GEOLOGY OF THE RANCHO SAN MARCOS DIKE SWARM

BAJA CALIFORNIA, MEXICO

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SAN DIEGO STATE UNIVERSITY

Summer 2004
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by

Philip Thomas Farquharson
DEDICATION

This thesis is dedicated to my grandmother, Ruth Thomas Porter, who inspired me to inquire and taught me that all things are possible; to my mother, Peggy Porter Farquharson, who supported and inspired our family after the premature death of her husband when I was only nine years old; to my Aunt Martha Porter Kilgour, who assisted me in my earliest geological quest; and to my dearest friend Janet, who recognizes the importance of their influences.
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CHAPTER I
INTRODUCTION AND PROJECT OVERVIEW

This thesis is a reconnaissance-level study of an intriguing dike swarm in northern Baja California, Mexico. The author was introduced to the area in August of 1998 by Dr. David Kimbrough on a trip to CICESE in Ensenada, when we took a side trip to the Ejido San Marcos area that had been studied by the San Diego State University 1995 Field Geology class. I was quickly impressed by the fact that a large part of this dike swarm consisted of erosion-resistant rhyolitic linear dikes exposed over large expanses of territory. A search of the literature soon pointed out that no other such felsic linear dike swarm existed in the world, or at least none has been described.

Figure 1. View northeast toward densely intruded northwest-striking dike swarm exposed above Rancho San Marcos. Hundreds of individual rhyolite and andesite dikes, locally sheeted, are exposed across the 460 meter-high skyline ridge in the distance. Rancho Vallecitos Formation turbidite flysch is hosting the swarm in this view. The most prominent dikes visible in the background are 5-10 m wide high-silica rhyolite dikes that are exposed along strike continuously for up to 3 km distance. The prominent dike in the foreground yielded a U/Pb zircon age of 120 ± 1 Ma.
As part of a San Diego State University Baja California Geology class in the Spring Semester of 1999, a series of field trips was made to the study area, accompanied by Dr. Gordon Gastil, as well as Dr. John Fletcher of Centro de Investigación Científica y de Educación Superior de Ensenada (CICESE). Samples were gathered, along with corresponding GPS locations and strikes and dips of the dikes in the northeast corner of the Valle Ojos Negros, a prominent feature which can be seen on airphotos, shuttle photos, and thematic mapper images of northern Baja California. The bulk of the exposed dikes at this location were rhyolite, but some mafic samples were collected, as was some of the host rock. A brief stop was made at an active gold mining operation at El Alamo (about 70 km southeast of Ensenada), where one mafic and two felsic dikes were sampled. All visited sites were photographed extensively. Another field trip was made during the Geology of Baja California class, to the El Marmol, Cataviña, and Valle Calamajue areas, where a broader understanding of the geology of Baja California was gained.

At the Geological Society of America Cordilleran Section meeting in Berkeley, in 1999, I presented a poster session of the SMDS, co-authored by Dr. David Kimbrough and Dr. Gordon Gastil (Farquharson et al., 1999).

Two sampling visits were made to the study area in the summer of 2002. The first was a transect from the Pacific coast to Highway 3 (La Mision to El Porvenir), then south along Highway 3 almost to the outskirts of Ensenada. The purpose of this trip was to examine Santiago Peak Volcanics, and to compare the bulk geochemistry to that of the SMDS dikes to the east. The second trip, somewhat dangerous because of traffic on the highway, sampled dikes northward along Highway 3 through the Cañon el Burro (southwest of Ignacio Zaragoza) to the vicinity of El Chaco.

Naturally, we always stand on the shoulders of the giants who went before us, and I was able to work with unpublished geochemical data from both the Tres Hermanos (50 km southeast of Ensenada) and Rancho San Marcos areas, provided by Dr. Kimbrough. It was also very helpful to “pick the brain” of Dr. Gastil, considered by many to be the father of Baja California geology.

Finally, for the 2002 San Diego Association of Geologists fall field trip, I gave a short poster session and talk on the campus of Universidad Autonoma de Baja California
(UABC) in Ensenada, then showed off one of the dikes along Highway 3 at Ignacio Zaragoza for the participants. These presentations helped me solidify my views of the dikes.

Figure 2. The author (at left) pondering the greater meaning of Baja California geology at UABC, September 2002. Also pictured are Lisa Guertin and Pat Brooks of the San Diego Association of Geologists. Photo by Carole Ziegler.

This project began as a general geology study, but transformed into more of a geochemical and petrographic study as time went on. Airphotos, Landsat Thematic Mapper images, and even Space Shuttle photos were utilized for mapping as well.

**Overview**

Dike swarms are an important mechanism for magma transport. Recent modeling and theoretical considerations suggest that dike transport of silicic magma is an efficient mechanism for large-scale transfer of silicic magma in the crust (Clemens & Mawer, 1992; Lister, 1995; Petford et al., 1994).

“Dikes versus diapirs” has been at the center of a vigorous debate over the past 10 years with respect to granite magma emplacement in the middle to upper crust (Petford,
Thermal calculations indicate that diapiric rise of granite is not a viable emplacement mechanism – i.e., they do not carry enough heat to thermally erode upwards through the crust. Dike transport of magma on the other hand gets around this problem, and can transfer very large volumes of material quickly from one place to another in the crust.

One of the problems with invoking dike transport of granitoids magma to emplace batholithic complexes like the Peninsular Ranges batholith (PRB) is the simple fact that such dikes are not widely exposed. The 800-km-long PRB is an example of a continental margin batholith that has been eroded to depths of mostly 5-20 kilometers (e.g. Todd et al., 1988) so that if dike transport is an important process – there should be more evidence for dikes.

This thesis describes the San Marco Dike Swarm (SMDS), a major northwest-striking regional dike swarm of mafic to silicic composition in the west-central part of the Peninsular Ranges batholith that extends for at least 100 km along strike. The SMDS is important because it has the potential to shed considerable light on the controversy of dike vs diapiric transport of silicic magmas in continental margin batholithic complexes. This thesis describes aspects of the structure, chemistry, and geochronology of the dike swarm and discusses the tectonic implications of the swarm for the evolution of the PRB.

The nearly complete absence of information in the literature on the SMDS is a bit mysterious, since it’s such a prominent feature in accessible areas in the northern part of the batholith just to the south of the US-Mexico international border. This is even harder to understand since the dikes may be directly associated with economic gold mineralization that has been actively mined off and on for nearly 100 years.
CHAPTER II

GEOLOGIC SETTING OF THE SAN MARCOS DIKE SWARM

The Peninsular Ranges Batholith (PRB) is one of the most intensively-studied segments of the great chain of circum-Pacific batholiths that ring the Pacific Ocean basin. The PRB is noted for its strong transverse asymmetry in terms of its age and composition. In fact, it has been described as two separate sub-parallel batholithic belts, referred to as the Western Province and the Eastern Province.

The western province of the PRB is characterized by gabbro-tonalite-granodiorite plutons with primitive island arc geochemical affinities (DePaolo, 1981; Silver & Chappell, 1988; Todd et al., 1988, 1994), and U/Pb zircon ages mainly of 125-105 Ma. The Eastern Province is dominated by tonalite and low-K granodiorite such as of the La Posta suite.

There is also transverse asymmetry in terms of depth of erosion across the batholith. The western province is only shallowly eroded, which preserves a nearly continuous belt of cogenetic supracrustal volcanic rock along the western margin of batholith. To the north of the Agua Blanca fault this western volcanic belt is referred to as the Santiago Peak volcanics; to the south of the AB fault these rock are part of Alisitos Group.

Gastil (1993) delineated the prebatholithic rocks of the Peninsular Ranges, as shown in Figure 3. Until mid-Paleozoic time, the region of the study area was deep-water ocean floor, just offshore from miogeoclinal facies to the east. By Permian time, a transition to a shelfal environment was taking place, the evidence for which is only seen on the Peninsula at Arroyo Zamora, some 300 km southeast of the study area, where the transition continued into the early Triassic. However, this study area was in a deeper water oceanic environment until the Mid- to Late Jurassic, when subduction apparently began and the continental margin arc started to develop.
Figure 3. Index map to the northern part of peninsular California and adjacent Sonora palinspastically repositioned for 300 km of Neogene right-lateral plate boundary translation. (from Gastil, 1993)
Santiago Peak Volcanics

Regional Setting and Distribution

Shallowly emplaced plutons along the western margin of the Peninsular Ranges batholith (PRB) are intruded into a nearly continuous ~800 kilometer-long belt of weakly metamorphosed volcanic, volcaniclastic and sedimentary rock (Gastil et al., 1975). These rocks have been interpreted as the supracrustal volcanic cover of the western zone of the Peninsular Ranges batholith (Herzig and Kimbrough, 1991; Kimbrough et al., 1990; Silver and Chappell, 1988; Todd et al., 1994). Farther to the east within the Peninsular Ranges batholith, Late Cretaceous and Tertiary episodes of uplift and erosion have stripped away 10 kilometers or more rock including all of the supracrustal volcanic cover of the batholith (e.g. Grove et al., 2003). The result is that PRB presents an oblique crustal profile across a continental margin batholith, from shallowly emplaced plutons and volcanic arc rocks in the west, to deeply exhumed amphibolite facies batholithic rocks in the east (cf. Todd et al., 1994). Study of this oblique crustal profile provides one of the outstanding opportunities worldwide to study the volcanic-plutonic magmatic plumbing system of a continental margin arc.

