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Structure of the Sentinel Granodiorite, Yosemite National Park, California

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STRUCTURE OF THE SENTINEL GRANODIORITE, YOSEMITE NATIONAL PARK, CALIFORNIA

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ABSTRACT

STRUCTURE OF THE SENTINEL GRANODIORITE, YOSEMITE NATIONAL PARK, CALIFORNIA

by Joseph M. Petsche

The ~240-km^2, ~94-Ma Sentinel Granodiorite is a poorly understood western "outlier" of the ~93-85-Ma Tuolumne Intrusive Suite of the central Sierra Nevada batholith. Contact relationships indicate the Sentinel Granodiorite is only slightly older than the undated Yosemite Creek Granodiorite and the formally recognized outermost unit of the Tuolumne Intrusive Suite, the Kuna Crest Granodiorite. The Sentinel Granodiorite contains two steep magmatic foliations attributed to internal magmatic processes and regional strain, with average strike orientations of WNW and NW, respectively. Internal contacts, schlieren, and dikes suggest a complex intrusive history. The only major modal trend in the Sentinel Granodiorite is that it is slightly more mafic in its western region. Sharp, stepped contacts with granitic host rocks and minor, discontinuous ductile aureoles indicate the emplacement of the granodiorite was in part aided by stoping and vertical ductile flow.

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> "No tongue can tell the relief to simply withdraw scientific observation, and let Nature impress you in the dear old way with all her mystery and glory, with those vague, indescribable emotions which tremble between wonder and sympathy"
>
> -Clarence King, 1872

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INTRODUCTION

The construction and emplacement of plutons are poorly understood, in part because evidence from the initial stages of pluton growth, such as internal contacts and early magmatic fabrics, are modified or destroyed as a pluton evolves (e.g., Paterson et al., 1996, 1998; Bergantz, 2000; Petford, 2003). The limited record of pluton construction processes causes several important questions to remain contentious. (1) How extensive are active magma chambers? (2) How big are the pulses of magma that eventually form plutons? (3) How do these pulses ascend through the crust (i.e., via dikes, diapirs, and/or interconnected fracture networks), and what is the rheological contrast between these pulses and the host rock? (4) What are the time scales of pluton assembly? (5) How are host rocks transferred to accommodate space for plutons? (6) What processes cause compositional variation in plutons, and where in the crust do these processes occur?

These questions are difficult to answer because plutons range in size over several orders of magnitude, vary in shape and complexity, intrude a wide variety of host rocks at different crustal levels and in a variety of tectonic settings, and have limited vertical exposure. For example, many sub-horizontal, tabular plutons are probably constructed by the stacking of horizontal sheets, with space made by depression of the pluton floor (Cruden, 1998; Wiebe and Collins, 1998; Cruden et al., 1999; Wiebe et al., 2002), or by roof uplift (Corry, 1988; McCaffrey and Petford, 1997; Cruden, 2006) as the pluton expands. Plutons that exhibit steep, planar internal contacts that in some cases include host rock septae are thought to be constructed by steeply dipping sheets (e.g., Pitcher and Berger, 1972; Ingram and Hutton, 1994; Miller and Paterson, 2001). Construction of a pluton by vertical sheets implies that lateral wedging of host rocks is an important material transfer process, unless the pluton was passively emplaced into dilational cavities or other tensional features associated with large shear zones (e.g., Hutton et al., 1990; Hutton, 1992; Tikoff and Teyssier, 1992; McNulty et al., 1996; Tobisch and Cruden, 2004; Titus et al., 2005). Wedging is typically considered to be accommodated by elastic host rock behavior, especially where fast strain rates associated with rapid emplacement of dikes or sheets occur (Paterson and Tobisch, 1992; Petford et al., 1993; Petford, 1996; Cruden, 1998, 2006).

Many plutons exhibit irregularly shaped, steep-sided margins, host rock xenoliths, and narrow structural aureoles. These plutons do not typically have exposed floors and roofs; therefore, their three-dimensional shapes are difficult to determine. For such plutons, a combination of stoping and downward ductile flow of host rocks within relatively restricted structural aureoles is proposed by some as a viable emplacement mechanism (Saleeby, 1990; Paterson and Vernon, 1995; Paterson et al., 1996; Paterson and Miller, 1998; Miller and Paterson, 1999), whereas others propose that roof doming or floor subsidence accommodates such plutons (e.g., Roman-Berdiel et al., 1995; Brown and McClelland, 2000; Cruden, 1998, 2006).

Mechanisms of magma ascent are also debated. Historically, "hot-Stokes" diapirs have been a popular model for rising magma. These diapirs are considered to be large, elliptical or teardrop-shaped batches of magma that rise through the crust by causing the surrounding host rocks to become heated and flow ductiley around the magma (e.g., Marsh, 1982; Weinberg, 1994; Petford, 1996; Miller and Paterson, 1999). Given their rate of heat loss, such simplified diapirs are unlikely to reach the upper crust (Marsh, 1982). Traditional models of hot-Stokes diapirs are also problematic because they do not take into account crustal heterogeneity and gradients in temperature, pressure, and deviatoric stress in the crust (e.g., Miller and Paterson, 1999).

An alternative model for magma ascent is diking, in which batches of magma rise rapidly along fractures and faults, and are accommodated during ascent by permissive or elastic deflection of host rock (Spera, 1980; Clemens and Mawer, 1992; Weinberg, 1999; Petford et al., 2003). Some authors argue against simple diking models because magma must ascend quickly enough (up to several meters per second) so that heat loss is minimal and magma viscosity remains low enough (10^2 to 10^3 Pa s) to prevent dike arrest (Miller and Paterson, 1999). Such fast ascent rates require that plutons be constructed on the scale of hundreds to thousands of years, and accommodated by very high host rock strain rates during emplacement (Paterson and Tobisch, 1992).

Whether magma ascends as hot-Stokes diapirs or dikes is an argument between two end-member models. Paterson and Miller (1998) and Miller and Paterson (1999) attempt to unify the hot-Stokes and diking models by proposing "visco-elastic" diapirs, which are vertically elongate, finger-like pulses of magma that rise through the crust with the aid of both brittle (i.e., stoping) and ductile deformation, and with downward translation of host rock within relatively restricted aureoles as the primary material transfer process.

Foliation and lineation patterns in plutons are also important considerations in the debate over pluton construction and emplacement (e.g., Bateman and Chappell, 1979; Cruden, 1990; Paterson and Tobisch, 1992; Paterson et al., 1998; Miller and Paterson, 1999; Zak and Paterson, 2006). For example, how can one distinguish a foliation caused by magmatic convection (Ramsay, 1989; Cruden, 1990; Bergantz, 2000) from one formed by regional tectonic stresses (Berger and Pitcher, 1970; Paterson et al., 1998)? To what degree are early-formed fabrics overprinted or destroyed by later fabrics? Paterson et al. (1998) provide several criteria for interpreting magmatic fabric patterns based on the degree of coupling between internal and host rock fabrics. They contend that magmatic fabrics typically record only the latest strain in plutons prior to solidification, not early stages of pluton construction as proposed by Bateman (1985) and Clemens et al. (1997).

One area where the issues discussed above have been of great importance is the central Sierra Nevada batholith, which is host to multiple zoned plutonic suites, typically of tonalitic, granodioritic, and granitic compositions (e.g., Bateman and Chappell, 1979; Bateman, 1992; Coleman and Glazner, 1997; Ducea, 2001). Of these suites, the ~94-85-Ma Tuolumne Intrusive Suite has received the most study, in part due to its accessibility and outstanding exposure (e.g., Calkins, 1930; Frey et al., 1978; Bateman and Chappell, 1979; Kistler et al., 1986; Reid et al., 1993; Coleman et al., 2004; Zak and Paterson, 2005; Zak et al., 2007).

The 1200-km^2 Tuolumne Intrusive Suite has been historically considered a normally zoned, ~N-S trending, elongate suite of granodiorite and subordinate tonalite and granite that is roughly concentric in map pattern and becomes progressively younger and more felsic inwards (e.g., Kistler, 1973; Bateman, 1992) (Fig. 1). In this thesis, the term "proper" will be appended to the name of the suite to denote this traditional interpretation. The Tuolumne Intrusive Suite proper is considered the type example of zoned intrusive suites in the central Sierra Nevada batholith (e.g., Bateman and Chappell, 1979; Huber et al., 1989; Bateman, 1992; Paterson and Vernon, 1995). Contacts between units of the suite range from gradational to sharp and vary in complexity (e.g., Bateman and Chappell, 1979; Bateman et al., 1983; Bateman, 1992; Coleman and Glazner, 1997, 2004; Zak and Paterson, 2005). Core-ward in the suite proper, the units are as follows: Granodiorite of Kuna Crest, also called the Granodiorite of Glen Aulin in the western margin of the suite; Half Dome Granodiorite, which is subdivided into an outer equigranular and inner porphyritic facies; Cathedral

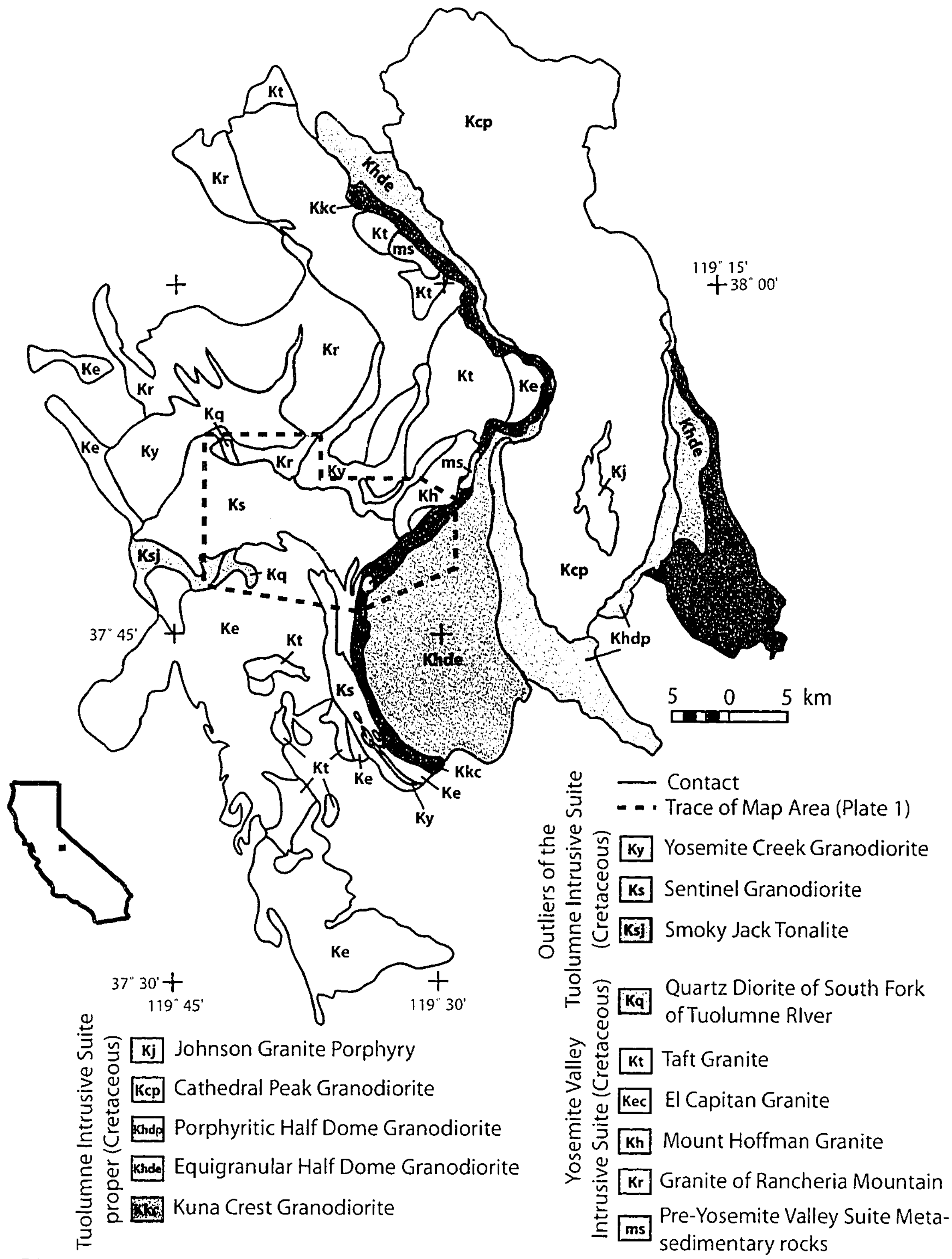


Figure 1. General geologic map showing the Sentinel and Yosemite Creek units, and their geographic relationship with host rocks and the Tuolumne Intrusive Suite proper. Modified from Huber et al. (1989), Bateman (1992), and Peck (2002).

Peak Granodiorite; and Johnson Granite Porphyry (Kistler, 1973; Bateman and Chappell, 1979; Bateman et al., 1983; Bateman, 1992) (Fig. 1). Typically, magmatic foliations are either parallel to internal and external contacts, or are approximately E-W-striking and cut across internal contacts at high angles (e.g., Bateman et al., 1983; Bateman, 1992; Teruya, 2005; Zak et al., 2007).

Numerous models have been proposed for the construction of the suite. These include: ballooning of a large magma chamber (Bateman and Chappell, 1979); intrusion into dilational cavities in a strike-slip system (Tikoff and Teyssier, 1994); amalgamation of a series of smaller, nested diapirs (Paterson and Vernon, 1995); and incremental assembly of many discrete, sheeted dikes (e.g., Glazner et al., 2004).

West of the Tuolumne Intrusive Suite proper are the ~94.5-Ma Sentinel Granodiorite and undated Yosemite Creek Granodiorite, which intrude granitic rocks of the ~103-100-Ma Yosemite Valley Intrusive Suite (e.g., Kistler, 1973; Coleman and Glazner, 1997; Ratajeski et al., 2001; Peck, 2002) (Fig. 1, Plate 1). The Sentinel and Yosemite Creek granodiorites were considered part of the Tuolumne Intrusive Suite by Calkins (1930), Kistler (1973), Kistler et al. (1986), Kistler and Fleck (1994), and Glazner et al. (2004), but were interpreted as separate units by Bateman and Chappell (1979) and Peck (2002). Bateman (1992) did not place the granodiorites in an intrusive suite, but considered them as "possible older units" of the Tuolumne Intrusive Suite. In his most detailed mapping of the Sentinel and Yosemite Creek granodiorites, Kistler (1973) assigned rocks mapped by others as the Kuna Crest Granodiorite not to the Tuolumne Intrusive Suite proper, but to the Sentinel Granodiorite.

The Sentinel and Yosemite Creek granodiorites constitute ~300-km^2 of well-exposed bedrock, but have received little study. The most detailed descriptions of the Sentinel Granodiorite are a few paragraphs in Calkins (1930), a single paragraph in Bateman (1992), and a few phrases of description in the maps of Kistler (1973) and Peck (2002). Even less has been written about the Yosemite Creek Granodiorite.

The goal of my thesis is to provide a history of the construction and emplacement of the Sentinel Granodiorite and parts of the Yosemite Creek Granodiorite, and to determine the relationship of these units to each other and the Tuolumne Intrusive Suite proper, based on their structural, petrological, and temporal relationships with the Kuna Crest Granodiorite, which is the formally recognized western margin of the Tuolumne Intrusive Suite. To do this, I evaluate through geologic mapping and structural analysis: (1) internal fabrics and structures, and how they relate to pluton growth and evolution; (2) modal and textural variations in the Sentinel and Yosemite Creek granodiorites; (3) structures in the host rocks related to emplacement of the Sentinel Granodiorite; and (4) contact relationships of the Sentinel Granodiorite with host rocks of the Yosemite Valley Intrusive Suite, the outer unit of the Tuolumne Intrusive Suite proper (Granodiorite of Kuna Crest), and the Yosemite Creek Granodiorite.

Geologic Setting

The Sentinel and Yosemite Creek granodiorites lie within the central Sierra Nevada batholith, which formed during a period of large-scale continental arc magmatism in the mid- to Late Cretaceous (e.g., Coleman and Glazner, 1997). These granodiorites intrude the El Capitan Granite, Mount Hoffman Granite, Granite of Rancheria Mountain, and Taft Granite, all of which are part of the ~103-100-Ma Yosemite Valley Intrusive Suite, and are intruded by the Kuna Crest Granodiorite (Kistler, 1973; Stern et al., 1981; Bateman et al., 1983; Bateman, 1992; Ratajeski et al., 2001; Peck, 2002; Petsche, 2006) (Fig. 1, Plate 1). Metamorphosed rocks with protoliths that are likely Proterozoic to Middle Cambrian in age are typically quartzose, calcareous, or pelitic in composition and form isolated bodies or septae between the Tuolumne Intrusive Suite proper and the El Capitan Granite and Sentinel Granodiorite (Lahren and Schweickert, 1989; Bateman, 1992; Peck, 2002; Glazner et al., 2004).

The Sentinel Granodiorite is exposed as a lobe that extends ~15-km WNW from the western margin of the Tuolumne Intrusive Suite proper, and as a narrow body that parallels the southwestern margin of the suite (Plate 1). The Yosemite Creek Granodiorite is exposed in an E-W swath north of the main lobe of the Sentinel Granodiorite, but is not in direct contact with the Tuolumne Intrusive Suite proper (Kistler, 1973; Bateman and Chappell, 1979; Peck, 2002; Petsche, 2006). These two granodiorites share an ~8-km-long contact that extends westward from the Mount Hoffman Granite. Farther west, these granodiorites are separated by an elongate ~8-km^2 body of Rancheria Mountain Granite (Kistler, 1973; Petsche, 2006) (Fig. 1, Plate 1).

Methods

Field data were collected for a total of six and a half weeks over the summers of 2004-2006 in Yosemite National Park, over an area that spans roughly 240-km^2. The orientations of magmatic foliations and lineations, dikes, schlieren, shear zones, and internal and external contacts were measured. Modes, textures, fabric intensities, kinematics of non-coaxial shear and other relevant features were also recorded. Fifty-two thin sections were examined to determine mineralogy, texture, and microstructures. Microstructures were analyzed to determine fabric type (i.e., magmatic or solid-state), fabric intensity, and flow kinematics.

PETROGRAPHIC DESCRIPTIONS OF UNITS

This chapter focuses on the petrographic characteristics of the units discussed in the thesis. Because the focus of the thesis is the Sentinel Granodiorite, this section also includes a discussion of internal features of the granodiorite, specifically enclaves, internal contacts, schlieren, and map-scale compositional variations. The Yosemite Creek Granodiorite is also discussed in more detail. The subsequent chapter provides an in-depth description of the structure of the Sentinel Granodiorite.

Pre-Yosemite Valley Intrusive Suite Rocks

Quartzite, Marble, and Schist

Metasedimentary rocks are sparsely distributed near the eastern margin of the Sentinel Granodiorite (Plate 1). These rocks are typically meter-scale, although several map-scale pendants and septae lie along the contacts between the Sentinel and Kuna Crest granodiorites, and the granodiorites and El Capitan and Mount Hoffman granites (Kistler, 1973). The xenoliths form a ≥15-km-long, NE-SW-trending swath that extends from south of Porcupine Flat Campground, up Hoffman Creek, and past the eastern boundary of the map area towards May Lake (Plate 1). They probably correlate with metamorphic rocks of the Proterozoic to Middle Cambrian Snow Lake pendant in northern Yosemite National Park (Lahren and Schweickert, 1989; Glazner et al., 2004), and are comprised of quartzite, calc-silicate rock, marble, biotite- and quartz-sillimanite schist, and amphibolite (metamorphosed mafic dikes).

Marble forms two bodies that lie within the Kuna Crest Granodiorite along Hoffman Creek (Plate 1), and constitutes the majority of metamorphic host rocks in the study area. Moderately dipping compositional layering, probably transposed bedding in the marble, strikes N-S to NW-SE. A few 1-2-m-thick boudinaged metasandstone layers are locally inter-layered with the marble.

Quartzite and schist are primarily found as scattered, meter-scale xenoliths that are most abundant north of the marble unit. A larger, ~0.3-km^2 body of quartzite also lies approximately 3.5-km south of Porcupine Flat. Quartz-sillimanite schist lies adjacent to rocks that appear to be weakly metamorphosed mafic dikes at Coyote Rocks (Plate 1). The schist contains approximately 85% quartz, 10% sillimanite, 5% biotite, and minor muscovite and plagioclase. Sillimanite lies parallel to, and overprints, the foliation. This sillimanite indicates high temperature metamorphic conditions, but its age relative to the adjacent Mount Hoffman Granite and Sentinel Granodiorite is uncertain. The mafic dikes are fine-grained, moderately recrystallized, and contain approximately 35% plagioclase, 30% clinopyroxene, 25% hornblende, 5% biotite, <5% quartz, and accessory sphene, epidote and opaque minerals. Foliation in the metamorphic rocks at Coyote Rocks strikes NE.

Yosemite Valley Intrusive Suite

The Yosemite Valley Intrusive Suite is composed of granitic and lesser dioritic units that have U-Pb zircon ages between 103- and 100-Ma (Stern et al., 1981; Ratajeski et al., 2001). Granites of this suite are typically medium- to coarse-grained, have low color indices (~5-10), contain locally abundant enclaves and schlieren, and are intruded by abundant aplite, pegmatite, and fine-grained granitic dikes. Calkins (1930) recognized two granitic units in the suite, the El Capitan and Taft granites, and reported that the Taft Granite is younger. Kistler (1973) correlated the Granite of Rancheria Mountain and Mount Hoffman Granite with the El Capitan Granite, and Bateman (1992) considered the Granite of Rancheria Mountain and Mount Hoffman Granite as part of the Yosemite Valley Intrusive Suite. Relative ages have not been established among the Granite of Rancheria Mountain, Mount Hoffman Granite, and El Capitan Granite.

Diorite (Undifferentiated)

Kistler (1973) mapped a quartz diorite next to segments of the western margin of the Sentinel Granodiorite, and correlated this unit with the Yosemite Valley Intrusive Suite. This unit, named the Quartz Diorite of South Fork of Tuolumne River by Kistler, includes several dioritic to tonalitic bodies, one of which is now re-assigned as the Smoky Jack tonalite. Bateman (1992) mapped the same body and referred to it as the Tonalite of Aspen Valley, including it with Early Cretaceous units.

This unit includes several gray to dark-gray, fine- to medium-grained biotite-hornblende diorites that are of different ages, based on contact relationships with respective host rock units. Color indices of the diorites range between 20 and 30. These rocks are locally surrounded by the Mount Hoffman Granite and the Sentinel and Kuna Crest granodiorites. Diorite bodies range from meters to several hundred meters across. In the Mount Hoffman Granite, some diorites are xenoliths and intruded by aplite and granite dikes. Other dioritic bodies mingle with the granite and grade into dense enclave swarms, and are thus co-magmatic with the felsic rocks. Apparent xenoliths of diorite at least 100-m wide are included in the transitional Sentinel/Kuna Crest granodiorite. Magmatic foliation in the granodiorite is deflected around these diorite bodies.

Granite of Rancheria Mountain

The Granite of Rancheria Mountain is a light-gray to light-tan (where weathered), fine- to coarse-grained biotite granite, but modes locally plot in the granodiorite and tonalite fields. The color index ranges between 5 and 12, and is normally ~10. Biotite is typically 0.4-0.6-mm and up to 3-mm long, and forms elongate aggregates up to 8-mm long that define a weak magmatic foliation. Biotite is poikilitic, includes plagioclase, and may be partially altered to chlorite. Rare hornblende is interstitial between biotite in mafic aggregates. Locally, two distinct size fractions of plagioclase are present: anhedral to subhedral crystals that are no longer than 1-mm, and subhedral to euhedral crystals that are 4-8-

mm long. Plagioclase, which comprises 10%-50% of the rock, may include biotite and/or exhibit minor alteration to epidote. Interstitial to subhedral potassium feldspar, which makes up 5%-40% of the rock, displays tartan twinning, and is typically 2-4-mm long but locally forms phenocrysts up to 2-cm long. Quartz composes ~20%-45% of the rock, and forms interstitial crystals that are generally 2-4-mm, and up to 1-cm in diameter. Accessory minerals include apatite and zircon.

Mount Hoffman Granite

The Mount Hoffman Granite is a light-gray to light-tan (where weathered), medium- to coarse-grained, locally megacrystic biotite granite. Small amounts ($\leq$5%) of hornblende are locally present in the granite (Bateman, 1992). The color index ranges between 5 and 15, and is normally ~10. Biotite and hornblende comprise 2- to 8-mm-long aggregates that define a weak to moderately strong magmatic foliation. Potassium feldspar megacrysts reach 4-cm in length, have average lengths of 2-cm, and are weakly aligned with foliation. Interstitial quartz is 2- to 10-mm, and is typically 4- to 6-mm across.

El Capitan Granite

The ~102-Ma El Capitan Granite (Ratajeski et al., 2001) is a light-gray to light-tan (where weathered), medium- to coarse-grained biotite granite (e.g., Calkins, 1930; Bateman, 1992; Ratajeski et al., 2001). The color index ranges between 5 and 15, and is typically less than 10. Biotite, which has a mode ranging between <5% and ~10%, is 0.5-3-mm long, typically forms elongate aggregates with hornblende, and defines a weak magmatic foliation. Subhedral to euhedral hornblende is locally present in small amounts (<5%) and is typically 2-3-mm long. Plagioclase makes up 20%-25% of the granite, and is mostly 3-6-mm long. Interstitial to subhedral potassium feldspar comprises 35%-45% of the rock, is 6-10-mm long, displays weak tartan twinning, and includes plagioclase, biotite, and hornblende. Quartz makes up 25%-35% of the granite, and is typically 3-8-mm across.

Quartz Diorite of South Fork of Tuolumne River

The Quartz Diorite of South Fork of Tuolumne River (Kistler, 1973), also mapped as the Tonalite of Aspen Valley by Bateman (1992), is a gray- to dark-gray, fine- to medium-grained biotite-hornblende quartz diorite, but modes are scattered across the quartz monzodiorite, quartz syenite, granite, and tonalite fields. The color index typically ranges between 25 and 35, but is as low as 15. Biotite is 1-5-mm long, and is isolated or intergrown with hornblende in aggregates. Anhedral to subhedral poikilitic hornblende is 1-4-mm long, includes biotite and plagioclase, and shows minor alteration to epidote. Plagioclase has a mode of 40%-60%, ranges between 1-mm and 1-cm, and is on average 5-8-mm long. Interstitial potassium feldspar comprises 0%-20% of the rock. Interstitial quartz is typically 3-8-mm in diameter, and makes up 10%-25% of the rock. Accessory minerals are sphene, allanite, and epidote.

Outliers of the Tuolumne Intrusive Suite

The Sentinel Granodiorite, Yosemite Creek Granodiorite, and Smoky Jack tonalite (which is discussed further below and in the Contact Relationships section) are interpreted to overlap magmatically with each other and the Kuna Crest Granodiorite (Petsche, 2006). This interpretation is the basis for including the units in the Tuolumne Intrusive Suite. They are considered spatial "outliers" because they do not fit the nested pattern of the suite proper.

Smoky Jack Tonalite

The Smoky Jack tonalite is a gray, medium-grained, biotite-hornblende tonalite, but also includes quartz monzodiorite, granodiorite, and quartz diorite. The color index ranges between 10 and 30, and is typically 20-25. Biotite is 1-5-mm long, forms single crystals or thin, foliation-parallel aggregates with hornblende, and is partially altered to chlorite. Interstitial hornblende is 1-2-mm long. Larger, tabular poikilitic hornblende crystals up to 1-cm long include plagioclase, biotite, and opaque minerals. Subhedral to anhedral plagioclase makes up 50%-65% of the tonalite, and is 1-10-mm (typically 6-8-mm) long. Plagioclase shows minor alteration to sericite. Interstitial potassium feldspar is 1-2-cm long, comprises 0%-15% of the rock, and includes all other minerals except quartz. Interstitial quartz comprises ~15% of the rock, and is 4-8-mm in diameter. Accessory minerals are epidote, allanite, zircon, apatite, and opaque minerals.

Sentinel Granodiorite

The ~94.5-Ma (Coleman and Glazner, 1997) Sentinel Granodiorite is a light-gray, medium-grained biotite-hornblende granodiorite. Rarely, modes plot within the granite and tonalite fields. The color index ranges between 10 and 25, and is normally ~15. Hornblende is tabular, typically 4-6-mm long, helps define a weak to moderately strong magmatic foliation and lineation, and comprises ~3%-10% of the granodiorite. Some hornblende is poikilitic, and encloses plagioclase and biotite. Biotite makes up ~7%-15% of the mode, is 1-5-mm long, and forms elongate, lineation-parallel aggregates with hornblende. Biotite is weakly to moderately chloritized and more rarely altered to epidote. Plagioclase comprises ~50% of the rock, ranges between 1-10-mm, and is typically 2-4-mm long and weakly aligned with lineation. Plagioclase shows minor alteration to sericite. Interstitial potassium feldspar makes up 5%-15% of the rock, is up to 4-cm long, and encloses plagioclase. Interstitial quartz comprises 10%-30% of the rock and is 2-5-mm across. Sphene is an abundant accessory mineral, but rarely exceeds 1% of the rock. It is wedge-shaped and typically ~0.1-1-mm long, but reaches lengths of 2-mm. Other accessory minerals are allanite, zircon, and apatite.

Yosemite Creek Granodiorite

Because only the southern portion of the Yosemite Creek Granodiorite was mapped for this study, the following description and subsequent discussion are based on features that may not represent the unit as a whole. Brief descriptions of the granodiorite in the maps of Kistler (1973), Huber et al. (1989), and Bateman (1992) suggest that the southern and northern portions of the unit are generally similar in texture and composition to the exposures investigated in this work.

The Yosemite Creek Granodiorite is a medium-grained, light-gray to light-tan (where weathered) biotite-hornblende granodiorite; modes locally plot within the quartz diorite and tonalite fields. The color index ranges between 10 and 20 and is normally ~15. Biotite is 2-4-mm long, and hornblende is 4-8-mm long; they make up ~5%-10% and ~2%-8% of the granodiorite, respectively. Elongate aggregates of biotite and hornblende are up to 1-cm long and define a weak to moderately strong magmatic foliation. Boxy (square-shaped in cross-section) plagioclase typically comprises 50%-60% of the rock, but as little as 30% in some places. It is typically 4-6-mm, but may be up to 1-cm long. Plagioclase is weakly aligned parallel to magmatic foliation. Interstitial potassium feldspar is generally less than 5-mm long, and makes up 0%-10% of the rock. Interstitial quartz is 2-12-mm across and constitutes 10%-20% of the rock.

Like the Sentinel Granodiorite, the Yosemite Creek Granodiorite contains abundant schlieren, enclaves, and mingled bodies of quartz diorite. The

Yosemite Creek Granodiorite is differentiated from the Sentinel Granodiorite by its texture; plagioclase is whiter on weathered surfaces and more euhedral, and hornblende is smaller and less euhedral.

Quartz dioritic magmas are abundant in the Yosemite Creek Granodiorite within 1-2-km of its southern margin. Because mapping did not extend significantly far into the Yosemite Creek Granodiorite, it is not known if these features are unique to the southern portion of the unit. Nearest the margin, these bodies are typically a few meters wide and form enclaves and enclave swarms that are elongate parallel to the contact. Farther away, bodies of quartz diorite reach several hundred meters in length, mingle with the granodiorite, and in places grade into enclave swarms along their margins. Thin (1-10-cm) dikes of granodiorite, aplite, and pegmatite intrude the mingled rock. Magmatic fabrics in the Yosemite Creek Granodiorite are generally chaotic near these mafic zones, and are partially or completely decoupled from fabrics in the mafic bodies.

Transitional Sentinel/Yosemite Creek Granodiorite

The transitional Sentinel/Yosemite Creek granodiorite is thus named because it lies between the Sentinel and Yosemite Creek granodiorites and shares characteristics of both units. Although described in this section after the Yosemite Creek Granodiorite, it is interpreted to be intermediate in age between the Sentinel and Yosemite Creek granodiorites. The earliest and latest intrusions of this unit overlap magmatically with the Sentinel Granodiorite and Yosemite Creek Granodiorite, respectively.

The transitional Sentinel/Yosemite Creek granodiorite is a light-gray, fine- to medium-grained biotite-hornblende granodiorite, but in some places plots within the granite, quartz diorite, quartz monzodiorite, or tonalite fields. Biotite has a modal abundance of 10%-15%, forms single grains or aggregates with hornblende, is typically 2-8-mm long, and is weakly to moderately chloritized. Hornblende has a modal abundance of 0%-10%, and forms interstitial crystals or twinned phenocrysts that include biotite and plagioclase. In places, hornblende is altered to sericite or sphene. Plagioclase is the dominant feldspar, forming boxy phenocrysts up to 1-cm long, and is partially altered to sericite and epidote. Interstitial potassium feldspar and quartz comprise 5%-15% and 10%-25% of the rock, respectively. Accessory minerals include allanite, apatite and opaque minerals.

The texture of the transitional unit is more similar to the Sentinel Granodiorite in the south, and the Yosemite Creek Granodiorite in the north. A northward decrease in the abundance of tabular hornblende and increase in boxy plagioclase phenocrysts (from 1% to ~25% of the rock) defines this transition.

Thin section analyses of samples collected along a SSE-NNW transect across the transitional zone reveals two other distinct modal trends: (1) from SSE to NNW, quartz decreases from around 30% to 15% modal abundance, and (2) the ratio of potassium feldspar to total feldspar decreases slightly. There is no apparent trend in the ratio of biotite to hornblende. Alteration of biotite, and particularly, plagioclase, increases towards the Yosemite Creek Granodiorite. Cores of zoned plagioclase near the northern margin of the transitional unit are typically highly altered to sericite, albite, and/or epidote, whereas rims show little or no alteration.

Transitional Sentinel/Kuna Crest Granodiorite

The transitional Sentinel/Kuna Crest granodiorite lies along the contact between the Sentinel and Kuna Crest granodiorites and shares characteristics with both units. This transitional granodiorite is interpreted to be intermediate in age between the two granodiorites.

The transitional Sentinel/Kuna Crest granodiorite is a gray, medium-grained hornblende-biotite granodiorite that also plots within the quartz monzodiorite and quartz monzonite fields. Biotite, which composes ~5%-15% of the mode, is 0.5-2-mm long and shows minor alteration to chlorite and epidote. Aggregates of biotite and hornblende define a moderate to strong magmatic foliation. Tabular, poikilitic hornblende includes plagioclase and biotite, is 3-8-mm long with an average length of 6-mm, and makes up ~10%-15% of the granodiorite. Plagioclase comprises 40%-55% of the rock, forms zoned, locally poikilitic crystals which include biotite and hornblende, is 4-10-mm and on average 6-8-mm long, and shows minor alteration to sericite. Interstitial potassium feldspar composes 5%-25% of the mode and includes plagioclase, hornblende, and biotite. Interstitial quartz comprises roughly 15%-25% of the rock and is 1-4-mm in diameter.

Tuolumne Intrusive Suite (Proper)

Kuna Crest Granodiorite

The ~93.5- to 93.1-Ma (Coleman et al., 2004) Kuna Crest Granodiorite is a gray to light-gray, medium-grained biotite-hornblende granodiorite. The color index ranges between 10 and 30, and is typically between 15 and 20. Biotite aggregates help define a strong magmatic foliation. Hornblende is 1-3-mm long, tabular to acicular, and also defines foliation. Subhedral to euhedral plagioclase is 5-10-mm long.

Equigranular Half Dome Granodiorite

The following description for the ~92.8- to 91.1-Ma (Coleman et al., 2004) equigranular Half Dome Granodiorite is limited, as only the outermost part of the unit is exposed in the southeast corner of the study area. The unit is a dark- to light-gray, medium- to coarse-grained, biotite-hornblende granodiorite. The color index is ~15, but is locally as low as 5 (Kistler, 1973; Bateman, 1992). Hornblende is tabular and up to 1-cm long. Biotite forms books up to 5-mm across.

Internal Features of the Sentinel Granodiorite

Enclaves

Enclaves are abundant throughout the Sentinel Granodiorite, although their concentration varies from less than 1% to over 10% of the rock in outcrop. They are typically dioritic to granodioritic in composition, and are fine- to medium-grained, although some enclaves include plagioclase phenocrysts up to 6-mm long. Enclaves range from 1-cm to >1-m, and are generally 5- to 15-cm across. Many are approximately equidimensional, and others range in shape from oblate to prolate. A few enclaves are sub-angular or irregular in shape. Enclaves typically have sharp boundaries, but in some cases their margins are gradational across several centimeters.

Most enclaves have very weak foliations that are decoupled from, or partially coupled with, foliation(s) in the adjacent host granodiorite. These internal foliations are characterized by aligned plagioclase, biotite, and hornblende, and are generally parallel to, and strongest within a few centimeters of, the enclave rim. Magmatic foliation in the Sentinel Granodiorite may or may not be deflected within a few centimeters of an enclave, and in some cases lies at high angles to the long axes of enclaves. In most places, elongate enclaves are oriented parallel to local magmatic foliations and lineations, and elongation is positively related to the intensity of such fabrics. In some places, however, spherical to weakly elongate enclaves are present in areas with strong foliations and lineations, or elongate enclaves are present where fabrics are weak or absent.

Enclaves are typically isolated. Rare enclave swarms are generally within several hundred meters of gradational external contacts. Most swarms are ≤10-m across, and are associated with mafic schlieren and granodiorite displaying locally elevated (~20) color indices. Some enclaves are surrounded by, or grade into, schlieren.

Internal Contacts

The term "internal contact" refers to interfaces between rocks of different texture and/or color index within the Sentinel Granodiorite. Internal contacts have a variety of manifestations. Some are diffuse over tens of meters across strike, such as where typical Sentinel Granodiorite grades into rock with a higher color index. Other internal contacts are sharp and defined by small changes in color index or grain size, truncation of older by younger foliations, and truncation of dikes, enclaves, mafic bodies, and schlieren. Most internal contacts are defined by changes in color index. Schlieren increase in abundance within several meters of sharp internal contacts.

