southwest crustal shortening. The crustal shortening developed the Los Osos reverse fault that separates the elevated SLP block from the southwest tilted Cambrian block in the northeast. The Los Osos fault was once a dextral strike-slip fault that created transtension and development of the Morro Bay basin (Clark, 1994).

The wave cut marine terraces of this study are more specifically a part of the Irish Hills sublock of the SLP structural block (Lettis, 1994). The marine terraces of coastal Irish Hills segment has undergone uplift since the late Quaternary epoch. The Los Osos reverse fault is a range front fault and has shown strong Holocene activity. Uplift of the Irish hills segment is entirely, or at least partially due to the Los Osos Valley fault displacement. The Los Osos fault trace, located 1.5 km north of Hazards Canyon, is covered by Pleistocene and Holocene eolian deposits. The reverse fault creates subsidence in the north at a rate of 0.1 mm/yr and uplift in the south at a rate of 0.2 to 0.23 mm/yr. Thus, no exposed marine terraces are present in Morro Bay (Hanson, 1994).

The southeast margin of the SLP block is boarded by a complex late Quaternary reverse fault system. The southwest trending, Wilmer Avenue fault system, which makes up the southern boundary of the SLP structural block, has a net displacement of 0.16 to 0.33 mm/yr. This displacement causes uplift to the north and subsidence (developing the Santa Maria Basin) to the south (Nitchman, 1994).

Crustal shortening of the SLP block is primarily accommodated by reverse faulting along the north and south margins of the structural block. The SLP structural block is compressed and uplifted between the Cambria block and Santa Maria block, because of transpression caused by converging crust from dextral motion of the Hosgri and West Huasna faults. The CAM block is tilted to the south and the SMV block is forced to subside (Figure 2).The entire central coast domain converges against the relatively stable Salinian crust and is locked into place to the east. Uplift is significantly less than areas closer to the restraining bend (Nitchman, 1994).

Horizontal compressional stress of the SLP block has been observed in previous studies. A northeast to southwest maximum compressional stress has been determined by earthquake focal mechanisms, borehole deformation, conjugate patterns of Andersonian reverse faults, axial fold data and predominant joint set orientations (Vittori, 1994). Late Pliocene northeast $\sigma 1$ agree with focal mechanism of earthquakes in the area. Borehole data shows a maximum stretch in the west-northwest direction, which also agrees with the σ1 direction. Andersonian models for conjugate reverse faults found in the SLP area reveal the same maximum northeast to southwest trending horizontal stress. Predominant joint sets of the SLP block are found to have strikes trending 30° and 110° and are consistent with northeast trending compression. Large scale fold axes, including the Pismo syncline, trend west-northwest. Synclines and anticlines accommodate shortening by means of ductile deformation and suggest a maximum compression perpendicular to the axial strikes. Joints are found to be parallel and orthogonal to large scale fold axis. This is consistent with the σ1 stress patterns. Vittori combined the five methods in determining stress field and stratigraphic ages to produce the following evolution of σ1 orientation: Cretaceous 021/001, early Miocene 310/085 and 208/011, Late Pliocene 177/076 and 202/006, Quarternary 028/002 (Vittori 35).

Methods

Data for this study was gathered at 30 separate sites from exposed Miguelito Member diatomite bedding (Figure 1). Strike and dip data of diatomite bedding planes was gathered using a Brunton compass. Strikes and dips of first and second generation tension fractures were recorded from corresponding station locatons (Table 1). Orientations of bedding planes, primary joint sets and secondary joint sets were translated to maps using Adobe Illustrator (Figure 3 and 5). The map of bedding plane orientations revealed possible antiform and synform features (Figure 3). Anticline and syncline limbs were compiled into a stereonet program. Poles to limbs were determined. Best-fit great circles were produced from the poles. Trends and plunges of the anticline and syncline were then determined by the poles of the two best-fit great circles (Figure 4). The locations of the axial traces were estimated based on station locations. A cross section Profile was inferred from the bedding plane and fold axis data (Figure 3).