The western volcanic arc belt of supracrustal rocks along the western edge of the PRB has been divided into two main groups: the Santiago Peak Volcanics and the Alisitos group. The Santiago Peak Volcanics (Larsen, 1948) occur mainly to the north of the Agua Blanca Fault in northern Baja California and are dominated by poorly stratified unfossiliferous volcanic flows, volcaniclastic rocks, and cross-cutting dikes in local depositional contact on continentally derived strata of the Middle Jurassic Bedford Canyon Formation in the Santa Ana Mountains (Herzig, 1991). Metasedimentary strata of the Bedford Canyon Formation represent continentally derived rocks initially deposited in a marine setting (mostly as turbidites) off the west edge of the North American continental landmass in mid-Mesozoic time (Criscione et al., 1978; Gastil and Girty, 1993).
South of the Agua Blanca Fault the Alisitos Group comprises mainly thick, well-bedded sequences of marine to nonmarine volcaniclastic rocks with locally abundant Aptian-Albian fossils. The Alisitos Group strata include distinctive thick Aptian-Albian rudistid reef limestones which only occur to the south of the Agua Blanca Fault (e.g. Gastil et al., 1975). The depositional basement of the Alisitos Group is not exposed. Wetmore et al. (2002) conclude that the Alisitos Group was deposited over oceanic basement and did not share a common history with the Santiago Peak Volcanics prior to their accretion in the Late Cretaceous. Wetmore et al. (2002) interpret nonmarine volcanic sequences immediately south of the Agua Blanca Fault as part of the Santiago Peak Volcanics and recognize a fault between these rocks and the adjacent Aptian-Albian Alisitos Group. The presence of Santiago Peak Volcanics south of the Agua Blanca Fault zone is also indicated by presence of Late Jurassic-Early Cretaceous arc volcanic sequences ~200 kilometers farther south in the southern Sierra Calamajue (Griffiths and Hobbs, 1993).

One of the major longstanding issues with respect to the Santiago Peak Volcanics up to the early 1990s was whether these rocks represent the volcanic and sedimentary cover of
the batholith (e.g. Anderson, 1991; Silver and Chappell, 1988), or alternatively whether they are the volcanic part of a Late Jurassic island-arc that accreted with western North America during the Early Cretaceous (e.g. Gastil et al., 1981; Todd et al., 1988). As indicated above, the Santiago Peak Volcanics are now widely regarded as the supracrustal volcanic cover of the batholith. Evidence for this is considered further in the sections below in more detail. Consideration of this question is important to any interpretation of the San Marcos Dike Swarm.

**Age of the Santiago Peak Volcanics**

Late Jurassic marine fossils assigned to the Santiago Peak Volcanics occur in several sections in western San Diego County (Fife et al., 1967). The fossiliferous strata occur within a restricted area and include rocks in Lusardi Canyon, Circo Diegueño Canyon, and Los Peñasquitos Canyon. Fossils are rare and poorly preserved and include Buchia piochii, which is a well know Tithonian bivalve from the Great Valley sequence of California, as well as the belemnite Cylindroteuthis sp., as well as oyster and echinoid fragments, sponge spicules, and radiolaria (Fife et al., 1967; Jones and Miller, 1982). These taxa indicate a late Jurassic age for the enclosing strata. These are the only known fossils north of the Agua Blanca Fault and constituted the best estimate for the age of Santiago Peak Volcanics. A late Jurassic age for these rocks was further supported by lead-alpha dates from the western part of the batholith in southern California that ranged mainly from 135 to 150 Ma (Bushee et al., 1963). On this basis of this evidence the age of the Santiago Peak Volcanics was widely regarded as Late Jurassic (e.g. Gastil et al. 1975). The Late Jurassic age assignment of these rocks indicates that they must be older than 144 Ma, which is the age assignment of the Jurassic-Cretaceous boundary in the Geological Society of America Geologic Time Scale (Palmer and Geissman, 1999).

The Jurassic fossils however occur in a marine facies of volcanic and volcanioclastic rocks, distinct from the nonmarine volcanic facies which dominates the Santiago Peak Volcanic belt through most of its length (Balch et al., 1982). Further, the fossil-bearing strata are locally folded and contain a weak slaty cleavage suggested that they have experienced an episode of deformation that the rest of the belt did not experience. For these reasons, the Late Jurassic volcanogenic strata in western San Diego County have been
considered by recent workers to be distinct from the main belt of Santiago Peak Volcanics and likely represent local basement over which the main belt was deposited. Kimbrough and Moore (2003) suggested that these rocks may be correlative with Late Jurassic marine volcanic arc deposits of the Eugenia Formation on the Vizcaino Peninsula in Baja California Sur. Other workers have alternatively suggested that the Late Jurassic volcanogenic strata in western San Diego County may correlate to the Bedford Canyon Formation.

Beginning in the early 1990s zircon U-Pb age data started to become available from the Santiago Peak Volcanics via the San Diego State University geochronology laboratory (e.g. Anderson, 1991; Herzig, 1991; Kimbrough et al., 1990; Herzig and Kimbrough, 1991; Meeth, 1993). The new U/Pb zircon ages indicate Early Cretaceous ages for the Santiago Peak Volcanics from ~130 to 116 Ma (e.g. Todd et al., 1994). The U/Pb ages support the interpretation that the isolated exposures of fossiliferous Late Jurassic strata in western San Diego County describe above represent an earlier group of rocks across which the main belt of Santiago Peak Volcanics was deposited. These ages also overlap with U/Pb ages of plutonic rock from the western zone of the Peninsular Ranges batholith suggesting a genetic link between plutonic and volcanic cover rocks as noted earlier (e.g. Herzig, 1991; Kimbrough et al., 1990; Silver and Chappell, 1988).

Zircon populations from the Santiago Peak Volcanics show evidence of Precambrian inheritance (Anderson, 1991; Herzig and Kimbrough 1998; Meeth, 1993). This aspect of the U/Pb systematics is consistent with an origin for the Santiago Peak Volcanics, and by extension the western Peninsular Ranges batholith, along the western margin of the North American continent in Cretaceous time. This conclusion is further supported by local the local depositional contact on the Bedford Canyon Formation which includes continentally derived Proterozoic zircon (Gastil and Girly, 1993).

**Metamorphism of the Santiago Peak Volcanics**

The Santiago Peak Volcanics preserve primary volcanic fabrics and textures throughout most of its exposure. Metamorphic minerals including albite, chlorite, epidote and chlorite indicate sub-greenschist or low greenschist facies static recrystallization characteristic of very low grade metamorphism in volcanic and volcaniclastic rocks and are
not the result of regional metamorphism. Penetrative dynamic recrystallization and the
development of foliation are restricted to local areas along the eastern edge of the belt which
is more heavily intruded by plutonic rocks of the batholith. The style and low grade of
metamorphism is of a type that permits petrologic characteristics of the rocks to be
determined by means of whole rock chemical analysis (Herzig, 1991; Reed, 1992).

Petrology and Depositional Setting of the
Santiago Peak Volcanics

The Santiago Peak Volcanics are a predominantly subalkaline volcanic suite which
ranges widely from basalt to andesite to rhyolite in composition (Gorzolla, 1988; Herzig,
1991; Reed, 1992). These are features in common with volcanic associations from modern
volcanic arcs. Trace element and strontium and neodymium initial isotopic ratios are
consistent with primitive mantle-derived sources for the volcanic rocks. These
characteristics match trace element and isotopic characteristics of plutonic rocks from the
western part of the Peninsular Ranges batholith (DePaolo, 1981; Gromet and Silver, 1987;
Herzig, 1991; Todd et al., 1994).

