WHAT DIKE ORIENTATIONS IN THE EASTERN SAN GABRIEL MOUNTAINS REVEAL ABOUT MIDDLE MIOCENE STRESSES AND BLOCK ROTATIONS

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ABSTRACT

The eastern San Gabriel Mountains expose a collection of Precambrian to Late Cretaceous igneous and metamorphic rocks intruded by Late Oligocene and Middle Miocene plutons and dikes. Henceforth the region was fractured and dismembered by dextral and sinistral strike-slip faults, beginning with late Miocene initiation of the right-lateral San Gabriel Fault, ~12 Ma. The Late Cenozoic intrusions and faults record a complex evolution of stress regimes, magmatism, and transrotational strain that accompanied larger-scale development of the transform plate boundary in southern California. My study focuses on the middle-Miocene mafic-intermediate (basalt to andesite) dike swarm that is ubiquitous north and south of the San Gabriel Fault with the exception of the Ontario Ridge Block, Potato Mountain Block and the Cucamonga Peak Block to the east of the San Antonio Canyon Fault. These dikes are significant because they intruded during early-stage rotation of the Western Transverse Ranges and opening of the Los Angeles basin to the south and west but predate the onset of conjugate strike-slip faulting that altered original dike swarm geometries. Therefore, these dikes may record middle Miocene emplacement stresses and further serve to track subsequent block rotations within the San Gabriel Mountains. Previous studies mapped and described the dikes (Ehlig, 1981, Dibblee, 1982, Morton, 1973, Nourse, 1998 and Nourse, 2002a) however, this study utilizes previously unmapped dike orientation measurements, recorded by Dr. Jonathan Nourse between 1992 and 1998, and new dike measurements, which I collected from 2014 to 2016, to analyze stresses and block rotations. A total of 988 orientation measurements were compiled, 449 north and 539 south of the north branch of the San Gabriel Fault (NSGF). Additionally, UTM coordinates were assigned
to 609 measurement locations to create a detailed GIS map of dike orientations in the study area. Additional measurements were taken in remote areas north of the San Gabriel fault that lacked data. Dikes to the north of the NSGF exhibit a dominant average northwest trend of 315.9º ± 23.5º, of 427 points, and a minor average northeast trend of 67.6º ± 14.0º, 22 points. South of the NSGF, dike trends exhibit two major trends, a major northeast trend of 40.5º ± 29.4º, 307 points and a minor northwest trend of 301.0º ± 18.8º, 232 points. The study area was divided into 11 total structural blocks: 5 north of the NSGF and 6 south of the NSGF, based upon major fault traces as defining boundaries. Measurements from these structural domains were plotted in equal area, lower hemisphere stereonet plots to define major and minor strike and dip patterns. Northeast trending dikes were intruded into fractures associated with early Miocene left-lateral faults such as the San Antonio Canyon Fault, and northeast trending joints and veins present in the late Oligocene aged Telegraph Peak Pluton. These northeast trending features were overprinted by northwest-striking fractures associated with an early to mid-Miocene northeast-southwest directed extensional event throughout the continental margin, prior to dike emplacement. The northwest trending dike populations are prominent throughout structural blocks north and south of the NSGF. While the strike orientations throughout the structural blocks do not reveal significant vertical axis rotations, stereonet data from blocks north of the NSGF indicate southward tilting has occurred. The entire study area was rotated ~20º counterclockwise when the San Gabriel Block was offset dextrally by the San Andreas Fault beginning ~5 Ma.
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INTRODUCTION

Purpose and Objectives

The purpose of my study is to evaluate the utility of a middle Miocene mafic dike swarm in the San Gabriel Mountains for deducing three dimensional stress conditions prior to the initiation of the San Gabriel Fault, and to further constrain Middle Miocene to recent block rotations and translations. To attain this purpose, my objectives are to:

A. Organize previous dike measurements and major fault trends from field notes of Nourse (1992-1998) and the geologic map of Morton (1973), as well as collect new data points in underrepresented areas

B. Create a GIS database showing distribution of these dikes throughout ten 7.5 minute quadrangles of the eastern and central San Gabriel Mountains

C. Study the spatial distribution of dikes in the context of mapped late Cenozoic dextral and sinistral faults

D. Utilize stereonets and rose diagrams from subsets of the data to recognize geographic domains characterized by specific strike trends

E. Interpret early to middle Miocene stress regimes and fracture patterns related to dike emplacement in context of models for regional extension and transtension

F. Evaluate if differences in strike between structural domains indicate horizontal and vertical axis rotations, which have been observed in nearby regions to the study area since the early Miocene.
Location and Access

My project study area is located in the eastern San Gabriel Mountains, a complex of highly fractured igneous and metamorphic rocks located approximately 30 miles to the east of downtown Los Angeles (Figure 1). The study area encompasses 10 USGS 7.5 minute quadrangles, with a total area of almost 1,600 km². The mountain range is bounded in the northwest and southwest by the branching San Gabriel fault system, a right-lateral fault system that was active in the late Miocene. The northern branch of the San Gabriel fault (NSGF) cuts through the middle of the mountain range and its trace is offset by post late Miocene sinistral faults (Figure 1) and the Icehouse Canyon and Middle Fork Lytle Creek faults are considered offset segments of the NSGF (Powell, 1993). The active Sierra Madre-Cucamonga thrust fault zone forms the southern border of the San Gabriel Mountains (Figure 2). The northeastern border of the San Gabriel Mountains is bounded by the active, right-lateral San Andreas Fault. The modern day San Gabriel Mountains form a separate structural entity from the Western Transverse Ranges, which is a block of continental crust that has rotated ~93° since the middle Miocene (Luyendyk et al., 1991)

Due to the sharp relief throughout most of the San Gabriel Mountains, access in my field area is dependent upon major roads and fire roads as well as flat canyon floors. Major roads include Mount Baldy Road, Glendora Ridge Road, Glendora Mountain Road, Highway 39, East Fork San Gabriel Canyon and West Fork San Gabriel Canyon (Figure 1). In addition to limited road access, there are several key regions within the study area closed off from the public, specifically Thompson Ranch, along Cattle Canyon is private property and the San Dimas Experimental Forest, a federally protected research
area. In the summer months, the dry climate of the San Gabriel Mountains is conducive to forest fires. Fires in July and August of 2015 and 2016 forced the closure of major roads and inhibited my ability to access sites that I planned to investigate. In October of 2014, the federal government decreed the San Gabriel Mountains a national monument under the Forest Service. This may greatly improve admission to inaccessible locations in future studies, and could hinder my ability to collect samples.

**Background and Geology**

The Vincent thrust fault system, active from the late Cretaceous to early Paleogene, defines the basement rock suites in the eastern and central San Gabriel Mountains and although its proposed trace outcrops out of the region of the dike swarm, these dikes intrude upper plate Vincent Thrust fault rocks in my study area. Upper plate rocks consist of Precambrian aged gneisses, Precambrian anorthosites and syenites with metagabbroic dikes, Triassic aged Lowe granodiorite intrusions, pre Cretaceous amphibolite and metarhyolite dikes and late Cretaceous granitic intrusions (Figure 2, Ehlig, 1982). Upper and lower plates are separated by a 10-1000 m thick mylonite zone (Nourse, 2002a), which consist of upper Vincent plate rocks that have undergone ductile deformation due to shear stress associated with movement of the fault. The lower plate rock unit of the Vincent Thrust fault, the Pelona Schist, consists of continental wedge sediments and oceanic basalts metamorphosed in the Paleocene during thrusting related to subduction (Jacobson, 1990). The protoliths of the Pelona Schist were underplated late Cretaceous continental wedge sediments and oceanic basalt which were later exhumed due to extensional faulting (Jacobson, 1990).
The study area in the eastern San Gabriel Mountains is adjacent to the Western Transverse Ranges (Figure 2), an area that was subjected to transtensional forces and a greater than 90° clockwise rotation in the middle Miocene due to oblique subduction of the Farallon Plate and the development of the transform boundary of southern California (Luyendyk et al., 1991). Starting ~12 Ma, after dike emplacements, the main strand of San Gabriel fault system northwest of the study area (Figures 1 and 2) experienced ~42 km of right-lateral offset (Powell, 1993). In the eastern San Gabriel Mountains, the San Gabriel Fault trace splits into northern and southern branches (Crowell 1952, Ehlig 1982, Nourse 2002a). The northern branch of this system (NSGF) accounts for 22 km of the dextral offset (Matti and Morton, 1993, Nourse, 2002a), and the offsets and trace of the southern branch is debated (Crowell, 1952, Powell, 1993, Nourse, 2002a). The northeast trending Sawpit Canyon-Clamshell fault has been interpreted as a right-lateral transform fault also active in the late Miocene (Powell, 1993, Nourse, 2002a). In the Pliocene, the San Gabriel Fault system became inactive, and the study area was dissected by four major northeast striking sinistral transform faults. From east to west, the San Antonio Canyon fault, the Sunset Ridge fault, the San Dimas Canyon-Weber fault and the Pine Mountain fault (Figure 2) experienced 3 km, 0.8 km, 1.5 km and 1 km of left-lateral offset respectively (Nourse, 2002a).
Figure 1. Index map of Southern California modified from Langenheim and Powell 2009 Figure 1. Grey areas indicate domains which have undergone significant clockwise rotations. Green indicates the San Gabriel block, which records late Miocene counterclockwise rotation (Terres 1984). Major faults are indicated in brown, with minor faults in red, and the San Gabriel Fault system in blue. The study area location is indicated by the pink box, which is shown in greater detail in Figure 2 and Plate 1.
Figure 2: Geologic basement map of the Eastern San Gabriel Mountains, California, from mapping by Morton and Miller (2003) and Nourse (2007). Base map is of the San Bernardino 1:100,000 Quadrangle. Major faults include North San Gabriel Fault (NSGF), Icehouse Canyon Fault (ICF), Middle Fork Lytle Creek Fault (MFLCF) and the Sawpit Canyon-Clamshell Fault (SCCF). The pink box outlines the study area shown in greater detail in Plate 1.
Previous Work

In the study area, there are two separate dike swarms which are very different in terms of composition and age. The older generation of dikes is rhyolite to rhyodacite with a presumed late Oligocene age. These dikes are genetically related to the Telegraph Peak pluton, dated at 26 ± 1 Ma (May and Walker, 1989, Nourse et al., 1998). The rhyolite dikes are not as useful in this study due to their lack of regional extent in the study area. This project focused on the middle Miocene, mafic to intermediate composition dikes that range from olivine basalt to hornblende andesite (Nourse et al., 1998). The swarm is ubiquitous west of the San Antonio Canyon Fault and is heavily concentrated directly north and south of the north branch of the San Gabriel fault (Plate 1). The dikes are believed to be genetically related to the Glendora Volcanics intrusion (Figure 2) dated at 15.3 to 17.3 Ma (McColluh et al., 2002). Preliminary geochronology of the dikes yield a $^{40}$Ar/$^{39}$Ar hornblende plateau age date of 14.8 +/- 0.1 Ma, from one sample and poorly constrained isochron ages of ~16 Ma to 18 Ma from hornblende in two other samples (Nourse and Iriando, personal communication). These results indicate a correlation between the ages of the dikes and the ages of the Glendora Volcanics, and new published ages of the dikes may strengthen the relationship. The ages of these dikes are significant because they are the youngest igneous rocks in the area, yet they predate late Miocene faulting and thus may be useful as offset markers on late Miocene to present day transform faults in the San Gabriel Mountains.