Strike and dip data of first and second generation joint sets were compiled into a stereonet program for analysis. Poles of primary and secondary joint sets were produced on separate stereonets. An unfolded bedding function was required to obtain an accurate finite stretch (σ3) to estimate the maximum compression (σ1) that caused the Mode 1 intensive fractures for both joint sets. The unfolded bedding function recalibrates all of the bedding plane data to having a dip of 0°. Assuming the law of original horizontality, the presently tilted bedding planes would produce an inaccurate stress field that caused joint fractures.

Orientations of poles to joint set planes define the principal plane of maximum stretch (σ3). A Conical Best-Fit function was performed on the joint set poles to obtain an average σ3 direction. σ1 could then be determined by calculating the trend and plunge of the points 90 degrees away from the average σ3 point. The σ1 trends and plunges should also be parallel to and along the same average joint set plane. The average σ1 should define the regional maximum compression of the study area (Figure 6).

Results

Hazard Canyon Reef Structural Data

Station	Bedding Plane		First Generation		Second Generation	
#	Strike	Dip	Strike	Dip	Strike	Dip
1	235	17	140	70	220	90
2	230	12	160	75	55	89
3	240	15	155	75	285	90
4	255	17	335	75	70	90
5	255	23	150	83	60	25
6	256	15	140	65	100	75
7	255	15	159	89	275	90
8	229	9	320	70	200	70
9	225	10	-	-	-	-
10	190	15	185	-	300	-
11	175	15	350	70	270	70
12	160	25	330	65	235	75
13	150	25	250	75	310	75
14	160	25	5	59	310	-
15	105	7	5	70	280	-
16	250	5	-	-	-	-
17	315	2	-	-	-	-
18	285	9	340	90	190	70
19	285	15	180	65	125	80
20	295	15	205	60	195	80
21	301	25	169	60	25	89
22	301	33	180	70	200	80
23	301	32	171	78	215	71
24	299	35	160	75	84	65
25	300	35	205	89	-	-
26	300	28	205	89	180	78
27	300	34	200	87	175	85
28	298	34	190	85	300	90
29	305	32	175	80	-	-
30	295	35	211	86	-	-

Table 1. Data was recorded from a Brunton compass. Missing data is due to lack of suitable outcrop.

Results from the mapped bedding plane data produced evidence of an anticline, located ~0.40 km south of hazards canyon and a syncline, located ~0.80 km south of Hazard Canyon. Stereonet results from anticline and syncline limbs show an antiform feature with a fold axis oriented ~304/013 and a synform feature with a fold axis oriented ~300/001 (Figure 4). In order to accommodate horizontal shortening, ductiley deformed bedding will contain fold axis that are perpendicular to the direction of maximum compression. Therefore, according to the bedding plane data, the orientation of σ1 of the stress field that caused folding of diatomite bedding is

~040/horizontal to ~044/horizontal. Northeast to Southwest horizontal compression must have caused the resulting orientations of fold axes at this site.