Tanaka et al. (1984) divided the Santiago Peak Volcanics into two independent
groups; one comprising basalts and andesites of the island-arc series, and a second
comprising calc-alkaline dacites and rhyolites. Gorzolla (1988) in similar fashion also
divided the SPV into two geochemical series based on major and trace element
concentrations of basaltic and andesitic flow rocks. The two series comprise a northern calc-
alkaline series and a southern tholeiitic series. Reed (1992) in a study of the SPV in the
Mission Gorge – San Diego area found no major differences with the results reported by
Tanaka et al. (1984) or Gorzolla (1988). The combined data demonstrates that the SPV does
in fact span a broad compositional range, includes both calc-alkaline and tholeiitic affinity
suites and is strongly subalkaline. The low Ti contents indicate an overall depletion of high
field strength elements which is consistent with a volcanic arc origin.

Reed (1992) recognizes the overall coherence of geochemical data from throughout
the Santiago Peak Volcanics. However three separate magmatic groups are tentatively
recognized. One group is a low silica high magnesium group primarily located in the Santa
Ana Mountains and Camp Pendleton areas as documented by data from Herzig (1991) and
Gorzolla (1988). This group is dominated by basaltic andesite and andesite. A second group of more diffuse mid-range silica content volcanic rocks is located primarily within the Mission Gorge and San Diego areas, but does overlap with the SPV rocks to the north. The third group consists of rhyolites and rhyodacites that are identifiable throughout the Santiago Peak Volcanic belt.

Specific volcanic source vents that fed the Santiago Peak Volcanics have never been mapped or recognized. Andesitic tuff breccia that dominates many areas of the belt, including the area around San Diego State University, have many characteristics consistent with proximally derived high density debris flow deposits associated with sector collapse of andesitic stratovolcanoes. If this in fact is the origin for at least portions of flows and volcaniclastics that make up the SPV, it would be exceedingly difficult to identify and map this out with confidence. The Quaternary Tuscan Formation in the foothills of the northern Sierra Nevada which was derived from Cascade arc volcanoes may be a good modern analog to the andesite tuff breccias of the SPV. Tanaka et al. (1984), based on geochemical and presumed age similarities, proposed that basaltic flows in the SPV are genetically related to gabbroic intrusions in the western zone of the PRB. In this model, some of the magmas that supplied gabbroic intrusions, reached the surface and were erupted as basalts that make up part of the SPV.
Locally, the Santiago Peak Volcanics are well-bedded. One such area is in the La Mision area immediately to the west of the type area of the San Marcos Dike Swarm. This area was originally mapped by Schulte (1966) as part of his senior thesis at San Diego State University. The eastern portion of his map area is dominated by what he called “Mesozoic basement rocks consisting of well-indurated epiclastic volcanic breccias interbedded with flows of varying thickness and composition.” At the time of his mapping no diagnostic fossils or any definite marine strata could be identified that would allow definite correlation with either the Santiago Peak Volcanics or the Alisitos Formation. For this reason he named the volcanic rocks in this area the San Miguel Formation. Meeth (1992) provided more detailed descriptions of the rocks in this area, which he referred to as the “San Columbano section”. The rocks here comprise a well-exposed gently west-dipping stratigraphic sequence of well-bedded rocks which are distinct from poorly stratified exposures of the SPV found north of the border. The section described by Meeth (1992) consists of over 300 meters of continuous, well-bedded andesitic volcanic breccia, volcanic sandstone, and pyroclastic flows with accretionary lapilli which are an indication of subaerial eruption clouds. This is the first locality where accretionary lapilli were discovered in the SPV.
An 18 m thick rhyodacite volcanic breccia from this unit with silica content of ~67% SiO$_2$ was dated by U/Pb zircon methods. The U/Pb systematics of the zircon population from this sample indicates the strong presence of inherited components of Proterozoic radiogenic lead and a crystallization age of approximately 116 ± 6 Ma. This age and the evidence of inherited components of Precambrian zircon suggest this stratigraphic sequence is part of the Santiago Peak Volcanics.

**Dike Swarm Distribution**

The known extent of the swarm is shown schematically in Figure 6, which is based on the Gastil et al. (1975) 1:250,000 map of Baja California. The “big picture” of how the SDMS fits into the PRB is shown in Figure 2-5.

The swarm is intruded into two main units; 1) Triassic-Jurassic turbidite flysch of the Rancho Vallecitos Formation (Reed, 1993) that is correlated to Julian Schist and Middle Jurassic Bedford Canyon Formation north of the border, and 2) older, presumably pre-120 Ma batholithic rocks for which little data is currently available. Low-grade greenschist facies of the Rancho Vallecitos Formation in the northwest area of the swarm indicate shallow emplacement depths. Significantly deeper crustal levels are exposed at Tres Hermanos where amphibolite facies schist occurs (Chadwick, 1987).

As shown on the Gastil et al. (1975) map, and supported by additional data presented below, dikes within the swarm parallel the overall trend of the swarm, which in turn is parallel to the overall approximately N30°W structural grain of the PRB. At its northern end, the dike swarm is intruded by younger ~120-100 Ma PRB intrusions. At its southern end, it is partly intruded by younger plutons and partly blanketed by Aptian-Albian supracrustal volcanic sequences, which form a nearly continuous ~10-30 km-wide belt of volcanic rocks along the western margin of the PRB throughout its ~800-km long extent.

The exposure of the SMDS within a restricted ~100 km-long segment of the 800 km-long PRB appears to be the result of two fortuitous circumstances; 1) the relative paucity of ~120-100 Ma intrusions in this segment which elsewhere heavily intrude the western zone of the PRB (e.g. Kimbrough et al., in review; Silver and Chappell, 1988), and 2) erosional stripping of the extensive Aptian-Albian supracrustal volcanic rocks (Santiago Peak
Volcanics) from this region to expose a deeper structural level relative to areas along strike to the north and south.

Dikes potentially correlative to the main 100 km-long swarm occur to the north in the Lakeside area of southern San Diego County, and to the south near San Telmo, Catavina, and at El Arco near the southernmost extent of the PRB (see inset map to Figure 6). These possible correlatives suggest the dike swarm may have been much more extensive than its present exposure suggests.

Figure 6. Schematic representation of the known extent of the San Marcos Dike Swarm. Modified after Kimbrough (1999).
Figure 7. Position of the SMDS within the Peninsular Ranges Batholith. (from Kimbrough, et al., 2001)
CHAPTER III
DIKE REVIEW

Volcanic dikes are magma-filled fractures that cut across rock bedding or other country rock structure. Dikes constitute one of the most common types of shallow intrusive rock and hence one of the most common ways by which magma is transported from place to place in the crust. Dikes form sheet-like intrusions with very small aspect ratios (aspect: width/length = $10^{-2}$ to $10^{-4}$). They typically are emplaced in near vertical orientation and generally are 1 to 2 meters in thickness. Dikes result when pressurized magma is forced into and along a crack – they propagate by hydraulically fracturing the rock through which the magma is traversing. The stress perpendicular to the fracture must be less than the magma pressure in order for a dike to propagate through brittle crust.

The state of stress in the crust determines the orientation of dikes. Stress at a point can be represented by a stress tensor matrix which depicts the normal and shear stresses across the faces of cube. Stress is conventionally indicated by the Greek letter sigma ($\sigma$). Principle stresses are all normal stresses and are parallel to principle axes of a stress tensor. Shear stress is stress that acts parallel to the face of the cube (rather than right angles). Three basic conditions of stress are illustrated below. If the three principle stresses are all equal in magnitude then there is no shear stress the $\sigma_1 = \sigma_2 = \sigma_3$. This condition is known as hydrostatic stress. Under conditions of hydrostatic stress, materials do not feel any shear stress; they may undergo volume and/or mineralogic changes but no deformation occurs. This type of stress is common in deeply buried rocks. Uniaxial stress occurs when only one of the principles axes is nonzero. Cases of uniaxial compression and uniaxial tension are illustrated in Figure 8.

1. Hydrostatic pressure, $\sigma_1 = \sigma_2 = \sigma_3 = \rho$. (Figure 8A) All principal stresses are compressive and equal. No shear stresses exist on any plane, so all orthogonal coordinate systems are principal coordinates.

2. Uniaxial compression, $\sigma_1 > \sigma_2 = \sigma_3 = 0$. (Figure 8B) The only stress applied is a compressive stress in one direction. This geometry is commonly used in testing the strength of rock samples in the laboratory.
3. **Uniaxial tension**, $0 = \sigma_1 = \sigma_2 > \sigma_3$. (Figure 8C) The only stress applied is tension in one direction. Engineers often use this geometry to test the mechanical properties of metals.