The middle Miocene volcanic rocks and dikes have been previously described in several studies, though these features have never been explicitly utilized for reconstruction purposes. Shelton (1955) mapped and described volcanic rocks from the
Glendora, CA area on the far eastern side of my field area. In his paper, he grouped
volcaniclastic conglomerates, andesite flows, andesite tuff breccias, fine grained basalt
flows, hornblende-biotite dacite dikes and rhyolitic dikes into a group he termed
“Glendora Volcanics” (Shelton, 1955). Miller and Morton (1977) performed
geochemical analyses and K-Ar dated samples of granodiorite which was intruded in the
Pelona Schist in the eastern San Gabriel Mountains and gleaned an age of 14-18.6 Ma.
These dates were compared with chemically similar quartz monzodiorite intrusions in the
Orocopia Schist in the Chocolate Mountains, east of the San Andreas Fault, which were
dated 20-23.4 Ma (Miller and Morton, 1977). The authors suggest a link between the
plutonic rocks due to their geochemical similarity, and that the discrepancy in ages could
represent different crystallization stages (Miller and Morton, 1977). This study further
tied the Pelona Schist unit in the eastern San Gabriel Mountains with the Orocopia Schist
unit in the Chocolate Mountains, and provided context as to where the San Gabriel Block
was located in the middle Miocene.

Terres (1984) used remnant magnetism from Oligocene to early Miocene volcanic
deposits of the Vasquez and Mint Canyon formation in the western San Gabriel
Mountains to resolve block rotations in the area, and they found that the deposit had been
rotated 53° clockwise during the early Miocene transtensional episode and 16°
counterclockwise during the episode of transpression, coincident with the initiation of the
San Andreas fault (Terres, 1984).

geologic map of the eastern San Gabriel Mountains (Figure 2, Nourse, 2007) to comment
on middle a Miocene extensional event in the eastern San Gabriel Mountains. He noted
the orientation of foliations, faults, slickenside surfaces, mylonitic projections and intrusive features including the andesite dikes.

Figure 3. Equal area stereonet plots of contoured poles-to-planes of middle Miocene mafic dikes in the Eastern San Gabriel Mountains, from Nourse et al 1998, Figure 4. Diagram on the left represents measurements south of the San Gabriel Fault, on the right, measurements north of the San Gabriel Fault.

Nourse (1998) suggested that the andesite dikes intruded pre-existing fractures associated with the development of the southern California transform boundary before the initiation of the San Gabriel Fault, indicating that dike orientations may reveal middle Miocene stress regimes. Additionally, the paper recognized differing strike patterns north and south of the San Gabriel Fault. North of the fault, dikes exhibited a unimodal, N 40 W average strike with minor northeast trends. However, south of the San Gabriel fault, average dike trends of ~N 60 E and ~N 60 W and ~N 10 E indicate a more convoluted stress environment (Figure 3).

The dike orientation patterns from Nourse (1998) are significant, however, the dataset lacks geographic context beyond north and south of the San Gabriel Fault. All of the measurements were made without the use of a GPS, though they were located on
mylar quadrangle maps and the rest were keyed to foliation measurements of specific basement rocks that were the focus of the 1990s mapping. Therefore, it is possible to locate and assign specific dike measurements and assign them UTM coordinates. My study aims to utilize the mafic dike orientation measurements within defined structural domains to model middle Miocene stress regimes in the eastern San Gabriel Mountains.

Hypothesis and Research Questions

My intent is to address the hypothesis that middle Miocene dikes are important geologic markers that constrain stress conditions imparted upon a structurally complex crystalline block within an evolving transtensional plate boundary. Important research questions include:

1. Is there a clear demarcation between areas of pure extension and areas of transtension?
2. What is the mode of dike emplacement? Synmagmatic tension cracks, conjugate normal faults or strike-slip shear fractures and can these modes be distinguished?
3. What is the spatial distribution of dike orientations?
4. Can variations in stress regimes be modeled convincingly?
5. Do differences in mean dike strike between crustal blocks record post emplacement rotations?
METHODS

In order to address these questions, I first needed to organize and catalog all the existing andesite and basalt dike orientation measurements into a useful Excel database (Appendix D). Some measurements were located on mylar topographic base maps, and could thus be georeferenced into ArcGIS and assigned UTM coordinates, others required more work. Finally, additional field work was conducted for underrepresented regions of the study area to fortify the database.

Reduction of Field Data

Measurements were taken by Dr. Jonathan Nourse, as well as Cal Poly Pomona student volunteers, from 1992 to 1998 during creation of a geologic map of the eastern San Gabriel Mountain basement rocks. Dike orientation and appearance were recorded along with foliations, fault traces, geologic contacts, folds and other regional geologic features including mylonite, rhyolite dikes and slickenside surfaces. These features were located qualitatively in field notebooks and topographic base maps without the aid of GPS devices. Shortly after these field observations were taken, foliations and some dikes were transcribed onto mylar topographic maps of the area using topographic features including cliffs, ridges and valleys as context markers.

I assigned UTM coordinates to all locatable mafic dikes, however, these data points were regularly intermingled with other foliation measurements and occasionally absent, thus context clues aided in isolating mafic dikes. For instance, Nourse’s field notes commonly observed the country rock of the intrusion which provided a means to confirm questionable dike measurements on the mylar geologic field maps. Additionally, orientations of features surrounding the mafic dikes, including fault traces, slickensides
and mylonite surfaces, were valuable in locating measurements, especially those which were not recorded on the field maps. Rarely, Nourse’s field maps specifically showed the mafic dikes. Some were denoted by a ladder pattern, which could be directly measured with a protractor and recorded and others by a date of collection which could be easily found in his chronological field notes.

I extensively reviewed Nourse’s notes for points which were locatable on the mylar maps. These data points were combined into an excel spreadsheet, the columns of which include the following (Appendix D):

- **OID**: an ArcGIS identifying number useful for locating points on the GIS map.
- **Block**: name of structural domain based upon relevant natural and geographic features.
- **Location**: an identifier referring to a general location within San Gabriel Mountains.
- **Easting and Northing**: if locatable, this indicates the UTM coordinate of the data point (North American Datum 1927, zone 11 N).
- **Strike and Dip**: the strike and dip of the mafic dike. The measurement was converted from quadrant notation read off from brunton compasses to azimuth notation.
- **N/S San Gabriel**: denotes whether the point is north or south of the San Gabriel Fault.

A total of 627 points were assigned UTM coordinates, however there were numerous data points which I was unable to locate on the mylar maps. For these points, I noted the general location from Nourse’s field notes in the excel database, so they may be
added to regional stereonet diagrams later. In total, I compiled 361 unlocated data points to bring the total number of points in my dataset to 988.

Morton (1973) focused on creating a geologic map of the Azusa and Mount Wilson quadrangles specifically. The mafic dikes were described on Morton’s map as a part of the “Glendora Volcanics” (Shelton, 1955) and were more specifically described on Morton’s map as “Intermediate to Basic Hypabyssal Dikes” and annotated by the symbol “Td1” (Morton, 1973). I measured the strikes of 106 mafic dikes (Appendix D), indicated in purple (Plate 1) by holding a protractor directly up to Morton’s map. Dip values of the dikes were not indicated on his map, so that information is missing. On Morton’s geologic map, there were a few dike measurements whose traces were curved in response to steep topography and it is possible to use contour lines estimate the dips of the dikes, however, curved measurement points were rare.

ArcGIS Database Construction

A primary objective in this study was to create an ArcGIS database of the mafic dike measurements. The first step to achieving this goal is to create a large topographic map of the study area, which spans 10 USGS 7.5 minute quadrangles from 2011. These quadrangles include, clockwise from the northwest: Chilao Flat, Waterman Mountain, Crystal Lake, Mount San Antonio, Telegraph Peak, Cucamonga Peak, Mount Baldy, Glendora, Azusa and Mount Wilson quadrangles. The “raster dataset to mosaic” feature in ArcGIS was utilized to seamlessly combine the 10 USGS quadrangles into a single map layer. Next, I scanned the 5 mylar field maps from Nourse’s field work and 7 geologic maps from Morton (1973) and georeferenced them atop the USGS topographic maps. Faults were drawn based on Nourse’s mylar field maps which were digitally
rendered in compilation map (Figure 2) with contributions from the 1:100,000 30’ x 60’
was used to draw faults in the Azusa and Mount Wilson quadrangles specifically. The
purpose of drawing these faults is not to create a palinspastic recreation, but to try and
understand the boundaries of structural blocks and how these blocks may have shifted
and rotated after the Miocene.

After creating the topographic and fault background map of the study area, the
next step was to plot mafic dike data points from my Excel database by converting the
Excel workbook extension “.xlsx” to a readable ArcGIS extension “.dbf”. The dike
measurements with UTM coordinates were plotted within the 1927 North American
Datum UTM zone 11 N, as individual points. I selected a strike and dip symbol within
ArcGIS’ catalog of symbols to represent my data, rather than the default circular data
point. Within the symbol property tab, I rotated each data point based upon the azimuth
strike defined in the excel database. Finally, the color of these data points was defined by
a range of dip values. Green represents dips of 0° to 45°, yellow is 45° to 60°, orange is
60° to 80° and red is 80° to 90°. Data points from Morton 1973 were represented by thin
purple rectangles that do not indicate dip direction and purple strike symbols were chosen
for continuity between Morton 1973 and this study (Plate 1). Plate 1 shows this
composite map onto which stereonets were later added.

Personal Field Work

After compiling Nourse’s field measurements, I noticed that the data set lacked
points to the north of the San Gabriel Fault specifically. The terrain to the north of the
San Gabriel fault is not as easily accessible and there is less road access than the areas to
the south of the fault. I pinpointed several locations which did not have previously collected measurements and are accessible by fire road or main road. To collect mafic dike orientations, I first noted the location via GPS, which is set on the NAD 1927 datum. Then, I used a brunton compass to measure the strike and dip of the feature in question. Sometimes the feature was not perfectly planar, in which case I would estimate the average strike of the feature and record it.

The first area I mapped in May of 2015 was along Cow Canyon fire road directly north of Cow Canyon, where the San Gabriel Fault passes through the northern canyon wall. I parked at the Cow Canyon Saddle at the intersection of the fire road and Glendora Ridge Road. I walked west on the fire road approximately 3 kilometers, before the point where switchbacks started down the hill to the canyon, and measured dikes as I walked back east to the car. I collected 25 total measurements along the fire road. I also tried to collect some measurements in a canyon which extends perpendicular to Cow Canyon, however, my intended traverse was entirely too steep and was hazardous to continue (Figure 4A).

The second traverse, in June of 2015, was to the west of Cow Canyon in the broader Cattle Canyon. I parked where East Fork San Gabriel Road turns into Glendora Mountain Road and walked towards the east into Cattle Canyon, measuring faults on the canyon walls to the north and south. I chose this traverse with the intention of continuing to the northern branch of Cattle Canyon, which is north of the trace of the San Gabriel Fault, however, near the intersection of Coldwater Canyon with Cattle Canyon, I encountered a private property boundary and was unable to continue however, I did collect 13 dike measurements along my traverse.
The third traverse I walked, also in June of 2015, was on Shoemaker Road, a fire road which parallels the north fork of the San Gabriel River on the western wall of the East Fork San Gabriel River canyon. I walked the portion of Shoemaker road that crosses the northernmost trace of the San Gabriel Fault trace and collected 9 dike measurements (Figure 4B), until the road ended abruptly. At a later date, I walked a traverse in the East Fork San Gabriel River canyon below Shoemaker road, along the path to the Bridge to Nowhere and collected an additional 4 measurements.