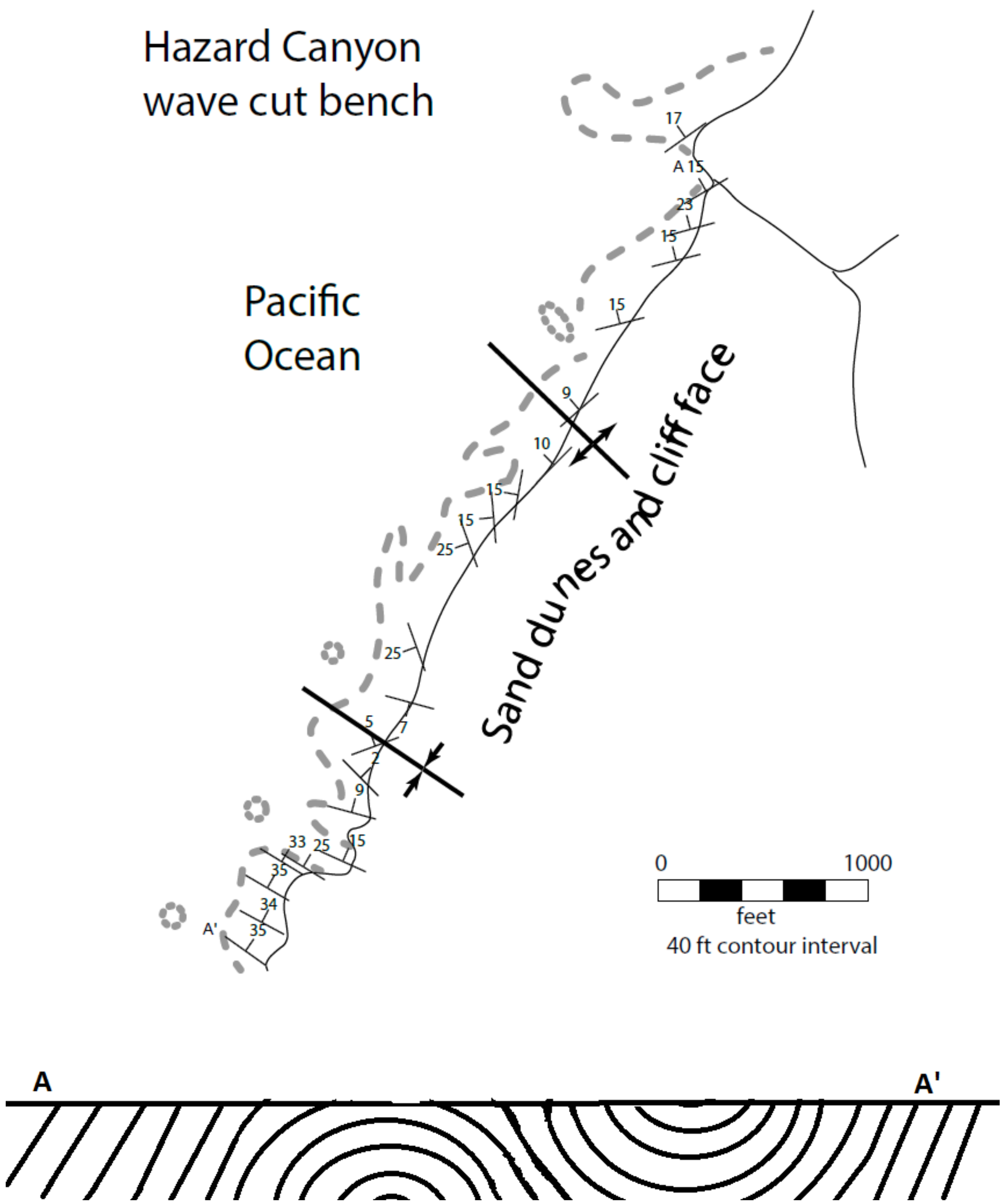

Figure 3. Map of the study area displaying bedding plane orientations and estimated location and orientation of axial traces. A vertically exaggerated northeast to southwest (A-A') cross-section profile is also provided to assist in interpreting the folded bedding data. Map template provided by Dr. Scott Johnston (Johnston, 2013).