![Mohr circle graphic representations](image)

Figure 8. Mohr circle graphic representations of the state of stress at a particular point at a particular time for three simple cases: A = hydrostatic stress, B = uniaxial compression, and C = uniaxial tension. The coordinates of each point on the circle represent the normal stress and the shear stress on a particular plane. In these examples there is no shear stress – only normal stress. (from Twiss & Moores, 1992, Figure 8.14)

The orientation of dikes can be understood in terms of such stress tensors. Dikes open in the direction of the least principal stress (*i.e.*, $\sigma_3$). This means also that they must lie in the plane of $\sigma_1$ and $\sigma_2$. For this reason they can be good paleostress indicators.

For example, the near vertical orientation of many dikes implies that $\sigma_3$ is horizontal (i.e., parallel to the surface of the earth). This type of situation is common in areas of the crust undergoing tectonic extension. An outstanding example is the evolution of oceanic spreading centers as inferred from study of ophiolite complexes where basaltic magma is injected vertically as sheeted dike complexes parallel to rise crests.

There are many other methods to determine the state of stress in the crust besides the orientation of dikes. For example stress may be determined by the structural analysis of folds, faults, fractures or cleavages in rock. One of the great advantages in using dikes however to determine the paleostress conditions under which geologic structures form is that dikes can be isotopically dated. This allows for the possibility to determine not only the state of stress but the absolute chronology for stress field trajectories.

**Orientation of Dike Swarms**

Consistent regular orientation of dikes reflects regional state of stress in the crust. There are many possible stress orientations under which dikes can be emplaced. As noted
above, oceanic spreading centers represent an important case where magma is injected into areas of crustal extension to form sheets dikes. Regional dike swarms are also characteristic of regions of continental extension and breakup. Such swarms for example record the breakup of Pangea as well as earlier episodes of continental rifting and breakup. In these instances, regional swarm exist as coast-parallel swarms along continental margins and mark the site of earlier episodes of rifts that evolved into ocean basin spreading centers. In areas of continental collision, the orientation of mafic dike swarms has been shown to be approximately normal to the collision zone and parallel to the maximum compressive stress (Feraud et al., 1987).

Dike swarms can be intruded radial dikes in which the local stress orientation is governed by a central intrusion. In this case $\sigma_1$ is perpendicular to the contact (radial) and $\sigma_3$ is horizontal and tangential to the contact. As a result dikes in this situation are radial from the intrusion; dikes intruded farther away from the intrusion assume the regional trend.
dictated by regional stress fields in the crust. However radial swarms have also been
documented over great distances extending many hundreds of kilometers. In some instance
these swarms may be related to triple junction rifts associated with the initial stages of
continental breakup and rifting. In others however great fan-shaped swarms such as the
Proterozoic McKenzie swarm of northern Canada, may reflect the plumbing system of large
igneous provinces (Ernst and Buchan, 2001).

Cone sheets are another type of dike intrusion that can form above an intrusion. In
this case the planes containing $\sigma_1$ and $\sigma_2$ are cones and magma intruded along these planes
form cone sheets. If magma pressure is diminished the roof of the magma chamber may
subside forming a ring fault. If magma intrudes this fault a ring dike is the result. Such ring
dike and cone sheet structures appear to have formed within the Peninsular Ranges batholith
and are readily apparent in map patterns associated with plutonic intrusions on the Gastil et
al. (1975) 1:250 000 maps of the batholith.

Regional dike swarms can also record the intrusion of dikes under conditions of shear
stress. The Late Jurassic Independence Dike Swarm of California (IDS) appears to be an
outstanding example of this (Carl et al., 1998; Carl and Glazner 2002). The IDP is now
recognized to extend over 600 km along regional strike in a northwest-southeast direction,
from the northern Sierra Nevada and White Mountains to southeasternmost California.
However individual dikes within the swarm tend to be oriented in a north-south direction,
oblique to the regional trend of the swarm. This orientation is consistent with a regional
transtensional sinistral shear regime during dike swarm emplacement. This pattern of
sinistral shear during dike swarm emplacement appears to be corroborated by detailed
structural study of individual dikes including magnetic fabrics associated with remnant
magnetization of the dikes.

It is important to note that the orientation of dikes can also be guided by earlier
fractures whose orientation is not necessarily perpendicular to the least principle stress
direction in a rock. Therefore it is important to determine in each individual case whether
dikes have propagated by hydraulic fracturing in response to regional stress fields or whether
pre-existing structures play an important role.
Composition of Regional Dike Swarms

Regional dike swarms are overwhelmingly mafic in composition (e.g. Ernst and Buchan, 2001; Halls and Fahrig, 1987). They represent mantle-derived basaltic melts generated in response to crustal extension in both oceanic and continental environments. In contrast regional dike swarms that contain a significant volume of silicic magma appear to be relatively rare in the geologic record. Major ring dikes or cone sheets associated with shallow-level batholithic intrusions are the best known examples of silicic dikes.

San Marcos Dike Swarm

The San Marcos Dike Swarm appears to be a faithful recorder of Late Cretaceous paleostress fields in the Peninsular Ranges batholith (Böhnel et al., 2002). The individual dikes within the swarm are generally parallel to the overall trend of the swarm. This indicates that the swarm was emplaced under conditions of regional extension in the absence of any regionally significant shear stresses. The regional steep NNE dip of the swarm further appears to reflect regional westwards tilting of the crust through the areas of the swarm around Rancho San Marcos and to the south and east toward Ojos Negros and Tres Hermanos. This is nicely corroborated by paleomagnetic studies (Böhnel et al., 2002) that indicate that if the tilting is restored, then the paleomagnetic position of northern Baja can be brought into agreement with the stable North American reference pole by simply closing down the Neogene Gulf of California. This restoration is in good agreement with regional geologic reconstructions (e.g. Gastil, 1993; Ortega-Rivera, 2003).
CHAPTER IV

OVERVIEW AND STRUCTURAL GEOLOGY OF
THE SAN MARCOS DIKE SWARM

Orientation of the dikes is remarkably consistent throughout the swarm. The 1995 San Diego State University field mapping class measured 66 dikes from the Rancho San Marcos area, Dr. Kimbrough evaluated 10 dikes in the Tres Hermanos region in 1997, and I examined 10 dikes in the Ojos Negros Valley in 1999 with Dr. Kimbrough. Strike and dip measurements of dike attitudes from the San Marcos, El Campito and Tres Hermanos areas are depicted in Figure 20 on lower hemisphere equal area stereonet plots. Trend and plunge of mean poles to dikes from each area are virtually identical and indicate a strike of approximately N30°W and a dip of 75°NE. If the dikes were emplaced originally as vertical sheets, this result indicates a consistent SW-directed tilt of 15° through this area consistent with the Butler et al. (1991) regional tilt hypothesis. However, many more dike attitudes must be measured from different areas of the SMDS to confirm this result. Böhnel et al. (2002) examined 113 dikes at the northern extremity of this thesis area, as part of a paleomagnetic study, with similar results.

Figure 11 (p.24) is an airphoto of the Rancho (Ejido) San Marcos area, where study of the dike swarm was first begun in earnest in 1995. Numerous parallel dikes are visible (appearing as thin white lineaments) trending approximately N30°W. The location of the dike which yielded a zircon U/Pb date is indicated. The ridge in the background of Figure 1 appears approximately 2 to 3 kilometers north of this site.

In Figure 12 (p.25), we see a plot of dike thicknesses versus frequency of occurrence for dikes in the field of view of the Rancho San Marcos area.

An airphoto of the El Campito area on the northeast corner of the Valle Ojos Negros, is shown in Figure 13 (p.25), with resistant rhyolite dikes again trending approximately N30°W. This is the major fabric seen on the northeast half of the photo. Note the San Miguel fault (Böhnel, et al., 2002) running from the center of the image to the southeast.
Figure 10. Stereonets of dike attitudes in the SMDS study area.

Some of the dikes seen in Figure 13 (p.25) exhibit are clearly dilation dikes as seen in outcrop. Figure 14 (p.26) is a magnified view of the area of interest, where the mafic dikes responsible for the offset can barely be seen. Unlike the more felsic dikes, which are very
resistant ridge-forming entities, the mafic dikes east of Valle Ojos Negros are seen as linear dark depressions running across the landscape.

Figure 11. Rancho (Ejido) San Marcos area, INEGI 1:75,000-scale airphoto 29-0004, 11/4/1993 (cropped and rotated).
Figure 12. A plot of dike thicknesses versus frequency, from the 1995 field notes of Carrasco and Kimbrough.

Figure 13. Northeast corner of Valle Ojos Negros, INEGI 1:75,000-scale airphoto 47-0011, 11/4/1993 (cropped).
Figure 14. Airphoto view of El Campito, NE corner of Valle Ojos Negros, showing faint surface expression of mafic dikes.