Sharp internal contacts can be traced for less than 10-m; diffuse contacts may be up to hundreds of meters long. Most internal contacts in the Sentinel Granodiorite are irregularly oriented or stepped. The more mafic rock along an internal contact tends to be younger and exhibit foliation, schlieren, and elongate enclaves oriented parallel to the contact. In the relatively felsic rock, foliation and other magmatic structures are typically truncated by the contact. Rarely, foliations on both sides of a sharp internal contact are discordant to the contact (Fig. 2).

Where sharp internal contacts are stepped, structures in the more mafic rock tend to be deflected, or bent around corners of the contact (Fig. 3). Within a few tens of meters of several sharp internal contacts, the more mafic rock includes fragments of more felsic rock. These fragments have internal schlieren and magmatic foliation that are truncated sharply by their host.

Internal contacts defined by changes in grain size are generally diffuse and can be traced for, at most, several tens of meters. Schlieren and stretched enclaves lie parallel to these contacts on either the finer- or coarser-grained side, but not on both. Age relationships across these types of contacts are uncertain.

Schlieren

Discontinuous, sub-planar mafic schlieren are ubiquitous in the Sentinel Granodiorite. Sub-planar schlieren strike predominantly WNW and have steep dips. Other schlieren are curved, convoluted, and more rarely concentric. Schlieren are more abundant near internal and external contacts, and are associated with xenoliths and zones of mingled mafic magmas.

Mafic schlieren are defined by thin (0.5-15-cm), alternating layers of relatively mafic and felsic rock. The degree to which mafic schlieren contrast

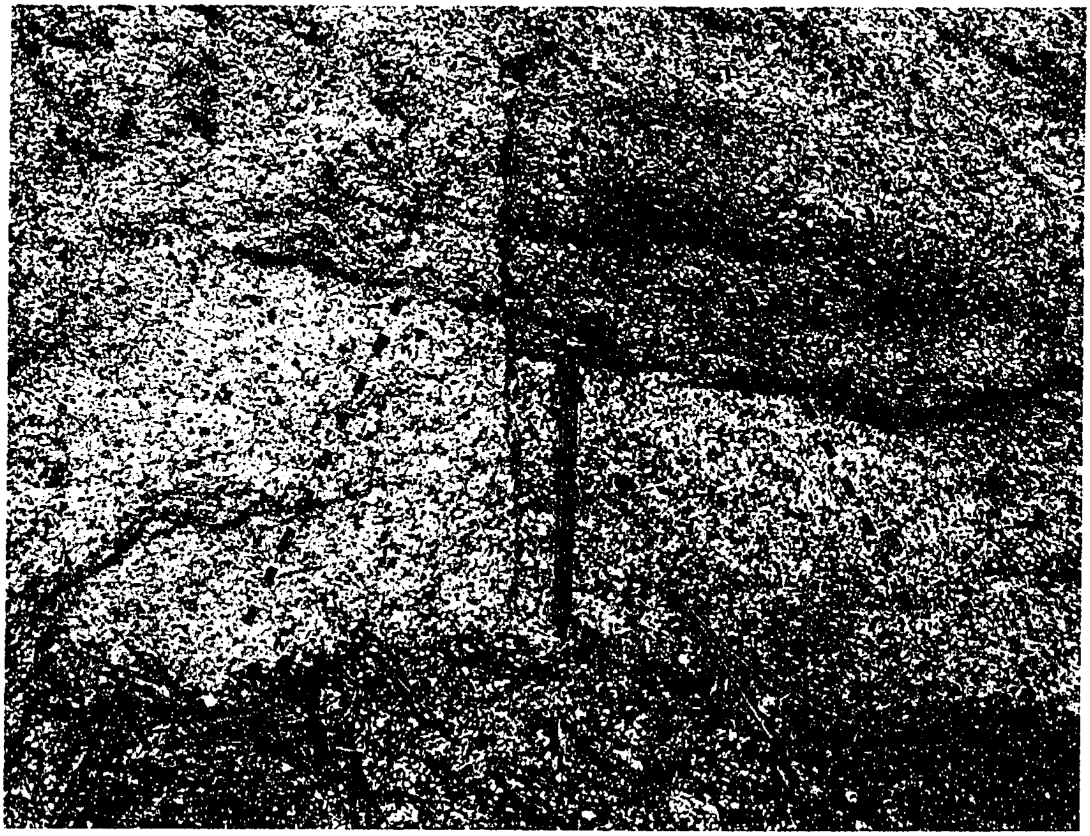


Figure 2. Sharp internal contact in the Sentinel Granodiorite. Note concentration of biotite and hornblende along the contact, and discordant foliations (shown by dashed lines) on either side of the contact. Pencil (15 cm long) for scale.

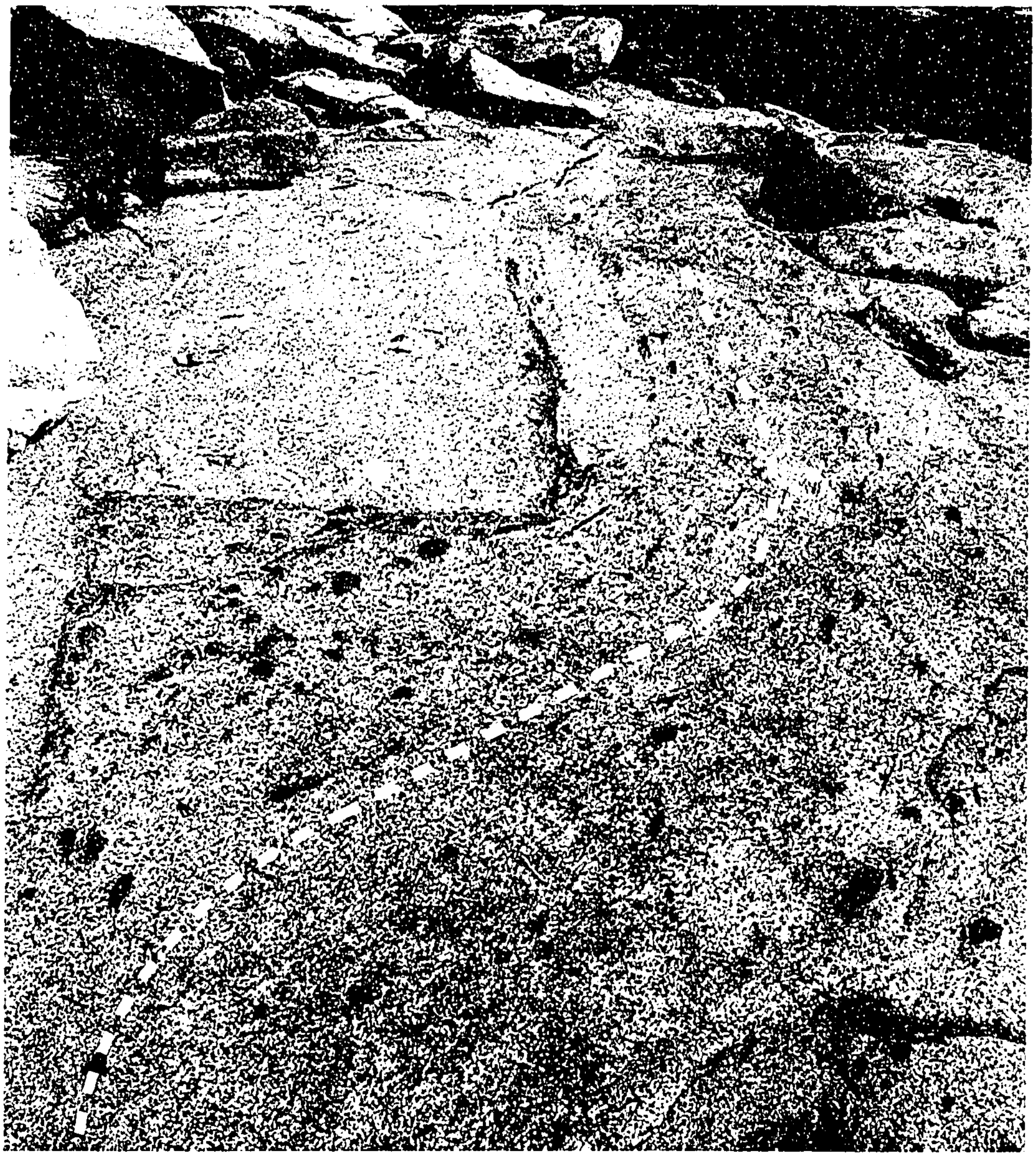


Figure 3. Stepped internal contact in the Sentinel Granodiorite. Note deflection of foliation (parallel to long axes of enclaves and emphasized by dashed line) in the more mafic rock (right side). Concordance of magmatic structures in the more mafic rock suggests it is younger than the felsic rock. 15 cm-long pencil for scale in center of photograph.

with the surrounding rock depends mostly on the color index of the mafic layers, which ranges from around 20 in the faintest schlieren to above 90. These layers typically grade from mafic to felsic towards the "younging" direction, as determined by trough truncations and flame-like structures; very few show felsic to mafic (reverse) grading. Mafic layers generally have sharp contacts with inferred older felsic layers and grade into those that are presumably younger.

Foliation is typically chaotic or swings sharply where schlieren are well developed. The long axes of biotite, hornblende, and plagioclase within schlieren are typically aligned parallel or sub-parallel to schlieren planes. Enclaves that are enclosed by schlieren tend to be elongate parallel or slightly oblique to layering.

Some schlieren define structures (e.g., Bergantz, 2000; Zak and Paterson, 2005) thought to result from instabilities along the surfaces of rigid or semi-rigid domains in magma chambers. The most typical structures in the Sentinel Granodiorite appear similar to trough cross-beds and load casts in sedimentary rocks, except they lie within steeply dipping or vertical schlieren. Troughs are typically tens of centimeters wide and are concentrated along the margins of planar schlieren zones. Less abundant structures that appear similar to load casts are found mostly along steeply dipping interfaces between layers of highly contrasting color index. In these cases, felsic layers may form flame-like structures that are a few centimeters wide and indent or break through mafic layers of the next younger sequence. The "younging" direction of schlieren that define cross-bed-like structures is inferred to be toward non-truncated layers, or the open ends of troughs (Barriere, 1981; Reid et al., 1993; Wiebe et al., 2002).

The Sentinel Granodiorite contains several ladder dikes (e.g., Reid et al., 1993; Weinberg et al., 2001) (Fig. 4). These are 30-100-cm wide and up to several meters long. A concentric, circular sequence of layers is found at one end of the ladder dike, and the rest of the dike consists of alternating mafic and felsic arc-shaped "rungs" that lie perpendicular to the dike margins, are concave towards the concentric end, and are spaced 5-10-cm apart. Directions of "younging" are suggested by truncated schlieren "rungs", which indicate that ladder dikes grew towards the concave direction.

Where chaotic, schlieren have a variety of shapes. Some are faint and wispy, forming swirling concentrations of hornblende and biotite with no significant associated concentrations of felsic minerals. These schlieren are abundant within or near zones of mingled mafic magmas, and connect to, and trail off from, mafic bodies, or form the matrix of enclave swarms.

Pluton-wide Compositional Variations

The Sentinel Granodiorite is on average only slightly more mafic in its western region than it is in the east. The most discrete map-scale compositional gradient is perpendicular to, and within a few hundred meters of, the contact with the Smoky Jack tonalite (see Contacts section). Compositional variations are more common at outcrop scale (i.e., schlieren and internal contacts), or in

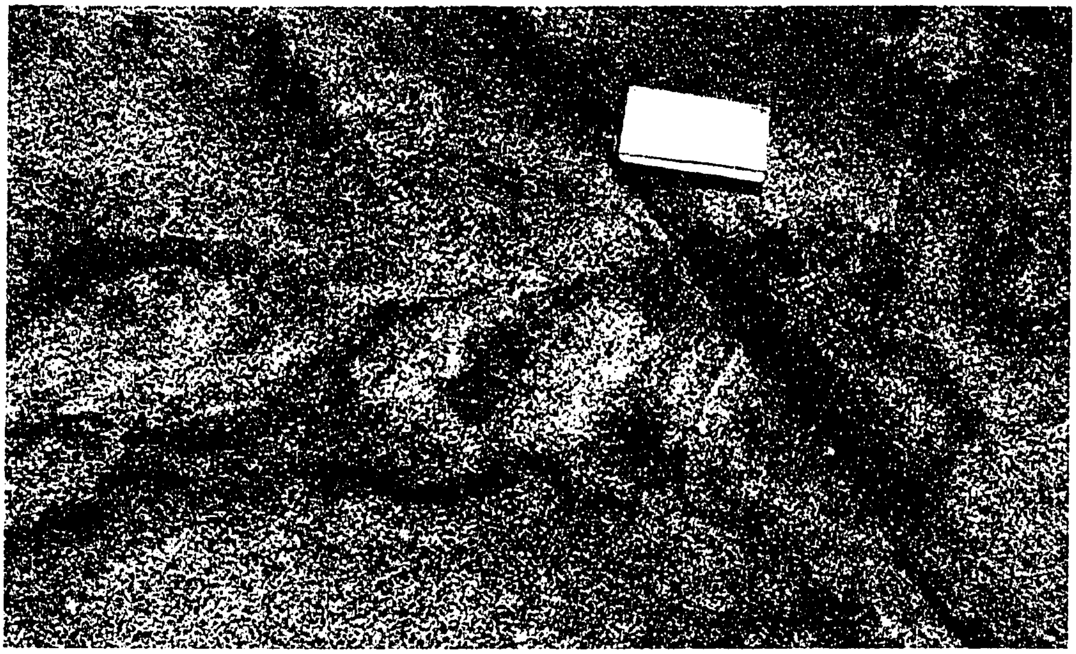


Figure 4. Slightly oblique view of ladder dike exposed on horizontal surface in the Sentinel Granodiorite. Growth of dike is towards the right. Field notebook (19 cm long) for scale.

specific domains of various shapes and extents that do not collectively define a pluton-wide pattern of compositional zonation.

Figure 5 illustrates the cumulative volume percent of the primary minerals composing the Sentinel Granodiorite. The data lie along a WSW-ENE-oriented transect across the southern portion of the granodiorite that extends from the contact with the Smoky Jack tonalite in the west to the contact of the Kuna Crest unit in the east. This transect connects with the western end of a transect across the Tuolumne Intrusive Suite proper published by Bateman and Chappell (1979) and Bateman (1992), which is modified and included in the figure.

Moving east along the modified transect in Figure 5, an abrupt increase in color index and a major decrease in quartz and potassium feldspar occur east of the Sentinel Granodiorite within a unit mapped by Bateman and Chappell (1979) that includes the Kuna Crest Granodiorite and various local quartz diorite and tonalite bodies. Continuing east along the transect through the outer equigranular Half Dome unit, color index decreases and the proportion of potassium feldspar and quartz increases so that the composition of the rocks composing the inner equigranular Half Dome Granodiorite, porphyritic Half Dome Granodiorite, and much of the outer Cathedral Peak Granodiorite are broadly similar to those found in much of the Sentinel Granodiorite.

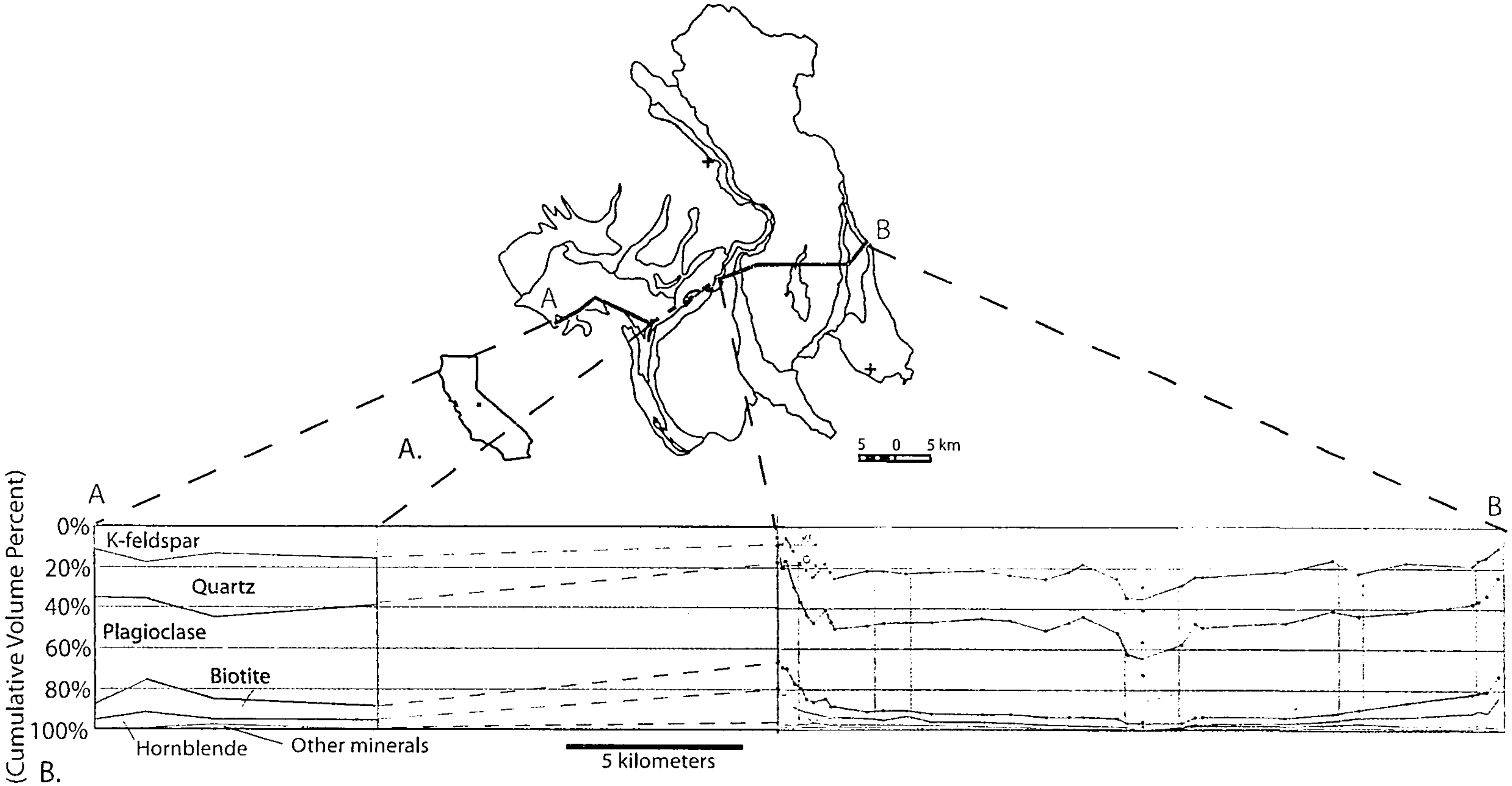


Figure 5. A. Map showing transect across the Tuolumne Intrusive Suite. The dashed segment connects the new western portion of the transect mapped in the Sentinel Granodiote and the eastern portion mapped by Bateman and Chappell (1979). B. Cumulative volume percents along traverse A-B, including data published in Bateman and Chappell (1979) and Bateman (1992). Dashed lines connect two transects and are extrapolated only for scale. Compositional data from Bateman and Chappell (1979) were collected using point counts; compositions were visually estimated in this study and are therefore less precise.

STRUCTURE OF THE SENTINEL GRANODIORITE

The Sentinel Granodiorite is characterized by many internal structures that provide evidence about the construction and evolution of the unit. These include dikes, magmatic foliations and lineations, faults, and ductile shear zones.

Dikes

Abundant aplite and pegmatite dikes intrude the Sentinel Granodiorite. Rare mafic dikes are concentrated near external contacts of the granodiorite (Fig. 6). Dikes range in width from <1-cm to >1-m, and are typically 10-15-cm wide. Dikes can be traced for up to several hundred meters, and irregularly shaped or web-like systems of dikes span up to several tens of square meters. Pegmatite dikes generally strike WNW and dip steeply, whereas aplite and mafic dikes lack a consistent regional orientation. Aplite and pegmatite dikes appear to have formed during the latest stages of crystallization of the Sentinel unit, as in most places they sharply truncate foliation, schlieren, enclaves, and other internal structures.

In two locations, segments of pegmatite dikes appear to be fragmented into ~1- to 2-m-long pieces that are rotated to different angles. Trailing from these fragments are thin schlieren that are continuous for at most a few meters (Fig. 7). In one location, xenocrysts of potassium feldspar are dislodged from the broken ends of dike fragments and are entrained in the schlieren, and their long

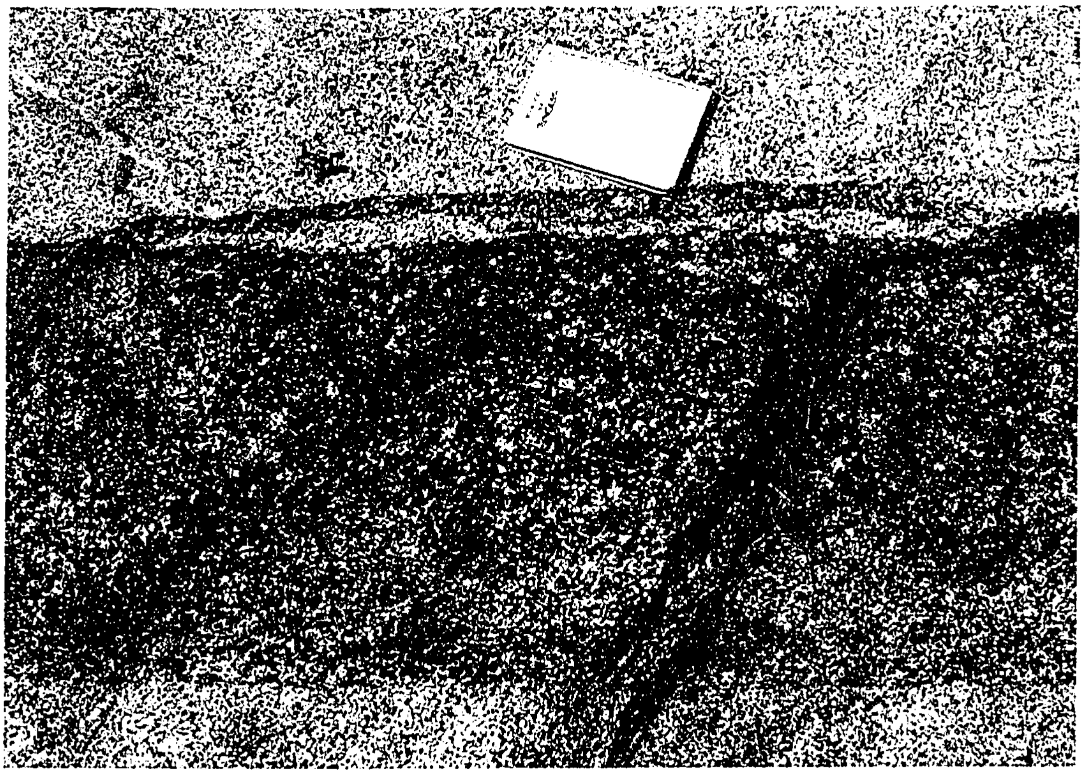


Figure 6. Rare mafic dike in the Sentinel Granodiorite. Note felsic schlieren (defined by concentrations of feldspar) within dike. Field notebook (19 cm long) for scale.

Figure 7. Fragment of pegmatite dike and associated schlieren. Pencil is 15 cm long.

axes are oriented parallel to layering. Rarely, pegmatite dikes include xenoliths of granodiorite. Potassium feldspar in pegmatites forms megacrysts that reach 30-cm, and are on average 5-10-cm, in diameter. Boulders of smoky and milky quartz up to a meter across are weathered out of pegmatite dikes in some locations. Hornblende and biotite typically compose <5% of the mode. Sphene, tourmaline, and epidote may be present in low abundance.

A late, biotite- and hornblende-rich, 50- to 100-cm-wide mafic dike in the eastern part of the Sentinel Granodiorite strikes west, dips moderately to the north, has sharp margins, and is continuous for ≥100-m (Fig. 6). The dike contains 3- to 5-cm-long potassium feldspar and 1-cm-long hornblende phenocrysts. Felsic schlieren in the dike are composed of subtle, discontinuous, 2- to 10-cm-wide layers of plagioclase and potassium feldspar.

Dikes of Sentinel Granodiorite, which reach widths of two meters, typically display mafic to felsic grading inward from their margins. Where these dikes intrude earlier pulses of Sentinel Granodiorite, they are relatively finer-grained, truncate enclaves, and have foliations concordant to that in the host granodiorite. Dikes of Sentinel Granodiorite also intrude El Capitan Granite (Fig. 8) and Granite of Rancheria Mountain.

Magmatic Foliation

The Sentinel Granodiorite contains two steep magmatic foliations: a weak but consistent NW-striking foliation, and a more variably oriented, ~WNW-striking

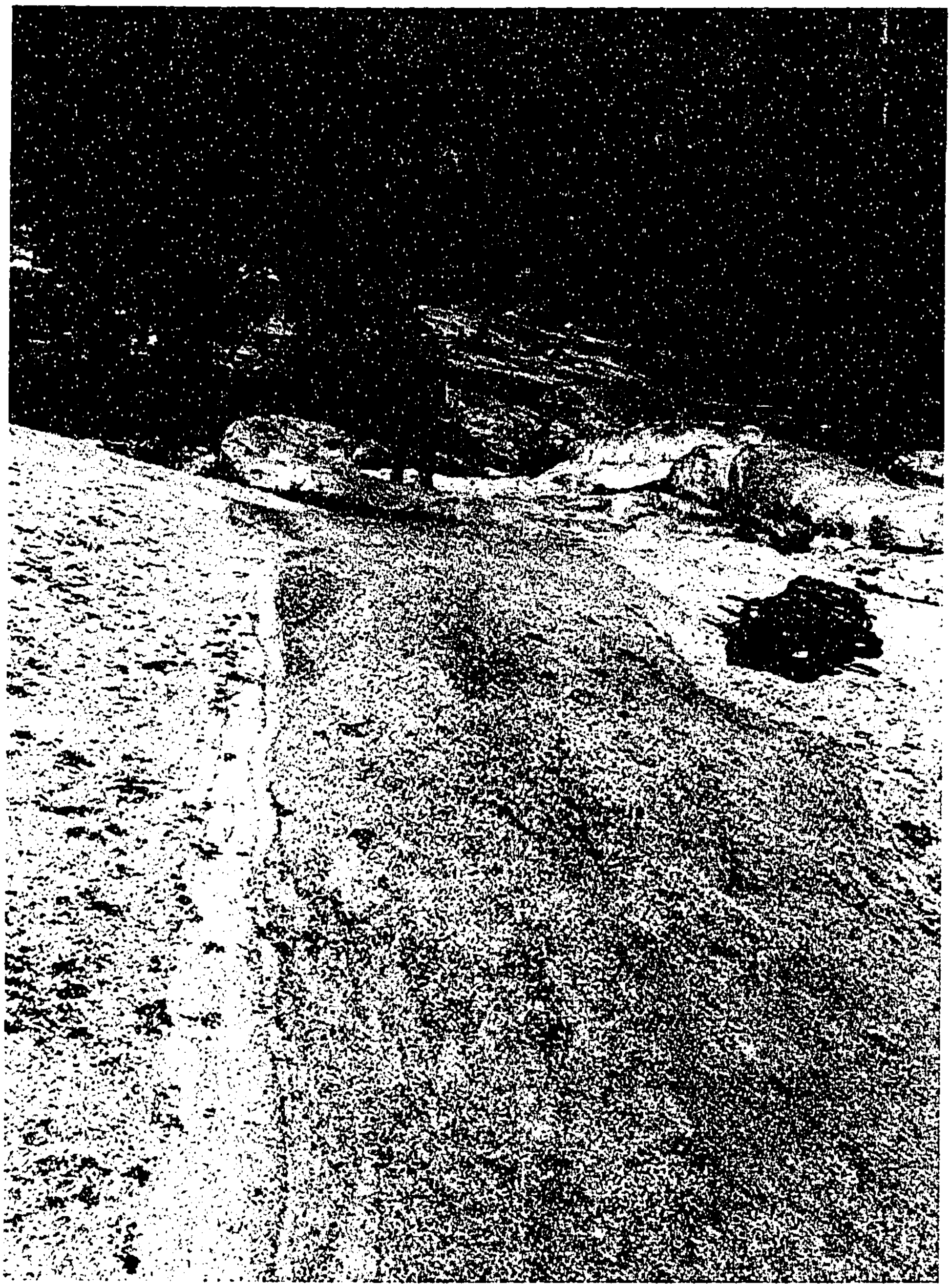


Figure 8. One of many dikes of Sentinel Granodiorite in the El Capitan Granite. Note stepped margins of dike (next to backpacks), and felsic schlieren along left margin. View is toward the northeast.

foliation (Fig. 9). The NW-striking foliation is less pervasive of the two, being present mostly in the western part of the granodiorite (Fig. 10, Plate 1). This foliation is concordant to a regionally developed magmatic foliation found locally in the El Capitan Granite and Granite of Rancheria Mountain (Bateman, 1992). It is discordant to most internal contacts in the Sentinel Granodiorite, and generally lies at high angles to the long axes of elongate enclaves. Where it crosses schlieren at high angles, this foliation is defined by the rotation of only a few scattered hornblende and biotite grains.

The WNW-striking foliation is more variable in direction and intensity than the NW-striking foliation. It is differentiated from the NW-striking foliation because it is typically concordant to local contacts, structures, and elongate enclaves, and does not transgress internal and external contacts. This foliation slightly intensifies within ~100-m of contacts with the Yosemite Valley Intrusive Suite. It is weaker and less consistently oriented in the interior of the Sentinel Granodiorite. This foliation is generally deflected around stepped internal contacts, and thus it can vary greatly (over 90°) in strike within a single outcrop (Fig. 3). Enclaves generally show greater elongation where foliation intensifies.

Regions of the Sentinel Granodiorite that contain a NW-striking foliation typically lack a WNW-striking foliation. Where two foliations are present, the population of hornblende and biotite that defines the WNW-striking foliation is typically greater in number, larger in size, and more euhedral than that defining the NW-striking foliation (see Discussion).

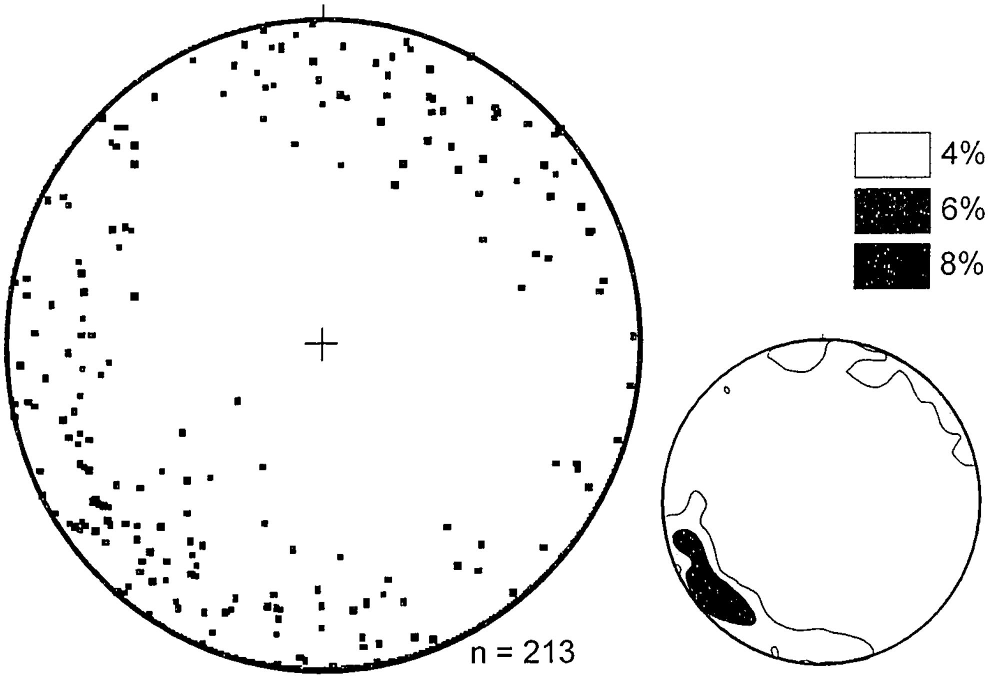


Figure 9. Poles to foliation planes in the Sentinel Granodiorite.

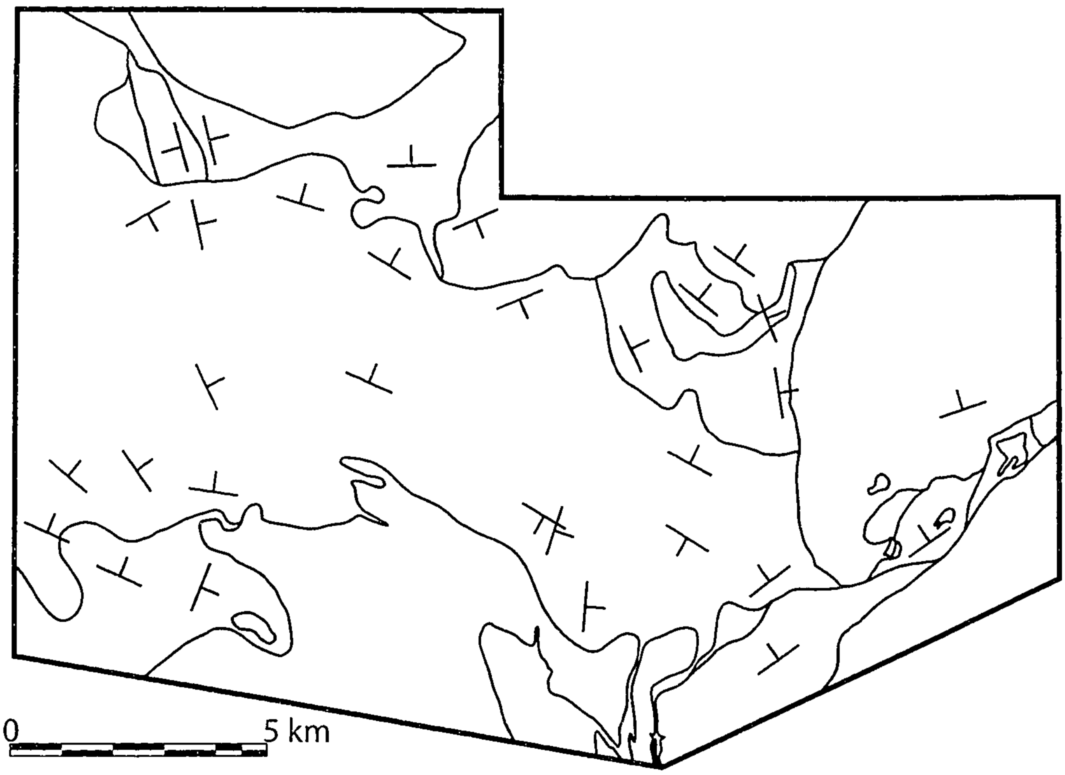


Figure 10. Simplified map of study area showing foliations representative of local dominant fabric orientations. Sentinel Granodiorite is shown by white areas.

Magmatic Lineation

Lineations in the Sentinel Granodiorite typically plunge ~50-75° to the NE, although sparse, moderately- to shallow-plunging lineations vary in trend (Fig. 11, Plate 1). Lineations in the NW-striking foliation are generally weaker than those in the WNW-striking foliation. Aligned hornblende and biotite typically form magmatic lineations; more rarely, lineation is defined by plagioclase.

Lineation intensity does not appear to be directly related to local foliation intensity or proximity to external contacts. A single lineation is typically present and associated with either one or two foliations. Rarely, two lineations are contained within one foliation. Where two foliations are present, it is difficult to assign a lineation to either foliation, unless that lineation is clearly an intersection lineation. This is because available sets of surfaces on which to measure lineation are rarely parallel to both foliation planes.

Figure 11 compares measured lineations in the Sentinel Granodiorite with every possible intersection between all measured foliations in the Sentinel Granodiorite. It shows that measured lineations are within the expected range of possible intersections between measured foliations. Therefore, it is likely that at least some of the lineations represent the intersection of two foliation planes.