Syncline Anticline

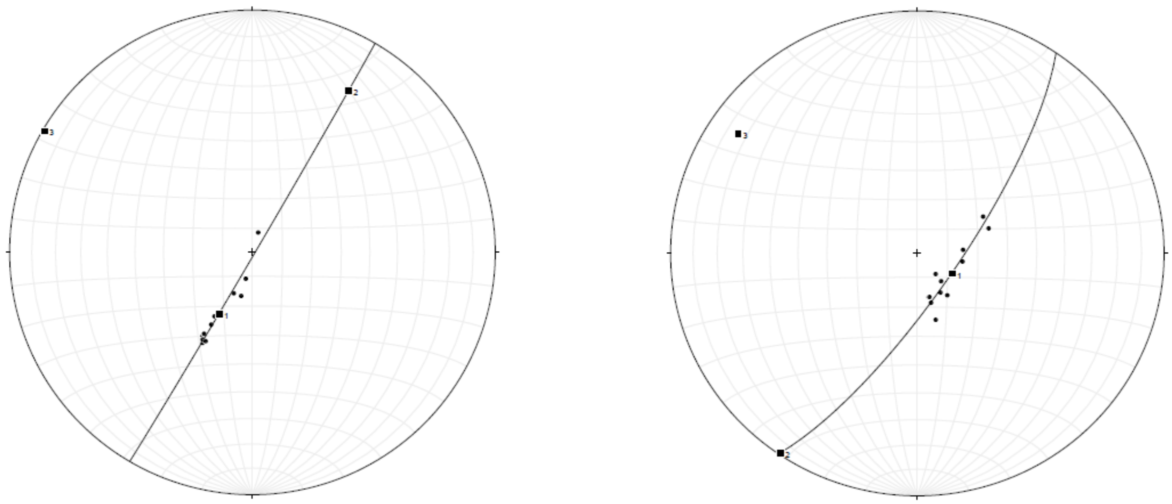

Figure 4. Stereonets display the calculated trends and plunges of the syncline (left) and anticline (right). The poles to the best-fit great circles (points are labeled with the number 3) are the trends and plunges of the fold axis.

Joints will be described as fractures with no apparent shear displacement. Observed systematic joints are Mode 1 tensile fractures perpendicular to the principal plane of minimum stress (σ3) and parallel to the principal plane of maximum stress (σ1). The joint plane contains σ1 and σ2 (intermediate stress) orientations (Van der Pluijm, 2004).

The master joints of the joint system are long, through going, parallel joints that are found to be consistently perpendicular to the bedding plane strike. The cross-strike master joints will be identified as the older, primary or first generation joint set. The smaller secondary joint sets were determined to be younger, because they appear to be offset by the predominant first set of joints. These joints are not offset, they are cross joints. Since joints cannot propagate through a free plane, the smaller set of joints must be relatively younger. The secondary joint sets are predominantly strike parallel sets that create an orthogonal “ladder pattern”. There are also secondary joint sets that form dihedral angles between primary joint sets that are 30 to 60 degrees. This study will refer to this joint system pair as a conjugate system (Van der Pluijm, 2004).

The mapped joint set orientations show strikes of primary joints to be mostly perpendicular to bedding plane strike and fold axis. Strikes of secondary joints were found to be mostly orthogonal. Conjugate joint systems were found with less frequency (Figure 5).

The average σ3 of the finite stress field of primary joints is ~095/010. Therefore, the maximum compressive force that created the brittley deformed primary joint sets is 005/010 (Figure 6). The resulting σ3 of the finite stress field of the secondary joints have a less consistent strike of ~090/horizontal to ~180/horizontal, averaging σ3=135/030. Therefore, the average σ1 for the secondary joint sets was determined to be 045/010 (Figure 6). North-northeast to south-

southwest horizontal compression must have caused the resulting orientations of first generation joint sets.

Dip data was unavailable for some joints because of buried cross-section profiles. Although the strikes of joint sets were visible, the stereonet program could not run an unfolded bedding function with missing dip data. As a result, only stations with both strike and dip data for bedding plane, first and second generation orientations were used to determine the stress field.