Figure 15. Photo of offset in rhyolite dike caused by later intrusion of mafic dike. View is looking south across the eastern edge of Valle Ojos Negros.
Figure 16. Schematic diagram of dilation offset.

Figure 17 is an airphoto of the Tres Hermanos area just north of the area studied by Chadwick (1987), with dikes again trending approximately N30°W. Note the “big dog” dike indicated by the oval. It is almost 4 km long, and shows step-overs at the ends.

Figure 17. Tres Hermanos area, INEGI airphoto 78-0013, 11/6/1993 (cropped).
While trends of individual dikes are parallel to the regional trend of the dike swarm, which implies extension with no shear forces, some of the dikes display step-over offset segments near their tips that imply shear stress across walls of dikes.

And just to the southeast of Tres Hermanos is the El Alamo area, an active gold mining operation which is extracting ore from the area of the San Marcos dikes. Figure 18 is an airphoto of the El Alamo area, with dikes again trending approximately N30°W. Note the white area in the left center of the image. This was the main mining operation at the time this airphoto was taken in 1993, and was still such when we visited and sampled there in 1999.

Figure 18. El Alamo area, INEGI airphoto 65-0007, 7/2/1993 (cropped).

We see a very consistent strike of N30°W and a steep NE dip of approximately 75° throughout the known extent of the dike swarm, as shown in Figure 4-1 and in the air photos.
CHAPTER V

WHOLE-ROCK GEOCHEMISTRY

Reconnaissance whole rock analyses have been obtained from 18 samples from the Rancho San Marcos and Tres Hermanos regions (Figure 19), plus 33 samples from Ojos Negros, El Alamo, and a La Mision – Valle Guadalupe – Highway 3 transect (Figure 20, p.31). Locations are shown in the spreadsheet in Figure 21 (p.32), and on the map in Figure 22 (p.34). Samples were chosen to represent volumetrically abundant dikes in each area as well as the full compositional spectrum occurring in each area. Dike compositions from the various areas vary significantly. Rancho San Marcos dikes are dominated by rhyolite and andesite along with subordinate basaltic andesite. Dikes in the Tres Hermanos and El Alamo regions in contrast comprise a strongly bimodal basalt-rhyolite suite. The dikes sampled and observed at the northeast corner of the Ojos Negros valley seem to be closer in character to those of Rancho San Marcos. The difference may relate to differences in depth of exposure in these regions. Rhyolites in all regions nevertheless are chemically similar, and resemble Late Tertiary high-silica rhyolite from bimodal volcanics fields in the Basin & Range/Colorado Plateau region (Moyer & Nealey, 1989).

Figure 19 shows the major element analyses for samples provided by Dr. Kimbrough from his previous research, and Figure 5-2 contains the major elements for my sampling from 1999 and 2002. Trace elements are shown in Appendix A.

Variation Diagrams

Data from the SMDS samples are displayed in a SiO₂ vs. K₂O plot that suggests medium-K calc-alkaline affinities typical of orogenic plate settings (Figure 23, p.35). Dikes with unusually high K₂O contents may be indicative of potassium metasomatism. A pronounced silica gap occurs between ~63-75% in the samples from Tres Hermanos and Rancho San Marcos, but is not seen in the samples from the La Mision transect. The two exceptions to this are samples TH974 (71.6%) and TH975 (70%) which were both collected
from composite dikes (cf. Snyder et al., 1997) that occur as ~8-meter thick rhyolite dikes with basalt-rich enclave zones in their central portions.

Subalkaline arc-related volcanic rocks of Aptian-Albian volcanic rocks to the west are chemically similar to SMDS samples, and display a silica gap from 63 to 67% (Herzig, 1991; Kimbrough, 1999).

Dike compositions in the Independence Dike Swarm also tend to be bimodal and vary along the length of the swarm from the northern Sierra Nevada to southeastern California (Carl et al., 1998). Mafic Independence dikes in the central Sierra Nevada yield Late

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<th>NAF1105</th>
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ICP-ES analyses from ACTLABS, Canada; provided by Stan Keith
RSMD95 zircon U/Pb age of 120 ± 1 Ma (SDSU lab)

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XRF analyses from Washington State University, Unnormalized Results (Weight %):
TH973 zircon U/Pb age of ca. 120 Ma (SDSU lab)
* these two samples collected from different parts of the same composite dike

Figure 19. Major element analyses for dikes sampled in 1995 and 1997.
Figure 20. Whole rock geochemistry results (major elements only) from dikes and extrusives sampled in 1999 and 2002.

Cretaceous ages and may be related to Late Cretaceous mafic plutons in the region (Coleman et al., 1994). The voluminous high-silica rhyolites of the SMDS however, is a feature that distinguished it from the predominantly fine-grained diorite porphyry to granodiorite dikes of the Independence swarm (Moore and Hopson, 1961).

Figure 24 (p.35) is a Peacock diagram (after Peacock, 1931), or alkali-lime index of the suite of samples. This is essentially a plot of weight % Na₂O+K₂O vs SiO₂ and CaO vs SiO₂. Where the two lines cross, this is the alkali lime index for the suite; in this case the index is approximately 61.7%, which falls in the calcic region, which is similar to plutonic rocks from the Peninsular Ranges batholith (e.g. Silver and Chappell, 1988).
Figure 21. Sample locations from GPS readings, given in both UTM and Latitude/Longitude formats.

The normative quartz-alkali feldspar-plagioclase whole-rock compositions for dike swarm and extrusive samples are shown in Figure 25 (p.36). This plot indicates that the bulk of the samples are equivalent to tonalites and granodiorites in terms of their major element compositions which is a feature similar to plutonic rocks of the PRB.

Figure 26 (p.36) is a Pearse et al. (1984) tectonic discrimination diagram plotting Nb versus Y. The data for the San Marcos Dike Swarm and Santiago Peak Volcanics are similar to one another and define a linear array falling mostly in the “volcanic arc granitoids + syn-collisional granitoids” field but extending across into the field of “oceanic ridge granitoids”.

Figure 27 (p.37) is another Pearse et al. (1984) tectonic discrimination diagram plotting Rb versus Y+Nb. Most of the samples fall within the volcanic arc granitoid field but a few cross over into the within-plate granitoids field.
Figures 29 and 30 (p.38) are plots developed by Winchester and Floyd (1977) using major and trace elements that demonstrate the compositional variability and subalkaline character of the San Marcos Dike Swarm and the Santiago Peak Volcanics.

Figure 31 (p.39) is the Irvine and Barager (1974) AFM diagram that is used to discriminate between tholeiitic versus calc-alkaline magma compositions by means of iron enrichment trends associated with fractional crystallization. The high silica rhyolite dikes form a tight cluster on this diagram. Many of the more mafic samples fall in the tholeiite field. However the different samples shown here are not necessarily related to one another by fractional crystallization.

The diagram in Figure 31 (p.39) was the first to get my attention that the Rancho San Marcos dikes may well have been the source for the Santiago Peak Volcanics. I was simply “playing around” in NEWPET with the whole-rock data given to me by Dr. Kimbrough, when I noticed that the trace element patterns between the SMDS and SPV were incredibly similar. But I wondered if it was a factor of sample selection that led to these similarities, so I collected more SPV and dike samples in 2002, and, thanks to San Diego State University’s brand-new Philips Magix Pro XRF machine (see Appendix B for details), I was able to obtain major- and trace-element data on these samples as well as those collected in 1999. A resulting extended spider diagram of a selection of these results is shown in Figure 32 (p.39).

In Figure 32 (p.39) diagram, the trace element data once again align quite well. Note that the earlier data shows a more complete selection of trace elements than does the SDSU data.
Figure 22. Sample locations are shown on a Landsat image. Locations of two SPV extrusives whose whole rock chemistry was provided by Dr. Kimbrough, CICESE and Carmen Serdan, are included.
Figure 23. Whole rock analysis comparison of all dike and extrusive samples.

Figure 24. Peacock diagram of all whole-rock analyses (alkali-lime index).
Figure 25. Normative quartz-alkali feldspar-plagioclase whole-rock composition plot of sample analyses; classification after Streckeisen (1976). Other abbreviations: t – tonalite; gd – granodiorite, g – granite; qd – quartz diorite; qmd – quartz monzodiorite or quartz monzogabbro; qm – quartz monzonite; gb – gabbro or diorite; md – monzodiorite or monzogabbro; m – monzonite. (diagram after LeMaitre, 1989, Fig. B4).