The final area I visited with Dr. Nourse to collect measurements was around Telegraph Peak in early August 2016. We parked above the Mount Baldy Ski Lodge around Thunder Mountain and hiked the “Three Tee’s” trail up the switchback trail to the saddle between northern and southern Telegraph Peaks. I collected 8 dike measurements along trail on the western edge of the summit and 10 measurements along a north-south transect along the ridgeline between the two peaks (Figure 4C). In addition to dike orientation measurements, I measured orientations of 1-5 cm quartz and aplite veins within the Telegraph Peak Granite pluton which makes up the southern and western edges of Telegraph Peak.
Figure 4. Photographs of andesitic to basaltic dikes from personal field work in three separate localities. Photo A is from fire road north of Cow Canyon and depicts brown-grey, nearly vertical dikes intruding into tonalite-quartz diorite cliff face. Photo B shows a badly weathered brown basalt dike intruding a granite-granodiorite cliff face. Photo C is from Telegraph Peak area and shows grey andesite dike intruded into Telegraph Peak granite.
Data Presentation

The visual representation of dike orientation data points was the driving force to analyzing and understanding the significance of these measurements. The ArcGIS database (Plate I) displays spatial distribution of data points in the study area. This map lends the ability to recognize changes in dike orientation patterns and differentiate these zones as defined structural blocks. Stereonet analysis (Plate I, Plate II and Figures 5 to 17) is important for recognizing major and minor dike orientation patterns and visualizing dikes in three dimensions. Finally, qualitative observations of the physical dikes in the field help to resolve the specific dike intrusion method.

The measurements are compiled into the two databases previously described: an Excel database (Appendix D) and an ArcGIS database (Plate 1). The Excel database is an all-encompassing database which includes all quantitative dike measurements including UTM coordinates, quadrant strike and dip (which is a bearing indicated by angle relative to cardinal directions and dip direction is indicated using the same notation) azimuth strike and dip (which is a trend direction indicated by angle from 0° to 360° and dip direction is 90° to the clockwise direction) and qualitative dike measurements, including general location and location north and south of the NSGF. This database was used primarily for generating stereonet diagrams of the mafic dike orientation measurements, allowing me to display three dimensional dikes graphically in a two-dimensional plot (Appendix D, Plate 1, Plate 2).

The ArcGIS database is limited to dike measurements that have been located and assigned UTM coordinates, though these points can be visually represented atop the georeferenced USGS quadrangles and fault traces to visually represent the data (Plate 1).
This summary map is useful for identifying regional strike patterns and locating the geographic boundaries of different structural domains within the field area north and south of the San Gabriel Fault specifically.

**Stereonet Analysis**

Stereonet projections (Plate 1, Plate 2 and Figures 5 to 17) allow me to visualize three dimensional dike measurements in a two dimensional plot. Individual dike measurements were plotted as planes by inputting azimuth strike, with dip direction $90^\circ$ clockwise from the strike direction. The dike planes display decreasing arc curvature with increasing amount dip with purely vertical dikes as straight lines parallel to the strike, and purely horizontal dikes intersecting with the outer edge of the circle. Poles are linear features perpendicular to the dike planes which plot as dots where the lines intersect the lower hemisphere of the sphere.

I used a program called Stereonet 9 version 9.5.8 developed by Dr. Rick Allmendinger from Cornell University to plot my dike orientation measurements into stereonet projections (Allmendinger, 2016). This user-friendly program allowed me to import text files from my large Excel dataset for different regions of my study area. Dike planes are denoted by the light gray lines and poles to the planes represented by black dots (Plate 1). The “Inspector” feature within the Stereonet program generates contours based on “1% area method”. This method generates contours by calculating density of pole data within a circle $1/10^{th}$ the radius of the stereonet (i.e. 1% of the area of the stereonet), which is useful for analyzing and dissecting major strike and dip patterns.

Additionally, the Stereonet 9 program generated rose diagrams of the data, which are circular histograms situated in the center of the stereonet plots which indicate patterns
of strike directions. These are calculated by counting the number of data points within 10 degree “bins” (0-9, 10-19….etc) and are normalized to a percentage of total and translated to different lengths of wedges of the circle, called “rose petals”. For the rose diagrams, I needed to convert south-striking measurements to equivalent northern quadrants in order to accentuate orientation patterns. This involved converting southwest striking dikes to northeast strikes by subtracting 180° and converting southeast striking dikes to northwest strikes by adding 180°. Thus, all rose petals indicated some form of a northerly strike; petal length indicates proportion of measurements with a particular strike range. Refer to Plate 1 as well as Figures (Figure 5 to Figure 17) for these stereonet diagrams and superimposed rose diagrams.
RESULTS

Resolution of Structural Domains

The first step in processing my data was to separate measurement points to the north and south of the North San Gabriel-Lythe Creek-Icehouse Canyon fault (hereafter referred to as NSGF) and plot them in separate stereonet plots (Figures 5 to 17). The northern and southern domains were offset 22 km dextrally by the NSGF, and thus I might expect to see differing dike orientation patterns north and south of NSGF.

I identified a total of 9 structural domains within my study area, specifically 3 north and 6 south of the NSGF (Plate 1). North of the NSGF (from the east) is Icehouse Ridge-Thunder Mountain-Telegram Peak-Timber Mountain, West Bear Canyon-Cow Canyon-Buckhorn Lodge and Shoemaker Road (Plate 1 and Plate 2). South of the San Gabriel Fault (from the east) is the Sunset Ridge-San Antonio Canyon, Glendora Ridge-Experimental Forest, San Dimas Canyon-Cattle Canyon, San Gabriel Canyon, West Fork San Gabriel River and Sawpit Canyon-Clamshell Peak blocks (Plate 1 and Plate 2). I used major fault traces in the San Gabriel Mountains by Morton and Matti (2006) and Morton and Miller (2003) and Nourse (2002a) as the major features in defining the boundaries of these domains. As previously mentioned there is one major dextral late Miocene fault in the study area, the San Gabriel-Icehouse Canyon-Middle Fork Lytle Creek Fault (NSGF). The study area also has five major sinistral Pliocene-Quaternary faults (from west to east) Pine Mountain, San Dimas Canyon-Weber Fault (south and north of the NSGF respectively) Sunset Ridge, San Antonio Canyon Fault and Stoddard Canyon Fault (Plate 1, Nourse, 2002a). Finally, the Sawpit Canyon-Clamshell fault is also late Miocene in age, and is also interpreted as a dextral transform fault (Nourse,
A majority of structural domain boundaries follow fault traces, however, secondary boundaries are estimated if there are no points beyond a specific region or there is a significant change in the dike orientation pattern from one area to another.

The rose diagrams transposed on the stereonet projections are an important visual guide driving the statistical analysis of dike orientation trends in the dataset. These diagrams aid in identifying local maxima in strike measurement frequencies which further serve to define primary, secondary and tertiary strike measurement populations within each geographic domain. In order to classify strike measurement populations, I first converted strike measurements to northern hemisphere strikes to accentuate strike populations. Using the 1% area contouring tool within Stereonet 9 program I was able to discern groups of points exhibiting an orientation trend. Once the ranges of trend populations were defined, I calculated the mean and standard deviation of the strike measurements within these populations (Table 1).

To visually display the statistical strike data in one place, I generated a Statistical Data Compilation Map (Plate 2). The map contains locations of pertinent faults, indicated by maroon lines, in the area as well as defined structural blocks, indicated by blue lines, including what I have called “Statistical Stereonets” (Figure 5 to 17) to summarize statistical data from raw stereonet diagrams. The statistical stereonets contain a thick white line oriented toward the direction of the population mean strike and increased line length corresponds to a greater percentage of measurements within the population relative to the geographic region as a whole. The thickness of the black wedge represents the standard deviation within each population. Small blocks of text on the outer edge of the circle identify the mean and standard deviation of each population.
Additionally, dike measurements are color-coded based on strike divisions of 20° from 270°, west-striking, to 90°, east-striking (Plate 2). This distinction provides visual context for differences in strike throughout the study area.

### Table 1. Summary of primary, secondary and tertiary strike populations in defined structural blocks. Refer to Plate 1 and 2 for specific locations of the structural blocks.

<table>
<thead>
<tr>
<th>Domain Name</th>
<th>Primary Pattern</th>
<th>Secondary Pattern</th>
<th>Tertiary Pattern</th>
<th>Strike (°)</th>
<th>error (°)</th>
<th># points</th>
<th>Strike (°)</th>
<th>error (°)</th>
<th># points</th>
<th>Strike (°)</th>
<th>error (°)</th>
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<tr>
<td><strong>North NSGF Fault Blocks</strong></td>
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<td>47.2</td>
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<td>13</td>
<td>281.2</td>
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<td>18.4</td>
<td>10</td>
<td>62.3</td>
<td>15.2</td>
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<td>68</td>
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### Description of Individual Structural Domains

**North and South San Gabriel Fault Blocks**

There are a total of 449 dike measurements to the north of the San Gabriel Fault, which exhibited bimodal orientation of 315.9° ± 23.5°, 426 points, and highly subordinate 67.9° ± 14.2°, 23 points (Figure 5). Note also that pole cluster indicates a dip of ~75 to 80° to the northeast. South of the San Gabriel fault, there are 539 dike measurements with two major orientations trends of 40.5° ± 29.4°, 307 points, and 301.0° ± 18.8°, 232 points (Figure 6). Pole clusters indicated that northwest striking dikes dip
Figure 5. Stereonet data of 449 dike plane orientations from fault blocks to the north of the NSGF. The diagram on the right was generated in the Stereonet 9 program. The grey lines are dike planes and the black dots are poles to those planes. The contouring method is 1% area method. The rose diagram in the center contains 10° bins, and the diameter of the circle represents 50%. The diagram on the left is a statistical stereonet diagram. The white lines represent the mean orientations for the dataset, the length of this line represents percentage of the population displaying the trend and the width of the wedge indicates the standard deviation of the population.
Figure 6. Stereonet data of 539 dike plane orientations from fault blocks to the south of the NSGF. The diagram on the right was generated in the Stereonet 9 program. The grey lines are dike planes and the black dots are poles to those planes. The contouring method is 1% area method. The rose diagram in the center contains 10° bins, and the diameter of the circle represents 50%. The diagram on the left is a statistical stereonet diagram. The white lines represents the mean orientations for the dataset, the length of this line represents percentage of the population displaying the trend and the width of the wedge indicates the standard deviation of the population.
steeply northeast and southwest, while northeast striking dikes tend to dip steeply southeast. These trends illustrate large-scale fracture trends within the larger San Gabriel Block and geographic variability in these trends aided in my determining boundaries of smaller structural blocks within the San Gabriel block.

The following discussion illustrates how these two large regions were divided into smaller structural domains. The biggest factor in determining the structural boundaries within the study area was the map traces of dextral and sinistral faults. Offsets along the left-lateral faults prior to dike emplacement differed and thus degree to which blocks were rotated in the late Cenozoic may vary. Often, strike populations changed significantly between regions without a mitigating fault, and in these cases boundary lines were inferred.

Domains to the North of the NSGF

*Icehouse Ridge-Thunder Mountain/Telegraph Peak-Middle Fork Lytle Creek/Timber Mountain*

This domain is the block to the uppermost northeast of the study area in the southwest section of the Telegraph Peak quadrangle and the southeast section of Mount San Antonio quadrangle (Plates 1 and 2). This block is bounded in the south by the Icehouse Canyon fault, a strand of the north San Gabriel fault, and to the west by the San Antonio Canyon fault. Dike measurements originate in three distinct regions within this block which display very different dike orientations. The first region is the westernmost section of the block which includes Icehouse Ridge, Thunder Mountain, Manker Creek and Big Butch Wash. The second region of dike populations is east of Thunder Mountain north of the Telegraph Wash, Telegraph Peak, and Middle Fork Lytle Creek in the east (Ehlig, 1958). Finally, the third region of dike populations in this block is the Timber
Mountain region bounded by the Telegraph Wash in the north, the Stoddard Fault in the east and the Icehouse Canyon Fault in the south (Ehlig, 1958). The Icehouse Ridge-Thunder Mountain sub-block (Figure 7) has 144 points, and the population exhibits a primary trend of $322.9^\circ \pm 21.3^\circ$, 140 points, and a very minor northeast trend of $47.2^\circ \pm 17.0^\circ$, 4 points. The Telegraph Peak-Middle Fork Lytle Creek sub-block (Figure 8) has 22 points and exhibits a generally bimodal trend of $325.7^\circ \pm 13.9^\circ$, 13 points, and $281.2^\circ \pm 11.7^\circ$, 9 points. The Timber Mountain sub-block (Figure 9) has 17 points and exhibits trends of $290.6^\circ \pm 18.4^\circ$, 10 points, and $62.3^\circ \pm 15.2^\circ$, 7 points.