Ductile Shear Zones

Ductile shear zones in the Sentinel Granodiorite are less than 30-m in width within the study area; however, thin (<2-m), discontinuous magmatic to

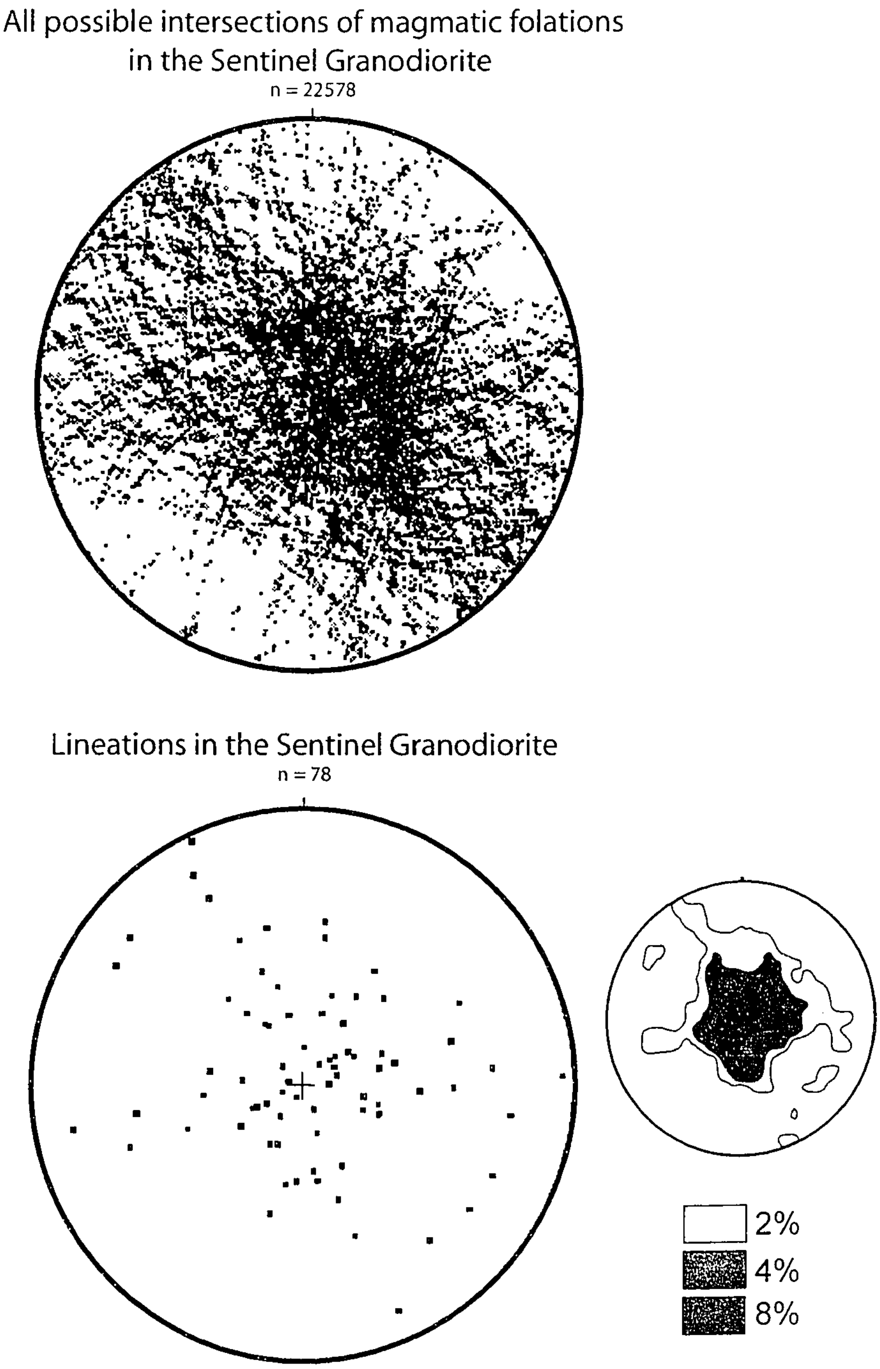


Figure 11. Magmatic lineations in the Sentinel Granodiorite compared to possible foliation intersections.

high-temperature solid-state shear zones are abundant, especially along transitional contacts with the Yosemite Creek and Kuna Crest granodiorites. These shear zones displace schlieren and dikes by no more than a few meters, deflect magmatic foliation, contain highly elongate enclaves, and are localized near areas of mingled mafic magmas or along internal and external contacts. They are defined by zones of intensified magmatic to sub-magmatic foliation and high-temperature recrystallization in the form of quartz subgrains, kinked or recrystallized biotite, and core-and-mantle texture in plagioclase.

A steep, ~30-m-wide, WNW-striking ductile shear zone is developed along a segment of the southern margin of the isolated body of Sentinel Granodiorite that lies within the transitional Sentinel/Yosemite Creek granodiorite (Plate 2). The shear zone deforms the Sentinel Granodiorite and a quartz-diorite body that appears to have intruded along the contact. An intense, concordant magmatic foliation is developed in the nearby transitional rock. The quartz diorite contains centimeter- to meter-scale rounded xenoliths of the Sentinel Granodiorite, and possibly the transitional rock. These xenoliths show solid-state ductile deformation.

The contact between the Sentinel and Kuna Crest granodiorites is overprinted by numerous, steep, NNE-striking, ESE-dipping, 10- to 50-cm-wide magmatic to high-temperature solid-state ductile shear zones. The shear zones dip steeply and contain steeply plunging lineations. Deflection of magmatic foliation and enclaves across the shear zones indicate primarily reverse (Kuna Crest-side up) shear.

Within 10-20-cm of internal contacts and the margins of some dikes, magmatic foliation in the Sentinel Granodiorite may curve. These deflections are typically restricted to the older rocks along internal contacts.

Magmatic Faults

Magmatic “faults”, which are abundant in the Sentinel Granodiorite, are defined in this thesis as relatively sharp (<1-cm-wide) magmatic shear zones. They are most conspicuous where they offset dikes and schlieren; in these cases, no more than a few meters of horizontal separation is apparent. Some magmatic faults that offset large aplite or pegmatite dikes are intruded by melt from those dikes.

Magmatic faults are generally observed on planar, horizontal surfaces, so the true magnitude and direction of slip is difficult to quantify. Some dikes show alternating dextral and sinistral horizontal separations where they are cut by sets of magmatic faults with parallel strikes, implying that slip was chiefly vertical.

Deflections in magmatic foliation are generally subtle or non-existent across the faults, which may be evidence that residual magma intruded along and sealed the faults. This relationship suggests the faults pre-date or are contemporaneous with local magmatic fabrics.

Solid-State Deformation of Units

With the exception of the metamorphic rocks, all units show weak but widespread solid-state deformation in the form of kinked or bent biotite, grain boundary migration of plagioclase, and minor elongation, undulose extinction, and/or subgrain development in quartz. Recrystallization of quartz is most prevalent, and recrystallized plagioclase and deformed biotite are generally most abundant in ductile shear zones near the margins of units (see Contact Relationships section).

Steeply dipping, <2-m-wide ductile shear zones are abundant in the Sentinel Granodiorite near contacts, particularly those that are transitional. These ductile shear zones are defined by intensified magmatic to sub-magmatic foliations, quartz subgrains, kinked or recrystallized biotite, and core-and-mantle texture in plagioclase.

CONTACT RELATIONSHIPS

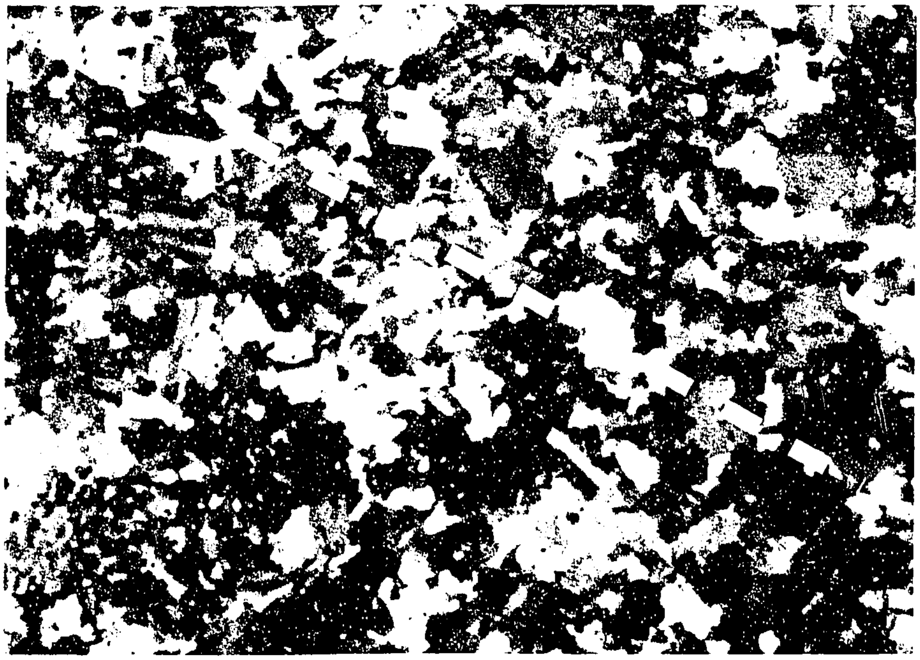
The following chapter begins by describing the contacts between the Sentinel Granodiorite and Smoky Jack tonalite, and the tonalite and El Capitan Granite. Next, contacts between the Sentinel Granodiorite and units of the Yosemite Valley Intrusive Suite are described. Finally, contacts of the Sentinel Granodiorite with the Yosemite Creek and Kuna Crest granodiorites are discussed. Particular emphasis is placed on these last two contacts, as they provide evidence regarding the relationship between the Tuolumne Intrusive Suite proper and its outliers.

Sentinel Granodiorite and Smoky Jack Tonalite

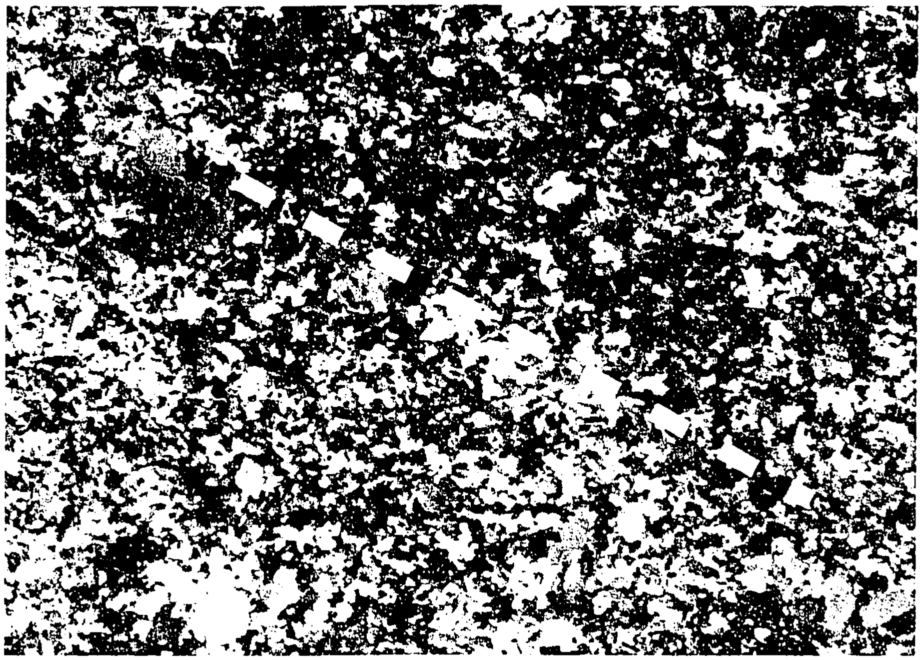
The Sentinel Granodiorite is in contact on the southwest with the Smoky Jack tonalite (Fig. 1, Plate 1). This contact is an irregular, compositionally diffuse zone up to 50-m wide that exhibits intense, contact-parallel, magmatic to solid-state foliation. A few segments of the contact are sharp for up to 10-m along their length and are stepped or curved. Diffuse segments are defined by a decrease in color index from 20-25 near the Smoky Jack tonalite to 15-20 closer to the Sentinel Granodiorite. Zones of mafic schlieren within the diffuse segments of the contact are a few tens of centimeters to several meters wide, and are typically contact-parallel. Where one set of schlieren truncates a second, the younging direction is towards the Smoky Jack tonalite. Enclaves are slightly more abundant in diffuse segments than in either unit and are elongate parallel to foliation. Most enclaves are fine-grained to microgranular and porphyritic, containing 2- to 3-mm-long plagioclase phenocrysts. Enclaves are generally 5-10-cm long, and aspect ratios range between 3:1 and 20:1 on horizontal surfaces; the highest ratios are found locally where foliation is most intense. A few meter-wide enclave swarms are scattered within and around the transitional zone.

An intense, magmatic to sub-magmatic foliation is present in the Smoky Jack tonalite near the contact and is strongest within meter-thick, foliation-parallel zones and is chaotic or folded between thin, steeply-dipping ductile shear zones that strike at various high angles to foliation. Folds are gentle, have wavelengths of ~10-cm, and have steep axial planes that strike parallel to the shear zone boundaries. The shear zones are magmatic to solid-state, spaced several meters apart, are 5-10-cm wide, offset enclaves, schlieren, and dikes, and generally have dextral separation of up to 50-cm on horizontal surfaces.

An abrupt change in fabric intensity best defines the contact, as foliation in the Sentinel Granodiorite is typically much weaker than that in the Smoky Jack tonalite (Fig. 12). Plagioclase in the tonalite near the contact shows high-temperature recrystallization in the form of core-and-mantle texture; 1- to 2-mm-diameter re-crystallized plagioclase forms mosaics around igneous cores containing bent twins. Quartz subgrain boundaries intersect each other at high angles to form a chessboard-like texture (Kruhl, 1996).



A.



B.

1 cm

Figure 12. Photomicrographs showing difference in foliation (defined by dashed line) intensity between: A) the Sentinel Granodiorite, and B) the Smoky Jack tonalite. Samples were taken within 10-m of either side of the contact. Note finer grain size of Smoky Jack tonalite due to development of contact-parallel solid-state foliation.

The color index in the Sentinel Granodiorite generally increases from around 15 to nearly 20 within several hundred meters of the contact, although in a few locations it decreases to around 10. In one of these locations, the Sentinel Granodiorite contains subtle, steeply dipping, NNW-striking layers of concentrated plagioclase that are several centimeters wide and continuous for only a few meters. A weak, E-W-trending magmatic foliation defined by the alignment of hornblende and biotite overprints the layering.

Randomly oriented, 5- to 10-cm-wide aplite and pegmatite dikes are more abundant near the contact and sharply cut the shear zones. Aplite dikes contain small, ~1-mm-wide garnets, and pegmatite dikes contain graphic potassium feldspars up to 5-cm in diameter.

Smoky Jack Tonalite and El Capitan Granite

The only direct contact between these units lies along the northwest end of a lobe of El Capitan Granite in the southwest corner of the map area, where a thin swath of the tonalite bends around the lobe and pinches out towards the east (Plate 1). Here, the contact is intruded by fine-grained gabbroic bodies and is marked by a complex, 30-m-wide magmatic shear zone. The shear zone strikes WNW and dips vertically. Deformed fragments of tonalite and granite less than a meter across are included in the mafic rock and are elongated parallel to the shear zone. On horizontal surfaces, these fragments are generally rhomboid-shaped; their orientations suggesting dextral shear. Magmatic and high-temperature solid-state foliation in the nearby tonalite and granite, respectively, dip steeply and are also parallel to the zone (Plate 1).

Contacts between the Smoky Jack tonalite, the quartz diorite and tonalite bodies mapped by Kistler (1973) and Bateman (1992), and the El Capitan Granite are difficult to locate due to poor exposure, and therefore age relationships between the units are not easily established. Kistler (1973), however, indicated that the Quartz Diorite of South Fork of Tuolumne River is older than the El Capitan Granite.

Two segments of a contact between the quartz diorite and El Capitan Granite were mapped in the southwest corner of the study area (Plate 1). The southern segment is choked with meter-scale xenoliths of quartz diorite. These xenoliths are randomly oriented, have sharp, sub-angular margins, and are similar in texture and composition to the main body of quartz diorite that lies in contact with the El Capitan Granite (Fig. 13). Foliation in the granite wraps around the xenoliths. The xenoliths indicate that the El Capitan Granite is younger than the quartz diorite. Kistler (1973) placed a symbol indicating this age relationship along the other segment of the contact, which lies ~1.5-km to the north.

The northern segment of the contact is more complex. It is defined by a steep, WNW-striking, ~50-m-wide ductile shear zone that is intruded by aplitic, pegmatitic, and fine-grained quartz dioritic dikes. The quartz diorite and El Capitan Granite lie southwest and northeast of the zone, respectively. Along the

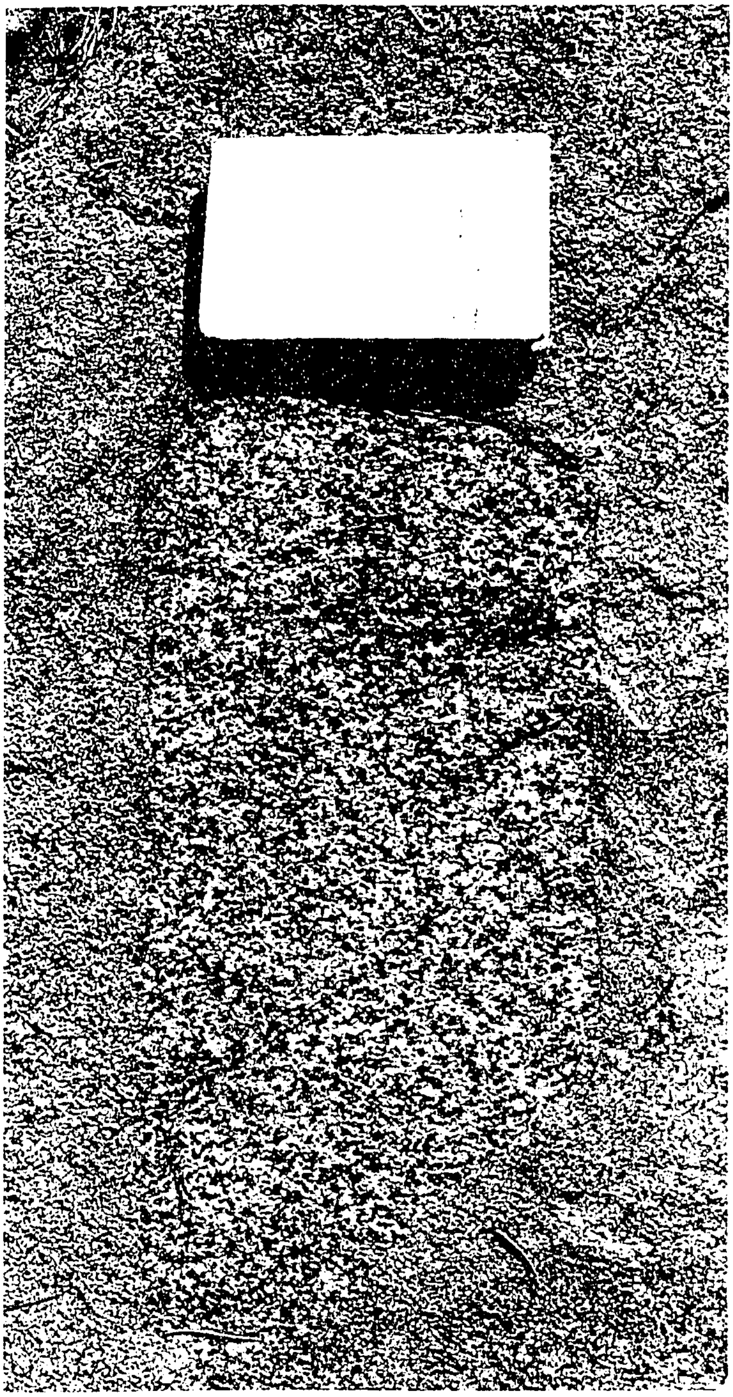
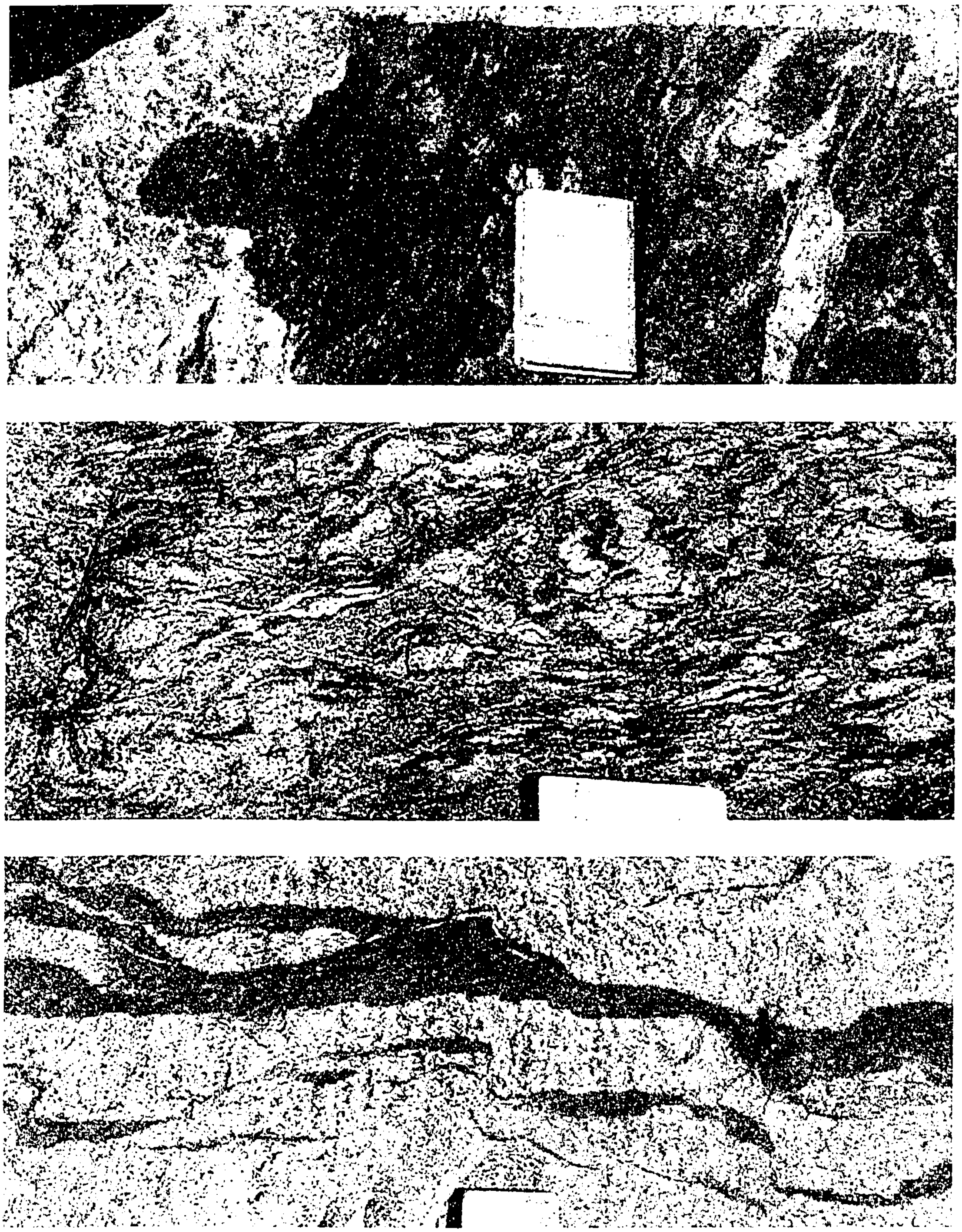


Figure 13. Xenolith of quartz diorite in El Capitan Granite. Field notebook (19 cm long) for scale.

southwestern margin of the shear zone, sinuous, 1- to 10-cm-wide aplite dikes intrude the quartz diorite. Farther into the zone, these dikes increase in thickness to over a meter, grade towards pegmatitic textures, and isolate angular, ≤1-m-wide fragments of the quartz diorite; these fragments exhibit intense, contact-parallel, high-temperature solid-state foliation, and have long axes parallel to the shear zone (Fig. 14A). Near the center of the shear zone, foliation in the fragments is complexly folded, and the fragments have a smaller grain size. Folds have 2-20-cm wavelengths (Fig. 14B) and axial planes that are generally perpendicular to the strike of the zone. Most of the distance across the zone towards the El Capitan Granite, quartz diorite fragments share diffuse contacts with very fine-grained dikes that are similar in composition and mode to the quartz diorite. The diffuse margins, which are up to two centimeters wide, may indicate that the partially melted outer margins of the quartz diorite fragments mixed or reacted with the dikes. These dikes are up to a meter wide, contain many small mafic enclaves, and also intrude the El Capitan Granite.

Strained quartz grains and recrystallized biotite and potassium feldspar define a moderately intense, high-temperature solid-state, contact-parallel foliation and steeply plunging, southwest-trending lineation in the El Capitan Granite. Aspect ratios of the quartz grains are approximately 4:2:1. Elongate quartz subgrains are oriented perpendicular to foliation. Some quartz grains between thin layers of biotite have sigmoidal shapes that indicate reverse-slip, El Capitan-side-up, non-coaxial shear. Lineation is strongest within a few meters of



A)

B)

C)

Figure 14. Contact zone between diorite unit and El Capitan Granite:
A) strained, fine-grained quartz diorite intruded by pegmatite dike;
B) complex folding of migmatitic layering in quartz diorite unit; and
C) folded El Capitan Granite intruded by very fine-grained quartz diorite dikes, which are also folded in places. Field notebook (19 cm-long) for scale.

the contact, where foliation is openly folded. Folds have 0.1-1-m wavelengths (Fig. 14C).

Sentinel Granodiorite and Yosemite Valley Intrusive Suite

Contacts between the Sentinel Granodiorite and units of the Yosemite Valley Intrusive Suite are generally sharp and stepped. The Sentinel Granodiorite is typically surrounded by a weak structural aureole in the Yosemite Valley granites that is several meters wide, and defined by weak solid-state strain of quartz. Granite xenoliths are scarce in the interior of the granodiorite, but increase in abundance within several hundred meters of the contacts. Granitic xenoliths comprise up to 80% of the rock within several tens of meters of the El Capitan Granite, but typically comprise less than 10% of the rock near contacts with other units of the Yosemite Valley Intrusive Suite. Next to some contact segments, the granites, particularly the Granite of Rancheria Mountain and El Capitan Granite, are intruded by finer-grained granitic dikes that are modally similar to the host granites. These dikes are typically less than a meter wide, have sharp margins, and contain magmatic to sub-magmatic fabrics that are parallel to the dike margins. These dikes do not appear to originate from the granodiorite, and may instead result from partial melting of the granite during intrusion of the granodiorite. Where present, structural aureoles overprint these dikes.

Sentinel Granodiorite and El Capitan Granite

The southern margin of the Sentinel Granodiorite shares a sharp, stepped contact with the El Capitan Granite. Individual steps are mostly tens to hundreds of meters long (Plate 1). Along the southern swath of granodiorite that crosses Yosemite Valley, steps are more variable in length, but are typically more closely spaced (meter-scale) because of the greater abundance of granodiorite dikes that intrude the granite. The swath is schematically mapped by earlier workers as a complex network of dikes that surround angular fragments of the El Capitan Granite (Calkins, 1985; Huber et al., 1989; Peck, 2002; Glazner et al., 2004) (Fig. 1).

Angular to sub-angular xenoliths of El Capitan Granite are concentrated within several hundred meters of the contact. Xenoliths range in diameter from a few centimeters to tens of meters and are on average one to three meters across. High-temperature solid-state foliation is generally strongest in smaller (<2-m-wide) xenoliths, and is weak or absent in larger xenoliths. The intensity of solid-state foliation in some small xenoliths is greater than that in the nearby granite. Magmatic foliation in the Sentinel Granodiorite wraps around most xenoliths.

A weak, discontinuous structural aureole is developed in the El Capitan Granite next to the Sentinel Granodiorite. This aureole is a few meters wide and is marked by contact-parallel, high-temperature solid-state foliation defined by solid-state strain of quartz, which also defines a weak, steeply plunging lineation.

Quartz shows elongate subgrains, biotite is kinked or bent, and recrystallized plagioclase and potassium feldspar form core-and-mantle structure and medium-grained mosaic textures. The maximum aspect ratio of quartz is ~1.5:1 on horizontal surfaces (perpendicular to lineation). The aureole is strongest where the contact is sharp and planar, and where there is a local paucity of granitic xenoliths in the Sentinel Granodiorite.

Within several hundred meters of the contact, the Sentinel Granodiorite exhibits a slight increase in color index and magmatic foliation intensity. Magmatic foliation is contact-parallel, and is deflected around granitic xenoliths. Enclaves and mafic dikes increase in abundance in the granodiorite near the contact, and mafic dikes lie along several segments of the contact near the Smoky Jack tonalite. These dikes: (1) intrude both the El Capitan Granite and Sentinel Granodiorite; (2) contain closely spaced, randomly oriented, cm-scale shear zones and magmatic faults with only slight (<5-cm) horizontal offset and no consistent kinematics; (3) include xenoliths of both the granite and granodiorite that exhibit high temperature solid-state recrystallization, and (4) are cut by 1- to 3-cm-wide dikes of granodiorite and aplite that display little or no deformation.

Sentinel Granodiorite and Granite of Rancheria Mountain

The contact between the Sentinel Granodiorite and Granite of Rancheria Mountain is sharp and stepped, and a weak structural aureole defined by elongate quartz (up to 3:1 on horizontal surfaces) extends only a few meters into the granite. Lineation plunges steeply to the north. Meter-scale, angular xenoliths of granite are concentrated in the Sentinel Granodiorite near the contact, and display both high-temperature solid-state and magmatic fabrics that vary in strike. Magmatic foliation in the granodiorite intensifies near the contact, and is deflected around granitic xenoliths.

Sentinel Granodiorite and Mount Hoffman Granite

The wide gradational contact between the Sentinel and Yosemite Creek granodiorites meets the roughly N-S-striking western margin of the Mount Hoffman Granite at a high angle (Fig. 1, Plate 2). The Mount Hoffman Granite is in sharp contact with the granodiorites. Magmatic foliation and modal layering in the Mount Hoffman Granite are locally E-W-striking, and are sharply truncated by the contact. No discernable structural aureole is developed in the granite.

Foliation and mafic schlieren in the Sentinel Granodiorite and transitional Sentinel/Yosemite Creek unit are parallel to the contact, and dip steeply towards the Mount Hoffman Granite. Foliation in the Sentinel Granodiorite does not intensify near the contact. Schlieren increase slightly in abundance. Short segments of the contact are intruded by ~5- to 10-cm-wide pegmatite and aplite dikes. No xenoliths are found in the granodiorite near the contact, and no dikes of granodiorite intrude the Mount Hoffman Granite.

Sentinel and Yosemite Creek Granodiorites

Between the Granite of Rancheria Mountain to the west, and Mount Hoffman Granite to the east, there is an ~8-km-long, E-W-striking contact between the Sentinel and Yosemite Creek units (Fig. 1; Plate 1).

The western half of this contact is a layered zone several tens of meters wide. Layering is defined by 1- to 20-cm-thick, discontinuous, alternating biotite- and plagioclase-rich layers. Biotite reaches 5-mm in diameter, and euhedral plagioclase up to 8-mm in diameter is concentrated in the more felsic layers. Truncated layers and trough-cross-bed-like structures in schlieren indicate growth towards the Sentinel Granodiorite (Fig. 15). Near the contact, the Yosemite Creek Granodiorite contains contact-parallel, elongate (~6:1 on horizontal surfaces) enclaves that range in length between one centimeter and one meter. Quartz diorite bodies that are mingled with the Yosemite Creek Granodiorite increase in abundance towards the contact. Irregularly-shaped quartz diorite bodies are up to tens of meters across. Both the Sentinel and Yosemite Creek granodiorites have steep, NNW- to N-striking, weak magmatic foliations that are continuous across the contact.

Farther east, this contact is defined by a progressively wider transitional phase (transitional Sentinel/Yosemite Creek granodiorite), reaching a width of 4-km (Fig. 16, Plate 2). The transitional zone is dominated by textures most similar to the Sentinel and Yosemite Creek units in the south and north, respectively. With the exception of an isolated 1-km^2 body of Sentinel Granodiorite that lies

Figure 15. Possible load casts or troughs within schlieren along the northern boundary of the transitional unit. Arrow denotes inferred growth direction, which is to the NE. Field notebook (19 cm long) for scale.

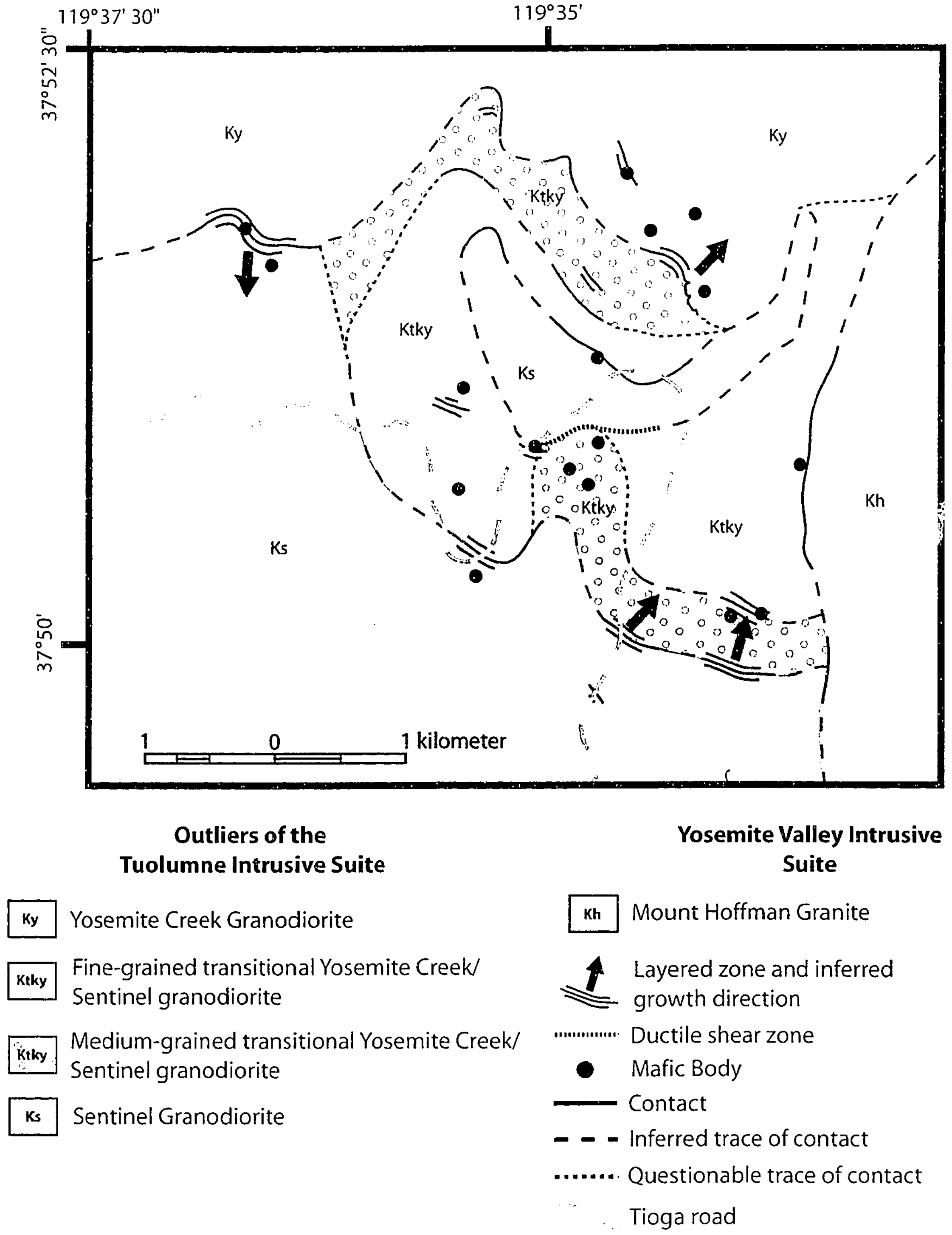


Figure 16. Schematic map of transitional Sentinel/Yosemite Creek granodiorite.

almost completely within it, the transitional unit grades from a Sentinel- to Yosemite Creek-like texture along a roughly NNE direction (Fig. 16). This gradient is interrupted by local grain size variations, variations in boxy plagioclase concentrations, and moderately abundant, sharp internal contacts. These internal contacts form where finer-grained rock intrudes and contains xenoliths of coarser-grained rock.

Layered zones that range between several meters and several hundred meters wide constitute the majority of the southern boundary and parts of the northern boundary of the transitional zone, and also surround parts of the isolated body of Sentinel Granodiorite (Fig. 16, Plates 1 and 2). There are generally only subtle differences in grain size and concentration of boxy plagioclase phenocrysts across these layered zones, except for the northern margin of the isolated Sentinel body, where textures in the transitional rock are more like the Yosemite Creek Granodiorite.

The northern margin of the transitional unit is intruded by ~5- to 50-cm-wide sheets of Yosemite Creek Granodiorite across an ~200-m-wide zone. The sheets are generally parallel to layering in the transitional rock, contain concordant layered schlieren, are discontinuous and gently curved, and are intruded by concordant, 5- to 10-cm-wide aplite dikes. Sheets can be differentiated from layers because they have sharp margins, and in a few places, truncate layering, whereas two adjacent layers exhibit slightly more diffuse boundaries. Boxy plagioclase phenocrysts and mafic schlieren dramatically increase in abundance in the transitional unit within ~20-m of the sheeted zone.

The southern boundary of the transitional zone is less discrete than the northern boundary. The transitional unit is locally similar in texture to the Sentinel Granodiorite, and the layered zones that typify the southern boundary are discontinuous. Within ~200-m of this contact, the Sentinel Granodiorite displays a slight increase in concentration of boxy plagioclase, and magmatic foliation swings into parallelism with the contact. The highest contrast in grain size and texture across the southern boundary is in areas where layering is present.

In the layered zones along the northern and southern boundaries of the transitional unit, layers are 5-mm to 50-cm thick, planar to highly irregularly-shaped or convoluted, discontinuous, and range from fine- to coarse-grained. Layers typically alternate between relatively mafic (color index between 20 and 50) and felsic (color index between 10 and 15), have sharp to diffuse boundaries, and may display mafic to felsic grading within individual layers. Mafic layers are finer-grained than felsic layers, have elevated biotite-to-hornblende ratios and modal sphene, and contain poikilitic hornblende, which encloses biotite.

Felsic layers are more variable in texture. In thin section, plagioclase exhibits subtle, layer-parallel alignment and minor recrystallization by grain boundary migration. Quartz is slightly elongate parallel to layering and displays well-developed elongate subgrains that are oriented at high angles to the long axes of the original grains. Potassium feldspar is interstitial.

Both mafic and felsic layers contain enclaves, which range between equidimensional and flattened, even within the same layer. Magmatic foliation and long axes of enclaves are typically concordant to layering. Trough-truncations of layers and load cast- and flame-type structures in the layered zones along the southern and northern boundaries of the transitional unit indicate a NNE younging direction (Fig. 15).

The transitional unit is characterized by weak, but widespread high-temperature solid-state deformation. Quartz shows parallel or chessboard sub-grain development, and plagioclase and potassium feldspar form isolated, <8-mm-long, recrystallized mosaics in foliation-parallel, elongate patches.

Yosemite Creek Granodiorite and Granite of Rancheria Mountain

The contact between the Yosemite Creek Granodiorite and Granite of Rancheria Mountain is poorly exposed. Angular, meter-scale granite xenoliths are found within the granodiorite, and both units retain their distinct textures and compositions within ~100-m of the contact.