Figure 26. Whole rock trace-element plot after Pearce et al. (1984), Figure 3, plotting Nb/Y. Abbreviations: VAG - volcanic arc granitoids; syn-COLG – syn-collisional granitoids; WPG – within-plate granitoids; and ORG – oceanic ridge granitoids.
Figure 27. Whole rock trace-element plot after Pearce et al. (1984), Figure 4, plotting Rb versus Y+Nb. Abbreviations: VAG = volcanic arc granitoids, syn-COLG = syn-collisional granitoids; WPG = within-plate granitoids; and ORG = oceanic ridge granitoids.

Figure 28. Whole rock trace-element plot after Winchester and Floyd (1977), Figure 2, plotting SiO2 vs. Zr/TiO2.
Figure 29. Whole rock trace-element plot after Winchester and Floyd (1977), Figure 2, plotting Zr/TiO2 vs. Nb/Y.

Figure 30. AFM diagram with the Irvine and Baragar (1974) dividing line for tholeiitic and calc-alkaline trends.
Spider Diagrams

Figure 31. Extended spider diagram of two SMDS samples and two SPV samples collected and analyzed by Kimbrough.

Figure 32. Extended spider diagram of four SMDS samples and three SPV samples collected and analyzed by Farquharson.
CHAPTER VI

PETROGRAPHY

Silicic dikes in the SMDS range tremendously in texture from glassy aphyric to porphyritic to medium-grained hypabyssal plutonic. Magmas with phenocryst contents more than about 50-60 volume percent have a rheology controlled by deformation rather than magma flow; phenocryst-rich magmas therefore have viscosities too high to be intruded as dikes (Kerr & Lister, 1995; Wada, 1994). This indicates that granitic textures in silicic dikes in the SMDS must reflect in-situ crystallization of magma after dike emplacement.

Flow-banding in some rhyolite dikes in the Rancho San Marcos region strongly resemble eutaxitic textures in welded tuffs suggesting that dike emplacement here was shallow enough to allow for violent vesiculation of magma within the dike conduit at present levels of exposure. Local evidence of rheomorphic deformation in flow-banded rhyolite dikes may represent late stage flow features as magma transport comes to a halt in the conduit. Rubin (1995) calculates that dikes can begin to vesiculate at 4 km depth in a 10 m dike supporting these tentative interpretations. Mafic dikes in general have much more uniform aphyric to sparsely porphyritic textures. Chill margins on basaltic-andesite dikes in the San Marcos region are common.

Of the 33 samples collected in this study, 11 were selected to be made into thin sections, all except two from dikes. The two specimens in question, LM02-04 and LM02-11, are from the La Mision transect, and the field relations were unclear, perhaps hypabyssal, perhaps extrusive. One thin section (ON99-08) was from a mafic dike (50% SiO₂), the rest were rhyolite ranging from 73 to 76% SiO₂.

Figure 33 is a collage of typical views of sample ON99-01 in thin section. This sample is from the interior of a 3.2 meter thick rhyolite dike at Ojos Negros, and shows typical porphyritic texture.
In Figure 33 A and B, we are seeing a sericitized plagioclase phenocryst and two subhedral quartz phenocrysts, one with inclusions, one without. The larger, triangular quartz crystal exhibits undulose extinction, which is common in the thin sections studied. Undulose extinction is indicative that the rocks have been strained (MacKenzie and Adams, 1994). Views C and D of Figure 33 illustrate another common feature of these rocks: spherulites, or intergrown radiating masses of fibrous crystals in a glassy matrix. These spherulites are usually composed of intergrowths of quartz or tridymite with orthoclase, sanidine, or sodic plagioclase, and probably formed as the magma was still moving through the dike (Williams et al., 1954).

Sample ON99-02 is from the same dike as ON99-01, but from the margin, rather than the interior. Its thin section is the subject of Figure 34.
Figure 34. Thin section ON99-02. Views A and B are of the same region, rotated approximately 15 degrees, and views C and D are from a different region of the slide, but similarly rotated. Cross polars, field of view in each is about 5 mm.

In Figure 34, we can see the effects of more rapid cooling of the same melt: much smaller mean grain size in the ground mass. The only phenocrysts seen in this thin section are plagioclase, no quartz was seen. Views A and B show an oscillatory zoned plagioclase crystal, somewhat sericitized and equant, indicating episodic growth in a possible magma mixing environment and/or variations in partial fluid pressures in the melt (Williams, et al., 1954). In views C and D, we see a plagioclase phenocryst with multiple twinning: simple twinning dividing the crystal roughly into two equal parts, and each part showing albite twinning. Although this sample is from a dike, the petrography shows a decidedly extrusive character with a fine-grained groundmass.

In Figure 35, note the undulose extinction in the quartz grains, indicating strain, which is a common feature of quartz grains in igneous, sedimentary and metamorphic rocks (MacKenzie and Adams, 1994).
Figure 35. Thin section RSMD95-1, the “dating sample” from the Rancho San Marcos area. Once again, views A and B, and C and D are from the same region of the slide, slightly rotated.

A very prominent spherulite is shown in the thin section in Figure 36, which is from a dike approximately 22 km west of Rancho San Marcos. Once again, the volcanic character of these dikes is illustrated.

Figure 36. Thin section LM02-11, from a dike approximately 8 km northwest of Guadalupe.
Figure 37. Thin section ON99-11, from a felsic dike at the edge of Valle Ojos Negros.
CHAPTER VII

SUMMARY AND CONCLUSIONS

The San Marcos Dike Swarm (SMDS) is an unusual linear regional dike swarm of predominantly silicic composition. It is situated within the western zone of the Peninsular Ranges Batholith (PRB) just to the east of a major outcrop belt of Santiago Peak Volcanics. The study of the SMDS had been limited although there has been gold mining within the outcrop area of the swarm over the last century.

Recent studies of the Santiago Peak Volcanics have shown the latter to be the volcanic cover of the Peninsular Ranges Batholith (Herzig, 1991; Todd et al., 1994). The ages of the dikes, 120 ± 1 Ma (Böhnel et al., 2002), and the ages of the Santiago Peak Volcanics in the region, 116 ± 6 Ma (Meeth, 1993), are in accordance. The geochemistry of the dikes and extrusives indicates a common magma source; the major-element, trace-element and rare-earth element analyses all are similar. The textures of the dikes examined in thin section indicate shallow emplacement depths and extrusive igneous or hypabyssal environments, showing that they were feeder extrusives. This evidence provides a convincing case that the San Marcos Dike Swarm acted as the feeder dikes to the Santiago Peak Volcanics outcropping along the western margin of the dike swarm exposure.

The San Marcos Dike Swarm is a strain marker for PRB deformation. The orientation of dikes from different areas within the ~100 km long outcrop area of the swarm vary narrowly around N30°W 75°NE. The uniformity of dike attitudes, as well as dike compositions, from the different areas provides circumstantial evidence that the dikes were all intruded together in a restricted time interval. Shallow level basaltic dike swarms are typically intruded in subvertical orientations. The consistent steep NE dip of dikes in the San Marcos Dike Swarm suggests the possibility that this portion of the batholith has been regionally tilted toward the SW. Paleomagnetic study of the dikes by Bohnel et al.(2002) provides supporting evident that the batholith has been tilted as previously hypothesized by Butler et al. (1991). The orientation of the dikes are parallel to the overall trend of the swarm.
and parallel to the trend of the PRB as well. The dike swarm thus indicates that the PRB underwent strong SW-NE regional extension in conjunction with dike swarm emplacement.

Further inquiry both north and south of this limited study area will undoubtedly reveal more dike related to the San Marcos Dike Swarm. For example, rhyolite dikes in the Lakeside area of San Diego County may be related to the swarm (Kimbrough pers. communication). It would not be surprising to even find such occurrences in the Santa Ana Mountains, or south of the Agua Blanca fault.
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APPENDIX A

WHOLE ROCK MAJOR AND TRACE ELEMENT GEOCHEMISTRY
Analytical Methods

Whole rock major and trace element concentration data presented in this thesis were obtained by a variety of instrumental methods and sample preparation procedures. Instrumental methods employed include:

- XRF (X-ray fluorescence spectroscopy)
- ICP-OES (Inductively coupled plasma optical emission mass spectroscopy)
- ICP-MS (Inductively coupled plasma mass spectrometry)

Data were determined from three different laboratories:

1. San Diego State University - XRF (33 samples)
2. Washington State University GeoAnalytical Lab - XRF, ICP-MS (9 samples)
3. Activation Laboratories - ICP-AES, ICP-MS (9 samples)

At San Diego State University, XRF concentration data were obtained for ten major element (SiO₂, Al₂O₃, TiO₂, FeO, MnO, CaO, MgO, K₂O, Na₂O, P₂O₅) and 23 selected trace elements (Sc, V, Cr, Co, Ni, Cu, Zn, Rb, Sr, Y, Zr, Nb, Mo, Ba, La, Ce, Nd, Sm, Yb, Hf, Pb, Th, U) using the Philips Magix Pro XRF system installed in February 2002.