**West Bear Canyon-Cow Canyon-Buckhorn Lodge**

This domain is a block to the southwest of the Icehouse Ridge-Thunder Mountain-Telegraph Peak-Timber Mountain directly west of the San Antonio Canyon Fault. This block is bounded to the east by the San Antonio Canyon fault, to the south by the San Gabriel Fault and to the west by Weber Fault. The region is named for the fact that all the points were taken from West Fork Bear Canyon, the cliff face adjacent to Buckhorn Lodge, the Cow Canyon fire road, the lower Ski Lifts Road, San Antonio Falls and a few points around Mount San Antonio. Individual stereonets have been made for each of these sub-regions (Plate 1). There are a total of 250 points in this block, with 112 points assigned UTM coordinates (Figure 10). The measurements in this block exhibit a generally unimodal trend of $310.9^\circ \pm 21.2^\circ$, 230 points, with greater than 90% of the points exhibiting the trend, additionally, the data exhibit a minor trend of $61.1^\circ \pm 27.6^\circ$, 20 points. Additionally, there is a distinct anomalous N 15 W trend that seems to be localized near the lower ski lift-Manker Creek area.
Figure 7. Stereonet data of 144 dike plane orientations from the Icehouse Ridge-Thunder Mountain Block. The diagram on the right was generated in the Stereonet 9 program. The grey lines are dike planes and the black dots are poles to those planes. The contouring method is 1% area method. The rose diagram in the center contains 10° bins, and the diameter of the circle represents 50%. The diagram on the left is a statistical stereonet diagram. The white lines represent the mean orientations for the dataset, the length of this line represents percentage of the population displaying the trend and the width of the wedge indicates the standard deviation of the population.
Figure 8. Stereonet data of 22 dike plane orientations from the Telegraph Peak-Middle Fork Lytle Creek Block. The diagram on the right was generated in the Stereonet 9 program. The grey lines are dike planes and the black dots are poles to those planes. The contouring method is 1% area method. The rose diagram in the center contains 10° bins, and the diameter of the circle represents 50%. The diagram on the left is a statistical stereonet diagram. The white lines represents the mean orientations for the dataset, the length of this line represents percentage of the population displaying the trend and the width of the wedge indicates the standard deviation of the population.
Figure 9. Stereonet data of 17 dike plane orientations from the Timber Mountain Block. The diagram on the right was generated in the Stereonet 9 program. The grey lines are dike planes and the black dots are poles to those planes. The contouring method is 1% area method. The rose diagram in the center contains 10° bins, and the diameter of the circle represents 50%. The diagram on the left is a statistical stereonet diagram. The white lines represent the mean orientations for the dataset, the length of this line represents percentage of the population displaying the trend and the width of the wedge indicates the standard deviation of the population.
Figure 10. Stereonet data of 250 dike plane orientations from the West Bear Canyon-Cow Canyon Cattle Canyon Block. The diagram on the right was generated in the Stereonet 9 program. The grey lines are dike planes and the black dots are poles to those planes. The contouring method is 1% area method. The rose diagram in the center contains 10° bins, and the diameter of the circle represents 50%. The diagram on the left is a statistical stereonet diagram. The white lines represent the mean orientations for the dataset, the length of this line represents percentage of the population displaying the trend and the width of the wedge indicates the standard deviation of the population.
Figure 11. Stereonet data of 16 dike plane orientations from the Shoemaker Road Block. The diagram on the right was generated in the Stereonet 9 program. The grey lines are dike planes and the black dots are poles to those planes. The contouring method is 1% area method. The rose diagram in the center contains 10° bins, and the diameter of the circle represents 50%. The diagram on the left is a statistical stereonet diagram. The white lines represent the mean orientations for the dataset, the length of this line represents percentage of the population displaying the trend and the width of the wedge indicates the standard deviation of the population.
Shoemaker Road

The Shoemaker Road domain (Figure 11) is the smallest block in my study area in terms of points and of area. The block is bounded to the east by the Weber Fault and to the south by the San Gabriel Fault. A majority of the measurement points were taken from Shoemaker Canyon Road above the East For San Gabriel River, while a few were taken in the Canyon below on the traverse towards the Bridge to Nowhere. There were a total of 16 measurements, with 11 assigned UTM coordinates, taken in this region because of the scarcity of mafic dikes that exhibit a bimodal trend of $300.8^\circ \pm 9.4^\circ$, 12 data points, and $348.7^\circ \pm 8.8^\circ$, 4 points. These statistics are skewed mostly due to the fact that nearly 70% of points fall between $340^\circ$ to $360^\circ$ and due to the scarcity of dikes in this block, the 5 measurements which fall between $270^\circ$ and $340^\circ$ have a significant effect on the overall trends. Nourse (personal communication, 2016) recalls a few additional measurements from the East Fork that may augment the $\sim 301^\circ$ strike population.

Domains South of the NSGF

Sunset Ridge-San Antonio Canyon

The Sunset Ridge-San Antonio Canyon domain (Figure 12) is the easternmost region south of the NSGF in my field area. The block is bounded in the east by the San Antonio Canyon Fault, to the north by the NSGF, to the west by the Sunset Ridge Fault and to the south by the Evey Fault. Measurements points in this domain were taken from Mount Baldy Road on the west side of San Antonio Canyon, along the easternmost section of Glendora Ridge Road and along Sunset Ridge Fire Road adjacent to Sunset Peak. There are a total of 56 measurements in this block, with 47 points assigned UTM
coordinates, that have exhibited three trends of $34.7^\circ \pm 22.7^\circ$, 34 points, $295.0^\circ \pm 10.1^\circ$, 12 points, and $334.7^\circ \pm 9.8^\circ$, 10 points.

**Glendora Ridge-Experimental Forest**

The East Glendora Ridge Road-Experimental Forest domain (Figure 13) is directly to the west of the Sunset Ridge-San Antonio Canyon domain across the Sunset Ridge Fault. The block is bounded to the east by the Sunset Ridge Fault, to the north by the NSGF and to the west by the San Dimas Canyon Fault. Measurement points in this domain were taken on the eastern section of Glendora Ridge Road from the Sunset Ridge Fire road to just before Peacock Saddle in the northern section of the block as well as within the government-protected research area the San Dimas Experimental Forest in the central part of the block. Individual stereonets for the East Glendora Ridge Road section and Experimental Forest section of the block have been included on Plate 1. A total number of 68 data points were collected for this block with 29 assigned UTM coordinates, that exhibit three trends of $49.2^\circ \pm 20.7^\circ$, 36 points, $300.1^\circ \pm 16.0^\circ$, 24 points, and $353.9^\circ \pm 6.0^\circ$, 8 points.

**San Dimas Canyon-Cattle Canyon**

The West Glendora Ridge-San Dimas Canyon-Cattle Canyon domain (Figure 14) is located west of the East Glendora Ridge Road-Experimental Forest block across the San Dimas Canyon-Weber Fault. The block is bounded to the east by the San Dimas Canyon-Weber Fault, to the north by the NSGF and to south by the Sierra Madre Fault. Measurements in this block were taken from Cattle Canyon in the northern section of the block, the section of Glendora Ridge Road west of Peacock Saddle to the town of
Glendora, Tanbark Flats, Johnstone Peak Truck Trail and Hummingbird Creek in the central section of the block, and around the San Dimas Reservoir in the southeast corner of the block. Individual stereonets for the West Glendora Ridge Road, San Dimas Canyon and Cattle Canyon are included on Plate 1. A total number of 96 data points were collected with 52 assigned UTM coordinates, that exhibit two trends of 305.5° ± 20.3°, 76 points, 70.6° ± 13.5°, 14 points, 5.7° ± 6.6°, 6 points.

San Gabriel Canyon

The San Gabriel Canyon domain (Figure 15) located west of the San Dimas Canyon-Cattle Canyon block and is the largest region in terms of area defined. The block is bounded to the west by the Sawpit Canyon-Clamshell Fault to the north by the San Gabriel Fault and to the south by the Sierra Madre Fault. Measurements in this block were taken from the East Fork of San Gabriel River before the Shoemaker Road turnoff, the San Gabriel Reservoir and San Gabriel Dam area with individual stereonets for each of these regions. Additional measurements for this block were ascertained from Morton 1973 map in southwest (without dip readings). A total number of 115 data points were taken with 83 points assigned UTM coordinates, exhibit two trends of 51.3° ± 20.8°, 62 points, 307.3° ± 24.8°, 53 points.

Sawpit Canyon-Clamshell Peak

The Sawpit-Clamshell block (Figure 16) is west of the San Gabriel Canyon block across the Sawpit Canyon-Clamshell Fault. The block is bounded on the east by the Sawpit Canyon-Clamshell Fault and to the south by the Sierra Madre Fault. A majority
Figure 12. Stereonet data of 56 dike plane orientations from the Sunset Ridge-San Antonio Canyon Block. The diagram on the right was generated in the Stereonet 9 program. The grey lines are dike planes and the black dots are poles to those planes. The contouring method is 1% area method. The rose diagram in the center contains 10° bins, and the diameter of the circle represents 50%. The diagram on the left is a statistical stereonet diagram. The white lines represent the mean orientations for the dataset, the length of this line represents percentage of the population displaying the trend and the width of the wedge indicates the standard deviation of the population.
Figure 13. Stereonet data of 68 dike plane orientations from the Glendora Ridge-Experimental Forest Block. The diagram on the right was generated in the Stereonet 9 program. The grey lines are dike planes and the black dots are poles to those planes. The contouring method is 1% area method. The rose diagram in the center contains 10° bins, and the diameter of the circle represents 50%. The diagram on the left is a statistical stereonet diagram. The white lines represent the mean orientations for the dataset, the length of this line represents percentage of the population displaying the trend and the width of the wedge indicates the standard deviation of the population.
Figure 14. Stereonet data of 96 dike plane orientations from the Cattle Canyon-San Dimas Canyon-Block. The diagram on the right was generated in the Stereonet 9 program. The grey lines are dike planes and the black dots are poles to those planes. The contouring method is 1% area method. The rose diagram in the center contains 10° bins, and the diameter of the circle represents 50%. The diagram on the left is a statistical stereonet diagram. The white lines represent the mean orientations for the dataset, the length of this line represents percentage of the population displaying the trend and the width of the wedge indicates the standard deviation of the population.
Figure 15. Stereonet data of 115 dike plane orientations from the San Gabriel Canyon Block. The diagram on the right was generated in the Stereonet 9 program. The grey lines are dike planes and the black dots are poles to those planes. The contouring method is 1% area method. The rose diagram in the center contains 10° bins, and the diameter of the circle represents 50%. The diagram on the left is a statistical stereonet diagram. The white lines represent the mean orientations for the dataset, the length of this line represents percentage of the population displaying the trend and the width of the wedge indicates the standard deviation of the population.
Figure 16. Stereonet data of 85 dike plane orientations from the Sawpit Canyon-Clamshell Peak Block. The diagram on the right was generated in the Stereonet 9 program. The grey lines are dike planes and the black dots are poles to those planes. The contouring method is 1% area method. The rose diagram in the center contains 10° bins, and the diameter of the circle represents 50%. The diagram on the left is a statistical stereonet diagram. The white line represents the mean orientations for the dataset, the length of this line represents percentage of the population displaying the trend and the width of the wedge indicates the standard deviation of the population.
Figure 17. Stereonet data of 119 dike plane orientations from the West Fork San Gabriel River Block. The diagram on the right was generated in the Stereonet 9 program. The grey lines are dike planes and the black dots are poles to those planes. The contouring method is 1% area method. The rose diagram in the center contains 10° bins, and the diameter of the circle represents 50%. The diagram on the left is a statistical stereonet diagram. The white lines represents the mean orientations for the dataset, the length of this line represents percentage of the population displaying the trend and the width of the wedge indicates the standard deviation of the population.
of the measurements were taken from Morton’s 1973 map, again these points do not have
dip components, only strikes. The points were taken from Rincon Red Box Road in the
north, Upper Clamshell Road and Santa Anita Canyon in the central section of the block
and Sierra Madre Debris Basin the south. A total number of 85 data points were
collected for this block, all of which have been assigned UTM coordinates, that exhibit
two major trends of $30.7^\circ \pm 22.0^\circ$, 68 points, and $334.4^\circ \pm 10.3^\circ$, 17 points.