Sentinel and Kuna Crest Granodiorites

The contact between the Sentinel and Kuna Crest granodiorites ranges from sharp to gradational within the study area. It is marked by contact-parallel, magmatic to solid-state high-temperature ductile shear zones (Miller and Miller, 2003) in both units. The shear zones are typically 10-20-cm wide and generally strike northeast with steep southeast dips. Enclave deflections and kinematics of microstructures within these zones indicate Kuna Crest-side-up reverse-slip, with displacements typically less than one meter.

Gradational segments are several hundred meters wide and discontinuous (Plate 1). They are defined by several NW to SE trends: plagioclase increases in diameter and is more euhedral; color index increases from ~15 to ~20; hornblende increases in modal abundance, but becomes finer grained; and biotite forms larger aggregates up to a centimeter across. Plagioclase in the transitional phase and late Kuna Crest dikes exhibits a greater range of compositional zoning than in the nearby Sentinel Granodiorite.

The transitional Kuna Crest phase (Ktkc) is in contact with the El Capitan Granite (Plate 1). This contact is sharp and truncates foliation in the granite. In places, contact-parallel aplite dikes intrude the contact. A weak solid-state fabric in the El Capitan Granite within several meters of the contact defines a narrow structural aureole. Meter-scale xenoliths of granite are enclosed in the transitional Sentinel/Kuna Crest granodiorite within a hundred meters of the contact.

Kuna Crest and Equigranular Half Dome Granodiorites

A contact between the Kuna Crest and equigranular Half Dome granodiorites strikes SW-NE across the southeast corner of the study area. Within the study area, the contact is marked by the presence of thin (<15 cm), NE-striking, steeply dipping solid-state ductile shear zones in the Kuna Crest Granodiorite and the absence of such structures in the equigranular Half Dome Granodiorite. A steep lineation and foliation curvature indicates reverse kinematics for the shear zones. Several of these shear zones are intruded by concordant aplite dikes. The Half Dome unit locally includes angular to sub-angular, meter-scale xenoliths of Kuna Crest Granodiorite. The xenoliths have a strong sub-magmatic to solid-state foliation that is discordant to those in adjacent xenoliths, implying some are rotated.

An ~1000-m^2, elliptical domain of concentrated enclaves and xenoliths is elongate in a SW-NE direction and lies in the equigranular Half Dome Granodiorite within tens of meters of the contact and roughly 600-m north of the Tioga Pass road. The xenoliths constitute about 40% of the domain. The interstitial material is typical of the Half Dome unit. Enclaves vary in texture and composition, but are generally round to elliptical in cross-section and between 5-cm and 10-cm in diameter. Most enclaves are fine-grained, and roughly half contain plagioclase phenocrysts up to 5-mm in length. Elliptical clots of relatively large hornblende and biotite comprise a small percentage of the enclaves. Some of these clots have diffuse edges.

Xenoliths of granite, granodiorite, aplite, pegmatite, and metamorphic rocks are intimately mixed with, and similar in abundance to, the enclaves within the body. The xenoliths vary in shape and angularity, but vary little in size; most are 10-20-cm in diameter. Less than 2% of the xenoliths are schistose metasedimentary rocks that resemble other metasedimentary xenoliths in the study area. The majority of xenoliths in the body are granodioritic and appear similar to the Kuna Crest unit, although a strong solid-state foliation in the xenoliths makes them difficult to identify. The granodiorite xenoliths lack a consistent foliation orientation. Granitic xenoliths lack foliation and are generally less angular and more irregular in shape than the granodioritic or metamorphic xenoliths. They are finer-grained than the Mount Hoffman Granite, the closest granitic unit. Angular to sub-angular aplite and pegmatite fragments comprise ~5% of the xenoliths.

Both enclaves and xenoliths, with the exception of the granitic xenoliths, exhibit igneous rinds of plagioclase and potassium feldspar. These rinds are up to 1.5-cm thick and surround roughly 80% of the enclaves and xenoliths.

The margin of the domain is generally diffuse and defined by an outward decrease in xenolith and enclave concentrations. In a few places, the margin of the body is sharp and surrounded by a <1-m-thick zone of concordant rhythmic schlieren in the equigranular Half Dome Granodiorite.

DISCUSSION

Emplacement of the Sentinel Granodiorite

The marginal areas of a pluton typically provide an incompletely preserved record of host rock material transfer processes related to construction and emplacement of the pluton. Because material transfer processes do not increase or decrease the volume of the crust, the ascent and emplacement of voluminous magma bodies are typically accompanied by simultaneous downward (i.e., ductile return flow, stoping, floor subsidence) and/or upward (roof uplift) transfer of surrounding host rocks (Saleeby, 1990; Paterson and Vernon, 1995; Paterson et al., 1996; Brown and McClelland, 2000; Cruden, 1998; 2006), except perhaps where permissive intrusions are aided by sub-horizontal crustal extension (e.g., Hutton, 1992; Tikoff and Teyssier, 1992). The rheological response of host rocks to pluton emplacement ranges from brittle to ductile. Brittle processes, such as stoping and roof uplift, are generally associated with the relatively cool, shallow crust (e.g., Buddington, 1959). Stoping is also recognized as a material transfer process in many deep-crustal plutons (e.g., Paterson et al., 1999). Conversely, ductile flow of host rock is typically favored in the deep crust but is also evident in structural aureoles surrounding many plutons emplaced in the mid- to shallow crust (e.g., Buddington, 1959; Miller and Paterson, 1999; Zak and Paterson, 2005; Cruden, 2006).

Structural aureoles surrounding many plutons emplaced in the mid- to shallow crust, including those surrounding the Sentinel Granodiorite, are relatively narrow, indicating ductile flow of host rocks played only a minor role in emplacement of such plutons (e.g., Paterson and Vernon, 1995; Paterson et al., 1996). The structural aureole surrounding the Sentinel Granodiorite is at most a few meters wide, which is roughly .001 body radii. It is possible that a wider aureole characterized by higher strain surrounded the Sentinel Granodiorite and was stoped out by later pulses of magma. The minimal ductile strain in granitic xenoliths, however, indicates that either extensive amounts of strained wall rock were removed from the present level by stoping, or that no such aureoles existed.

Stoping is evidently an important material transfer process associated with at least the final stages of emplacement of the Sentinel Granodiorite, as indicated by granitic xenoliths in the granodiorite, and sharp, stepped contacts between the granodiorite and granitic host rocks that truncate structures in the granites.

Given that the final stages of growth of the granodiorite were likely accommodated at least in part by stoping, there are few xenoliths in the granodiorite at this crustal level. This issue is encountered in many plutons and used as an argument by some against stoping as a significant material transfer process (e.g., Glazner and Bartley, 2006). Proponents of stoping cite sharp truncations of older host rock structures along stepped contacts of plutons, xenoliths, and the lack of significant lateral shortening in surrounding host rocks.

It may be that the majority of stoped granitic xenoliths in the Sentinel Granodiorite were assimilated or descended to greater depths (e.g., Pitcher and Berger, 1972; Clarke et al., 1998; Beard et al., 2005).

Sharp contacts such as those forming the margins of the Sentinel Granodiorite may also form along plutons that were emplaced with little or no downward host rock transport. Tikoff and Teyssier (1992) propose that plutons of the nearby Cathedral Range Intrusive Epoch (including the Tuolumne Intrusive Suite proper) were passively emplaced into *en echelon* P-shear bridges related to a syn-magmatic strike-slip system along the magmatic arc. This method of emplacement can explain the mutual deficit of xenoliths and lateral shortening along the margins of the Sentinel Granodiorite; however, it is an unlikely scenario for this granodiorite because no large, continuous faults or shear zones cut, bound, or extend away from the granodiorite.

The lack of marginal faults along the external contacts of the Sentinel Granodiorite indicates it is also unlikely that piston-like roof uplift (e.g., Corry, 1988; McCaffrey and Petford, 1997; Cruden, 2006) was an important space-making mechanism for the granodiorite. Roof uplift by bending and draping of overlying rocks (e.g., Jackson and Pollard, 1988; Roman-Berdiel et al., 1995) is a plausible material transfer process for shallow plutons such as those in the study area. It is difficult to evaluate this mechanism for the Sentinel Granodiorite, as no apparent remnants of the roof are present in the study area, and the scarce metamorphic host rocks that surround the granodiorite were likely already steeply foliated during the time of intrusion (e.g., Bateman, 1992). Similarly, floor depression (e.g., Cruden, 1998; Wiebe and Collins, 1998; Cruden et al., 1999) may have provided space for the granodiorite, but the floor of the granodiorite is not exposed. Only minor downward ductile flow is indicated by the thin, discontinuous aureoles in host rocks of the Yosemite Valley Intrusive Suite.

Based on the sharp, stepped contacts between the Sentinel Granodiorite and host rocks, it is likely that the final stages of emplacement of the Sentinel Granodiorite were aided by stoping of units belonging to the Yosemite Valley Intrusive Suite, and that ductile flow of host rocks, as indicated by weak, narrow structural aureoles, played a minor role. Roof uplift and floor sinking may have also accommodated emplacement, but no direct field evidence of these mechanisms has been found in the study area.

Construction of the Sentinel Granodiorite

Pluton shapes depend on a variety of factors, including host rock material transfer processes (in part a function of emplacement depth, host rock type, and temperature), pre-existing host rock structures such as fractures and faults, and the volumes, shapes, viscosities, and flow rates of ascending magma pulses. Diapirism and diking are two end-member models traditionally cited as magma ascent mechanisms, and require very different respective host rock material transfer processes. Recently, several models have been introduced that take into account crustal heterogeneity; visco-elastic diapirs (McNulty et al., 1996;

Paterson and Miller, 1998; Miller and Paterson, 1999) ascend and are emplaced by both brittle and ductile processes, and pervasive flow (Weinberg, 1999) allows magma to ascend through dense networks of fractures in the upper crust.

The El Capitan Granite next to the southern margin of the Sentinel Granodiorite is intruded by numerous granodiorite dikes suggesting that at least some of the granodiorite was constructed by dikes (Fig. 8). It is unlikely that the granodiorite was only constructed by dikes for the following reasons: dikes are only present along parts of the margin; and dikes of Sentinel Granodiorite that intrude the El Capitan Granite are randomly oriented, not sub-parallel as is typical for plutons emplaced by dike or sheet intrusion (e.g., Ingram and Hutton, 1994; Miller and Paterson, 2001; Cruden, 2006).

The shapes and sizes of individual pulses of magma that constructed the majority of the Sentinel Granodiorite are difficult to determine. This is because internal contacts are discontinuous and their existence implies that portions of older, semi-rigid pulses have been partly removed by, or assimilated into, newer intrusions, possibly by scouring and within-chamber stoping (e.g., Paterson and Vernon, 1995; Zak and Paterson, 2005). Layered schlieren in the Sentinel Granodiorite likely formed along internal boundaries (e.g., Barriere, 1981; Bergantz, 2000; Zak and Paterson, 2005) and may consequently provide information on the orientation and shape of temporary interfaces between semi-rigid and non-rigid magmas. The average strike of planar schlieren, although representative of a wide range of orientations, is ESE (Fig. 17), parallel to the

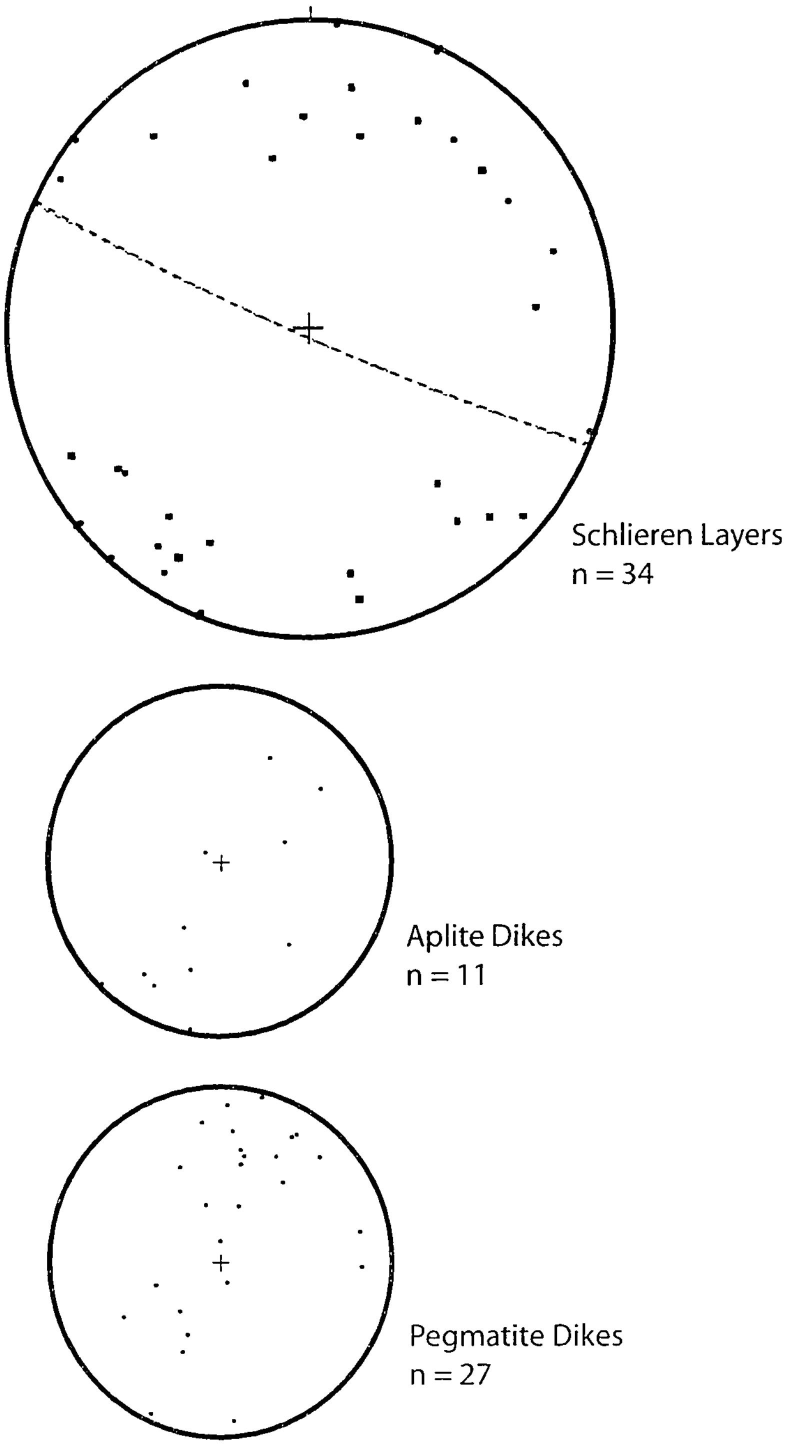


Figure 17. Comparison of poles to schlieren layering and dikes within the Sentinel Granodiorite. Dashed line for schlieren layers is a projection of the plane representing the average orientation.

general strike of the northern and southern margins of the main lobe of Sentinel Granodiorite (Plate 1).

The average strike of pegmatite dikes is also WSW-ESE, although there is more variation of dip and less variation of strike in pegmatite dikes compared to schlieren (Fig. 17). As dikes are likely oriented normal to the direction of local extension, and probably minimum stress, during their intrusion, they may have formed parallel to isotherms in regions of the magma chamber that were experiencing thermal contraction, in particular where proximal to solid/liquid interfaces, such as internal contacts or crystallization fronts. This interpretation is supported by observations that some pegmatite dikes in the Sentinel Granodiorite appear to be fragmented (Fig. 7). It is evident that scouring by younger pulses of magma along internal contacts or the retreat of crystallization fronts likely dislodged and entrained these rigid dikes in low-crystallinity magma causing them to break apart. The ~WNW-ESE strike of temporary solid-liquid interfaces inferred from schlieren and pegmatite dikes therefore implies isotherms of the cooling Sentinel Granodiorite were generally parallel to the northern and southern margins of the unit, yet variable in dip.

Interpretation of Magmatic Fabrics in the Sentinel Granodiorite

Early Fabrics (S1)

The highly variable, but generally WNW-striking, population of foliations in the Sentinel Granodiorite is interpreted to be an early-formed magmatic fabric

(S1) that resulted from internal processes related to the construction of, and flow within, a magma chamber. Fabrics that lie near and parallel to external and internal contacts and are deflected by asperities along these contacts most likely formed where flowing crystal-rich magma encountered and spread laterally along interfaces with more rigid magma, or where crystal mushes were deformed by stresses related to internal magma chamber processes such as magma convection and/or the forceful intrusion of new batches of magma (e.g., Barriere, 1981; McBirney and Nicolas, 1997; Tobisch et al., 1997; Paterson et al., 1998). Frictional drag of magma pulses flowing parallel to internal contacts may have caused larger grains, which are typically felsic, to migrate away from the contact, resulting in rhythmically graded schlieren with mafic minerals along the base of each layer (Barriere, 1976).

Later Fabrics (S2)

The NW-striking foliation is considered a later fabric (S2) that recorded NE-SW regional shortening. This fabric is coupled with similar NW-striking magmatic foliations that are present in, and cut across contacts between, granitic units of the Yosemite Valley Intrusive Suite (Bateman, 1992). The presence of a NW-striking, probably regional foliation in units ranging in age from ~102- to ~94.5-Ma suggests that the orientation of the regional strain field during crystallization of the Sentinel Granodiorite was similar to that for the Yosemite Valley Intrusive Suite. Although this strain field is recorded in the granodiorite as a later-stage fabric, it would have been present before and during the development of local flow-related fabrics. This interpretation suggests that local, not regional strain fields in the Sentinel Granodiorite were generally a greater influence on the development of magmatic fabrics.

In parts of the Sentinel Granodiorite, both S1 and S2 are present, and either may have a greater intensity. The intensity of S1 may be related in part to the crystal-melt fraction of the magma; flowing magma pulses containing a denser concentration of crystals likely better record S1 fabrics because there are more grains to act as flow-induced strain markers (e.g., Paterson et al., 1998; Zak et al., 2007).

Once magmatic flow is impeded by increasing viscosity and a rigid framework of crystals begins to develop, smaller pockets of melt within the crystallizing magma may be able to record regional strains without interference by magma convection or surges (e.g., Marsh, 1988; Paterson et al., 1998). Considerable melt fractions (up to 30%) may exist in "rigid" or static crystal-rich mushes (e.g., Paterson et al., 1998; Petford, 2003), and such magmas are capable of recording strain while maintaining structural integrity, and therefore, pre-existing fabrics.

The relatively small size of minerals that form S2 may be evidence that they had little space in which to crystallize. This interpretation relies on the assumption that fabrics recording regional strain develop best in relatively static (non-flowing or semi-rigid) crystal-rich mushes, and local stresses related to magma flow and nearby forceful magma intrusions have a greater influence on the orientation of mineral grains than regional stress fields (Paterson et al., 1998).

Fabrics formed by internal magmatic processes can also be completely overprinted by regional fabrics. This may explain the presence of elongate enclaves cut at high angles by magmatic foliation in the Sentinel Granodiorite. This scenario is more likely where original flow-related foliations are relatively weak and easy to erase, and crystallization rates are slow enough to allow for the re-orientation of a larger population of grains.

Relationship of the Sentinel Granodiorite to the Smoky Jack Tonalite

The contact-parallel, high-temperature solid-state foliation in the Smoky Jack tonalite next to its contact with the Sentinel Granodiorite defines a structural aureole that is several tens of meters wide. This aureole, gradational zones, and the absence of tonalitic xenoliths in the Sentinel Granodiorite next to the contact indicate the tonalite responded to the intrusion of the granodiorite primarily by ductile shortening and vertical extension, and/or mixing. Where the contact is sharp, magmatic currents in the granodiorite may have scoured partially molten domains of the tonalite (e.g., Mahood, 1990; Bergantz, 2000; Zak and Paterson, 2005).

Because the Sentinel Granodiorite shows a weaker magmatic foliation next to the contact (Fig. 12), it was likely more melt-rich than the tonalite when the foliation formed. Given that the fabrics in both units are parallel to the contact, even where the contact is irregularly oriented, the Sentinel Granodiorite and Smoky Jack tonalite likely experienced simultaneous foliation development at magmatic to sub-magmatic temperatures, respectively. This hypothesis is supported by the mutual deflection of both magmatic foliations by ductile shear zones that cut across the contact in places.

Gradational segments of the contact may have formed by mixing or fractional crystallization. Turbulence associated with gravitational collapse and assimilation (e.g., Bateman and Chappell, 1979; Mahood, 1990; Bergantz, 2000; Zak and Paterson, 2005) of semi-rigid tonalite into the granodiorite may have stirred the magmas to create the gradational zones. Conversely, gradational segments may have formed by the fractional crystallization of mafic minerals (Reid et al., 1993; Zak and Paterson, 2005) in the granodiorite against cooler, semi-rigid parts of the tonalite.

In summary, the following evidence indicates the Smoky Jack tonalite magmatically overlaps with the Sentinel Granodiorite: (1) concordance of magmatic and sub-magmatic fabrics across the contact; (2) evidence of mixing and scouring along the contact; and (3) mutual deflection of sub-magmatic fabrics in the tonalite and granodiorite by shear zones.

Age Relationship Between the Sentinel and Yosemite Creek Granodiorites

The Yosemite Creek Granodiorite is interpreted to be younger, not older, than the Sentinel Granodiorite, in contrast to previous reports (Kistler, 1973; Bateman, 1992) for the following reasons: (1) sheets of Yosemite Creek Granodiorite intrude the northern margin of the transitional zone; (2) schlieren in the Yosemite Creek Granodiorite are margin-parallel near the contact; and (3) the ductile strain within and along the southern margin of the isolated body of Sentinel Granodiorite indicates that it probably was strained prior to, or in response to, intrusion of the transitional unit, which shows much weaker, primarily magmatic deformation along the contact.

The contact between the Sentinel and Yosemite Creek granodiorites is unusual because it is gradational over an uncharacteristically wide (up to 4-km) and complex zone. Other gradational contacts in the central Sierra Nevada batholith are generally more than an order of magnitude narrower (e.g., Bateman and Chappell, 1979; Bateman, 1992; Coleman et al., 2004; Zak and Paterson, 2005).

Construction of the Transitional Yosemite Creek/Sentinel Granodiorite and Yosemite Creek Granodiorite Proper

Gradational contacts in the central Sierra Nevada batholith are commonly thought to result from mixing induced by the gravitational collapse of the contact zone into younger, more melt-rich phases (Mahood, 1990; Bergantz, 2000; Zak and Paterson, 2005). Given the large distance across the transitional zone, it was not likely formed at the exposed crustal level by end-member-mixing between the Sentinel and Yosemite Creek granodiorites. Crystal fractionation has also been proposed to cause compositional gradation in plutons (e.g., Frey et al., 1978; Bateman and Chappell, 1979), but it typically results in variations in mineral modes and would not likely lead to variations in the morphology of a single mineral, as is observed across the transitional contact between the Sentinel and Yosemite Creek granodiorites.

Zak and Paterson (2005) described sheeted zones up to hundreds of meters wide that separate the Kuna Crest and equigranular Half Dome granodiorites and appear to contain detached magmatic blocks of the Kuna Crest unit. The authors contend that the sheeted zones formed within dilating, mode 1 extensional fractures that expanded by crack-seal-type processes, and that consecutive sheets wedged aside and further widened these fractures. This process may be partly responsible for the formation of the isolated body of Sentinel Granodiorite within the transitional unit. If so, the isolated body of Sentinel Granodiorite would be an order of magnitude larger than those found within gradational contacts in the Tuolumne Intrusive Suite (Fig. 16, Plates 1 and 2). Smaller xenoliths of Sentinel Granodiorite may also exist in the southern part of the transitional unit, but would be difficult to discern due to subtle textural contrasts.

Considering the isolated body of Sentinel Granodiorite as a detached block requires that the proposed crack-seal-type emplacement was asymmetric; the transitional unit appears slightly more like the Yosemite Creek Granodiorite in the northern part of the zone south of the detached block. This asymmetry suggests that each new magmatic pulse intruded along the northern margin of the zone between the main mass, and detached body, of Sentinel Granodiorite. The asymmetric crack-seal model may explain the ductile shear zone developed along the southern margin of the isolated body of Sentinel Granodiorite (Fig. 18); if that were the general location of each new pulse of magma, localized vertical ductile flow may have developed in the Sentinel unit adjacent to the site of replenished heat.

Due to the relative scarcity of internal contacts in the transitional unit, the shape and size of individual intrusions are not known. The isolated body of Sentinel Granodiorite is flanked on the west and east by the transitional unit; thus the inferred dilating fracture or fractures would have been active only during the earlier stages of emplacement of the transitional unit, and more localized intrusions were subsequently emplaced on either side of the isolated body as the locus of magmatism moved northward.

Temporal Implications of the Contact Between the Sentinel and Yosemite Creek Granodiorites

The sharp to gradational contact between the transitional unit and the Sentinel Granodiorite indicates that during intrusion of the transitional unit, the

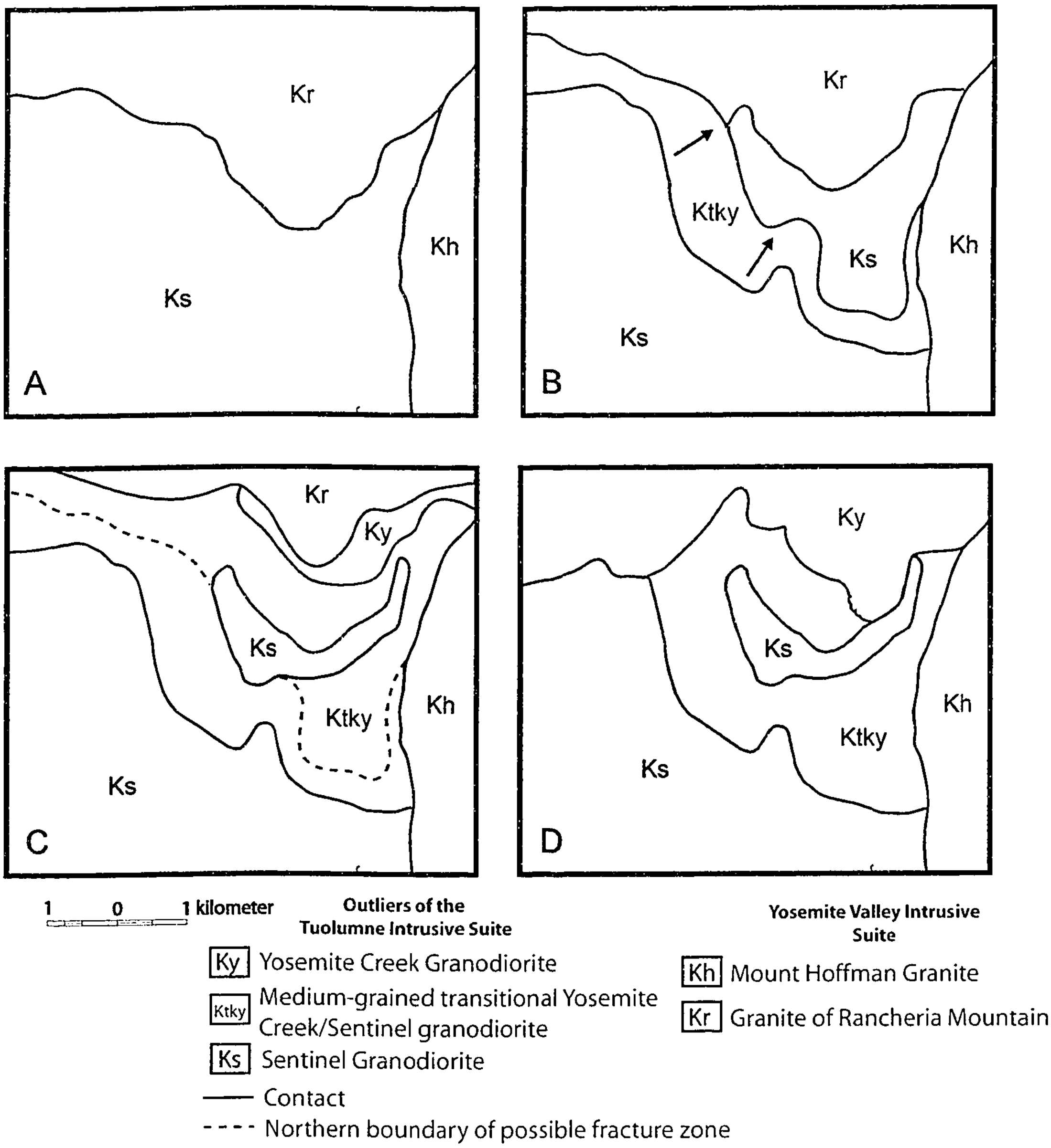


Figure 18. Proposed origin of transitional contact between Sentinel and Yosemite Creek Granodiorites. A) Before emplacement of transitional unit. B) During initialemplacement of transitional unit within an extensional fracture or series of fractures. C) After emplacement of rest of transitional unit and early intrusions ofYosemite Creek Granodiorite. D) After subsequent intrusion of Yosemite CreekGranodiorite.

Sentinel Granodiorite was likely at temperatures high enough so that it was locally "defrosted" (Mahood, 1990) and remobilized by the transitional unit, while other parts remained rigid enough so that layering in the transitional rock developed against them (e.g., Barriere, 1981; Tobisch et al., 1997; Paterson et al., 1998). Interpreted age differences between the Sentinel Granodiorite and the earliest pulses of the transitional unit are therefore probably much smaller than those between the Sentinel Granodiorite and units of the Yosemite Valley Intrusive Suite.

The isolated body of Sentinel Granodiorite in the transitional unit shows a greater textural contrast with transitional rocks towards the north (Fig. 16), implying that each new intrusion of the transitional unit was generally more texturally similar to the Yosemite Creek Granodiorite independent of proximity to the Sentinel Granodiorite. If the Sentinel Granodiorite mixed laterally with the Yosemite Creek Granodiorite to form the transitional unit, then only a subtle textural contrast with the transitional unit would be present across the entire margin of the isolated body of Sentinel Granodiorite, as is observed across the contact of the transitional unit with the main mass of Sentinel Granodiorite. Mixing at this scale would also require convection across a 3.5-km-wide zone, apparently unobstructed by the large body of Sentinel Granodiorite that lies within it.

The gradual textural changes observed in the transitional zone are interpreted to result from processes occurring below the presently exposed crustal level, either deeper in the magma chamber, or within a common magma source region. These processes may include deeper-level mixing between the Yosemite Creek and Sentinel granodiorites or fractional crystallization within a single magma (Bateman and Chappell, 1979; Kistler et al., 1986; Kistler and Fleck, 1994; Coleman et al., 2004). Geochemical analyses of rocks across this transitional zone may help identify which, if either, of these mechanisms are responsible for such a broad transition.

Proposed Origin of the Transitional Contact

It is my interpretation that NNE-directed migration of the locus of magmatism occurred during construction and emplacement of the transitional zone. In this model, the SSW-NNE-trending textural gradient across the zone is an artifact of a series of discreet pulses, each having a slightly more similar texture to the Yosemite Creek Granodiorite proper than the previous one. Localized mixing or mingling along the boundaries of the pulses probably destroyed many internal contacts within the transitional unit, smoothing the textural gradient.

The following scenario, which is illustrated in Figure 18, is proposed as a possible origin of the transitional unit. Much of the exposed Sentinel Granodiorite was emplaced and cooled to sub-solidus temperatures when incoming magma pulses began to show subtle characteristics of the Yosemite Creek Granodiorite. Some of these pulses intruded into and detached a rigid region of the Sentinel

Granodiorite. Pulses of transitional magma continued to intrude into and widen a WNW-ESE-oriented fracture or series of fractures that developed south of the detached body of Sentinel Granodiorite.

Eventually, emplacement of the transitional magma continued northward along the western and eastern margins of the isolated body. Subsequent intrusion of the Yosemite Creek Granodiorite proper occurred initially by sheeting into the northern margin of the transitional unit, then by a northward and westward migration of its locus of magmatism, forming relatively sharper contacts with the older, cooler Sentinel Granodiorite to the west of the transitional zone.

Several questions about the origin and structure of the transitional unit remain unanswered: (1) If early pulses of the transitional unit began intruding into a dilational fracture, what caused the fracture? (2) Why do contacts in the transitional zone between the Sentinel and Yosemite Creek granodiorites appear to truncate against the simple, linear contact between the zone and the Mount Hoffman Granite? (3) Did the transitional unit extend farther west than its current position, and if so, was it truncated by later intrusions of the Yosemite Creek Granodiorite? (4) How far north did the eastern Sentinel Granodiorite extend prior to intrusion of the transitional unit and Yosemite Creek Granodiorite? (5) Why are the northern and southern boundaries of the transitional unit characterized by schlieren and localized mafic bodies? More detailed studies, including the establishment of isotopic ages and geochemistry of the transitional unit and Yosemite Creek Granodiorite, are needed to better understand the history of, and mechanisms responsible for, the transitional contact between the Sentinel and Yosemite Creek granodiorites.

Emplacement of the Yosemite Creek Granodiorite

The northern margin of the transitional zone is different from the southern margin because it is intruded by sheets of Yosemite Creek Granodiorite in addition to being modally layered. Sheets of Yosemite Creek Granodiorite possibly intruded the transitional rock in a reduced stress zone caused by thermal contraction perpendicular to the cooling southern margins of a northward-migrating magma chamber (e.g., John and Blundy, 1993; Zak and Paterson, 2005). The subsequent construction and emplacement of the Yosemite Creek Granodiorite is poorly understood. Inferred NNE growth directions of modal layering in the southeastern Yosemite Creek Granodiorite indicate the unit is older adjacent to the Sentinel Granodiorite than it is farther north.

Emplacement of Kuna Crest and Equigranular Half Dome Granodiorites

Gradational segments of the contact between the Sentinel and Kuna Crest granodiorites are interpreted as zones of mixing, where partially solidified regions in the Sentinel Granodiorite were "defrosted" (c.f., Mahood, 1990) and incorporated into younger pulses of the Kuna Crest Granodiorite. These mixing zones may be the product of unstable, semi-rigid “walls” of Sentinel Granodiorite that in places slumped or disintegrated into the Kuna Crest Granodiorite.

The reverse-slip, Kuna-Crest-side-up ductile shear zones that overprint the contact region suggest that downward ductile flow of the Sentinel Granodiorite and adjacent intrusions of the Kuna Crest Granodiorite accommodated, to a limited extent, emplacement of younger pulses of magma to the east. Within the study area, the shear zones are abundant where the Kuna Crest Granodiorite nearly pinches out between the Half Dome unit and transitional Sentinel/Kuna Crest unit (Plate 1). At this location, there are no ductile shear zones in the Half Dome unit, but many are present in the Kuna Crest unit.

The equigranular Half Dome Granodiorite also includes xenoliths of Kuna Crest Granodiorite. These xenoliths contain a high-temperature solid-state foliation, which has a different strike in each xenolith, indicating they are likely stoped blocks. Therefore, emplacement of the Half Dome unit was probably locally accommodated by ductile flow and stoping of the Kuna Crest unit.

Regional Strain Patterns and the Tuolumne Intrusive Suite

According to Tobisch et al. (1995), regional magmatic fabric patterns in plutons and the development of shear zones in the eastern Sierra Nevada batholith indicate that regional strain fields in the mid-Cretaceous were complex and changed from weakly extensional to transpressional at ca. 90-Ma due to changes in the angle of convergence and dip of the subducting Farallon plate beneath North America. This age corresponds roughly to the time of emplacement of the porphyritic Half Dome Granodiorite (Coleman et al., 1997, 2004; Glazner et al., 2004).

An E-W-striking magmatic foliation cuts internal contacts in all of the units of the Tuolumne Intrusive Suite proper and is considered to record regional N-S shortening during emplacement of the suite (e.g., Bateman, 1992; Bateman et al., 1993; Paterson and Vernon, 1995; Glazner et al., 2004; Teruya, 2005; Zak et al., 2007). The NW-striking regional foliation observed in the Sentinel Granodiorite and units of the Yosemite Valley Intrusive Suite (McFarlan, 2007) indicates that prior to intrusion of the Kuna Crest Granodiorite, regional shortening was NE-SW-directed. Therefore, the regional stress field in the central Sierra Nevada probably changed ~94-Ma, just prior to emplacement of the Tuolumne Intrusive Suite proper.

The Case for Inclusion in the Tuolumne Intrusive Suite

Intrusive suites are considered to be groups of cogenetic plutons and/or lithodemes which crop out together and share similar ages, compositions, fabrics, and strain patterns (e.g., Bateman, 1992). Ages of these units are spaced no more than a few million years apart, and younger units are generally more felsic than older units of the same suite (Bateman and Chappell, 1979; Bateman, 1992). Although the name "intrusive suite" was formally adopted by the North American Commission on Stratigraphic Nomenclature (1983), its usage, in varying form, dates back to at least Calkins (1930), who was the first to recognize distinct groups of granitoid rocks in the Yosemite Valley region (Bateman, 1992).

Field evidence suggests that the Smoky Jack tonalite, Sentinel Granodiorite, Yosemite Creek Granodiorite, and Kuna Crest Granodiorite overlap magmatically; that is they share contacts that show little or no hiatus between intrusions of each consecutively younger unit. This inference is supported by geochronological data that indicate the Sentinel Granodiorite is only slightly older than the Kuna Crest Granodiorite (Coleman and Glazner, 1997; Coleman et al., 2004). In contrast, the Tuolumne Intrusive Suite, including the "outliers", has sharp, stepped contacts with granitic units of the Yosemite Valley Intrusive Suite and older metasedimentary rocks, implying a relatively greater span of time elapsed between the two suites than between intrusion of units of the Tuolumne Intrusive Suite proper and outliers.