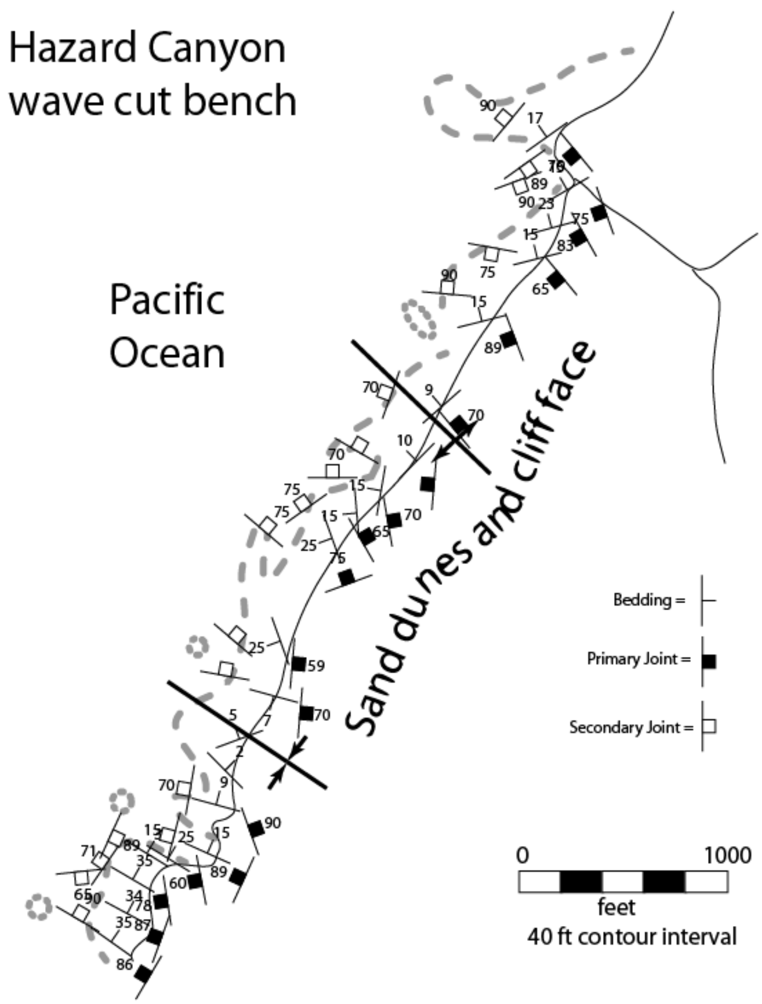

Figure 5. Map of the study area showing orientations of bedding planes, primary joints and secondary joints. The bedding plane symbol is positioned on the accurate corresponding station location. The primary and secondary joint symbols are staggered on either side of the bedding plane symbol for viewing convenience. Dip data was unavailable for two joint sets, but their strikes are displayed for analysis. Map template provided by Dr. Scott Johnston (Johnston, 2013).

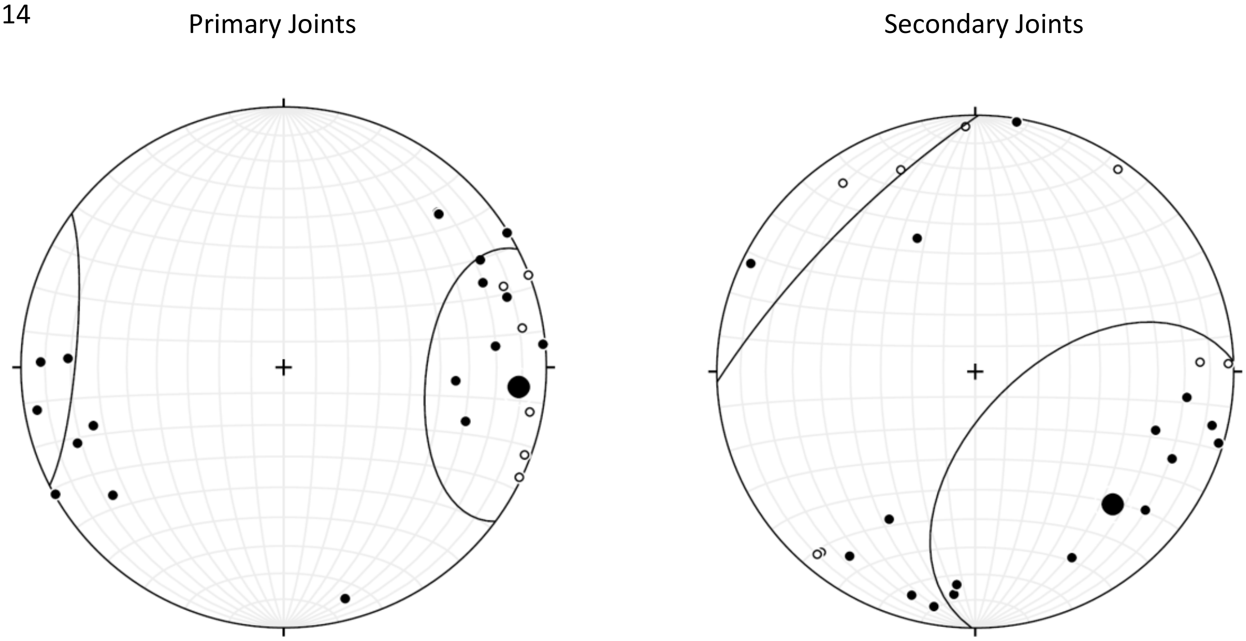

Figure 6. Stereonets display poles to primary joint set (Left) and secondary joint set (Right) orientations on an unfolded plane. The unfolded bedding plane function created poles that plunge above horizontal. Hallow filled points denote poles plunging above horizontal. Stereonets also display conical best-fit circles with larger black points denoting the average σ3 orientation.