West Fork San Gabriel River

The West Fork San Gabriel River block (Figure 17) is directly to the north of the
Sawpit Clamshell Fault. The block is bounded to the north by the San Gabriel Fault and
to the east by the Sawpit Canyon-Clamshell Fault. Measurement points in this block
were taken from the West Fork San Gabriel River road leading up to the Cogswell
Reservoir in the north of the block, West Fork Red Box road in the western part of the
block and Rincon Red Box Truck Trail around Pine Mountain in the east of the block. A
total number of 119 data points were taken for this block with 86 points assigned UTM
coordinates, and these points exhibit 2 major trends of $66.8^\circ \pm 17.5^\circ$, 60 points, and
$297.3^\circ \pm 18.5^\circ$, 59 points. Pole clusters show that the northwesterly strike set has a
pronounced northeast dip.

Personal Field Observations

As previously mentioned, I visited two new areas north of the San Gabriel Fault
to collect measurements of strike and dip and location to add to my database including
north Cow Canyon and Shoemaker Road, however there is additional motivation for
visiting these regions in the field. Certain on-site qualitative observations of the dikes
and the surrounding host rock may serve to fortify or weaken models developed from the
quantitative measurements. Specifically, the types of dike margins encountered provide context to the environment in which magma cooled and resulting dikes were altered later by younger faulting. A chilled dike margin (Figure 18) occurs when hot intruding magma from the Glendora Volcanics source melt cooled quickly after intruding into the cold country rock (middle Miocene) resulting in a sharp contrast between the two rock suites.

The San Gabriel Mountains were heavily fractured by dextral and sinistral faults that affected these magma intrusions starting with the initiation of the San Gabriel Fault ~12 Ma. Dike margins provide important information about how the dikes were originally emplaced. Chilled dike margins (Figure 18) in theory provide the most reliable measurements of original emplacement orientation and fracture geometry, because dike orientations can be inferred as the same as the margins. Sheared or faulted margins generally indicate a post-emplacement tectonic disturbance. Some intrusions show offset bedrock units on either sides of the dike which may occur for two reasons. Either the magma intruded into a pre-existing normal or strike-slip fault or, post-intrusion faults propagated due to contrasts in rock strengths along the margins. Often dikes with chilled margins have irregular shapes controlled by either pre-existing fractures or weak zones within the surrounding country rock. Additionally, some dikes themselves were offset nearly perpendicular to their margins as a result of late Miocene faulting.
Figure 18. Photo A is of an andesite dike with chilled margins from Telegraph Peak-Middle Fork Lytle Creek block. Photo B is of a dike with sheared margins from Glendora Ridge Road.
DISCUSSION AND INTERPRETATION

It is imperative to interpret the results of this study through the lens of the research questions stated earlier. Below, I summarize my main thoughts and interpretations that are supported in detail by succeeding discussion and arguments.

Two of these questions were: “Is there a clear demarcation between areas of pure extension and areas of transtension?” and “What is the mode of emplacement?”. The data reveal two major orientation trends: a northwest strike and a northeast strike. North of the NSGF, the northwest strike is dominant, whereas in southern blocks, both trends are important with the northeast strike sometimes dominant. I interpreted the northeast trends to represent early Miocene “inherited” features based upon evidence of active northeast trending left lateral faults at the time (Nourse, 1994, Nourse, 2002a) as well as other northeast trending veins within the Telegraph Peak Granite. I interpreted the northwest trending dikes as being intruded into fractures propagated during extension, most likely Mode 1 tension cracks. These northwest trends are prevalent throughout the study area and consistent north and south of the NSGF; also, their trend agrees with a regional ~N 60 E extensional event that occurred just prior to dike emplacement (Walker et al., 1990, Jacobson et al., 2007). Furthermore, the relatively large range in these trends may be related to the structural anisotropies within the San Gabriel Mountains basement host rock that affected the fracture patterns opened as a conduit for magma.

Another research question I sought to answer was: “Do differences in mean dike strike between crustal blocks record post emplacement rotations?”. Variance in strike population groups between adjacent structural blocks was not significant enough to infer vertical axis rotations. However, stereonets show that a majority dikes in blocks north of
the NSGF dip towards the northeast. Assuming that the dikes were intruded into originally vertical Mode 1 tension fractures, this may indicate a southward tilting of blocks to the north of the NSGF related compression of San Gabriel Block with the development Big Bend of the San Andreas Fault. It is also possible tilting in these blocks occurred along a listric normal fault which coincided with an early trace of the NSGF. In this perspective, horizontal axis rotation occurred in the hanging wall of a north-dipping north San Gabriel normal fault after dike emplacement but prior to major right-lateral translations along the same zone. Finally, these dikes may have intruded into a homogenous network of northeast dipping normal faults related to northeast-southwest directed extension. Such a scenario should be considered because domains of unimodal normal faults and tilt blocks are common in extensional regions where “dominal style” faulting prevails. A close examination of individual dike margins in the region is needed to clarify mode of emplacement to interpret rotational mechanisms.

The final research question was: “Can variations in stress regimes be modeled convincingly”. In the last section of this discussion, I combine my dike orientation data with a palinspastic reconstruction of the San Gabriel Mountains (Nourse, 2002a) to create a ~18 Ma tectonic reconstruction of my study prior to dike emplacement and further developed a timeline of larger-scale tectonic events to put the trends in greater context. Below I develop some important concepts and arguments that bear on that reconstruction.

**Unimodal vs. Bimodal Strikes**

An interesting result from the dike orientation data is the contrast in strike patterns north and south of the NSGF. Specifically, blocks north of the fault overall exhibit a unimodal northwest with a minor northeast trend in dike orientations whereas
dikes to the south of the San Gabriel Fault exhibit bimodal and often trimodal orientations including a strong northeasterly trend.

Transtensional stresses dominated southern California and the modern-day San Gabriel Mountains during the middle Miocene with the development of the transform boundary (Atwater, 1989, Luyendyk, 1991, Nicholson et al., 1994, Atwater and Stock, 1998). By the very definition of transtension, we would expect to see evidence of extensional stresses and strike-slip stresses in our data. The block diagrams in Figure 19 illustrate how dikes might intrude into three dimensional stress environments of pure extension versus pure strike-slip. In the case of pure extensional stress, magma might intrude into tension, or “Mode 1” cracks with a vertical dip as well as along conjugate normal faults, with dips differing by 60° and dip directions in opposite quadrants. The strikes of these cracks would be all parallel to the secondary stress direction ($\sigma_2$) and perpendicular to the tertiary stress direction or extensional direction ($\sigma_3$), with the primary stress direction ($\sigma_1$) oriented vertically. Thus I would expect a cluster of dikes that intruded into a body of rock undergoing pure extension would exhibit a unimodal strike parallel with the $\sigma_2$ direction and perpendicular to the extension direction.

A pure strike-slip stress environment (Figure 19) is different in that magma would intrude into conjugate strike-slip shear fractures with nearly vertical dips. The dike population in a pure strike-slip environment would be bimodal with strike measurements differing by 60° or 120°. The primary stress direction ($\sigma_1$) is horizontal and bisects the angle separating the measurement population, horizontal tertiary stress direction ($\sigma_3$) bisects the obtuse angle with the secondary stress direction ($\sigma_2$) is oriented vertical.
My study area deviates from these theoretical models for a number of reasons, specifically, the bimodal distributions seen in the data are difficult to explain with these models that are predicted by Anderson (1951) fault theory of isotropic rocks. I believe that the bimodal distribution patterns seen in my data can be explained by pre-magmatic structural anisotropies; e.g. northeast trending faults and fractures that were overprinted by prevailing northwest trending, middle Miocene extensional fractures.

**Figure 19.** Block diagrams (modified from Davis and Reynolds 1996) which illustrate fracture patterns, indicated by dark black lines, generated in two defined stress fields. The diagram on the left displays a “pure extensional” setting and the diagram on the right displays a “pure strike-slip” setting. Primary stress ($\sigma_1$) direction, secondary stress ($\sigma_2$) direction, and tertiary stress ($\sigma_3$) direction are indicated by arrows of decreasing widths, respectively. Arrows indicate the sense of motion on generated faults.

**Northern Fault Blocks**

The competing patterns of dike trends seen in the study area may be explained by regions of the San Gabriel Block affected by a combination of extensional and shear stresses in the middle Miocene. Dikes within blocks to the north of the modern-day NSGF generally exhibit a unimodal trend of $314.3^\circ \pm 21.8^\circ$, with 92.4% of the 449 dikes contributing to this trend (Plate 1 and 2). There is a very minor northeast trend of $47.9^\circ \pm $
30.1°, with a mere 7.6% of dikes contributing to the overall trend. Northern blocks including the Icehouse Ridge-Telegraph Peak-Thunder Mountain-Timber Mountain block and the West Bear Canyon-Cow Canyon-Buckhorn Lodge-Mount Baldy block display this strong northwest trend. The Shoemaker Road block has very few measurement points (16) and it is therefore difficult to make any definitive statements about the paleostress environments as a whole in this region.

The data for the blocks north of the NSGF exhibit a generally unimodal strike trend throughout with fairly tightly clustered dip values. This suggests that magma intruded into tension cracks (i.e. Mode 1 fractures) due to extensional stresses being applied to a coherent block. If dikes were emplaced along conjugate normal faults, stereonets would show two mean pole clusters in opposite quadrants and a larger dip angle between these clusters, however, this is not seen in the data. The majority of the data from the Icehouse Ridge-Telegraph Peak-Thunder Mountain-Timber Mountain block and the West Bear Canyon-Cow Canyon-Buckhorn Lodge-Mount Baldy block supports the hypothesis that dikes intruded into Mode 1 fractures propagated within an extensional environment. Greater than 70% of the northwest trending dikes dip towards the northeast, and there is therefore a possibility that the magma intruded into a zone of uniformly northeast dipping normal shear faults, rather than being later rotated. A detailed study of dike margins in the region is needed to clarify the mode of emplacement for northwest trending dikes. The northeast trending strike populations may reflect earlier, minor development of conjugate strike-slip fractures, an artifact of structural inheritance. Only 34 of the 449 total dikes in the northern blocks strike northeast (~7.6%) which is significant because northeast trending dikes are abundant south of the NSGF.
Southern Fault Blocks

Blocks south of the NSGF exhibit noticeably different patterns of dike orientation than blocks to the north of the fault. Northwest trends in these blocks are very similar to blocks north of the NSGF, and the average trend for this population is 306.6° ± 23.4°. In southern blocks, the average trend for northeast trending dikes is 46.4° ± 24.9°, and this trend represents 51.2% of the total population (Plate 1 and 2). Clearly the northeast trend is much more pronounced in these blocks than in the northern blocks, and I believe that this trend reflects a strike-slip stress regime coinciding with pre-middle Miocene movements on northeast trending left-lateral faults in the region. Additionally, dike trends east of the Sawpit Canyon-Clamshell Fault are very different from trends west of this fault. It is unclear why dike trends in blocks west of the Sawpit Canyon-Clamshell fault are so anomalous, though this fault is believed to have been the part of the southern branch of the San Gabriel Fault system (Powell, 1993, Nourse, 2002a) and western blocks may have been rotated differently than others, however the timing and extent of the offsets on this fault are not well constrained. I interpret these complicated patterns to record a combination of “structural inheritance” overprinted by extensional stresses imposed prior to magmatism.