The Sentinel and Yosemite Creek granodiorites are also relatively similar in texture and composition to the outer units of the suite proper (Fig. 5). The basis by which the Tuolumne Intrusive Suite was assigned, that is, the criteria used by Bateman (1992) to define "plutonic suite", does not preclude inclusion of the Smoky Jack tonalite, Sentinel Granodiorite, and Yosemite Creek Granodiorite in the suite. I therefore conclude that the Smoky Jack tonalite, Sentinel

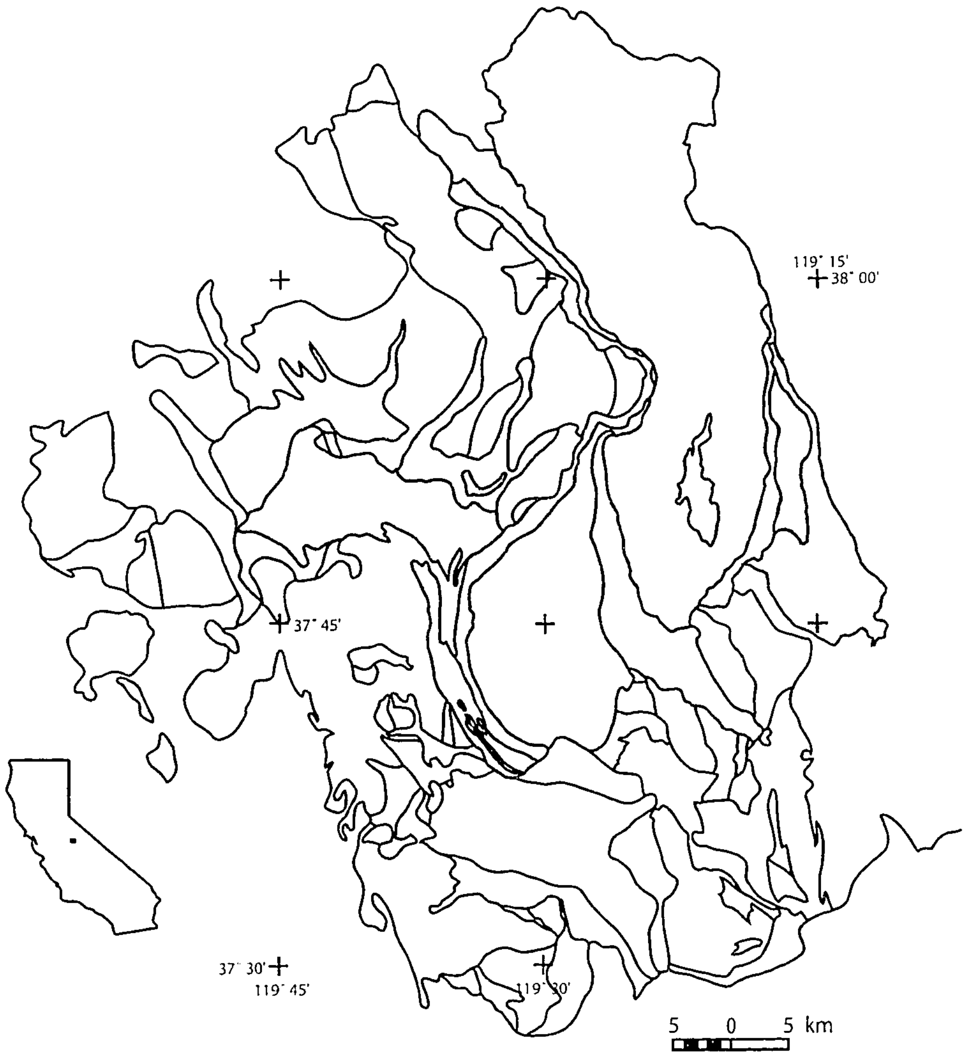
Granodiorite, and Yosemite Creek Granodiorite should be included in the Tuolumne Intrusive Suite.

The addition of these new granodiorites to the Tuolumne Intrusive Suite proper leads to a disruption in the latitudinal compositional zoning of the suite, which was a general decrease in color index, and increase in potassium feldspar towards the core of the suite proper (Bateman and Chappell, 1979). As illustrated in Figure 5, this disruption lies within the Kuna Crest Granodiorite. Aside from this disruption, the rocks along the transect from the western edge of the southern Sentinel Granodiorite to the inner margin of the Cathedral Peak Granodiorite show similar relative proportions of quartz, plagioclase, and potassium feldspar, and a general decrease in color index. Poor exposure prevents the observation of compositional trends across the northern portion of the Sentinel Granodiorite.

The compositional discontinuity in the suite lies within the Kuna Crest Granodiorite, roughly parallel to and along it's contact with the Sentinel Granodiorite. This relationship is probably responsible for the exclusion of the Sentinel Granodiorite from the Tuolumne Intrusive Suite proper in previous literature.

Relationship Between Host Rocks and the Shape of the Tuolumne Intrusive Suite

Figure 19 shows contacts between the different host rock units that surround the Tuolumne Intrusive Suite, including those of the Yosemite Valley Intrusive Suite. Similarities between the strikes of contacts within the host rocks and those defining the margins of the Tuolumne Intrusive Suite suggest that contacts between host rocks may have influenced the shapes of the younger units. The western margin of the Tuolumne Intrusive Suite proper forms a "Z", which mimics contacts up to 10-km away within host rocks of the Yosemite Valley Intrusive Suite. The elongate protrusions of the northeastern part of the Yosemite Creek Granodiorite appear to intrude along contacts within the Yosemite Valley Intrusive Suite, and the protrusions of the northwestern part of the granodiorite are oriented similarly to local protrusions of the Yosemite Valley Intrusive Suite to the west and southwest. The E-W orientation of the main body of the Sentinel Granodiorite is similar to that of many contacts within host rocks to the north and south. Strikes of internal contacts of the southern Tuolumne Intrusive Suite proper are oriented similar to those of adjacent crystalline host rocks to the south (Fig. 19). The eastern margin of the Tuolumne intrusive Suite is sub-parallel to adjacent metamorphic host rocks to the east. I thus conclude that the discrepancy between the nested shapes of the Tuolumne Intrusive Suite proper and the generally E-W orientations of the Sentinel and Yosemite Creek granodiorites may be the product of crustal anisotropy.



- Tuolumne Intrusive Suite proper
- Outliers of the Tuolumne Intrusive Suite
- Yosemite Valley Intrusive Suite
- Other host rocks

Figure 19. Map showing Tuolumne Intrusive Suite and surrounding host rock contacts. Yosemite Valley Intrusive Suite is shown in yellow. Modified from Kistler (1973) and Bateman (1992).

CONCLUSIONS

1. The ~94.5-Ma Sentinel Granodiorite is characterized by abundant schlieren, enclaves, and aplite and pegmatite dikes, and has sharp, stepped internal contacts. The granodiorite contains two steep magmatic foliations: an early, ~WNW-striking fabric that is related to internal magmatic processes, and a later, NW-striking fabric that likely represents time-transgressive NE-SW regional shortening.

2. Stoping was an important material transfer process during emplacement of the Sentinel Granodiorite; downward ductile flow and/or lateral shortening of granitic host rocks of the Yosemite Valley Intrusive Suite were relatively minor processes responsible for the weak, discontinuous structural aureoles along the contact. The role of roof uplift and floor depression in emplacement of the granodiorite is poorly understood because the floor of the intrusion is not exposed and only a few possible roof pendant rocks are present near the field area.

3. The newly named Smoky Jack tonalite is not part of the Yosemite Valley Intrusive Suite, as implied by Kistler (1973). The tonalite is interpreted to be a relatively mafic precursor of, and closer in age to, the Sentinel Granodiorite. Mixing between the tonalite and granodiorite occurred prior to the development of strong, margin-parallel, magmatic to solid-state foliations and lineations. Other tonalites and quartz diorites in the study area mapped by Kistler (1973) and

Bateman (1992) are co-magmatic with, or older than, the Yosemite Valley Intrusive Suite.

4. The Sentinel Granodiorite was emplaced as a series of discreet pulses, as indicated by abundant internal contacts. Internal stoping and scouring of consecutive pulses probably formed the sharp internal contacts. The average shape and size of individual pulses are not known.

5. The contact between the Yosemite Creek and Sentinel granodiorites is a broad, complex gradational zone that probably formed by mixing or differentiation of magmas at some deeper level, either within the same magma chamber, or in the magma source region. The transitional zone is defined by a gradation from SSW to NNE of Sentinel- to Yosemite Creek-like textures. The isolated body of Sentinel Granodiorite within the transitional zone is interpreted to have detached along one or multiple extensional fractures. Intrusive relationships between the two units suggest that the Yosemite Creek Granodiorite is slightly younger than the Sentinel Granodiorite, which is contradictory to age relationships determined by Kistler (1973) and Bateman (1992). This relationship is also indicated by trough truncations and mineral grading in the transitional unit, but such features are observed to contradict established age relationships in other parts of the batholith.

6. Localized mixing between the Sentinel and Kuna Crest granodiorites was followed by development of reverse, dip-slip, Kuna-Crest-side-up movement along ductile shear zones. These shear zones led to minor vertical ductile flow of

the contact zone, and may have been in response to emplacement of the nearby Kuna Crest and/or equigranular Half Dome granodiorites.

7. The Smoky Jack tonalite, Sentinel Granodiorite, and Yosemite Creek Granodiorite were emplaced with apparently little time between each intrusion. This pattern of temporally overlapping intrusions continued through the construction of the Tuolumne Intrusive Suite proper.

8. Based on established definitions of an intrusive suite (i.e., Bateman, 1992) the Tuolumne Intrusive Suite should include the Smoky Jack tonalite, Sentinel Granodiorite, and Yosemite Creek Granodiorite. By including these outliers in the suite, inward compositional zonation is interrupted, as the Kuna Crest Granodiorite is more mafic than the Sentinel and Yosemite Creek granodiorites.

9. Map patterns indicate that the shapes of units belonging to the Tuolumne Intrusive Suite proper and outliers may be related to crustal anisotropy formed by contacts between units of earlier intrusive suites. This relationship may explain the dissimilar orientation between the outliers and the main mass of the Tuolumne Intrusive Suite.

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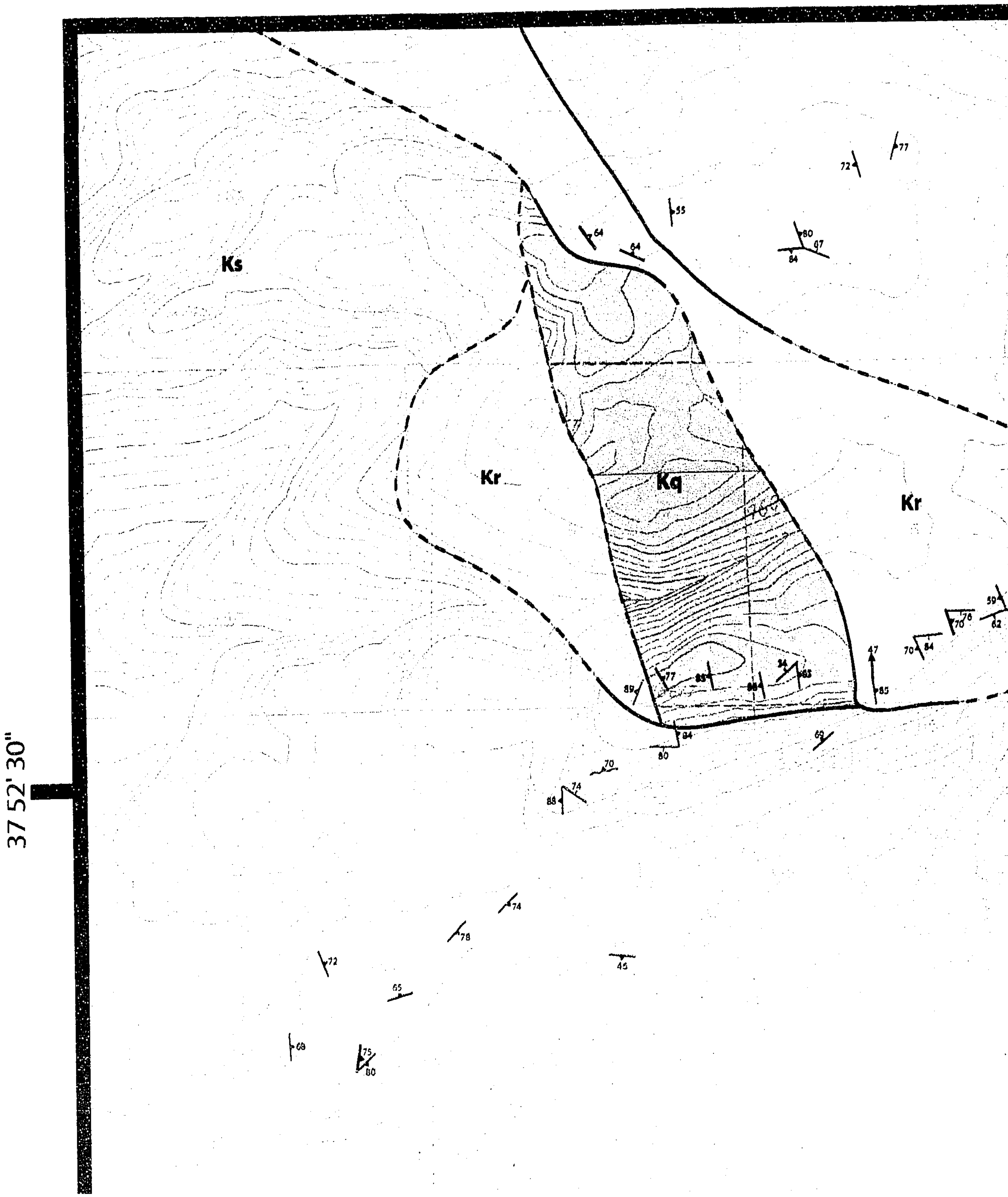
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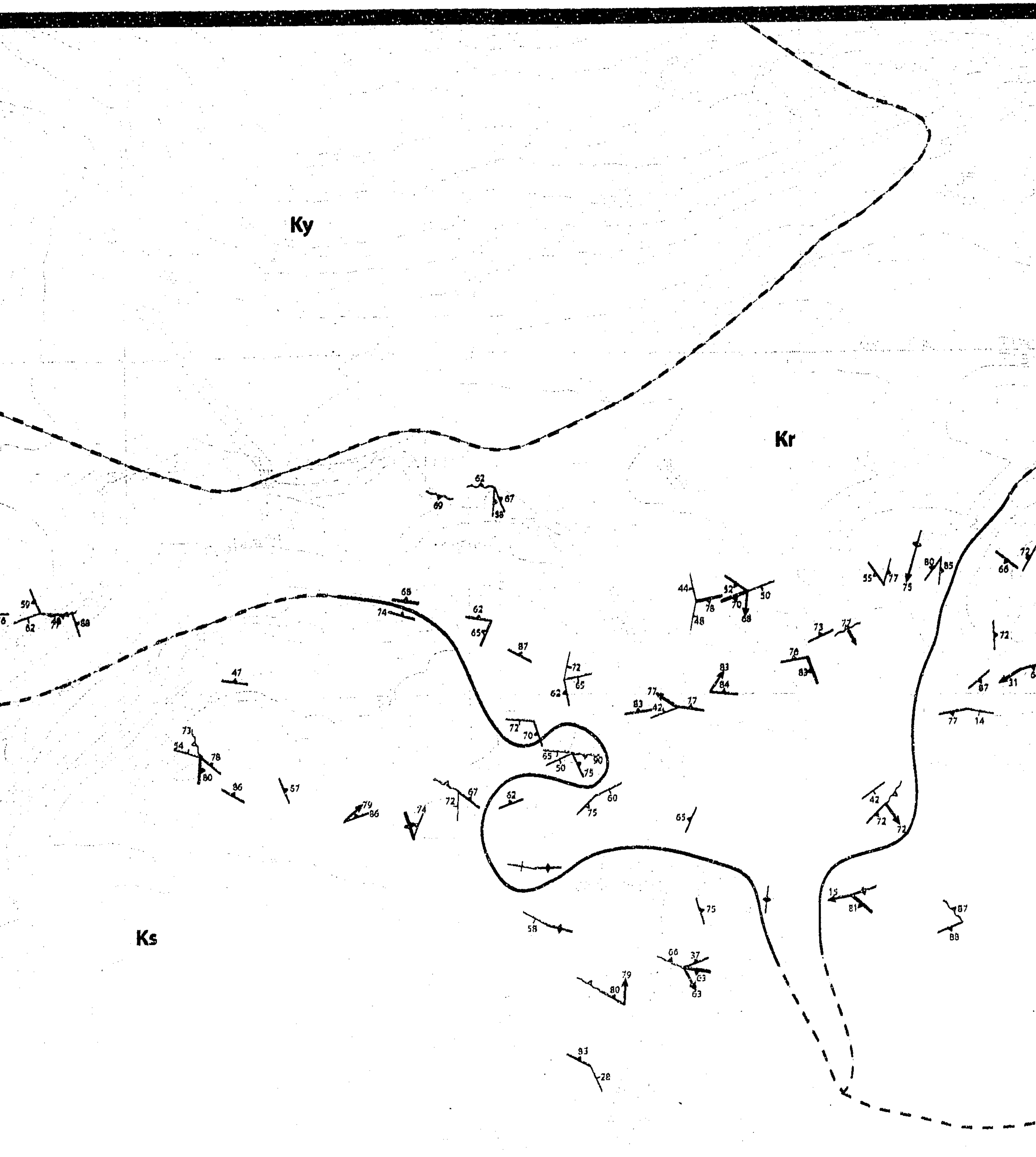

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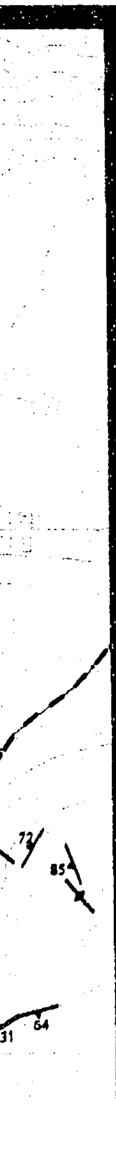

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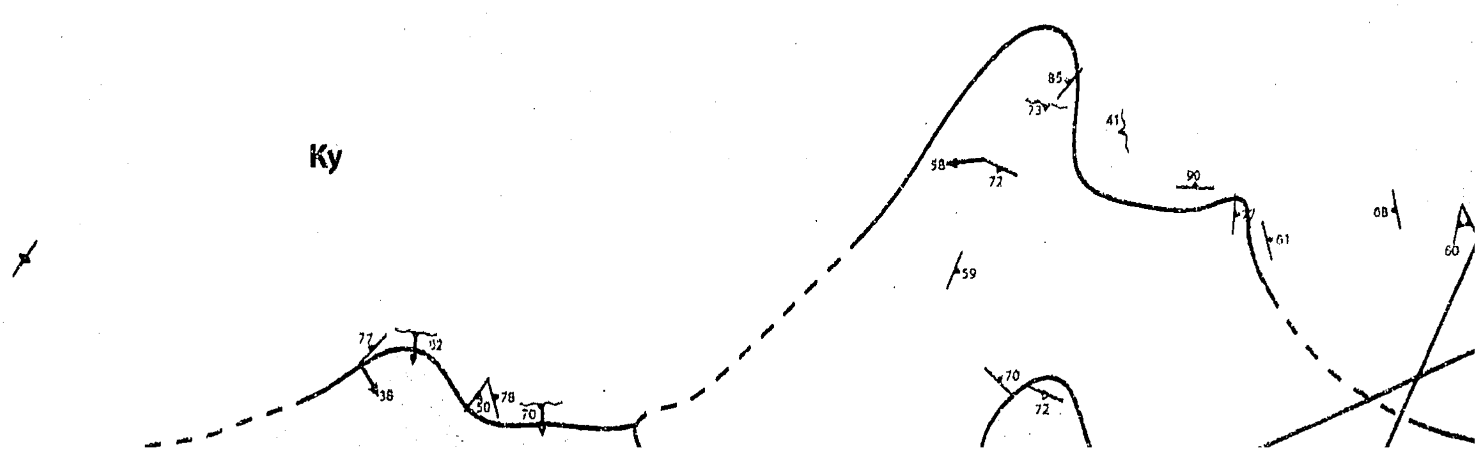

Bedrock Map of the

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Mapped By

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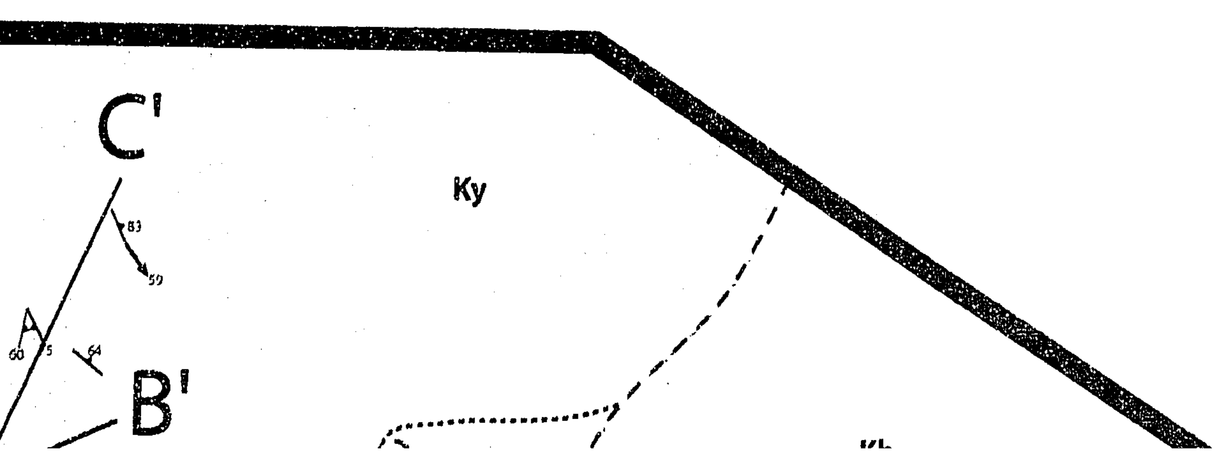

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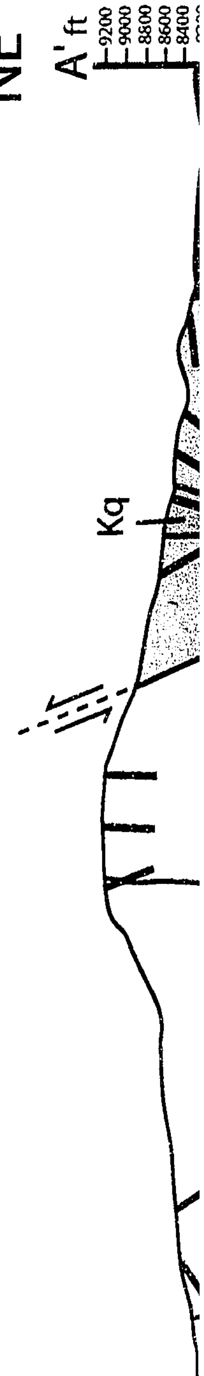

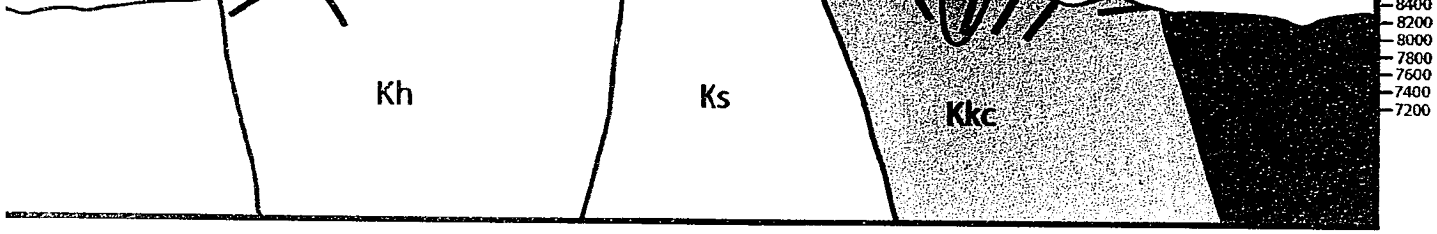
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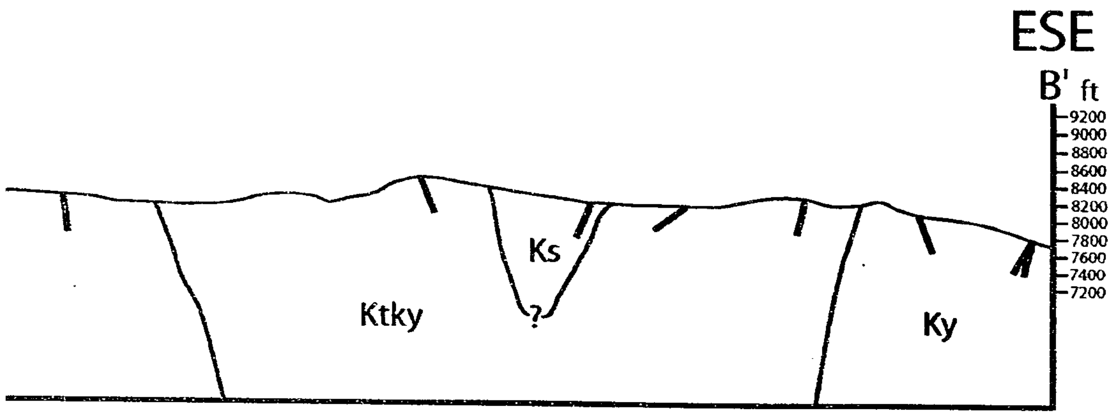
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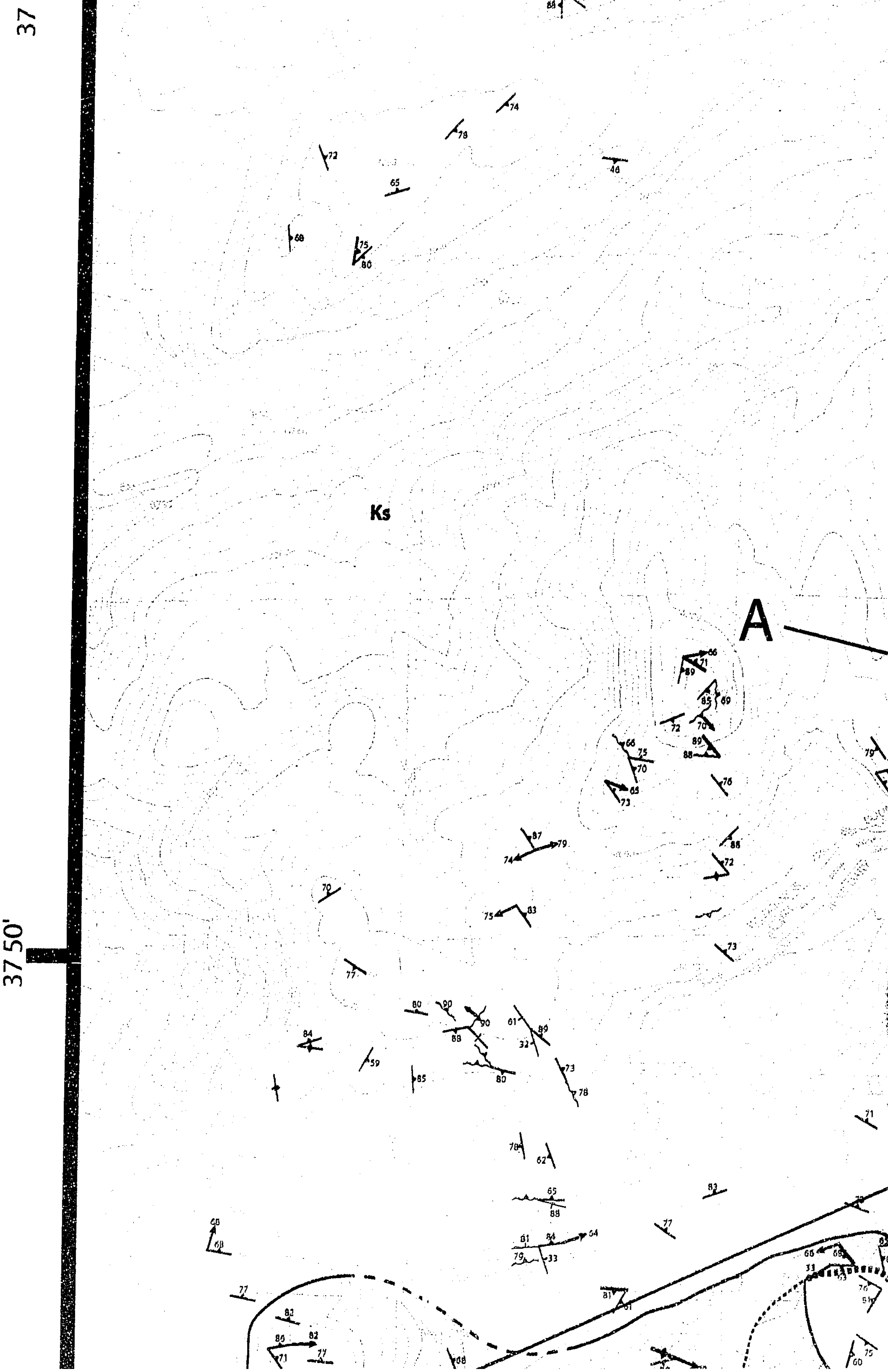
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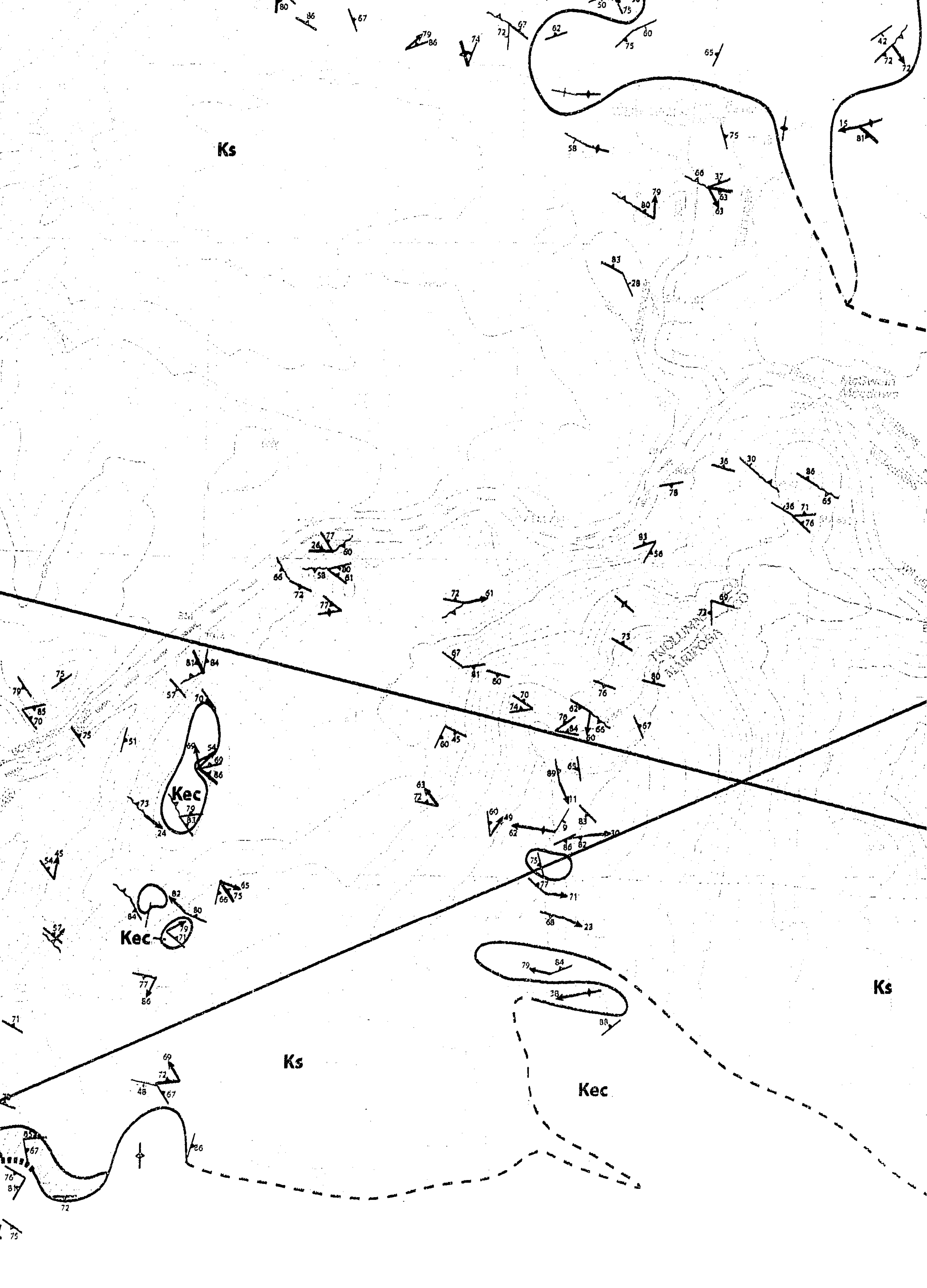
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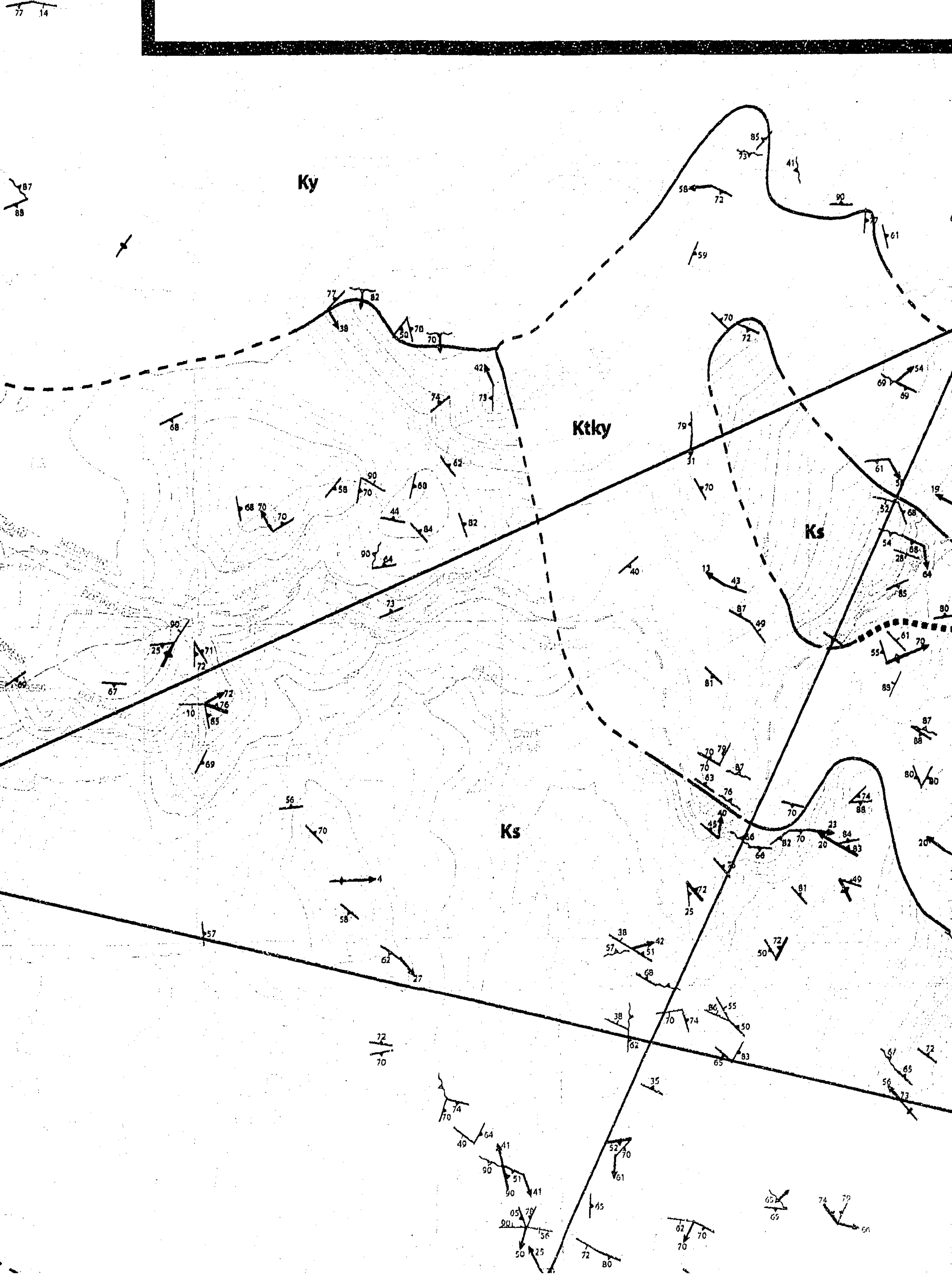
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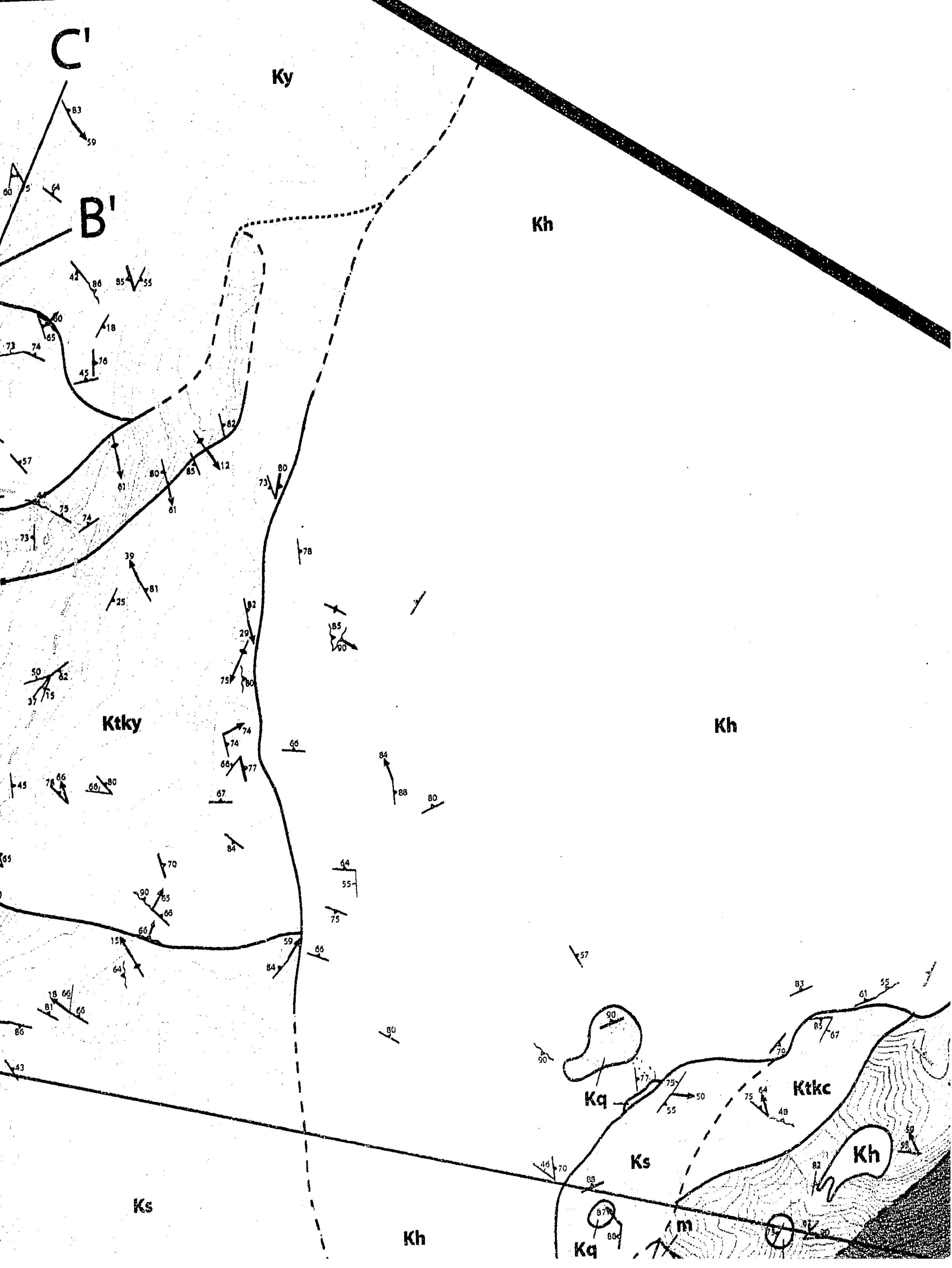
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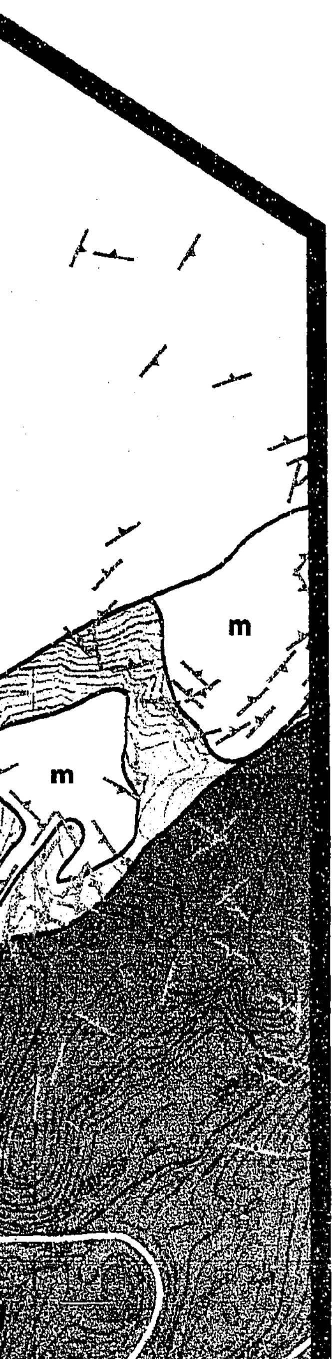