Discussion

According to the stereonet results, the estimated direction of maximum stress that caused ductile and brittle deformation of the Miguelito Member diatomite bedding are similar. Less than 40 degrees separate the calculated σ1 for the two conducted methods. More importantly, the results from this study support the estimated stress field of the Los Osos area determined from previous studies. A present regional stress field oriented σ1=028/002 is the consensus among Vittori, Keller, Lettis, Clark, Hanson and others cited in this paper (Vittori, 1994). My investigation revealed a σ1 oriented ~005/010 (primary joint set data) to ~042/000 (fold axis data).

Discrepancies in stress field orientations are most likely due to matters of scale. I determined a stress field from a much smaller area compared to previous studies. Also, I only used two separate methods, fold axis data and joint set data, to determine maximum shortening. Previous studies used several different methods and more sophisticated means to acquire a stress field (Vittori, 1994). Despite the limitations of my project, this small study area of diatomite bedding displays an accurate representation of the post-Miocene stress field of the SLP structural block. This data affirms the theory of a northeast to southwest maximum horizontal compression of the area.

After discovering the orientation of the joint sets relative to the folded bedding, assumptions can be made about the origins and specific types of intensive fractures that developed from this stress field. The Miguelito Member rock is composed of highly hydrated siliceous material. The diatomaceous rock formed at cold temperatures in deep oceanic basins. Thus, the diatomite still contains a lot of water after lithification (Keller, 1992). The Mohr circle diagram can be used to explain why intensive stress fractures developed parallel to maximum compression in this type of rock (Van der Pluijm, 2004).

Fluid pressure makes rocks more brittle, because water molecules disrupt the rigid crustal lattice of minerals within the rock. For example, Opal is more brittle than pure crystalline quarts (Behl, 2011). According to the Mohr-Coulomb failure envelope, the first fractures that develop from a brittle rock with high fluid pressure and subject to low confining pressure near the earths surface will be 90 degrees from the normal force direction to the pole of the fractured plane (Van der Pluijm, 2004). Systematic, Mode 1 tensile fractures in rock with high fluid pressure are referred to as syntectonic hydrofractures. This is exactly what we observe in the systematic fractures found in the exposed Miguelito Member diatomite (Figure 5). The master joint sets, referred to as primary joint sets in this experiment, are found to be syntectonic hydrofractures. The Syntectonic hydrofractures are parallel to $\sigma 1$ and perpendicular to the fold axis (Van der Pluijm, 2004).

The fold axis data and the primary joint set data leads me to believe that there is a positive relationship between ductile and brittle deformation of the diatomite bedding in this study area. The identification of the syntectonic hydrofractures perpendicular to the fold axis is the most compelling evidence proving that the same northeast to southwest stress field that caused folding is the same stress field that caused brittle jointing of the Miguelito Member.

Mapped strikes and dips of primary and secondary joint sets are shown to be mutually perpendicular. These orthogonal joint sets, formed by the primary and secondary joint sets, are found with regularity in the diatomaceous rock (Figure 6). The shorter secondary cross joints terminate at the intersection with the longer primary joint sets, creating a “ladder pattern”. There are a number of possible ways for orthogonal joint sets to develop. The secondary cross-joints could have been created by outer arc extension of folded bedding layers. When brittle diatomite bedding is folded the outer layer stretches and fractures bittley as linear fractures parallel to the strike of the fold axis. Outer arc extension results in stike-parallel joints observed on the map of secondary joints near the anticline axis (Figure 5) (Van der Puijm, 2004). However, outer arc extension only explains strike-parallel joints near the anticline axis. Secondary cross-joints can also develop as release joints with the removal of overburden. Because of regional uplift, hundreds of feet of younger diatomite bedding have been eroded away from the presently exposed bedding (Keller, 1992). Orogenic stresses could have been relaxed and planes of weakness, 90 degrees away from primary joints, open up perpendicular to the regional $\sigma 3$ (Van der Puijm, 2004). Release joints, caused by regional uplift and exhumation, is a more plausible explanation for the resulting orthogonal joint systems found throughout most of the study area.