Blocks east of the Sawpit Canyon-Clamshell fault including the Sunset Ridge-San Antonio Block, East Glendora Ridge-Experimental Forest Block, West Glendora Ridge-Cattle Canyon-San Dimas Canyon and the San Gabriel Canyon Block share two and often three distinct strike patterns. The two trends most often seen in these blocks are a northwest trend averaged at 307.8° ± 23.2°, and a northeast trend averaged at 46.5° ± 23.8°. Additionally the Sunset Ridge-San Antonio Block, East Glendora Ridge-
Experimental Forest Block and West Glendora Ridge-Cattle Canyon-San Dimas Canyon blocks exhibit a prominent tertiary trend, averaged at 349.7° ± 26.8°. The northwest strike population in this region is nearly identical to the trends north of the San Gabriel Fault, which fortifies the idea that the region underwent the same extension event, directed ~N 35 E, in terms of present day geography. Additionally, northeast-striking dike populations in these blocks follow a similar strike of northeast trending left-lateral faults in the area, most notably the San Antonio Canyon Fault, which was believed to have undergone and early stage of movement prior to dike emplacement (Nourse, 2002a, Heaton, 2008).

Patterns for the blocks west of the Sawpit Canyon-Clamshell Fault are anomalously different both regionally and spatially. In the West Fork San Gabriel River block, directly south of the San Gabriel Fault, dike orientations are 297.3° ± 18.5° and 66.8° ± 17.5°. The northwest striking dike population for this block is consistent with other southern blocks and the northeast-striking population is much closer to east-west trending than blocks east of the Sawpit-Clamshell Fault. Farther south of the San Gabriel Fault, in the Sawpit-Clamshell Block dike orientations are on average 334.4° ± 10.3° and 30.7° ± 22.0°, drastically different than regional trends. The convoluted dike orientation patterns for this region may be related to the unknown timing and uncertain offset on the southern branch of the San Gabriel Fault system (Nourse, 2002a). A total of ~45 km of dextral offset has been estimated for the entire San Gabriel Fault system (Crowell 1952) with at least 22 km attributed to the northern branch (Dibblee, 1982, Ehlig, 1983, Nourse, 2002a). An additional 15 km of dextral offset is attributed to the Sawpit-Clamshell Fault (Nourse, 2002a), which is postulated as part of the southern branch of the San Gabriel
Fault. Additionally, it has been theorized that another southern branch has been overprinted by the currently active Sierra Madre Thrust fault, further complicating efforts to sequence events on the San Gabriel Fault system (Nourse, 2002a). If the Sawpit Canyon-Clamshell Fault is actually a strand of the San Gabriel Fault, its trend and curvature are highly anomalous, creating possibilities for significant post-dike block rotations. Pliocene to recent compression between the Sierra Madre Fault and San Andreas Fault may have also contributed to a quasi-pure shear flattening effect.

Pre-Middle Miocene Structures

There is substantial evidence from a few areas that significant northeast striking structural features in the San Gabriel Mountains existed prior to the emplacement of the middle Miocene mafic dike swarm (Nourse, 1994). Heaton (2008) postulated that the San Antonio Canyon Fault on the eastern part of my study area underwent two stages of left-lateral movement (Figure 20). A late phase of Pliocene or younger sinistral movement of 3 km is estimated based on offset strands of the north San Gabriel Fault and the Vincent Thrust Fault by the San Antonio Canyon Fault (Nourse, 1999, 2002a). X-ray fluorescence analyses on a late Cretaceous assemblage of three distinct units: granite-granodiorite, quartz hornblende monzonite and tonalite-quartz diorite, which outcrop on either side of the San Antonio Canyon Fault reveal a genetic relationship (Heaton, 1998). Further, very similar outcrops are located in Sugarloaf Peak east of the fault and the Shinn Road Marble Quarry near San Antonio Dam west of the fault, sites offset by ~10 km left-laterally (Heaton, 1998, Nourse et al., 1994). Therefore, ~6.5 km of left-lateral offset on the San Antonio Canyon Fault existed prior to 12 Ma to 5 Ma movements on the NSFG. Nourse (1994, 2002a) postulates that the sinistral offsets occurred during
early Miocene time, because related fault surfaces were intruded by the middle Miocene dikes (Figure 20).

**Figure 20.** Diagram illustrating two-phase left-lateral movement on the San Antonio Canyon Fault based on analysis by Nourse 2002a, Heaton 2008. A total of 10 km of left-lateral movement is suggested by displacements of a late Cretaceous quartz hornblende monzonite unit, “Khqm”, by the San Antonio Canyon Fault. Late Miocene-Early Pliocene left-lateral displacement of 3.5 km is inferred from deflection of San Gabriel Fault and Icehouse Canyon Fault traces, leaving a 6.5 km early phase of left lateral motion of the San Antonio Canyon Fault. Maps on the left are from Heaton 2008 Figure 3 (below) and Figure 4 (above), and geologic map on the right is cropped from a larger geologic base map, Morton and Miller 2006.
Other studies have suggested the existence of northeast-trending pre-middle Miocene left-lateral faults in the San Gabriel Mountains. Wilkins (2004) postulated early-phase movement on the Stoddard Canyon Fault due to significant left-lateral basement rock offsets which are greater than the 1.75 km left-lateral deflection of the Icehouse Canyon Fault from the Middle Fork Lytle Creek Fault (Wilkins, 2004). Geologic mapping along the San Dimas Canyon-Weber Fault and Sunset Ridge Faults (Nourse, 2002a, Morton and Miller, 2003) reveals a discrepancy between basement rock offsets south of the NSGF and offsets of the trace of the San Gabriel Fault. It is possible that a similar early-stage of left-lateral movement occurred along the southern segments of the San Dimas Canyon Fault and the Sunset Ridge Fault prior to dike emplacement in the middle Miocene, creating northeast striking structural anisotropies and possible northerly conjugates that influenced the patterns of dike orientations seen in the study area.

Personal field measurements which I collected from Telegraph Peak in the Icehouse Ridge-Thunder Mountain-Telegraph Peak-Timber Mountain block in August of 2016 strengthen the argument for early Miocene conjugate strike-slip faulting. Telegraph Peak is comprised of two peaks connected by a generally north-south trending ridge. The northern peak is comprised of mylonitic granodiorite from the Vincent Thrust system and the southern peak is comprised of Telegraph Peak Granite, or the pluton which fed the felsic rhyolite-dacite dikes. Several kilometers to the east-southeast, the Telegraph Peak Granite has been U/Pb dated at 26 +/- 1 Ma (May and Walker, 1989). Within the Telegraph Peak Granite pluton in addition to cross-cutting middle Miocene andesite dikes, I found 1-5 cm dikes ranging in composition from aplite to pure quartz. Although
undated, these features are interpreted to be last stages of the melt of the Telegraph Peak Pluton and thus are the same age or slightly younger than the Telegraph peak pluton. Additionally, this block maybe restored back 22 km west along the San Gabriel Fault (Nourse, 2002a) to its middle Miocene location north of the West Fork San Gabriel River block. I measured a total of 18 orientations of these features as well as any offset features associated with the veins (Figure 21). The major trends of these veins are NS to N 20 E and N 40 E to N 60 E, a conjugate set of fractures that represent structural joints that formed after the pluton cooled (Figure 21).

![Figure 21](image-url). Equal-area stereonet plot of poles to planes of various intrusive features in the Telegraph Peak Granite, around Telegraph Peak itself. Measurements were collected by myself and Dr. Jonathan Nourse in August of 2016. Features measured include quartz veins, aplite veins and mafic andesite dikes.

The orientations of these veins reflect the stresses on the pluton during the late Oligocene, which provides evidence why many patterns of fractures exist that cannot be explained with one mechanical model. Specifically, the northeast trending fractures propagated in the late Oligocene may have provided a conduit for magma in middle
Figure 22. Photo compilation of pre-middle Miocene structures in the Telegraph Peak Granite intrusion, around Telegraph Peak. The photo on the top left is a sheared, bull quartz vein intruded into the Telegraph Peak Granite pluton. The photo on the top right is a 2-3 cm quartz vein with parallel smaller quartz veins. The bottom photo is of a 2 cm thick felsite with quartz vein within.
Miocene. On the western margin of the pluton, vein measurements tended to be almost all N 40 W to N 60 W, however this may be a stress effect of being on the edge of the pluton, and there is a NS trending vein in the vicinity which strengthens the idea these are conjugate sets of structural joints (Figure 22).

On the eastern portion of the Telegraph Peak Granite pluton, in the Middle Fork of Lytle Creek Canyon, numerous features were measured that record a pre-middle Miocene northeast-directed extensional event manifested by conjugate normal shear zones (Figure 23) (Nourse, 2002b). Displayed in Figure 23 below, Nourse (2002b) measured 1 to 8 cm thick mylonitic foliations (green stars) and lineations (gold ovals) as well as millimeter scale shear surfaces (purple triangles) and N 30 E to N 40 E mylonitic lineations (orange ovals) that crosscut the pluton. Some of the middle Miocene mafic dikes mapped in this area crosscut these ductile extensional structures (black dots). The San Gabriel Block as a whole underwent ~20° of counterclockwise rotation as it was translated by the San Andreas Fault in late Cenozoic. When this rotational event is restored, the structural measurements record a post 26 Ma N 50-60 E – S 50-60 W extensional event, consistent with N 60 E sense of shear on the Waterman Hills Detachment in the central Mojave Desert, dated at ~18 Ma (Walker et al., 1990).
Impact of Anisotropy on Fracture Generation

Some interpretations in the previous section are based upon a set of assumptions (e.g. Anderson 1951) made to predict the orientations of faulting due to differing magnitudes of applied stress. However, these assumptions may not apply perfectly to the San Gabriel Mountains due to differing rheological properties. Coulomb’s Law of Failure states that shear stress required for faulting ($\sigma_c$):

$$\sigma_c = \sigma_0 + \sigma_N \cdot \tan \phi$$  \hspace{1cm} (Equation 1)

where $\sigma_0$ is equal to cohesive strength of a rock, $\phi$ is the angle of internal friction for a rock, equivalent to the rock strength, and $\sigma_N$ is the normal stress. The angle of internal friction can be used to determine $\theta$, or the angle between the fault surface and the direction of maximum principal stress ($\sigma_1$) with the following equation (Anderson 1951):

$$2\theta = 90^\circ - \phi$$  \hspace{1cm} (Equation 2)

Laboratory tests have determined that for most rocks, $\phi$ averages at $30^\circ$ across isotropic rock types, which when plugged into Equation 1 plots as a line known as the
Coulomb Failure Envelope. In the same plot as this line, we can calculate normal and shear stress from the maximum and minimum principal stresses in what is known as a Mohr Circle. The circle has a radius of the difference between magnitudes of the maximum stress ($\sigma_1$) and of minimum stress ($\sigma_3$) and with the center of the circle defined by $(\sigma_1 + \sigma_3)/2$. The diameter of the circle is equivalent to the differential stress, or the difference between maximum and minimum principal stresses. When stress builds up in a rock due to applied force, the difference between maximum and minimum principal stresses increases, thus increasing the size of the Mohr Circle. The point at which the Mohr Circle touches the Coulomb Failure Envelope is equivalent to normal and shear stress required to break the piece of rock (Figure 24). In isotropic rocks, $\theta$ is equivalent to 30° from the direction of $\sigma_1$ and determines fault geometries seen in extensional and strike-slip environments (Figure 19).