At the Washington State University GeoAnalytical Lab, XRF concentration data were obtained for ten major element (SiO₂, Al₂O₃, TiO₂, FeO, MnO, CaO, MgO, K₂O, Na₂O, P₂O₅) and seventeen selected trace elements (Ni, Cr, Sc, V, Ba, Rb, Sr, Zr, Y, Nb, Ga, Cu, Zn, Pb, La, Ce, Th) using a Rigaku 3370 XRF Spectrometer. Concentration data for additional 26 trace elements including the rare earth elements (REE) were obtained by ICP-MS (La, Ce, Pr, Nd, Sm, Eu, Gd, Tb, Dy, Ho, Er, Tm, Yb, Lu, Ba, Th, Nb, Y, Hf, Ta, U, Pb, Rb, Cs, Sr, Sc).

Analyses provided by Activation Laboratories, courtesy of Stan Keith, were obtained by ICP-AES for 10 major elements and seven trace elements (SiO₂, Al₂O₃, TiO₂, FeO, MnO, CaO, MgO, K₂O, Na₂O, P₂O₅, Ba, Be, Sc, Sr, V, Y, Zr) and 44 trace elements by ICP-MS (Ag, As, Ba, Bi, Ce, Co, Cr, Cs, Cu, Dy, Er, Eu, Ga, Gd, Ge, Hf, Ho, In, La, Lu, Mo, Nb, Nd, Ni, Pb, Pr, Rb, Sb, Sm, Sn, Sr, Sy, Ta, Tl, Tm, Tn, U, V, W, Y, Yb, Zn, Zr).
San Diego State University methods and procedures

Sample collection and preparation is at the heart of whole rock chemical analysis. Proper sample collection and preparation procedures provide the foundation for obtaining representative and reliable whole rock chemical analyses. Sophisticated analytical instrumentation and measurement techniques cannot overcome mistakes made during sample collection and/or preparation.

Reproducible sample preparation methods for XRF analysis are essential. Samples must be in a form that is similar to available standards in terms of matrix, density and particle size. There are two basic types of samples used in XRF analysis: (1) Powders and pellets, powdered samples are pressed into pellets, and (2) Fusions, with sodium or lithium or a tetraborate (Na₂B₄O₇ or Li₂B₄O₇) provide a homogenized sample.

A principal goal of this work is to establish the main geochemical variations represented by the San Marcos Dike Swarm. In order to accomplish this, a sufficient number of random samples, with wide geographical distribution, must be selected in order to avoid sampling bias. Once an outcrop was selected for chemical analyses care was taken to obtain representative fresh rock. This was achieved by using big hammers capable of breaking the hard rocks typically dealt with in this investigation. Rock samples at the outcrop were typically obtained using a 4 lb hand sledge or a full-sized 12 lb sledge. The sledges were used in combination with a chisel or smaller rock hammer in many cases. Many of the samples were collected from stream drainages or road outcrops that afforded accessibility to relatively unweathered outcrops. In cases where an outcrop had surficial weathering or heavy fracturing, time was spent locating large relatively un-fractured blocks that were subsequently broken down with a sledgehammer to obtain fresh rock. Typical weights of hand samples ranged from 2 to 4 kilograms. Samples were carefully labeled in the field and returned to the rock-processing laboratory at San Diego State University.

In the SDSU laboratory samples were then broken up further on a steel plate using sledge hammers. Fresh rock chips completely free of any weathered surfaces were individually selected by hand picking with vinyl or latex gloves. Fine dust and grit were avoided to reduce the possibility of significant iron, chromium or nickel contamination. Hands picked rock chips (~200 to 300 grams) were transferred into new plastic zip lock bags or new plastic containers with snap-top lids. Hand samples were retained for thin sections.
and archiving. The "rock chipping" area was thoroughly cleaned in between samples using wire brushes and a powerful vacuum system.

Fresh rock chips prepared by the methods described above were sent to Washington State University and Activation Laboratories for analysis. Samples analyzed in the XRF laboratory at San Diego State underwent further processing as described below.

**Preparation of XRF powders at SDSU**

1. Latex or vinyl gloves, or latex finger cots are worn during the entire procedure.
2. Handpicked rock chips free of weathered surfaces are broken down to <0.5 cm in longest dimension.
3. Rock chips are then crushed in tungsten carbide shatterbox (<100 grams/batch) for 3 minutes. The sample is very finely ground at this stage - the consistency of flour. Pulverization using tungsten carbide is known to introduce W (up to 0.1% by weight, as well as Co, C, Ta, Nb, and Ti to samples.
4. The shatterbox is thoroughly cleaned between each sample by vacuuming, cleaning with acetone, and pre-contaminating with each successive sample.
5. When necessary, ignited silica sand is crushed in the shatterbox as an abrasive cleaning agent.

**Preparation of pressed powder pellets:**

1. Sample powder is dried overnight at 105°C
2. Pressed powder pellets are made using an Elvacite™ binder solution which is prepared by mixing 200 grams of Elvacite™ powder (a finely ground plastic) into 1 liter of acetone. The pellets are made by mixing 2 ml of the Elvacite™ solution (= 0.4 grams of Elvacite™) with 13 grams of rock powder.
3. Mixture is blended in a Diamonite mortar and pestle and pressed at 22 tons in a Spex Certiprep press (model 3264B) with a 40mm die assembly.

**Fused glass discs:**

1. Sample powder is dried overnight at 105°C
2. Flux:sample ratio is 6:1
3. Flux is Spex ultrapure lithium tetraborate.
4. 1.2500 grams sample and 7.5000 grams flux are weighted in a Mettler AE160 analytical balance, combined, and then lightly mixed in plastic boat.

Mixed sample and flux is transferred to a crucible for melting. An HD Elektroniks VAA2 automatic fuser with platinum crucibles and molds is used to prepare the final glass discs. The HD Elektroniks VAA2 automated fuser provides fine temperature control for the Pt crucibles and molds because the propane, oxygen, and air mixtures to individual burner heads are individually adjustable. The VAA2 automated fuser also provides an agitation mode that allows alternate swirling/stirring of the melt with static heating. Molds and crucibles do not have to be handled while hot. The Pt mold provides a flat and smooth surface for analysis. Crucibles are cleaned between samples in 10% HCl in an ultrasonic
cleaner followed by rinsing in deionized water and drying with a heat gun to speed up the pellet making process. Fused pellets can be produced at a rate of 4-6/hour.
APPENDIX B

PHILIPS MAGIX PRO XRF X-RAY SPECTROMETER
XRF data at SDSU were collected using the Philips Magix Pro wavelength dispersive sequential X-ray spectrometer instrument that was installed in February 2002. This instrument is designed for fast, high precision, quantitative elemental analysis. Samples can be run as fused glass discs, loose or pressed powders, or liquids. Sample preparation methods for fused discs and pressed pellets are described above. Preparation and calibration of standards is required for quantitative analysis; while qualitative analysis is possible with the standardless software.

The Philips Magix Pro wavelength dispersive sequential X-ray spectrometer system is equipped with a 4kW light element super sharp Rh target end window X-ray tube, close-coupled optics for maximum signal strength, a full set of analyzer crystals for the analysis of elements in the mass range from oxygen to uranium, 3 detectors (a flow and a sealed proportional detector in tandem, plus a scintillation detector in parallel), a range of beam filters and collimators, vacuum operation for the analysis of solids, helium environment for liquids and loose powders, a 4kW/125mA solid state X-ray generator, automatic sample changer set up to handle 36 samples but capable of 168 samples. The system utilizes the Philips SuperQ Data Collection and Evaluation Software, v3.0 and the IQ+ Standardless Analysis Software.