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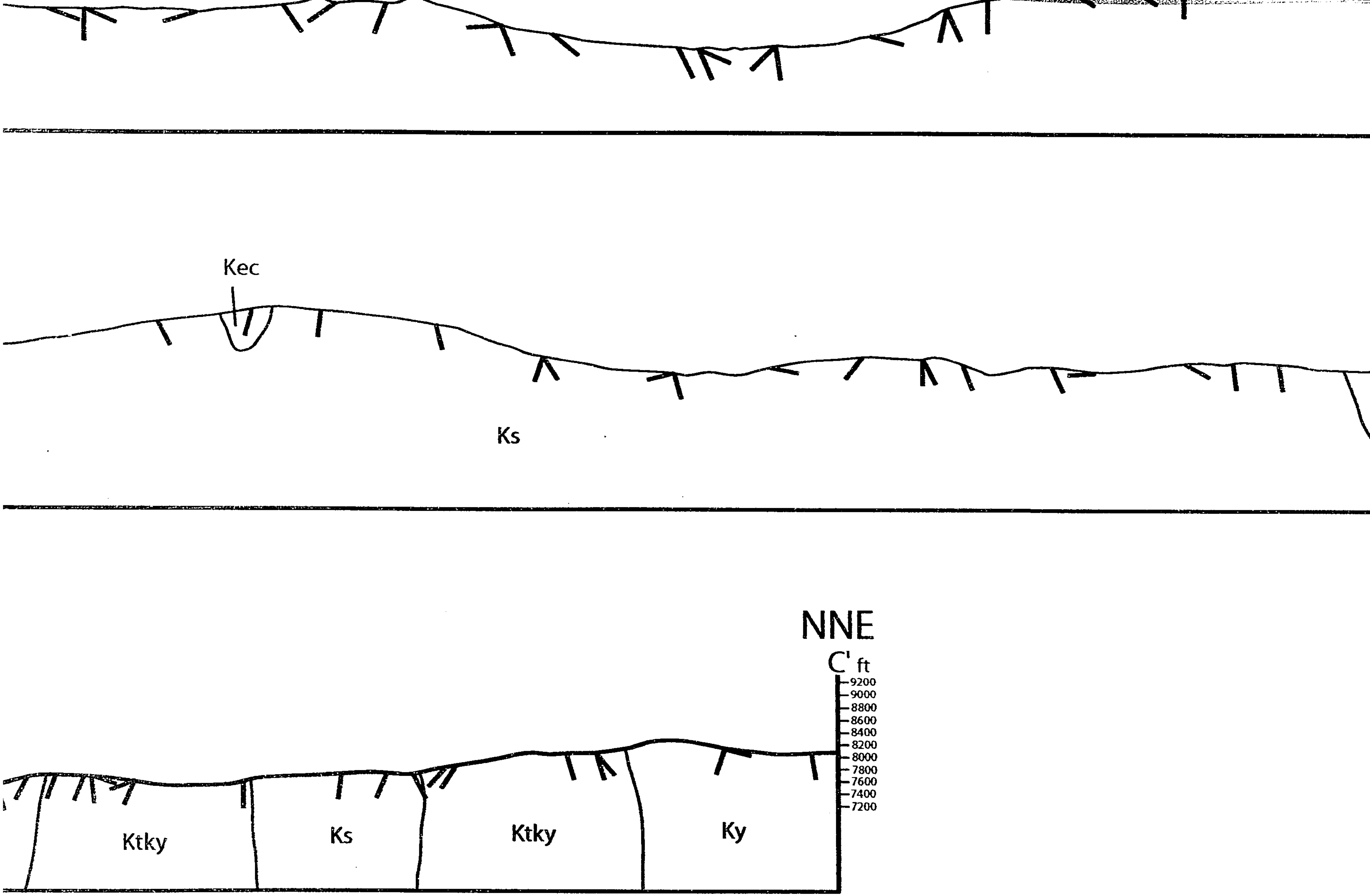

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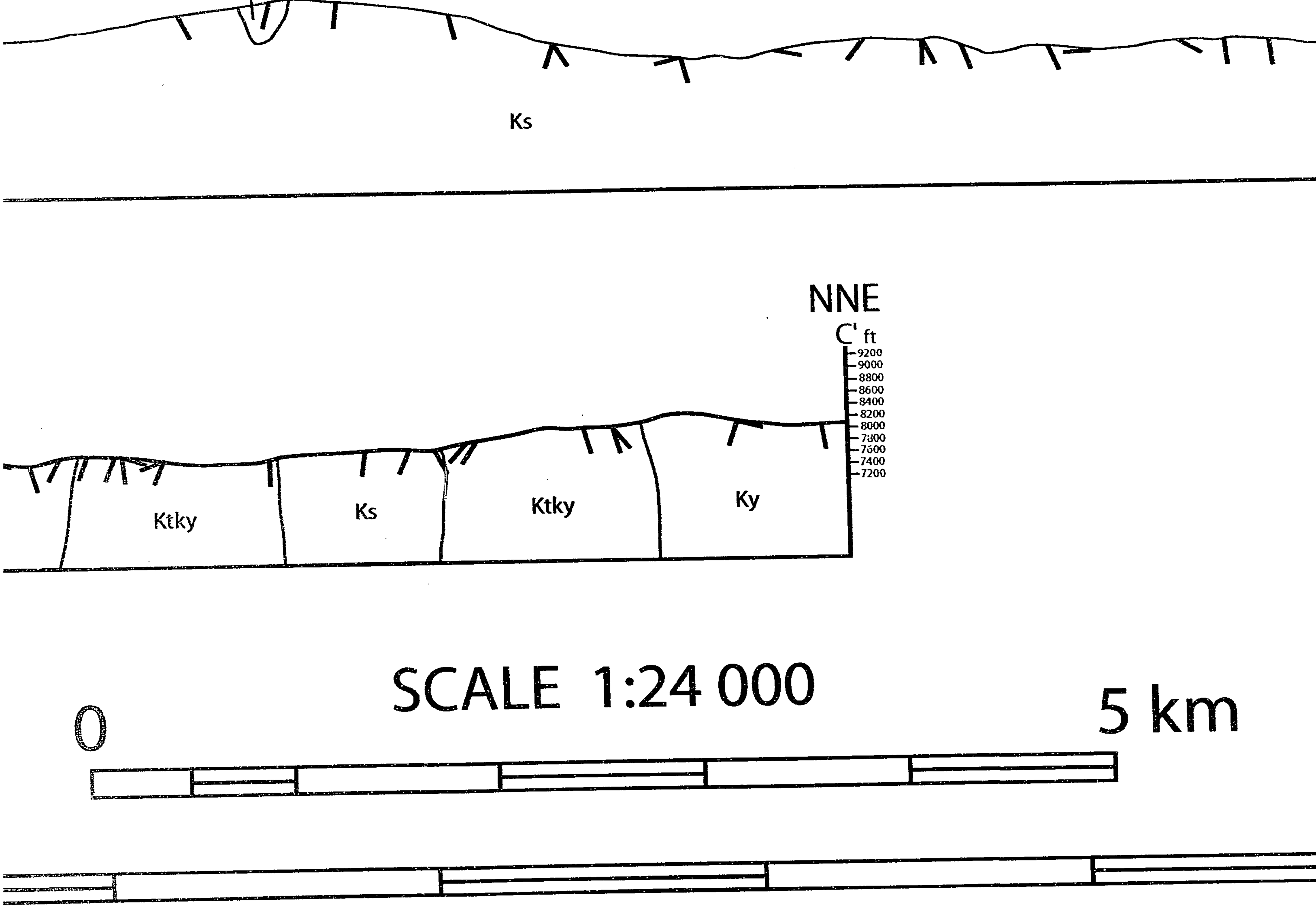
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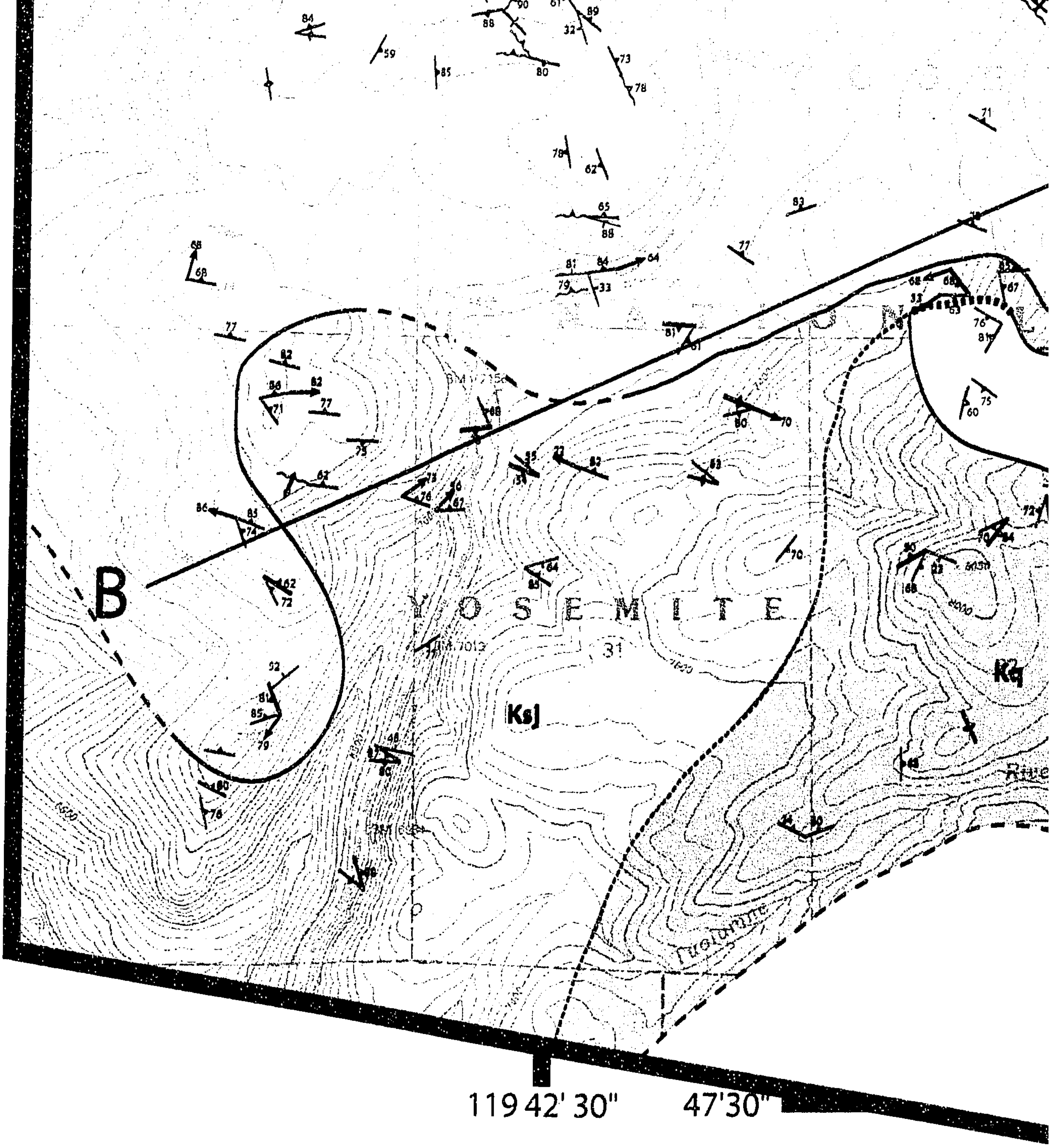

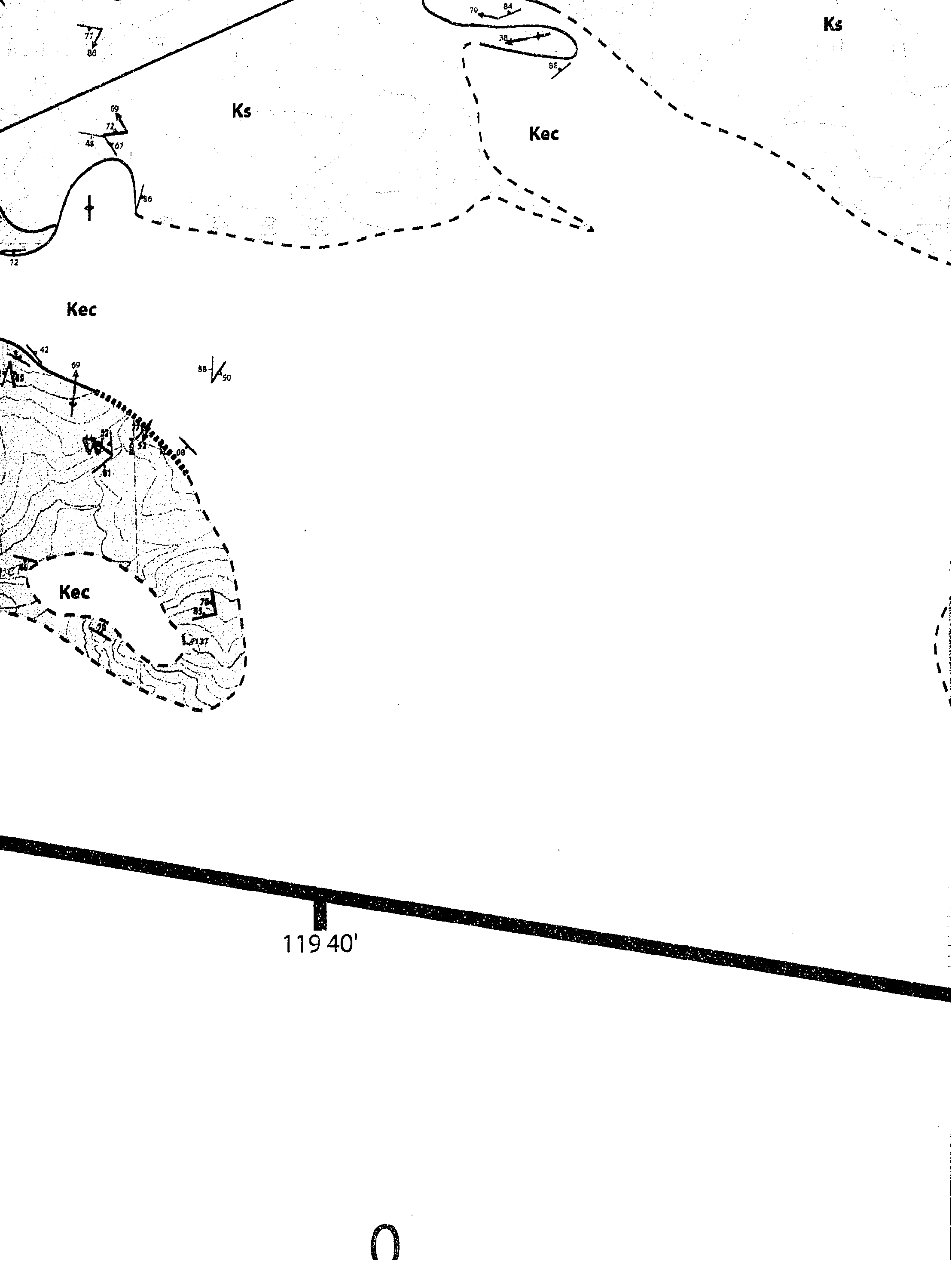

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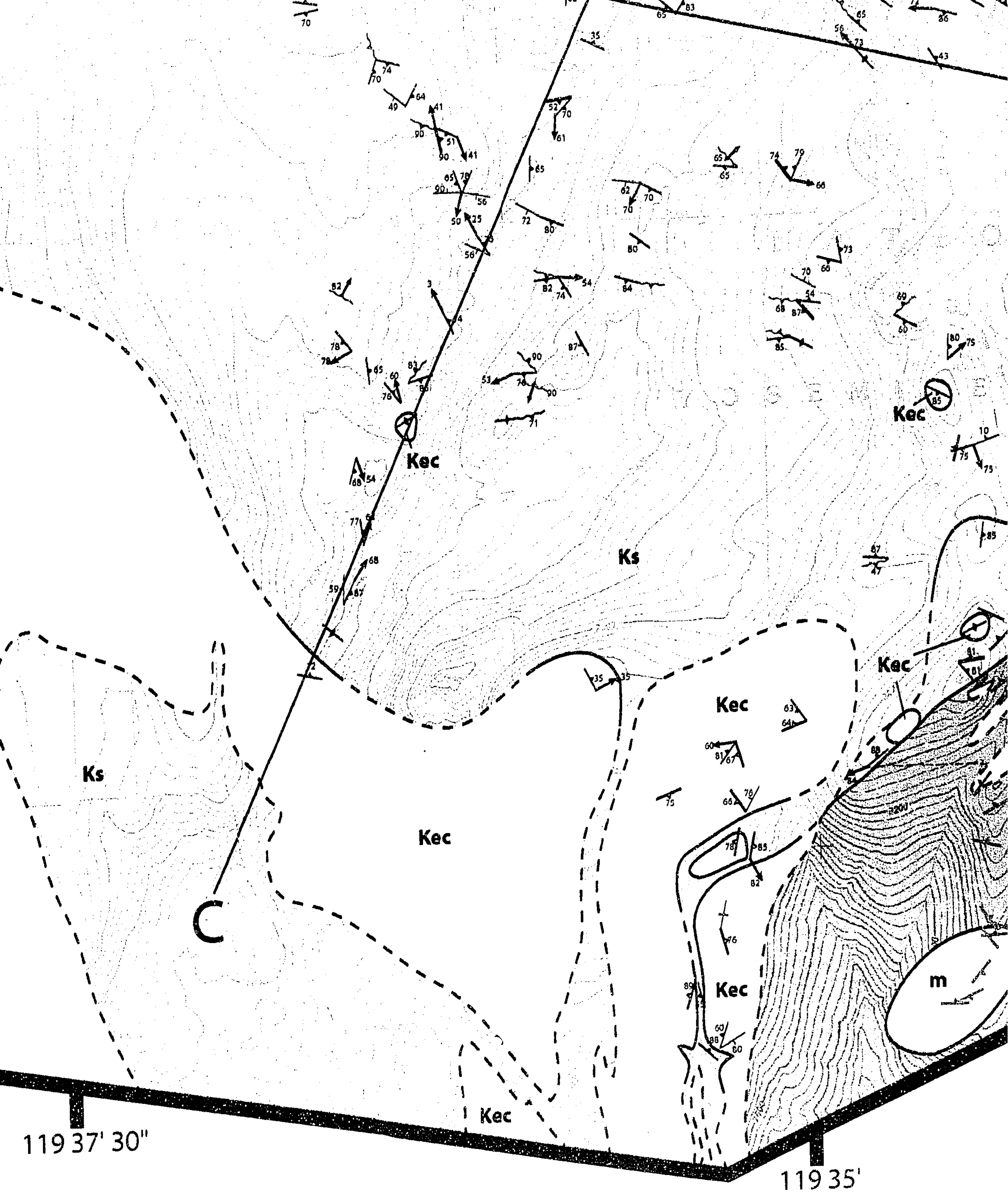

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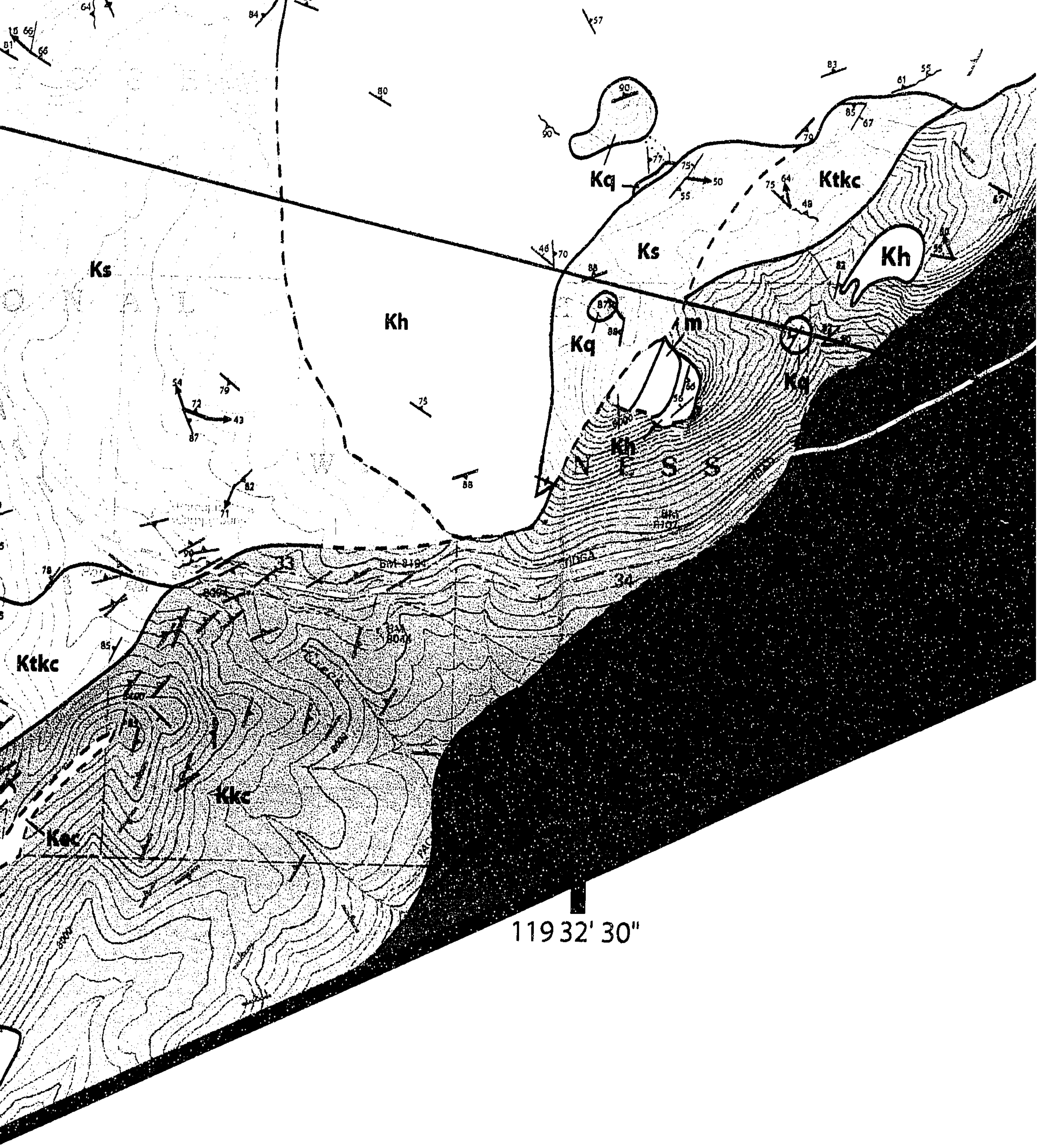
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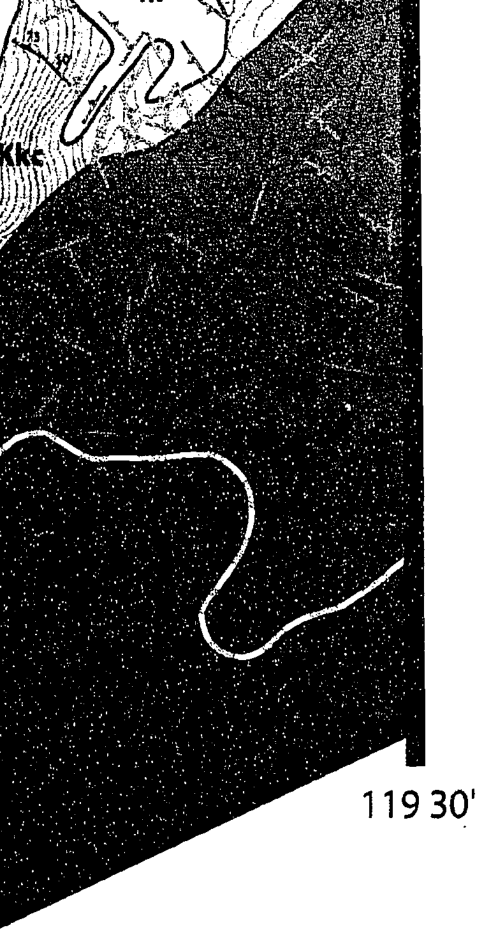

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(Bold symbol denotes dominant foliation)

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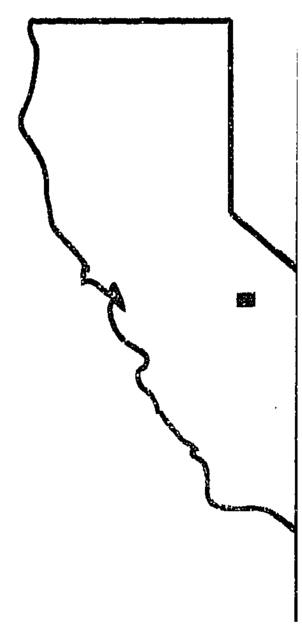

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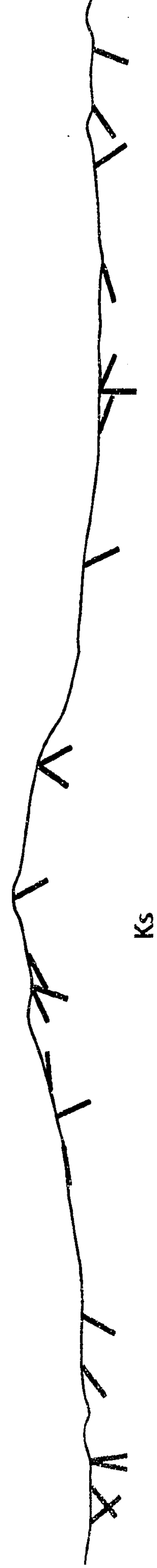

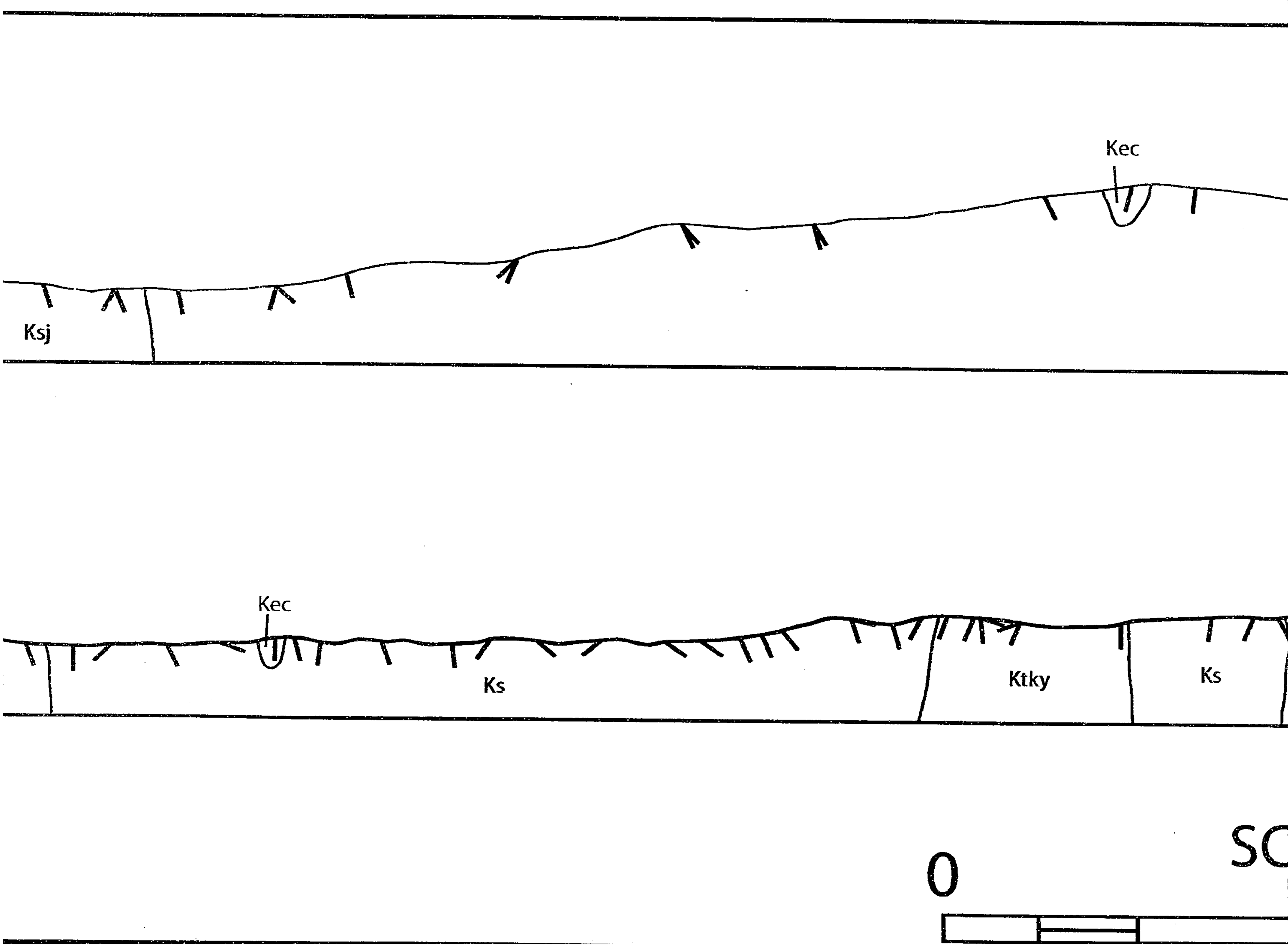
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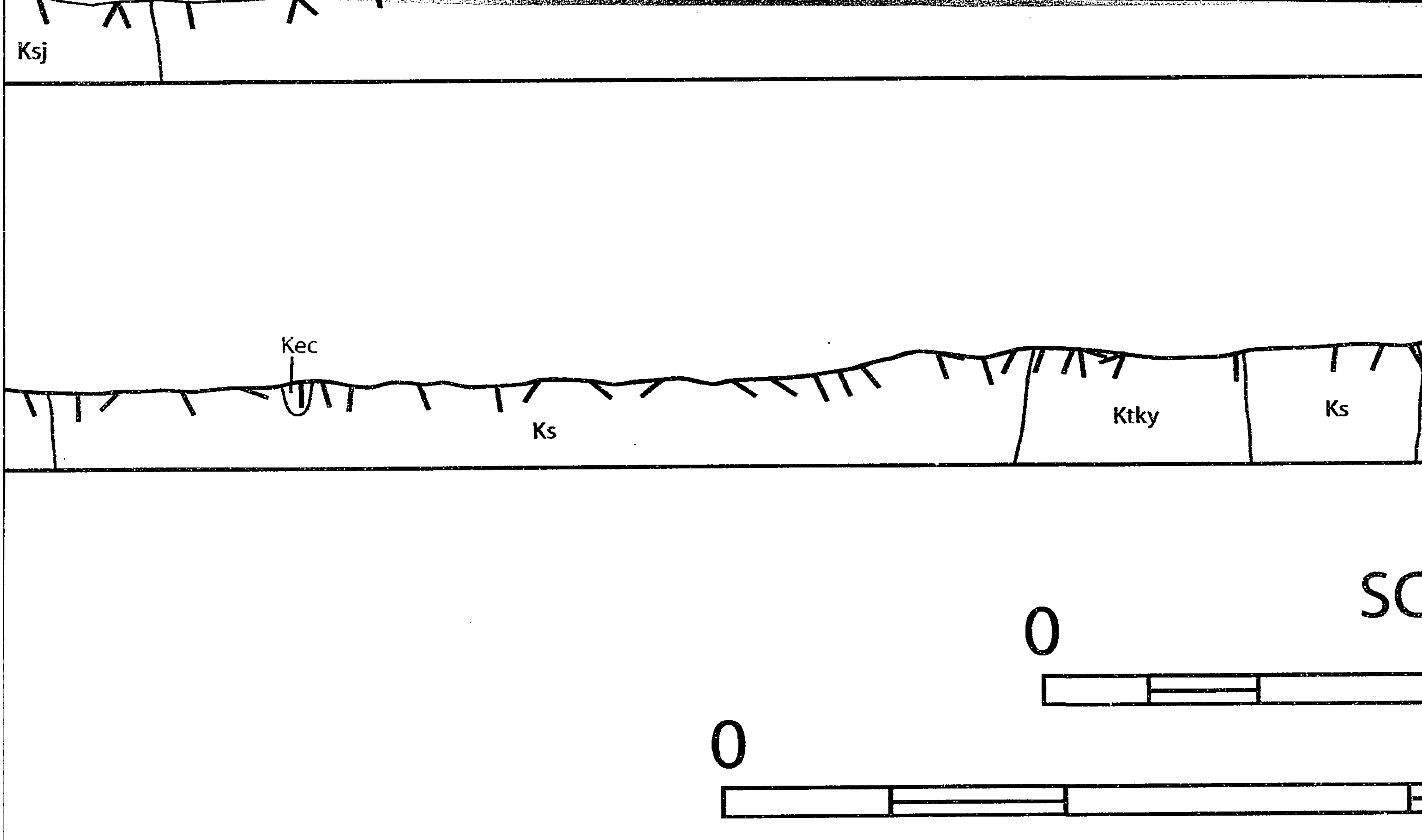
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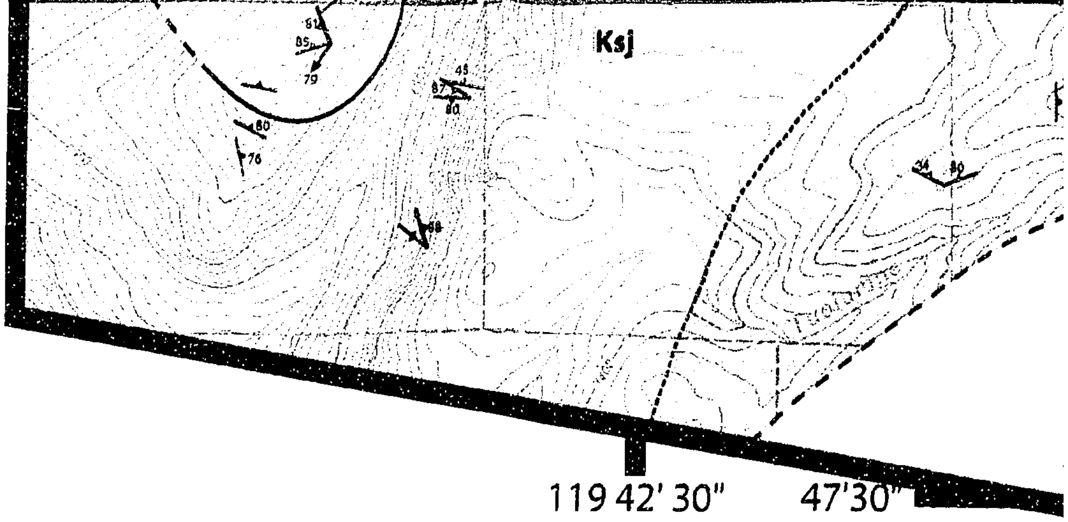