Anderson 1951 recognized the relationship between fault propagation and magnitudes of principal stresses, however the basis for this relationship relies upon the assumption that the rock host is isotropic, meaning that the rock body is homogeneous in all directions with no pre-existing fractures, bedding planes or other weaknesses. However, this is not the case in the San Gabriel Mountains, which contains many different collections of rocks riddled with mechanical weaknesses due to a variety of tectonic processes which occurred beginning in Precambrian time. A rock with mechanical weaknesses has a lower cohesive strength in specific directions, which means that the slope of the Coulomb Fracture Envelope is shallower, thus changing the orientation of faults propagated in the rock body (Figure 24). A detailed rheological investigation of basement rocks in the eastern San Gabriel Mountains may help clarify
fracture geometries seen in the data, however this would be very time consuming and is beyond the scope of this study. However, this phenomenon may clarify why we are seeing a wide range of dike orientations throughout certain structural domains.

**Figure 24.** Plot of Mohr failure envelope with a Mohr stress shear stress circle, with shear stress ($\sigma_S$) plotted versus normal stress ($\sigma_N$) (Davis and Reynolds, 1996). The Coulomb Failure Envelope Line has a slope of $\tan \phi$, where $\phi$ is equivalent to the angle of internal friction in isotropic rocks (30°). Structural anisotropies decrease the internal friction angle and further affect the orientation of fractures generated.

**Block Rotations**

I anticipated that mean strike differences between crustal blocks may record evidence of post-emplacement vertical axis rotations, but these results only reveal small scale relative strike differences between these blocks. However, the data do suggest that a majority of northwest trending dikes were intruded into Mode 1 fractures, which have subvertical dips. Therefore, stereonet analysis of dikes in these blocks provides an
opportunity to assess both regional vertical axis rotations and horizontal axis rotations (tilting).

**Vertical Axis Rotations**

Dike orientation patterns exhibit a northwest trend of $314.3^\circ \pm 21.8^\circ$, in northern blocks, and $306.6^\circ \pm 23.4^\circ$, in southern blocks. Northeast trending dike populations average $47.9^\circ \pm 30.1^\circ$, north of the NSGF, and $46.4^\circ \pm 24.9^\circ$, south of the NSGF. These trends are within the margin of error of average trends for the entire region, $311.3^\circ \pm 22.7^\circ$ and $46.6^\circ \pm 25.5^\circ$. Therefore, because dike orientation trends between individual structural blocks north and south of the NSGF deviate by very small margins, I cannot project any vertical axis block rotation numbers. The Sawpit Canyon-Clamshell Peak Block is the only area with anomalous dike trends compared with other southern blocks; one possible suggestion for this discrepancy is that this block was rotated differently than others. The Sawpit Canyon-Clamshell Fault is thought to have been part of the earliest developing part of the San Gabriel Fault system: the southern branch. The timing and offsets on the southern branch of the San Gabriel Fault have not been measured due to poor exposures along possible fault traces (Powell, 1993, Nourse, 2002a) and thus vertical axis rotations in this block are difficult to estimate. Fortunately, there are other methods to ascertain the relevant rotational data.

On average, the Western Transverse Ranges have undergone $\sim 93^\circ$ of clockwise rotation from the early Miocene to present day (Luyendyk, 1991), however this reflects the amount of rotation of the entire range. Different structural blocks within the Central Transverse Ranges have undergone varying amounts of clockwise and even
counterclockwise rotations during this time period. For example, paleomagnetic data from the Oligocene to early Miocene Vasquez formation in the western portion of the San Gabriel block indicates the region has undergone a 53° of clockwise rotation from 17 Ma to 10 Ma. The late Miocene Mint Canyon formation preserves 16° of counterclockwise rotation from 10 Ma to present day (Terres, 1984, Terres and Luyendyk, 1985, Hornafuis et al., 1986). However, this information is not applicable to our area because the Mint Canyon Formation and Vasquez Formations are in an area with differing configuration of dextral and sinistral faults than the San Gabriel Mountains and because the Vasquez Formation is Oligocene in age, much older than the andesite dike swarm meaning much of the documented clockwise rotation may have predated emplacement of the mafic dikes. The San Gabriel Mountain Block is separated from the Vasquez-Mint Canyon basement by the left lateral Soledad Canyon Fault. The San Gabriel Mountains were decoupled from the rotating Western Tranverse Range when the San Gabriel Fault system initiated 12 Ma. Thus, crustal blocks north of the south branch of the San Gabriel Fault, including my study area, experienced lesser amounts of clockwise rotation.

The San Andreas Fault has accumulated between 160 km (Powell, 1993, Matti and Morton, 1993) and 240 km (Ehlig, 1981, Dillon and Ehlig, 1993) of dextral offset since transform motion shifted from the San Gabriel Fault ~5 Ma. Though the displacement numbers disagree, previous studies do agree that the Pelona Schist unit in San Gabriel Mountains aligned with the Orocopia Schist in the Chocolate Mountains east of Salton Sea prior to the initiation of the San Andreas Fault. Along this distance, the strike of the San Andreas Fault changes from ~N 40 W in the Chocolate Mountains Salton Trough area to ~N 55 W to N 60 W in the San Gabriel Mountains area. This
means as the block containing the eastern San Gabriel Mountains was translated northwestward along the “Big Bend” by the San Andreas Fault it underwent ~15° to 20° of counterclockwise rotation. This value is consistent with the value from Terres and Luyendyk (1986), which is 16° of counterclockwise rotation for the Mint Canyon Formation, which was translated along with the San Gabriel Mountains. Therefore, it can be suggested that the entire dike swarm has been rotated counterclockwise at least 15° since 5 Ma.

**Horizontal Axis Rotations**

Analysis of stereonet data may suggest horizontal axis rotations of structural blocks in my study area, especially, in blocks north of the NSGF. Stereonets reveal that a majority of dikes in these northern blocks, 65.2% of these measurements, strike northwest and dip towards the northeast, with average dip values of 73.3° ± 13.2°. One interpretation of the data suggests that the tight clusters of dip indicate that dikes were intruded along Mode 1 tension cracks associated with extension. Presuming that these Mode 1 tension cracks had a vertical dip at the time of emplacement, significant southward tilt has occurred in these blocks since middle Miocene time. It is possible that tilting was caused by compression which occurred as the San Gabriel Mountains were squeezed by the “Big Bend” of the San Andreas Fault from 5 Ma to present day. Alternatively, southward tilting may have been facilitated by a listric normal fault coincident with the NSGF, before that fault was activated as a dextral transform fault. A third alternate theory is that the dikes are not rotated, but intruded into a zone of uniformly northeast-dipping normal faults propagated due to regional extension. A
detailed investigation of individual dike margins is needed to distinguish between these mechanisms.

Stereonet data from the southern blocks show differing strike and dip patterns east and west of the Sawpit Canyon-Clamshell Fault. Results from blocks to east of the Sawpit Canyon-Clamshell Fault overall do not show any significant horizontal axis rotations. The average northeast strike for the blocks are $46.7° \pm 23.6°$, and dip of $76.9° \pm 15.2°$ southeast and $72.2° \pm 10.9°$ northwest. The average northwest strike for blocks east of the Sawpit Canyon-Clamshell Fault is $307.3° \pm 23.7°$, and dip of $69.7° \pm 14.6°$ southwest and $73.8° \pm 14.8°$ northeast. To the west of the Sawpit Canyon-Clamshell Fault, there are fewer dip measurements associated with strike measurements, and a majority of them are in the West Fork San Gabriel River block. The average northeast strike trend is $66.8° \pm 17.5°$ and dips $75.0° \pm 12.7°$ southeast and $77.2° \pm 8.4°$ northwest. The average northwest trend is $297.3° \pm 18.5°$ and dips $68.6° \pm 11.5°$ southwest and $77.9° \pm 9.7°$ northeast. The data show that a majority of northwest and northeast trending dikes dip to the south, suggesting that the block may have experienced northward tilting. A comprehensive study of individual dike margins can help to clarify mode of emplacement and will further help to understand the nature of horizontal axis rotations occurring in these blocks.

*Paleomagnetic Resolution*

Resolving the amount of likely smaller scale block rotations for the eastern San Gabriel Mountains is more difficult to constrain given the configuration of dextral and sinistral faults and possible unknown pre-middle Miocene displacements of some of the
left-lateral faults. One possible method which could resolve the block rotation question is a paleomagnetic investigation of orientated andesite or basalt dike samples within each of the defined structural blocks in the study area. Remnant magnetization is a phenomenon by which magnetic minerals including magnetite, an accessory mineral found in andesite, align with earth’s magnetic field when the magma reaches the surface and lock into place this orientation when the magma cools. Deviations in the orientation of middle Miocene magnetic north vector field from the orientation of magnetite minerals within the sample would indicate that the sample has been rotated. There are methods and instruments that exist which could constrain three-dimensional rotation of andesite dikes from the middle Miocene to present. Previous paleomagnetic studies of the Western Transverse Ranges (Kammerling and Luyendyk 1979, Hornafuis 1984, Hornafuis 1985, Luyendyk 1985, Terres 1985) have sampled numerous volcanic and sedimentary rocks of late Oligocene to late Miocene ages, however, no studies of intrusive rocks have been conducted in the eastern or central San Gabriel Mountains. The dikes have good age constraints with more measurements currently being conducted. Oriented andesite cores might be collected and sent to a paleomagnetic laboratory for analysis.

A paleomagnetic investigation, while logistically plausible and potentially significant in resolving block rotations the San Gabriel Mountains, is out of the scope of my investigation for several reasons. The process of collecting cores in the study area is difficult due to rough terrain, made more complicated by carrying heavy coring equipment and rock samples, however this alone does not discourage attempting the investigation. California State University Polytechnic does not have the resources to conduct paleomagnetic analysis on rock samples, and laboratories with the proper
equipment undoubtedly have a massive backlog of material to be sampled. The time required to collect samples, to send them into a lab to be processed and to analyze the results exceeds my timeline. Furthermore, the primary purpose of my project is to investigate how effectively mafic dike orientations reflect existing regional middle Miocene stress models. Individual block rotations are more difficult to pinpoint exactly with just dike orientation data, however pre-existing fault kinematic knowledge may help to explain uncharacteristic strike populations. However, a successful paleomagnetic investigation of the andesite dikes would hopefully help to explain block rotations and may clarify dike orientation patterns displayed.

Late Cenozoic Timeline and Tectonic Model

I have developed a tectonic model of the San Gabriel Mountains to contextualize how the larger-scale geologic forces affecting southern California, starting in the Oligocene, were manifested in the San Gabriel Mountains (Plate 3). The main element of this model is a tectonic reconstruction at 18 Ma that shows the geographic distribution of crustal blocks and regional stresses at the approximate time of dike intrusion. I start by outlining relevant events leading up to and immediately preceding middle Miocene dike emplacement to ultimately explain how magma-filled fractures propagated, and were later disturbed by faults of the San Gabriel and San Andreas systems.

Regional Tectonic Events:

≈30 Ma: In the early Cenozoic, a relatively young and thin Farallon Plate was subducting underneath the North American continental crust (Atwater, 1989, Atwater and Stock, 1998). Coincidently, during the early to middle Cenozoic, the East Pacific Rise ridge
spreading center was approaching the subduction zone trench as well due to increasing convergence rates between the Farallon Plate and the North American Plate. Starting around ~30 Ma, the Farallon Plate fractured due to differing subduction rates and was separated, from north to south, into the Farallon, the Monterey and the Arguello microplates (Nicholson et al., 1994). At ~29 Ma, the East Pacific Rise spreading center hit the North American Trench (Atwater and Stock, 1998).