Calibration Standards that closely approximate the samples in overall composition and physical properties are necessary. The SDSU laboratory used U.S. Geological Survey standards AGV-2, BCR-2, BHVO-2, BIR-1, DNC-1, DTS-1, G-2, GSP-2, RGM-1, and W-2 for this work.
# Whole Rock Geochemistry Results from Farquharson Samples

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Figure. Whole-rock results for samples taken in 1999, analyzed by SDSU Philips XRF.
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Figure. Whole-rock results for samples taken in 2002, analyzed by SDSU Philips XRF.
APPENDIX C

WASHINGTON STATE UNIVERSITY
GEOANALYTICAL LAB
At the Washington State University GeoAnalytical Lab, XRF concentration data were obtained for ten major element (SiO$_2$, Al$_2$O$_3$, TiO$_2$, FeO, MnO, CaO, MgO, K$_2$O, Na$_2$O, P$_2$O$_5$) and seventeen selected trace elements (Ni, Cr, Sc, V, Ba, Rb, Sr, Zr, Y, Nb, Ga, Cu, Zn, Pb, La, Ce, Th) using a Rigaku 3370 XRF Spectrometer. Concentration data for additional 26 trace elements including the rare earth elements (REE) were obtained by ICP-MS (La, Ce, Pr, Nd, Sm, Eu, Gd, Tb, Dy, Ho, Er, Tm, Yb, Lu, Ba, Th, Nb, Y, Hf, Ta, U, Pb, Rb, Cs, Sr, Sc).

For XRF, the concentrations of 27 elements in unknown samples are measured by comparing the X-ray intensity for each element with the intensity of USGS standard samples. The WSU lab analyses both major and trace elements from a single fused bead (2:1) Li-tetraborate method. Complete details of analytical methods and precision and accuracy of analyses are presented in Johnson et al. (1999). This approach contrasts with the SDSU lab procedure that utilizes a (6:1) Li-tetraborate fused bead for major elements, and a separate pressed powder pellet for trace elements.

The precision and accuracy of a low fused bead technique by X-ray fluorescence analysis is demonstrated by comparison to accepted values of standard samples and to values acquired by other techniques in other laboratories. They maintain that the increased efficiency of using a single bead for major and trace elements is achieved without loss of precision or accuracy and the beads may be stored for tens of years without degradation.

The Rigaku 3370 XRF has a rhodium (Rh) target X-ray tube that is run at 50kV/50mA with full vacuum and a 25mm mask for all elements. This procedure contrasts with that used at SDSU with the Magix Pro Instrument for which X-ray tube voltage and amperage is varied between individual elements to maximize count rates for individual elements.

Complete details of the ICP-MS analytical methods employed in the WSU lab are available from an on-line report entitled “Trace Element Analyses of Rocks and Minerals by ICP-MS” written by Charles Knaack, Scott Cornelius and Peter Hooper of the GeoAnalytical Laboratory Department of Geology, Washington State University in December, 1994.

Liquids introduced into the plasma (7000°C) are ionized and then passed to the mass spectrometer through a two-stage ion extraction interface. The ICP-MS is capable of
quantitatively determining trace elements in liquids in the range of fractions of a part per billion. For routine REE analysis of rocks and minerals, the detection limit is at or below chondrite levels. Its capability for rapid multi-element analysis at low cost, high sensitivity, and relative freedom from interferences make the ICP-MS an excellent instrument for the determination of many trace elements in rocks and minerals.

In the routine procedure practiced in the GeoAnalytical Laboratory for trace elements in rocks and minerals, the following 26 elements are analyzed: all 14 naturally occurring rare earth elements (La through Lu) together with Ba, Rb, Y, Nb, Cs, Hf, Ta, Pb, Th, U, Sr and Zr. Zr is measured only as a check for complete dissolution of the sample.
APPENDIX D

ACTIVATION LABORATORIES LTD
Activation Laboratories Ltd employs an innovative and cost effective approach to major and trace element analyses. Samples analyses for this study were done with a standard Lithogeochem analytical package offered by the company. The samples are put into solution using an aggressive fusion technique employing a lithium metaborate/tetraborate flux. The resulting molten bead is rapidly digested in a weak nitric acid solution. The fusion ensures that the entire sample is dissolved. It is only with this attack that major oxides including SiO2, REE and other high field strength elements are put into solution.

The sample solution is then analyzed by two different ICP techniques: inductively coupled plasma emission spectroscopy (ICP/OES), and Inductively Coupled Plasma Mass Spectrometry (ICP-MS).

Inductively Coupled Plasma Optical Emission Mass Spectrometry (ICP-OES) is a multi-element technique, capable of measuring 40 to 70+ elements to very low detection limits (ppm to ppb or in many cases, ppt) in just about any material or substance (waters, biological materials, inorganic materials of all sorts, environmental samples, geological samples, etc.) in solution. Most of the periodic table can be measured using ICP-OES. The major rock forming elements and some important trace elements can be determined simultaneously to sensitivities better than X-ray fluorescence.

The ICP-OES technique employed for these samples relies on placing the sample material into solution using fusion techniques using fluxes as mentioned above. The sample solution is then introduced into a radio frequency excited plasma (~8000°K). Atoms within the samples are excited to the point that they emit wavelength-specific photons or light that is characteristic of a particular element. The number of photons produced is directly related to the concentration of that element in the sample.

Inductively Coupled Plasma Mass Spectrometry (ICP-MS) is a versatile, rapid and precise analytical technique which provides high quality multi-element and isotopic analyses for samples in solution. It is capable of determining the concentrations of 70+ elements in a single analytical run. The detection limit for most elements in solution is in the sub-ppb range. For some elements it may lie in the sub-ppt range. The ICP-MS instrument employs an argon plasma as the ionization source and a quadruple mass spectrometer to detect the ions produced. During analysis, the sample solution is nebulized into flowing argon gas and passed into an inductively coupled plasma. The gas and nearly everything in it is atomized.
and ionized, forming a plasma. The plasma is a source of both excited and ionized atoms. The positive ions in the plasma are then focused down a quadrupole mass spectrometer where they are separated according to mass, detected, multiplied and counted.

The ActLabs samples also were analyzed for FeO (0.1%) by Titration to determine the relative concentrations of ferric and ferrous iron in the samples. Additionally, loss on ignition (LOI) was determined for these samples by weight difference following ignition of samples in a furnace.

**Act Labs**
ICP-AES: Ba, Be, Sc, Sr, V, Y, Zr
XRF: Ag, As, Ba, Bi, Ce, Co, Cr, Cs, Cu, Dy, Er, Eu, Ga, Gd, Ge, Hf, Ho, In, La, Lu, Mo, Nb, Nd, Ni, Pb, Pr, Rb, Sb, Sm, Sn, Sr, Sy, Ta, Tb, Tl, Tm, Tn, U, V, W, Y, Yb, Zn, Zr

**SDSU**
XRF: Sc, V, Cr, Co, Ni, Cu, Zn, Rb, Sr, Y, Zr, Nb, Mo, Ba, La, Ce, Nd, Sm, Yb, Hf, Pb, Th, U

**WSU:**
XRF: SiO₂, Al₂O₃, TiO₂, FeO, MnO, CaO, MgO, K₂O, Na₂O, P₂O₅
XRF: Ni, Cr, Sc, V, Ba, Rb, Sr, Zr, Y, Nb, Ga, Cu, Zn, Pb, La, Ce, Th
ICP-MS: La, Ce, Pr, Nd, Sm, Eu, Gd, Tb, Dy, Ho, Er, Tm, Yb, Lu, Ba, Th, Nb, Y, Hf, Ta, U, Pb, Rb, Cs, Sr, Sc
ABSTRACT
ABSTRACT

The San Marcos Dike Swarm (SMDS) is a densely-intruded, north-northwest-striking, predominantly silicic regional dike swarm that is exposed over an approximately 100 km-long segment in the west-central portion of the Cretaceous Peninsular Ranges batholith (PRB) in northern Baja California. Dikes range mostly from 1 to 8 meters in thickness and individual dikes outcrop continuously for up to 4 km along strike. Reconnaissance whole rock analyses suggest medium-K calc-alkaline affinities typical of orogenic plate settings. Dike compositions range from basalt to rhyolite and are locally strongly bimodal. Rhyolites are a ubiquitous feature of the swarm and are similar in composition to high-silica rhyolite in the Basin & Range province.

Cross-cutting field relationships and a U-Pb zircon age of 120±1 Ma clearly establish the swarm as an integral feature in the magmatic evolution of the PRB. The SMDS crops out adjacent to an extensive belt of Santiago Peak Volcanics (SPV) which has been previously interpreted as the supracrustal volcanic cover of the western PRB. The similarity in composition and age of the SMDS and the SPV suggests that the dike swarm fed the SPV.

The dike swarm provides a strain marker for PRB deformation history. Reconnaissance data on dike attitudes from widely separated areas of the dike swarm suggest a regionally consistent N30°W strike and 75°NE dip. The dike attitudes are consistent with a common westward tilt of 15° about the N30°W longitudinal axis of the PRB. The SMDS may present the first clear structural evidence in support of hypothesized regional tilting, hence allowing for the mechanics and timing of this process to be understood.