Plate 1. A. Bedrock map of the Sentinel Granodiorite and ac
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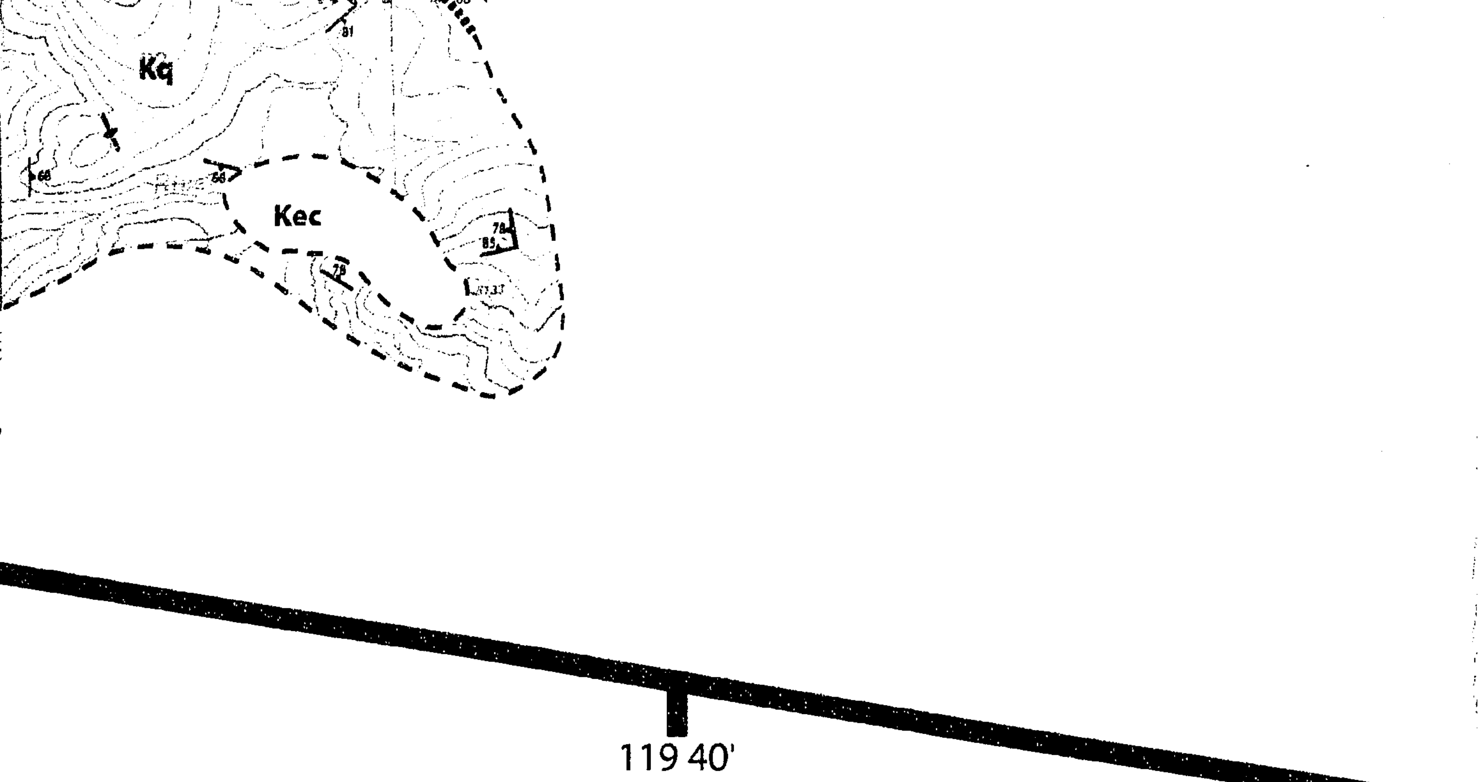
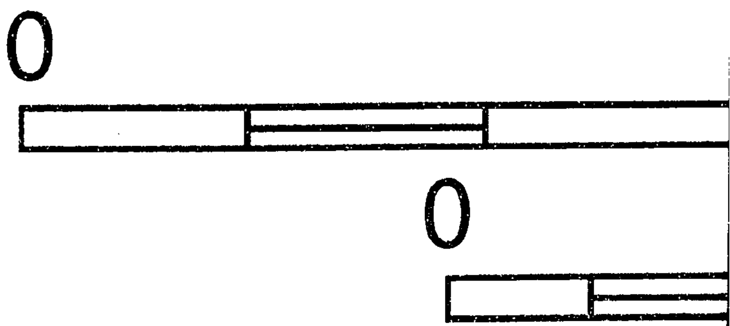
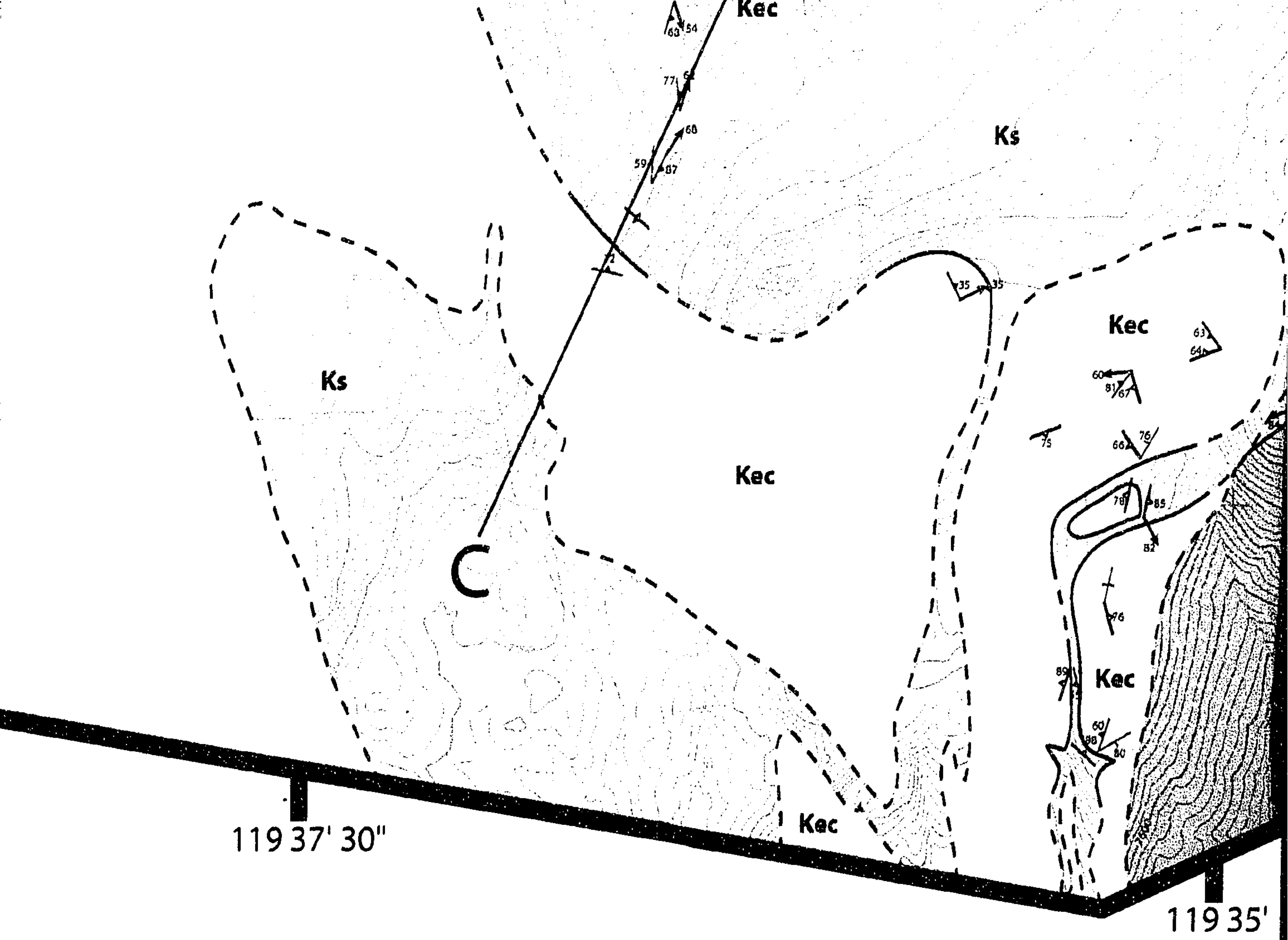
apparent dips of magmatic foliation.





CO

l adjacent Units. Some contacts modified
;. Lines below cross-sectional profile represent



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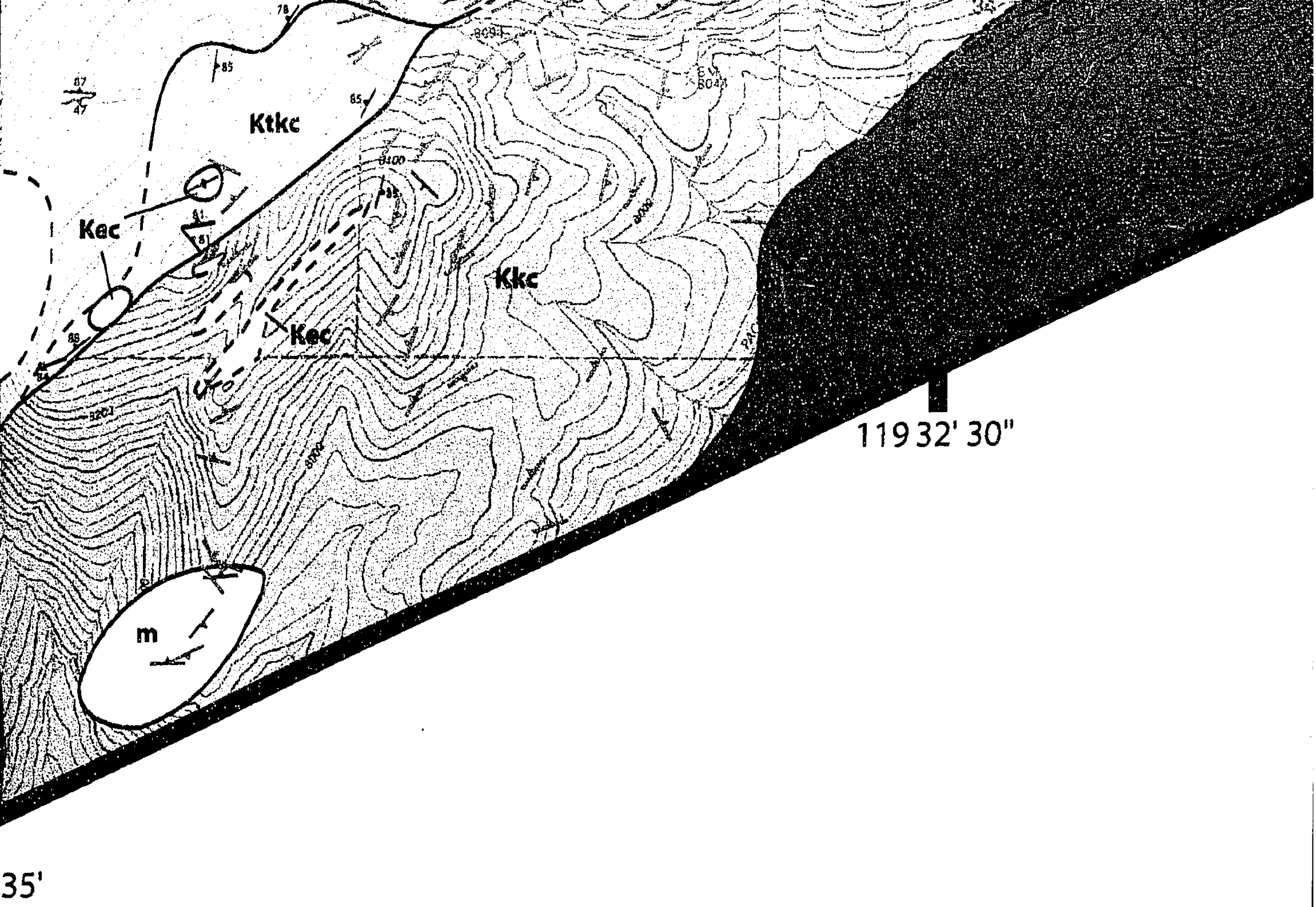
5 km

CONTOUR INTERVAL 40 FEET



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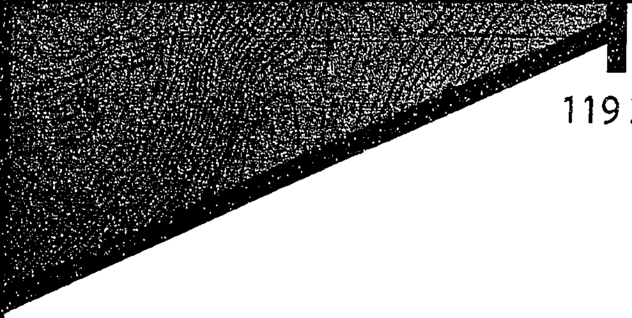

Vertical foliatio

Station with two foli
(Bold symbol denotes dominant fo

Lineation

Layering and inferrec

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ant foliation)

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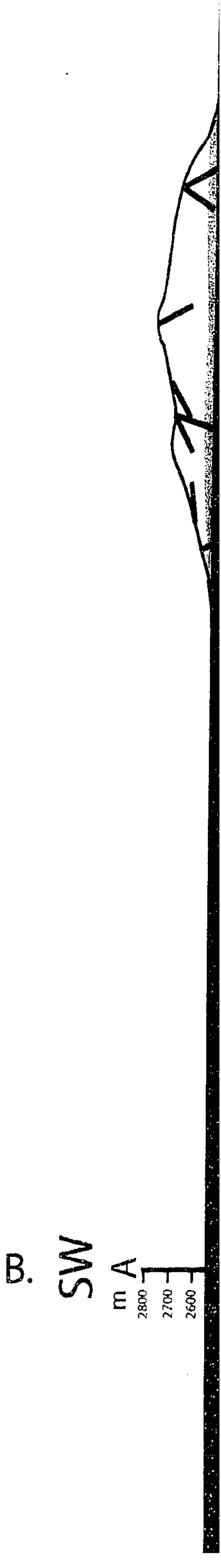

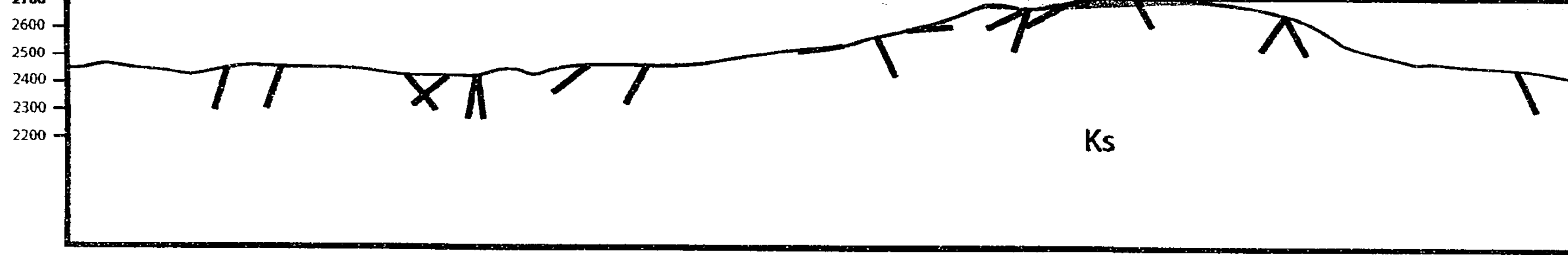
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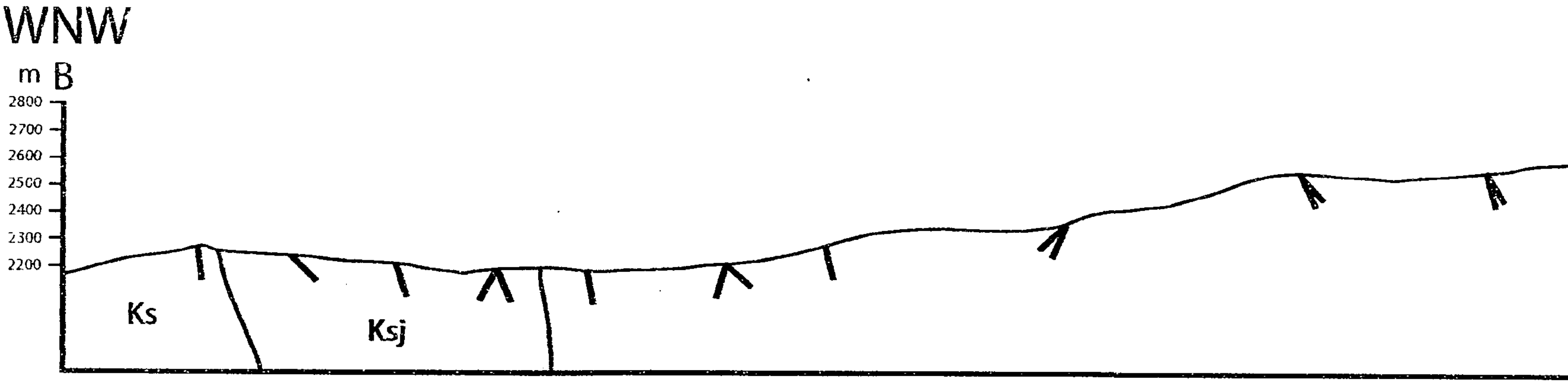
2500
2400
2300
2200
Ks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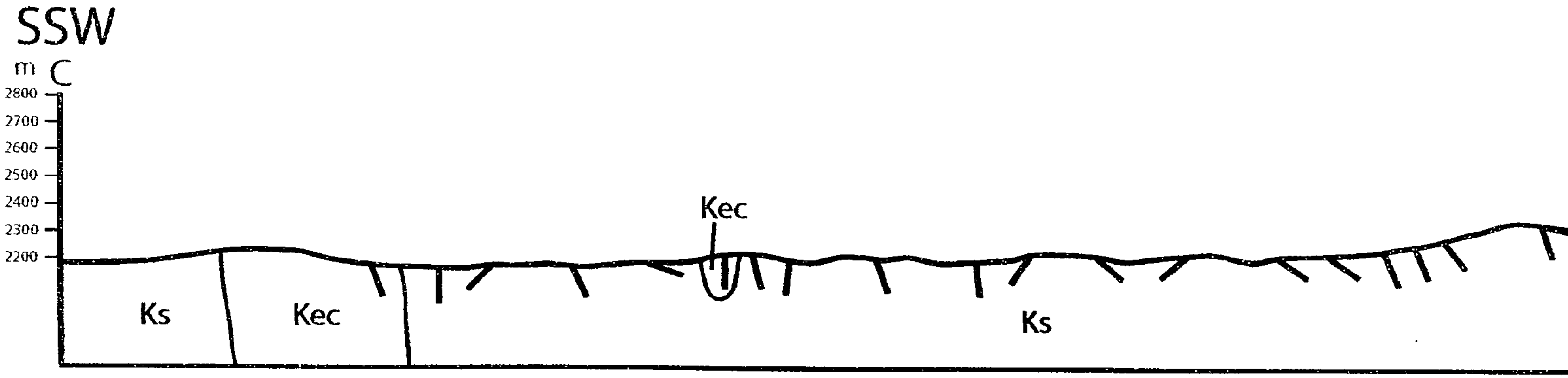
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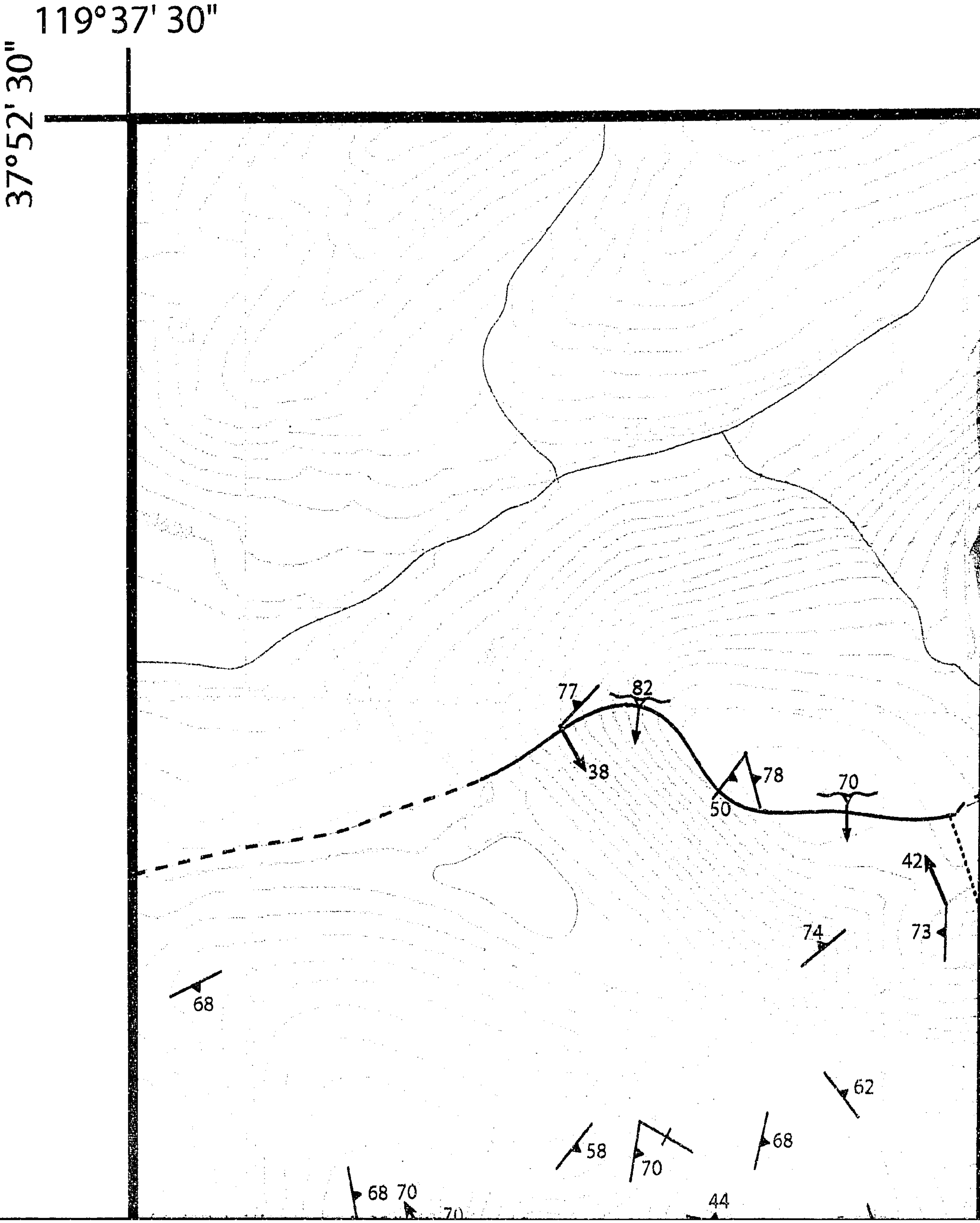
119°37' 30"
37°52' 30"
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38
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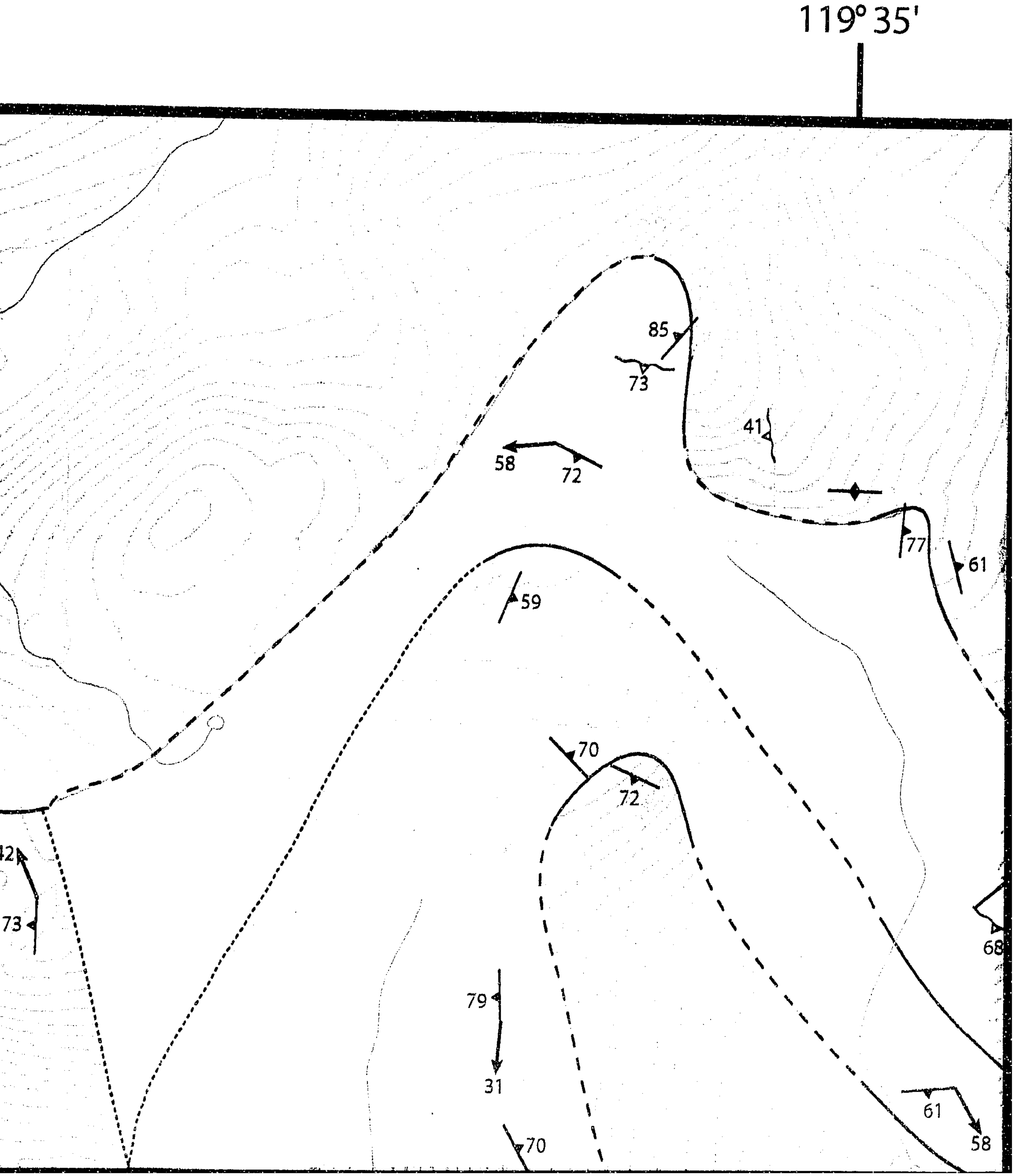
68 70
44


119° 35'
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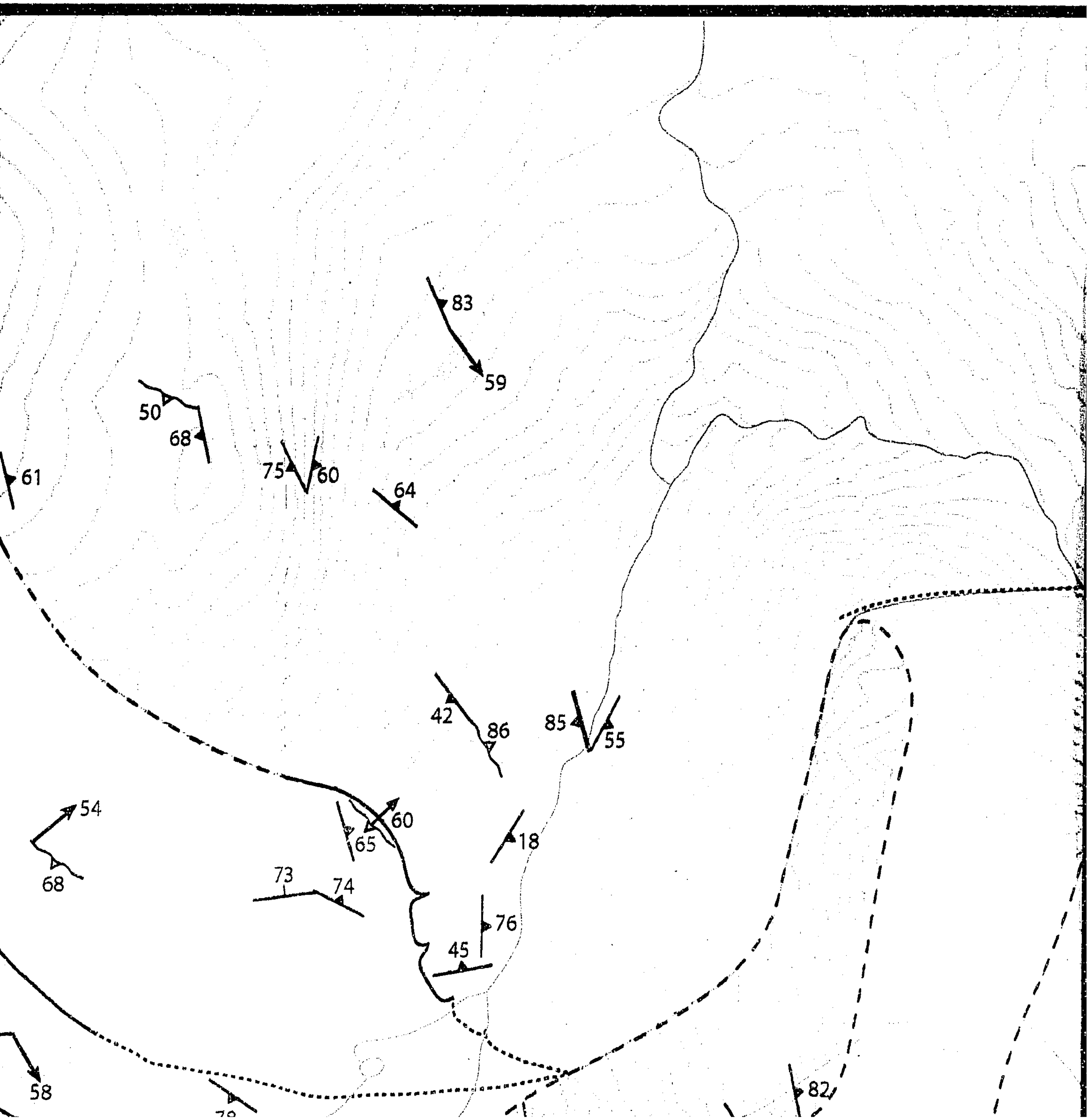
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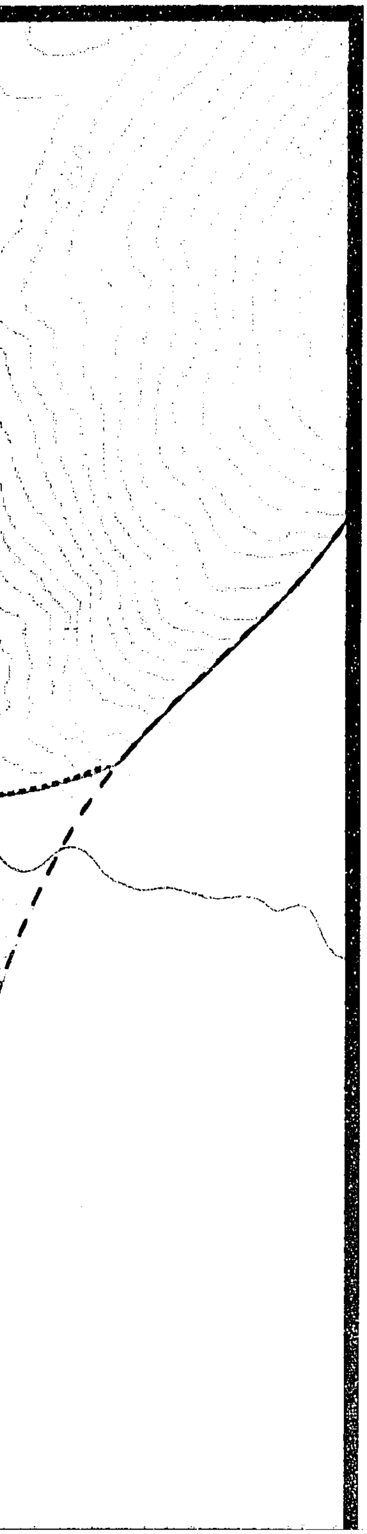


Bedrock Map of

Transitional Zone B
Sentinel and Yosemite Cr

Yosemite National Par

Mapped By

Joseph Petsche (200

Outliers of the
Tuolumne Intrusiv

Ky	Yosemite Creek Granodio
Ktky	Fine-grained Transitional Sentinel Granodiorite
Ktky	Medium-grained Transitio Sentinel Granodiorite

Bedrock Map of the

ansitional Zone Between the
and Yosemite Creek Granodiorites,

Yosemite National Park, California

Mapped By

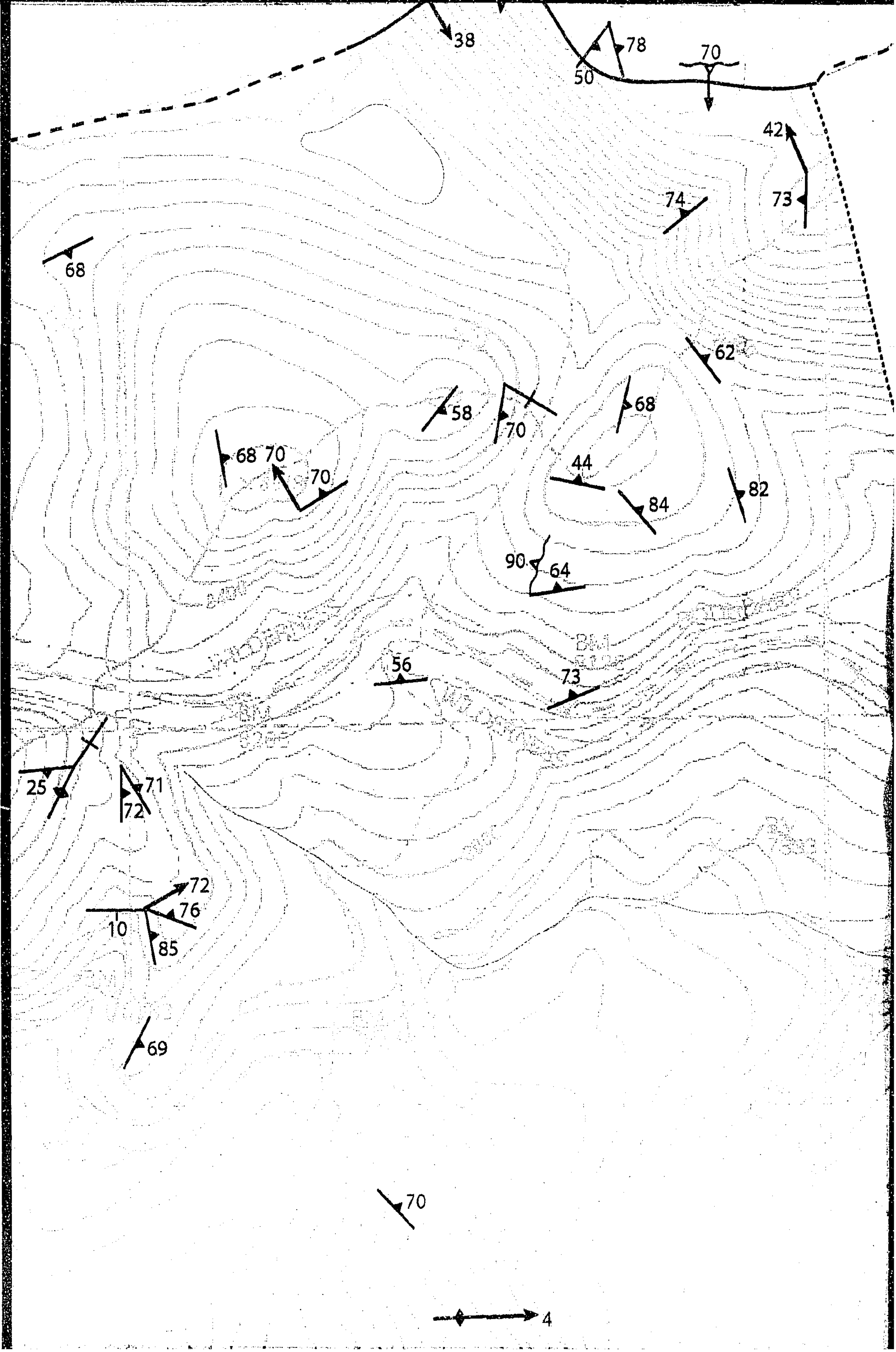
Joseph Petsche (2004-2006)