26-27 to 23 Ma: Silicic crustal melts produced the 26 Ma Telegraph Peak Granite (May and Walker, 1989) and the 27 Ma Mountains Meadows Dacite (Hazelton personal communication 1998, McColluh et al., 2001). Due to a fractured Farallon Plate subducting underneath the North American Plate at different rates, a “slab window” formed between the Farallon and Monterey microplates (Atwater and Stock, 1998). Fragmented remnants of the previously subducted Farallon plate allowed asthenosphere to leak through to the continental upper plate driving bimodal magmatism. Associated mafic rock suites include alkalic basaltic magmas from Vasquez Rocks basalt ~27 Ma (Frizell and Weigand, 1993) and the Diligencia Basin basalts 22-23 Ma (Law et al., 2001).

23-18 Ma: No magmatism occurred during this time, however the southern California transform boundary began to develop. Subduction of the Farallon Plate directed at S 50 E, was oblique relative to the orientation of Pacific-North American trench, oriented at N 30 W. Strain partitioning due to oblique subduction (Fitch, 1972) generated right-lateral faults in the continental borderland parallel to the trench and conjugate right-lateral and
left-lateral faults in the overriding North American plate (Figure 25 A) (Nicholson et al., 1994). The San Antonio Canyon Fault, Sunset Ridge Fault, San Dimas Canyon Fault and Stoddard Canyon Fault were probably active during this time (Plate 3). At this time, the future north branch of the San Gabriel Fault may have been the northern boundary of the developing transform plate margin (which is why we see far fewer northeast striking faults north of the NSGF). Also during the early Miocene period, 18-20 Ma, Pacific-Monterey spreading ceased altogether and the interaction between the Monterey and North American plates changed from oblique subduction towards the southeast to dextral transform motion (Figure 25 B), and the strike-slip stress field shown in Figure 19 prevailed (Atwater, 1989, Luyendyk, 1991, Nicholson et al., 1994).

Figure 25. Tectonic model of Pacific-North American plate interactions from 24 Ma to 12 Ma, from Nicholson (1994) Figures 3 A-D. The study area is in the San Gabriel Block (SG) labeled above and WTR indicates the Western Transverse Ranges.

18-15 Ma: When the Farallon Plate subduction ceased, Pacific-North American relative plate motion was directed ~N 60 W at a rate of 33 millimeters per year (Atwater and Stock 1998). This direction was oblique to the continental margin and most lithologic structures in southern California. A regional ~N 60 E extensional event occurred,
perpendicular to the N 30 W trending continental margin, shown at a larger scale from Figure 26 B to 26 C above, which subjected the North American Plate to shear stress and resulted in a microplate capture of a piece of terminal Monterrey Microplate. The crust above this captured microplate, known as the Western Transverse Ranges, began rotating clockwise, aided by the pre-existing network of left-lateral faults (Figure 25 C) (Nicholson et al., 1994, Luykendyk, 1991, Atwater and Stock, 1998). The San Antonio Canyon Fault may have been an important boundary structure that localized magmatism at this time (Nourse, 2002a). The Glendora Volcanics were extruded and an associated mafic-intermediate dike swarm was injected into the fracture network in the San Gabriel Mountains at 15-17 Ma.

**12-8 Ma:** Pacific-North American relative plate motion, still directed at N 60 W, sped up abruptly at 12 Ma from 33 millimeters per year to 52 millimeters per year during this period (Atwater and Stock, 1998). The San Gabriel Fault system also developed abruptly as the locus of transform plate motion shifted eastward into the North American Plate (Figure 25 D). The San Gabriel Fault system probably developed from south to north, accommodating 45-60 km of right lateral motion during this period (Nourse, 2002a, Beyer et al., 2009). The northern branch of the San Gabriel Fault accommodated 22 km of this motion, and displacements on the southern branches are controversial. However, my model theorizes three possible paths for the southern branch of the San Gabriel Fault: (from south to north) the Canton-Verdugo-Whittier Fault, the Vasquez Creek-Sierra Madre Fault (swallowed up by a thrust fault system) and finally the Sawpit Canyon-Clamshell Fault. The initiation of this fault system interrupted clockwise rotation of the
San Gabriel Mountains region while the Western Transverse Ranges continued to rotate clockwise to the south and west of the fault zone.

8 Ma to Present: Pacific-North American relative plate motion vector dramatically shifted from N 60 W to N 37 W (Atwater and Stock, 1998), perfectly parallel to the modern-day San Andreas Fault while the Pacific-North American plate rate remained the same at 52 millimeters per year (Atwater and Stock, 1998). Dextral transform motion shifted from the San Gabriel Fault system to the San Andreas Fault system at ~ 5 Ma. The San Gabriel Mountains were translated between 160 km (Powell, 1993, Matti and Morton, 1993) and 240 km (Ehlig, 1981, Dillon and Ehlig, 1993) to the northwest to their modern-day location, undergoing 15° to 20° of counterclockwise rotation in the process.

A Middle Miocene Tectonic Model

My middle Miocene tectonic model in Plate 3 has been compiled to reconstruct the eastern San Gabriel Mountains at the close of the early Miocene, ~18 Ma, immediately prior to andesite-basalt dike emplacement. Structural blocks, outlined in blue, have been translated to their early Miocene location based upon a palinspastic reconstruction (Nourse 2002a, Figure 9) of the study area. The San Gabriel Fault system, including proposed southern and northern branches is indicated by black dashed lines. Three possible traces of the southern San Gabriel branch are shown, including the Sawpit-Clamshell branch, the Sierra Madre branch and the Canton and Verdugo-Whittier branch. Proposed ancestral left-lateral faults, including the San Antonio Canyon Fault, the San Dimas Canyon Fault and the Sunset Ridge Fault are indicated by red lines. In addition, the entire region has been rotated 15° clockwise to account for Pliocene-
Quaternary counterclockwise rotation of the San Gabriel Block along the San Andreas Fault. This figure for counterclockwise rotation in my study area is in agreement with paleomagnetic measurements of the late Miocene Mint Canyon Formation, which underwent 16° of counterclockwise rotation.

The reconstructed dike populations in the 18 Ma tectonic reconstruction model (Plate 3) reveal several important conclusions related to Miocene stresses and tectonic events. The northwest-trending dike populations, ubiquitous throughout both northern and southern tectonic blocks, record a northeast-southwest directed extensional event likely driven by tensional stress associated with the rotating Western Transverse Ranges. Northeast-trending dikes common in southern structural blocks represent pre-existing anisotropies and left-lateral faults formed during early Miocene time. Conjugate northeast trending, left lateral, and northwest trending, right lateral, fractures that were initially propagated due to strain partitioning in the North American Plate accompanied by oblique subduction of the Farallon Plate. I believe the NSGF represented the northernmost boundary of the forming transform plate boundary which may explain relatively absent northeast trending dikes in the northern fault blocks. Additionally, dikes are completely absent east of the San Antonio Canyon Fault (in the Potato Mountain Block, the Cucamonga Peak Block and the Ontario Ridge Block) and south of the proposed trace of the South San Gabriel Fault (in the Verdugo Hills Block). The southern branch of San Gabriel Fault system is convoluted; it is very interesting that dikes only occur within this specific zone.
CONCLUSIONS

As a result of compiling, mapping, referencing and modeling 988 andesite dikes, the data reveal the following significant conclusions about evolution of the Middle Miocene dike swarm with respect to evolving stress conditions and block rotations:

1. Northeast trending dike populations, prominently displayed in blocks south of the modern-day NSGF, were intruded into fractures produced by a strike-slip stress environment that predated the middle Miocene magmatic event. Ancestral left-lateral movements on the San Antonio Canyon Fault, Sunset Ridge Fault and San Dimas Canyon Fault, suggest that these fractures represent the structural anisotropies developed in the early Miocene.

2. Northwest trending dike populations preserve an average strike of N 60 W throughout the study area. With 20° of late Miocene counterclockwise rotation restored to the San Gabriel Block, the trends are nearly perpendicular to an early Miocene N 50-60 E directed extensional event that was developed in the Mojave and Colorado desert regions east of the present-day San Andreas Fault.

3. The present-day north branch of the San Gabriel Fault (NSGF) separates a domain of bimodal northeast and northwest-striking dikes in the south from a domain of uniformly northwest-striking dikes to the north. I speculate that the NSGF represented an important boundary structure that portioned strain between the two regions prior to the mid Miocene dike emplacement.

4. Still unresolved is the question of whether the northwest trending dikes were emplaced into extensional structures (Mode 1 fractures or normal faults) or right
lateral conjugate faults associated with early Miocene left-lateral faults. Careful examination of individual dike margins for offset host rock markers is needed to distinguish between these three possible fracture types.

5. A wide range of orientations is seen for dike populations due to the anisotropic nature of the host rock in the San Gabriel Mountains. Many of the rocks in this region contained pre-existing mechanical weaknesses including foliations, faults and fractures that undoubtedly affected how Miocene fractures were propagated.

6. Dextral transform motion on the San Andreas Fault from ~5 Ma to present rotated the entire San Gabriel block 15° to 20° counterclockwise as it moved 160 km to 240 km to the northwest through the “Big Bend” along the San Andreas Fault from the modern-day Salton Trough to its current location (Ehlig 1981, Dillon and Ehlig 1993). Although many areas of the Western Transverse Ranges have been rotated greater than 90° clockwise, and the block northeast of the study area rotated 37° clockwise overall (Terres and Luyendyk 1986), I cannot confirm any significant clockwise rotation from the dike orientation data as a whole. Initiation of right-lateral movements on the San Gabriel Fault at ~12 Ma appears to have interrupted extension within the San Gabriel Block. Meanwhile, the rotating Western Transverse Ranges Block was decoupled from the San Gabriel Mountains by the south branches of the San Gabriel Fault system.

7. Southward tilting of the blocks north of the NSGF is suggested by the ubiquitous 60° to 80° northeast dips if one assumes original vertical dike emplacement into Mode 1 fractures. Such horizontal block rotations might record: (1) compression related to the north-dipping faults in this area (Sierra Madre, Middle Fork Lytle Creek,
Telegraph Wash, Icehouse Canyon and North San Gabriel faults) associated with Late Pliocene to recent development of the Big Bend of the San Andreas Fault system: or (2), rotation along a listric normal fault coinciding with the trace of the NSGF. Alternatively, one should consider the possibility that these dikes have not been rotated but instead were originally emplaced into a uniformly northeast-dipping network of normal faults.

8. The mid Miocene mafic-intermediate dike swarm is spatially restricted to a region of the central and eastern San Gabriel Mountains bounded on the east by the ancestral San Antonio Fault. This region coincides with the place where the Western Transverse Ranges block “broke away” from the San Gabriel Mountains. Unless this spatial relation is a coincidence, the N 50-60 E directed extensional stress implied by the dike swarm was likely induced by early stages of Western Transverse Ranges rotation.

9. Assessment of absolute block rotations is beyond the scope of my study. A detailed paleomagnetic study of the andesite-basalt dikes may resolve numerous questions related to block rotations. Given that the mafic dikes should yield enough magnetic minerals to be tested, my data provides targets for many possible sampling sites. This investigation would provide rotational data for a key area and add to a paleomagnetic dataset for the Western Transverse Ranges (Kammerling and Luyendyk 1979, Hornafuis 1984, Hornafuis 1985, Luyendyk 1985, Terres 1985). Further, paleomagnetic results may serve to explain certain dike orientation results seen in my study.
WORKS CITED


Nourse, J. A., 2002a, Middle Miocene reconstruction of the central and eastern San Gabriel Mountains, southern California, with implications of evolution of the San


APPENDIX A: PLATE 1: MAFIC TO INTERMEDIATE DIKE SWARM REGIONAL MAP

(See Supplementary Materials)
APPENDIX B: PLATE 2: STATISTICAL DATA COMPILATION MAP

(See Supplementary Materials)
APPENDIX C: PLATE 3: 18 MA SAN GABRIEL MOUNTAINS TECTONIC RECONSTRUCTION MODEL

(See Supplementary Materials)
APPENDIX D: EXCEL FILE OF MAFIC DIKE MEASUREMENTS

(See Supplementary Materials)