Conjugate secondary joint systems, found with less frequency, could have formed from a separate and more recent compressional event. The conjugate, secondary joints are found to be formed from a stress field with a σ_3: >~090/000, < ~180/000 (Figure 6). It can be speculated, that the compression that formed these joints appears to be rotating clockwise through time. This hypothesis, agrees with the wrench tectonic kinematic model for strain in this area.

It is thought that quaternary deformation by transpression renewed late Cenozoic, clockwise rotation of the transverse ranges. This kinematic model for wrenching, can explain the newer conjugate stress field needed to make the conjugate joint systems. There are two distinct kinematic models for the strain causing the tectonic shortening in this area, defined by Mounte and Soupe (Mounte, 1987). The observed compressional deformation could have developed by either “Strain Partitioning”, the kinematic model argued for by Mounte and Suppe, or “Transpressive wrench faults”, the kinematic model argued for by Harding. The “strain partitioning” end member, kinematic model explains observed deformation as a result of horizontal stress partitioned into two vectors. The “Transpressive wrench fault” model explains the observed brittle deformation as a result of compression caused by en echelon faults oriented perpendicular to $\sigma 1$. The en echelon faults develop from high frictional drag and joints would expect to develop parallel to $\sigma 1$. The main difference between the two end member models is that an observed joint in a strain partitioning environment will not rotate, through time, into parallelism. However, a joint observed in a transpressive wrench fault regime will rotate into parallelism, through time (Clock-wise in the SAFZ) (Mounte, 1987).

However, this dataset does not include enough temporal or spatial conjugate joint set data to argue for or against fault wrenching. The data is limiting and development of conjugate joint systems is a controversial subject amongst the scientific community (Van der Pluijm, 2004). Therefore, assumptions about a rotating and newer stress field cannot be made from conjugate joint systems in this area. What can be known from conjugate joint sets is that they developed in response to a stress field in a different orientation and at a more recent time compared to the post-Miocene primary joint sets.

Conclusion

Research indicates that the presently exposed diatomite bedding of the Miguelito Member is estimated to be late Miocene in age. Therefore, it can be assumed that brittle and ductile deformation occurred sometime after the late Miocene. Development of the Oligocene to early Pliocene SAFS was needed to create the stress field to produce folding and jointing in the Miguelito Member. The tectonic shortening was caused by tangential shearing of the northwestern region of the San Andreas Fault restraining bend and caused northeast to southwest maximum horizontal compression of the SLP structural block. Earthquake focal mechanisms, borehole deformation, conjugate patterns of Andersonian reverse faults, fold axis data and predominant joint set orientations from previous studies indicate a northeast to southwest maximum horizontal crustal shortening (Vittori, 1994).

Orientations of observed fold axis and joint sets found in the Miguelito Member of the SLP structural block are consistent with the late-Pliocene stress fields determined by previous studies (Vittori, 1994). An anticline and syncline were determined from bedding plane data. The orientations of the axial traces indicated a maximum crustal shortening (σ1) in the northeast to southwest direction.

Strikes of the systematic primary and secondary joint sets are also consistent with the late-Pliocene stress fields determined by previous studies. Strikes of the primary, master joint sets are oriented parallel to the maximum crustal shortening (σ1) direction. The principal plane for maximum compression determined from the primary joint sets was north-northeast to south-southwest. First generation joint sets where determined to me syntectonic hydrofractures, because of their consistent cross-strike orientation to fold axis and the hydrated composition of the brittle host rock, which formed at a low confining pressure (Van der Pluijm, 2004).