Outliers of the
Tuolumne Intrusive Suite

Yosemite Creek Granodiorite

Fine-grained Transitional Yosemite Creek / Sentinel Granodiorite

Medium-grained Transitional Yosemite Creek / Sentinel Granodiorite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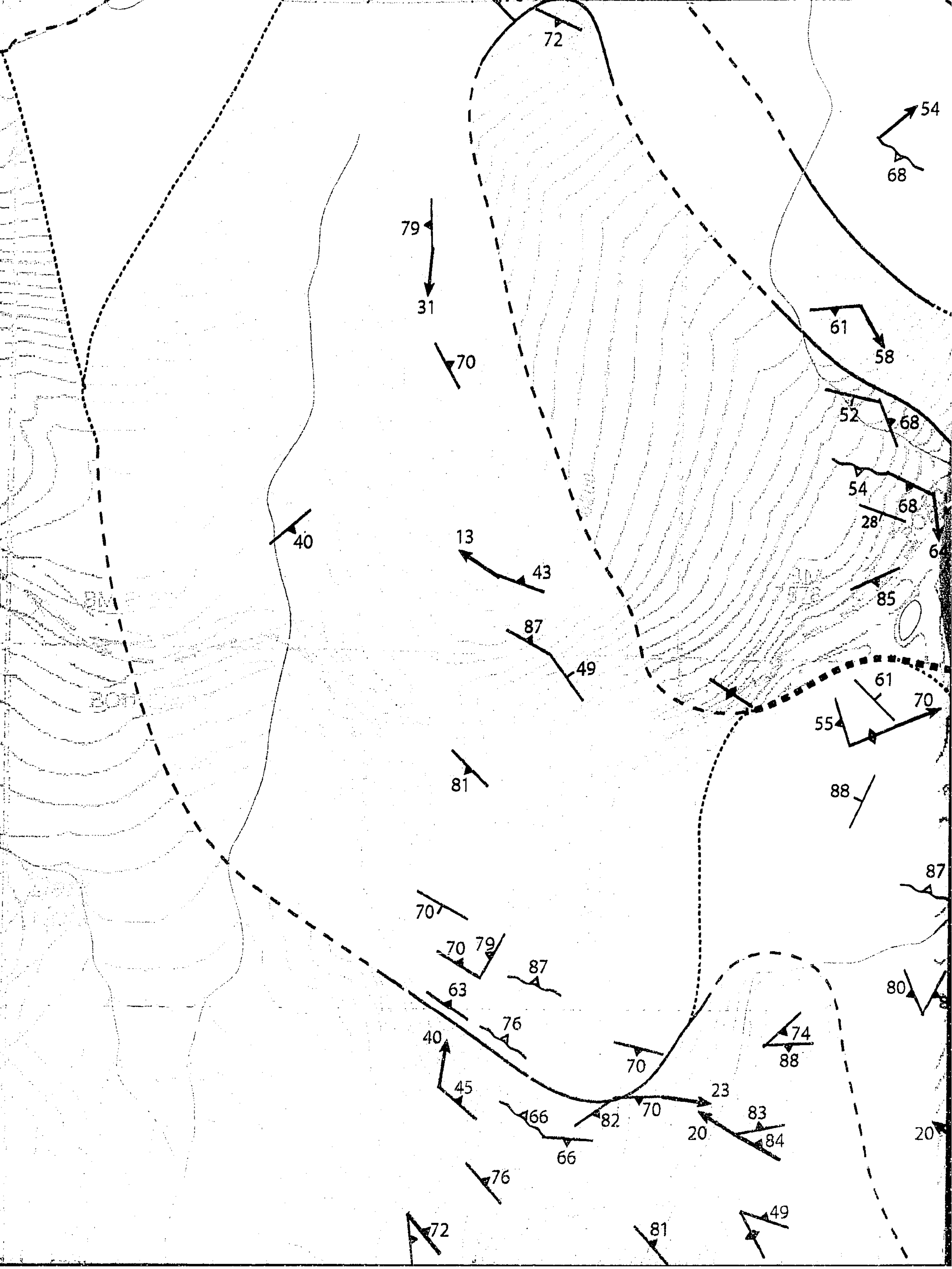
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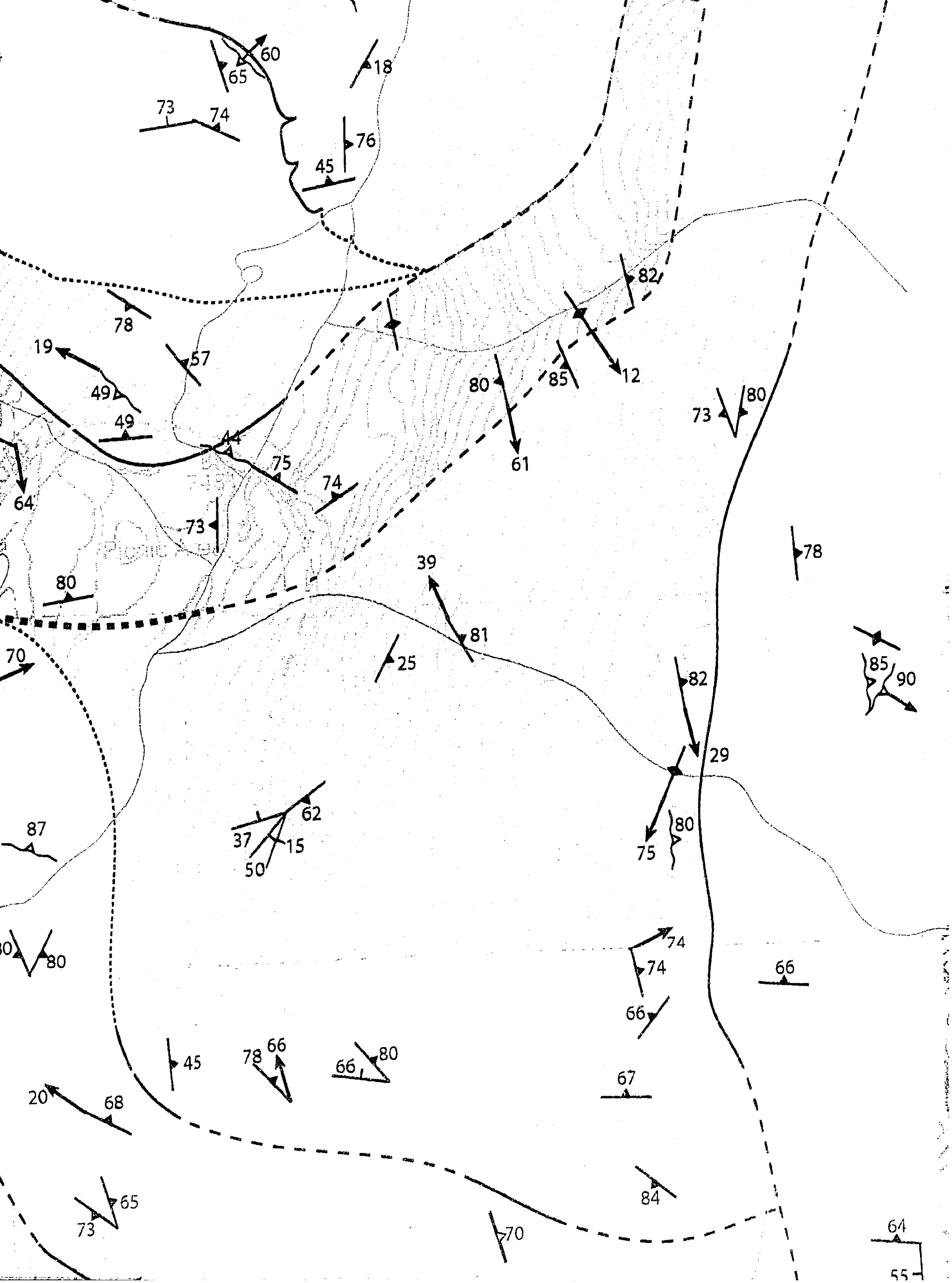

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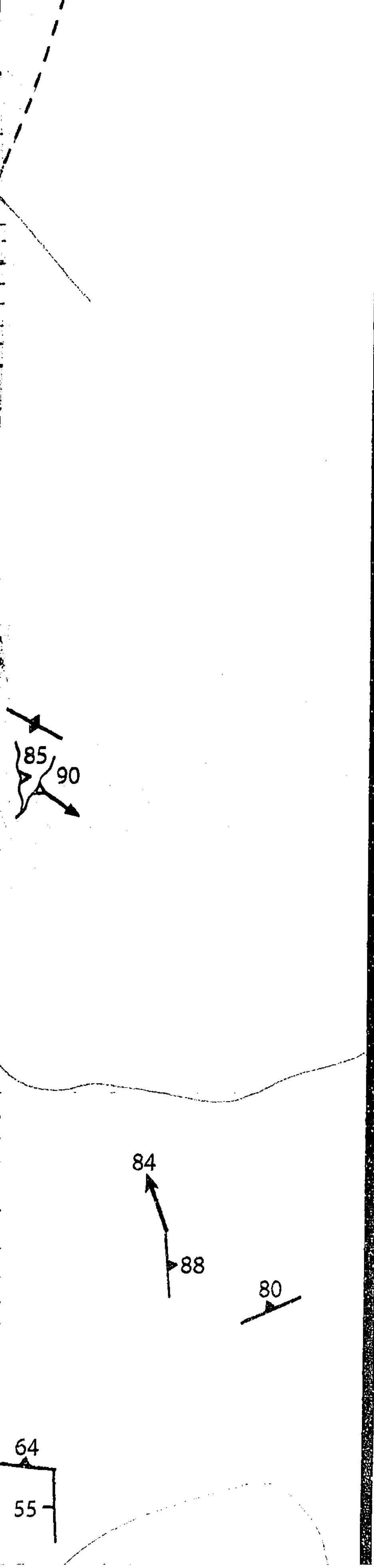


Ktky | Fine-grained Transitio
Sentinel Granodiorite

Ktky | Medium-grained Tran
Sentinel Granodiorite

Ks | Sentinel Granodiorite

Yosemite Valley
Suite

Kh | Granite of Mount Hof

Contact
Inferred trace of conta
Questionable trace of
Ductile shear zone
Tioga Pass road
Magmatic foliation
Solid-state foliation
Vertical foliation

Ktky Fine-grained Transitional Yosemite Creek / Sentinel Granodiorite

Ktky Medium-grained Transitional Yosemite Creek / Sentinel Granodiorite

Ks Sentinel Granodiorite

Yosemite Valley Intrusive Suite

Kh Granite of Mount Hoffman

Contact

Inferred trace of contact

Questionable trace of contact

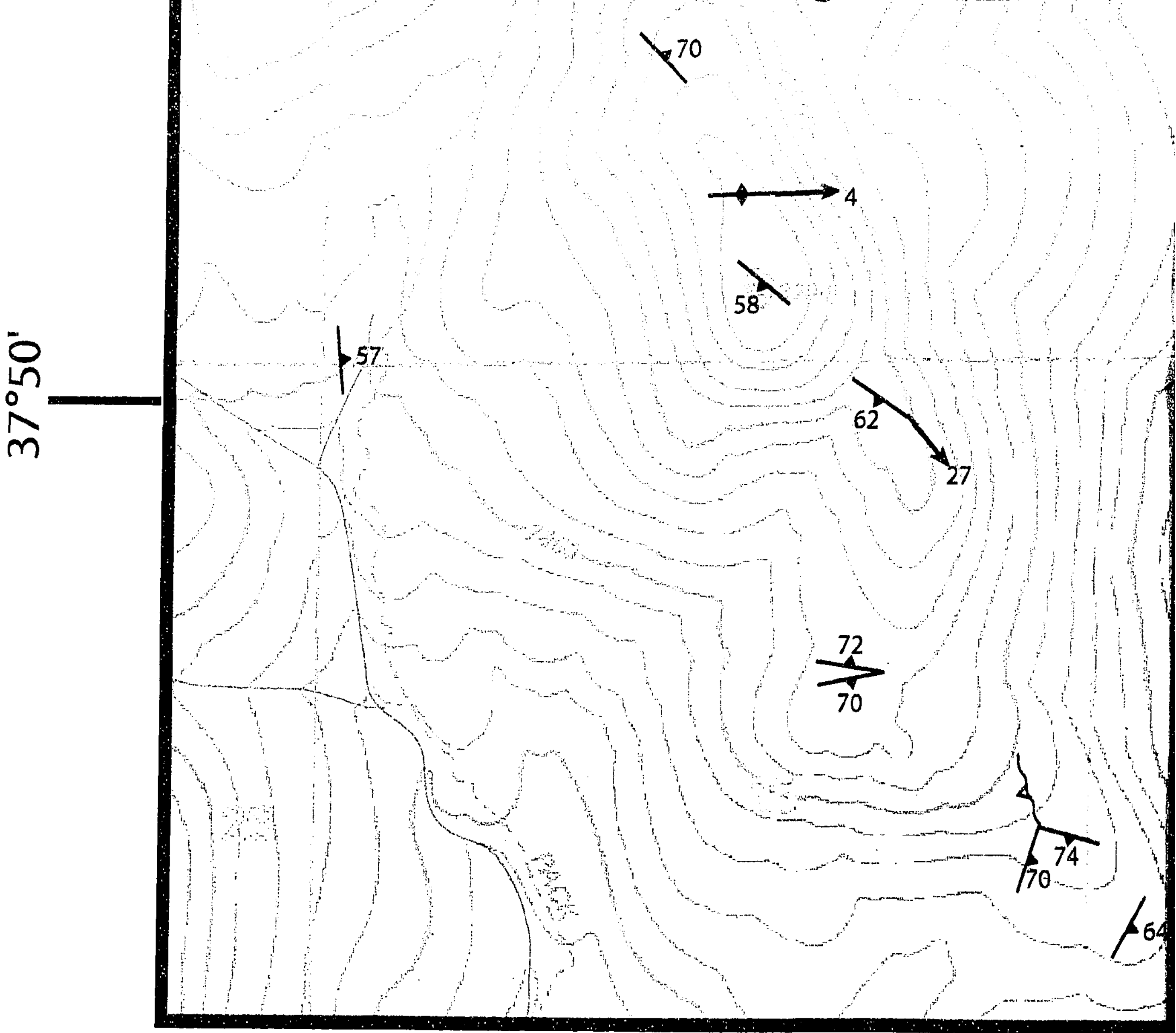
Ductile shear zone

Tioga Pass road

Magmatic foliation

Solid-state foliation

Vertical foliation



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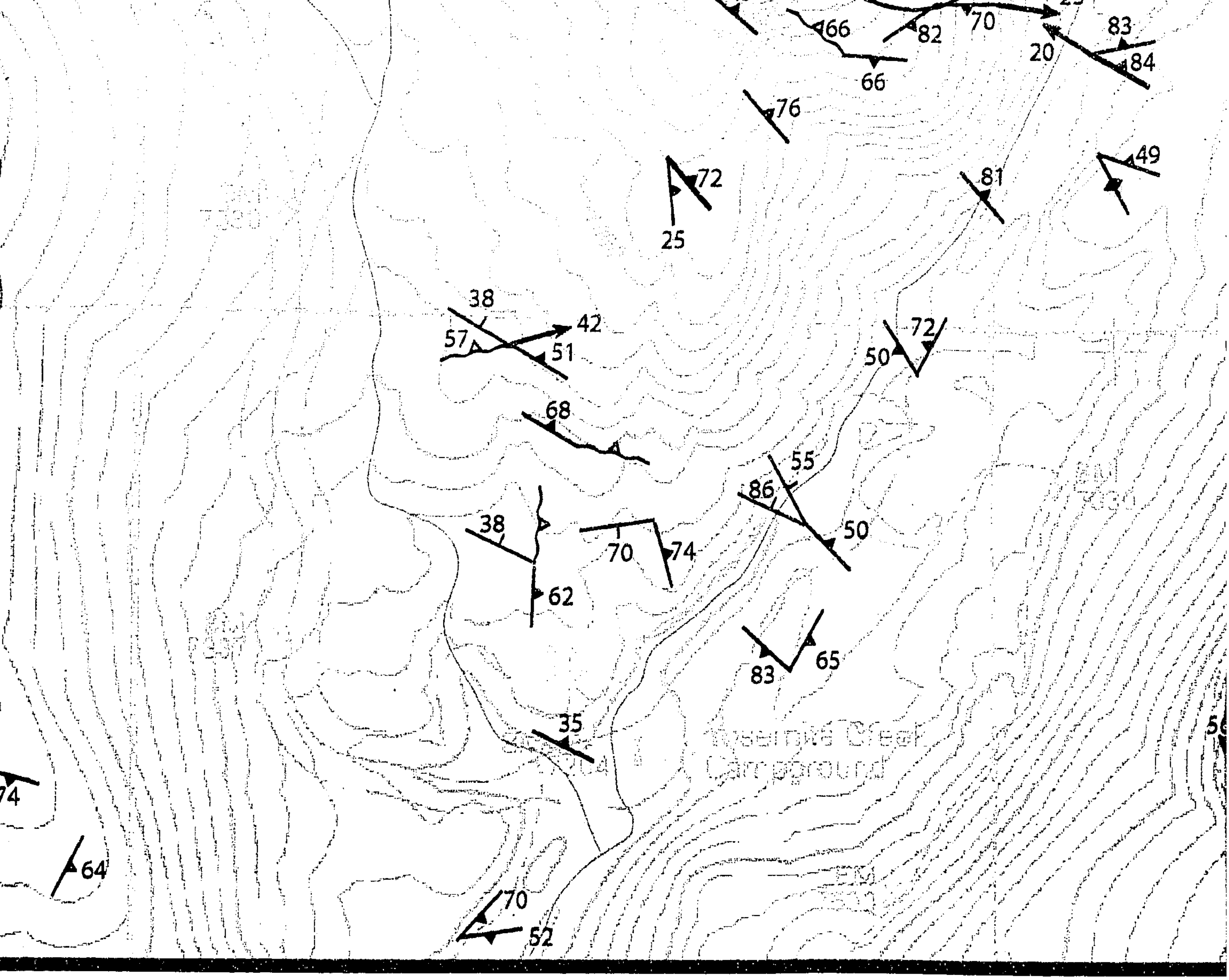

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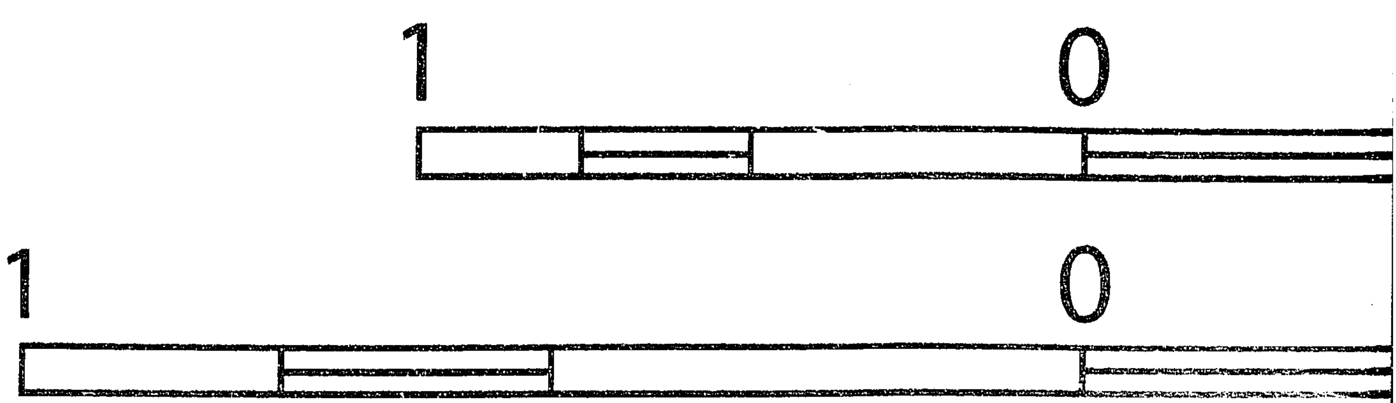
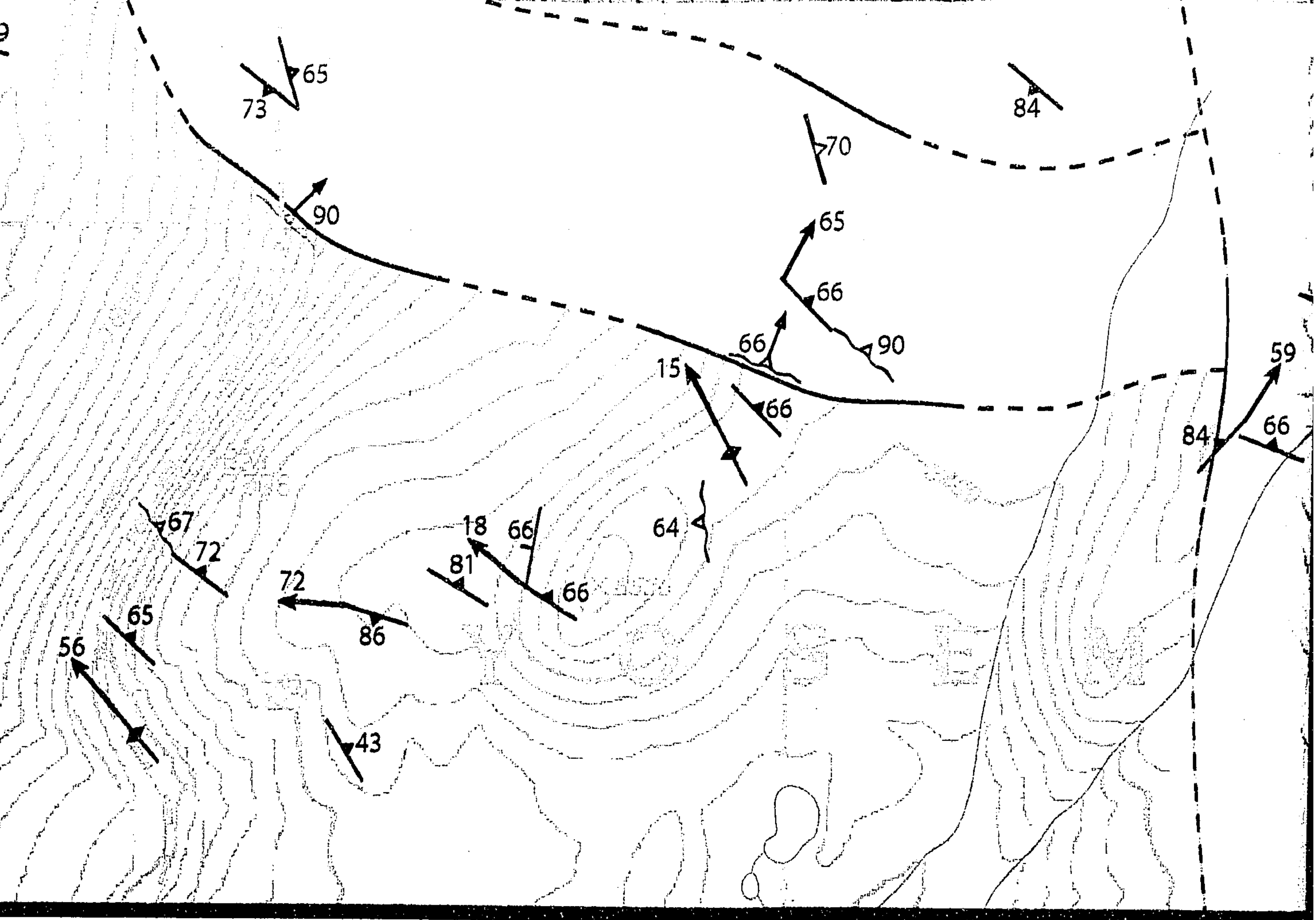


CONTOUR INTERVAL



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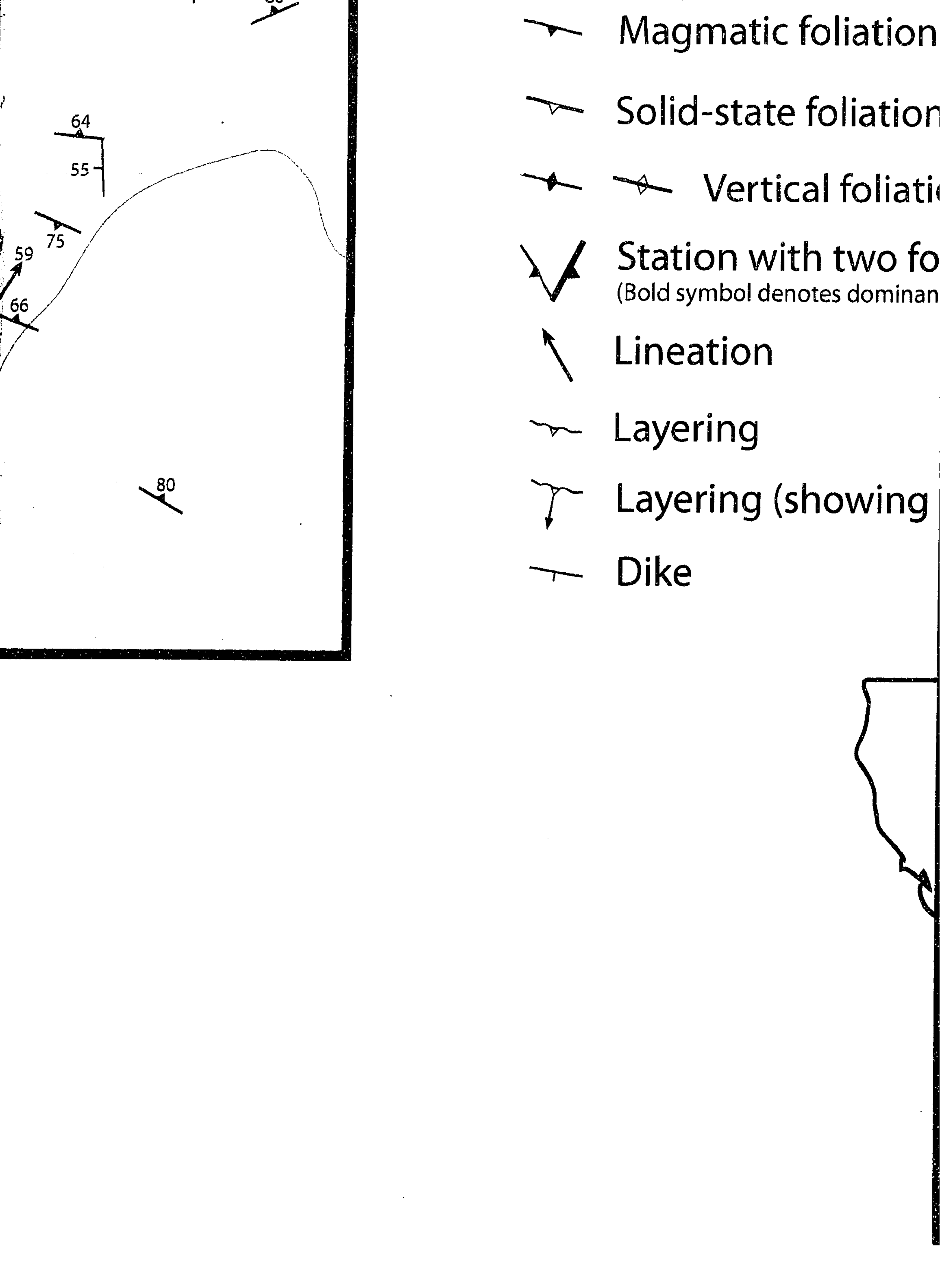

64
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Magmatic foliation
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Station with two fo
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Magmatic foliation

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Station with two foliations
(Bold symbol denotes dominant foliation)

Lineation

Layering

Layering (showing direction of growth)

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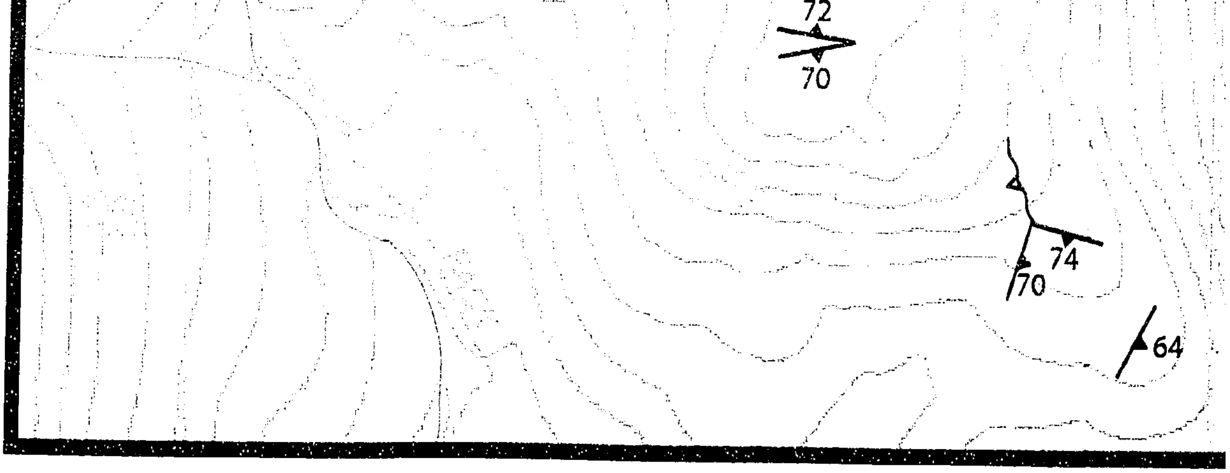


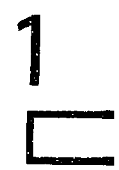
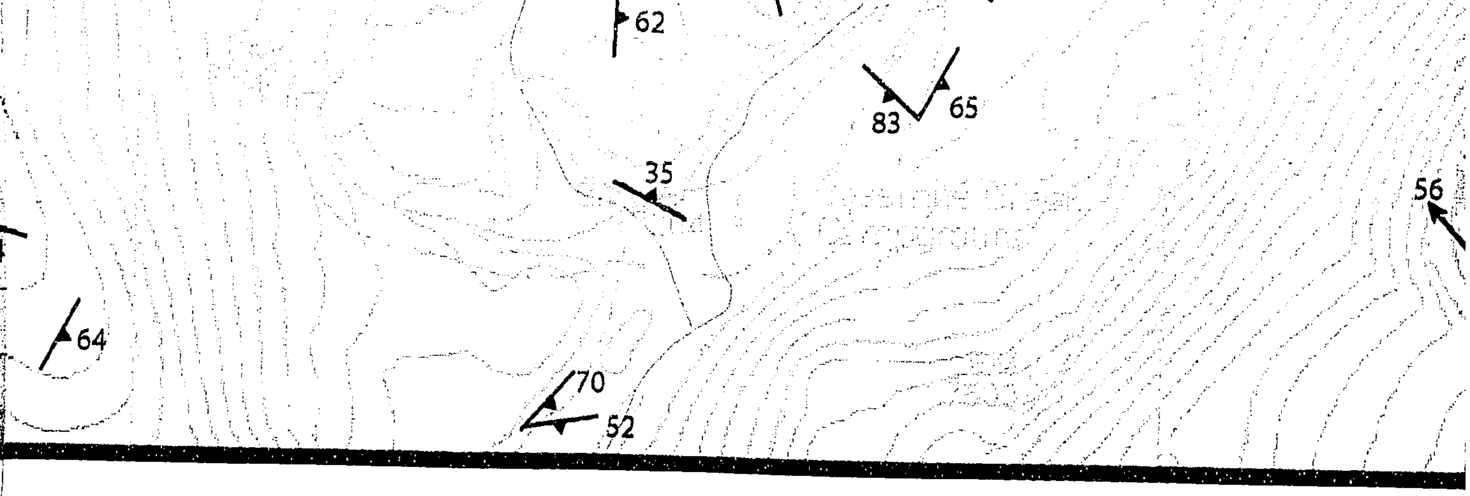


Plate 2. Detailed bedrock map of the transitional zone between the Sentinel and Yosemite Creek granodiorites



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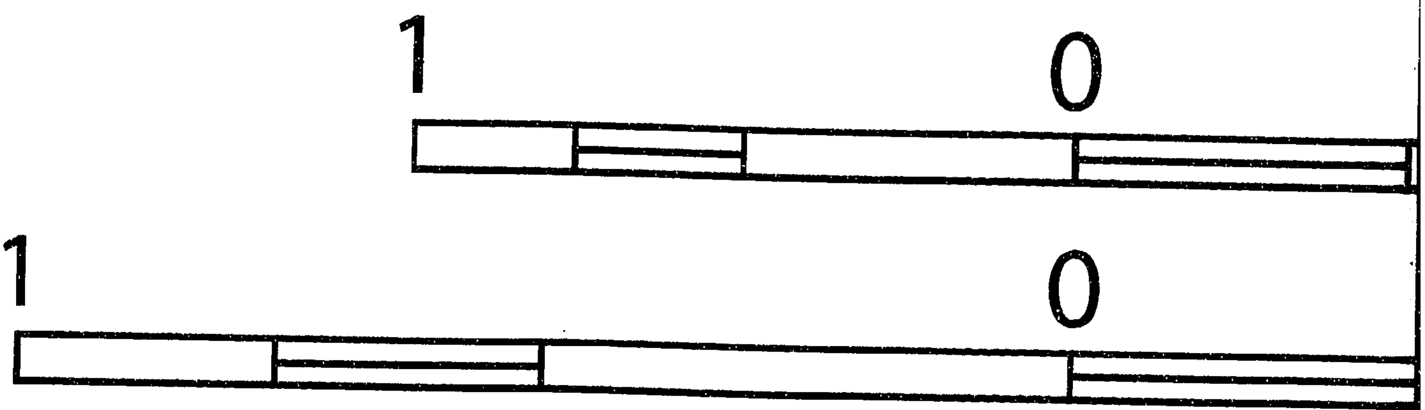

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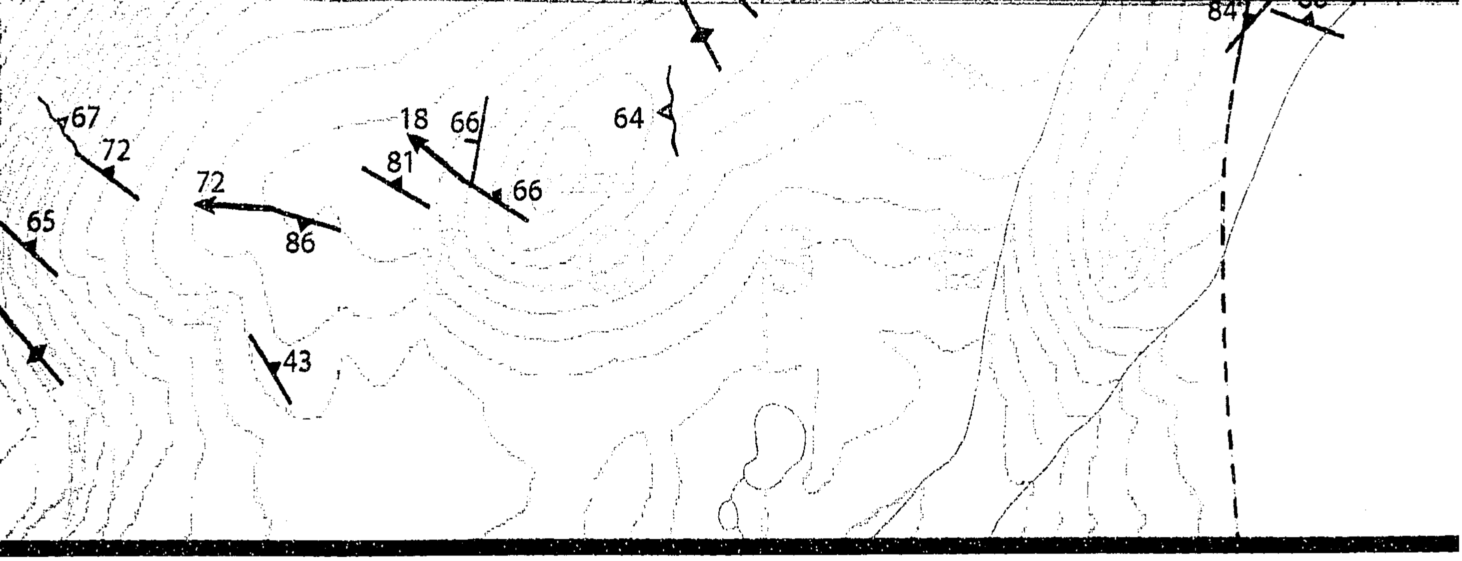

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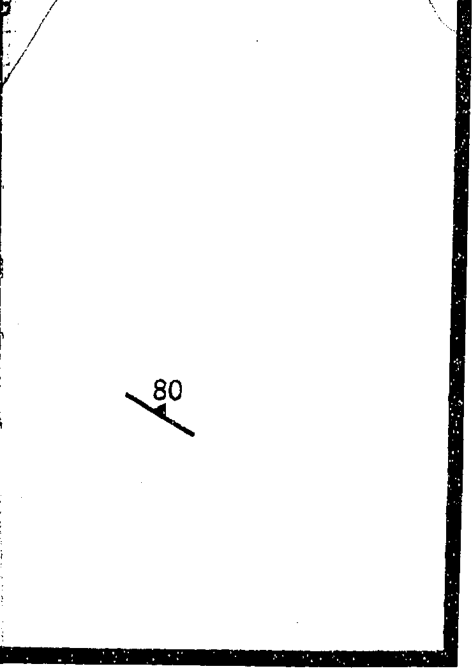

Station with two foliati
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Lineation

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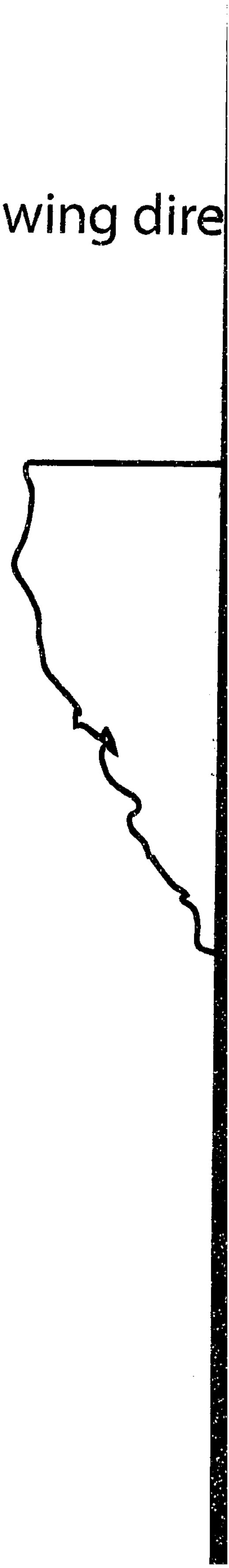

Vertical foliation

Station with two foliations
(Bold symbol denotes dominant foliation)

Lineation

Layering

Layering (showing direction of growth)

Dike