Secondary joint fractures were determined to be primarily orthogonal to primary joints. The origin of these strike-parallel joints is outer arc extension and/or regional uplift and unloading of overburden through erosion of upper layers. However, uplift and orthogenic pressure release is most likely the main cause of orthogonal joint systems found throughout the study area. Conjugate joint systems where also observed in less frequency, but may provide information on an evolving stress field. However, insufficient conjugate joint data was available to determine if the newer stress field agrees with the clockwise rotation of a wrench tectonic regime (Mounte, 1987).

Comparison of the brittle and ductile deformation methods of this study results in similar stress field patterns. The same northeast to southwest trending σ1, found by fold axis data, is consistent with the direction of shortening that led to systematic joint development. Therefore, it can be concluded that there may be a positive relationship between the primary joint sets and the folded bedding of the Miguelito Member. The northeast to southwest compressional forces that caused folding of the Miguelito Member diatomite bedding is the same compressional force that caused the observed orientations of the joint systems. The results found in this study can help define the current regional stress field observed in the coastal region of Montaña de Oro State Park.

Image 1. Example of an orthogonal joint system located at the southernmost end of the study area.

Image 2. Example of a conjugate joint system located 1 km south of Hazard Canyon.

Literature Cited

Keller, Margaret A. "A Field Guide to the Upper Miocene Siliceous Coastal Sequence of Montana de Oro State Park, California". *Sequence Stratigraphy in Fine Grained Rocks; Examples from the Monterey Formation.* Menlo Park, CA: U.S. Geologic Servey. 1992. pp. 67-80. Print.

Los Osos, Baywood-Los Osos, CA, USA. USGS. Dec. 16, 2013. http://earthexplorer.usgs.gov/

Johnston, Scott. Hazard Canyon Wave Cut Bench Lab. Structural Geology 414. California Polytechnic State University, San Luis Obispo. Fall, 2013. Print.

Clark, D.G., Slemmons, D.B., Claskey, S.J., and DePalo, D.M. "Seismotectonic Framework of Coastal Central California". *Seismotectonics of the Central California Coast Ranges*. Washingtion D.C. Geologic Society of America. Special paper 292. 1994. pp. 9-30. Print.

Vittori, E., Nitchman, S.P. and Slemmlons, D.B. "Stress Pattern from Late Pliocene and Quarternary Brittle Deformation in Coastal Central California". *Seismotectonics of the Central California Coast Ranges*. Washingtion D.C. Geologic Society of America. Special paper 292. 1994. pp. 31-44. Print.

Lettis, W.R. and Hall, N.T. "Los Osos Fault Zone, San Luis Obispo County, California". *Seismotectonics of the Central California Coast Ranges*. Washingtion D.C. Geologic Society of America. Special paper 292. 1994. pp.73-102. Print.

Hanson, K.L., Wesling, J.R., Lettis, W.R., K.I. Kelson and Mezger, L. "Correlation, Ages, and Uplift Rates of Quaternary Marine Terraces: South-Central Coastal California". *Seismotectonics of the Central California Coast Ranges*. Washingtion D.C. Geologic Society of America. Special paper 292. 1994. pp. 45-72. Print.

Nitchman, S.P. and Slemmons, D.B. "The Wilmer Avenue Fault: A Late Quarternary Reverse Fault Near Pismo Beach, California". *Seismotectonics of the Central California Coast Ranges*. Washingtion D.C. Geologic Society of America. Special paper 292. 1994. pp. 103-110. Print.

Van der Pluijm, Ben and Marshak, Stephen. *Earth Structure: An Introduction to Structural Geology; Second Edition*. New York: W.W. Norton and Company, 2004. pp. 127-131, 138-158. Print.

Behl, Richard J. "Chert spheroids of the Monterey Formation, California (USA); early-diagenetic structures of bedded siliceous deposits". *Sedimentology*. Wiley-Blackwell : Oxford, United Kingdom. February, 2011, Vol. 58, Issue 2, pp. 325-351. Print.

Mounte, Van S., Suppe, John. "State of Stress Near the San Andreas Fault: Implications of Wrench Tectonics". Department of Geological and Geophysical Sciences, Princeton University, New Jersey, December, 1987. Print.