DEPARTMENT OF THE INTERIOR

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Chronology of Displacement on the San Andreas Fault in Central California: Evidence from Reversed Positions of Exotic Rock Bodies near Parkfield, California

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ABSTRACT

This paper presents a synthesis of data pertaining to post-early Miocene slip on the San Andreas fault in central California and suggests a three-phase evolution of the San Andreas system. The critical evidence that supports the three phases of evolution comes from the reversed positions of two exotic rock fragments in the vicinity of Parkfield, California. The three-phase evolution of the San Andreas is also supported by the correlation of other exotic fragments, the basement rocks on which they lie, overlying Tertiary statigrpahic sequences, and distinctive Miocene strata derived from these fragments during their transport along the fault.

The 40-km-long section of the San Andreas fault near Parkfield is characterized by exotic blocks composed of Cretaceous hornblende quartz gabbro at Gold Hill and lower Miocene volcanic rocks in Lang Canyon. The gabbro is correlated petrographically with similar rocks near Eagle Rest Peak 145 km to the southeast and near Logan 165 km to the northwest. The lower Miocene volcanic rocks, informally termed the volcanic rocks of Lang Canyon, are correlated with the Neenach Volcanics 220 km to the southeast and the Pinnacles Volcanics 95 km to the northwest. All three fragments of volcanic rocks are unconformably overlain by similar successions of Tertiary sedimentary rocks.

The original positions of the bodies of gabbro and volcanic bodies, and their overlying sedimentary cover may be reconstructed from these exotic fragments that now lay along the San Andreas fault between San Juan Bautista and the northwestern Mojave Desert. The original undeformed gabbroic body was composed of the hornblende quartz gabbro of Eagle Rest Peak, Gold Hill, and Logan. In its initial prefaulted position the original gabbroic body lay about 55 km northwest of the early Miocene volcanic assemblage. The undeformed volcanic assemblage was composed of the Neenach Volcanics, Pinnacles Volcanics, and volcanic rocks of Lang Canyon. The spatial relationship between the undeformed gabbro and volcanic assemblage and their sedimentary cover is preserved in the present position of the gabbro of Logan and the Pinnacles Volcanics. However, in the Parkfield segment of the San Andreas, the gabbro of Gold Hill lies east of the main trace of the San Andreas fault and the volcanic rocks of Lang Canyon lie 2 km west of the fault. The reversed relative positions of the gabbro of Gold Hill and the volcanic rocks of Lang Canyon suggests a complex history of movement on the San Andreas fault.

Consequently, palinspastic reconstruction of these bodies and their overlying sedimentary cover is constrained by the unusual distribution of exotic blocks near Parkfield. The resulting proposed history of movement is divided into three stages that begins with the eruption of the early Miocene volcanic rocks about 24 Ma. The Neenach-Pinnacles Volcanics, erupted after passage of the Mendocino triple junction, were soon cut by the growing San Andreas fault.

During the first phase of movement the Salinian block, which contains the Pinnacles and Logan bodies, was detached from the Mojave and Sierran blocks. The Pinnacles and Logan bodies were transported about 95 km northwest from the Neenach Volcanics and the gabbro of Eagle Rest Peak. At the end of the first phase the Logan and Pinnacles fragments lay adjacent to the west side of what is now the San Joaquin Valley. Concurrently, fan-deltas deposited debris derived from the Gabilan Range. The fan-deltas spread across the San Andreas fault into the middle Miocene sea in the San Joaquin trough.

During the second phase of movement the San Andreas, at least locally, stepped eastward and detached a second fragment from the Neenach Volcanics. This fragment consists of the volcanic rocks of Lang Canyon. Slip was transferred to the new trace of the San Andreas fault and the older trace became completely or largely inactive. After transferral of

slip to the new trace of the San Andreas fault the volcanic rocks of Lang Canyon and the Pinnacles Volcanics remained about 95 km apart on the Salinian Block west of the San Andreas fault.

During the third phase, the Gold Hill fragment was slivered off of the Logan fragment and tectonically emplaced on the east side of the San Andreas fault when the Logan fragment lay at the latitude of Gold Hill. The process of slivering off of the Gold Hill fragment was accomplished by deformation of the San Andreas in an eastward bend along what is now the Jack Ranch fault. The bending of the fault was stimulated by the presence of highly sheared Franciscan rocks that crop out near the San Andreas and extending to great depth. Eventually the San Andreas bent to such a degree that slip could not be conducted around the bend and a new stable straight segment was formed. The straightening of the fault resulted in the slivering of the Gold Hill fragment from the Logan fragment.

After detachment of the Gold Hill fragment, the Salinian block containing the gabbro of Logan, the Pinnacles Volcanics, and the volcanic rocks of Lang Canyon, was transported an additional 160 km northwest to its present position. This reconstruction honors the current positions of all the related exotic fragments of gabbro, volcanics, and sedimentary rocks. The timing of the sequence of movements required to reconstruct the original bodies suggests that the three phases of evolution of the San Andreas fault in central California are characterized by increasing slip rates. The rate for the first phase probably averaged about 12 mm/yr over a period of about 8 m.y. The rate for the second phase averaged about 8 mm/yr over a period of about 7 m.y. The rate for the third phase averaged about 33 mm/yr over a period of about 5 m.y.

INTRODUCTION

Large-scale right-lateral movement of the San Andreas fault on the order of hundreds of kilometers was first demonstrated in the seminal paper by Hill and Dibblee (1953). They used the lithologic and faunal similarities of widely separated rock bodies on opposite sides of the San Andreas fault to show that younger strata are displaced shorter distances than older strata. They also suggested that the total offset since late Oligocene to early Miocene time was on the order of 280 km. Later studies built upon this theme (for example: Bazeley, 1961; Addicott, 1968; Turner, 1968, 1970). However, all these cross-fault correlations were based on broadly defined features such as ancient shorelines, latitudinally restricted faunal distributions, and paleoisobaths offset by movement along the San Andreas. The point of intersection of these broadly defined features with the San Andreas fault required the straight-line projection of their trends over distances between about 2 to 20 km. Projection of these kinds of features over such distances considerably reduced the precision of the offset determination. These imprecise estimates of offset prompted a search for more areally restricted and distinctive rock units that are offset by the San Andreas. Several distinctive volcanic units and crystalline basement rocks were focused on as likely candidates for the more precise cross fault correlations that were needed.

One early estimate of the magnitude of large-scale strike-slip movement along the San Andreas fault was based on the presence of distinctive flow-banded rhyolite clasts in the Santa Margarita Formation of the southwestern Temblor Range (Berry and others, 1968; Fletcher, 1967, 1962). Flow-banded rhyolite from the Pinnacles Volcanics[1] was identified as the source of these distinctive clasts because both the clasts in the Santa Margarita Formation and the rocks of the Pinnacles are petrographically similar and have similar potassium-argon ages (Turner, 1968, p. 67). This work was further expanded and the Pinnacles Volcanics were demonstrated to be correlative with the Neenach Volcanics[2] (Turner and others, 1970; Matthews, 1973a), which are now separated by a distance of 315 km along the strike of the San Andreas fault.

At about the same time that studies of the volcanic rocks were being conducted the gabbroic basement in the San Emigdio Mountains was correlated with similar rocks near San Juan Bautista. Later, the sedimentary and volcanic rocks that unconformably overlay these volcanic rocks were also correlated (Fig. 1 and Table 1). The gabbroic basement consists distinctive hornblende quartz gabbro of Cretaceous and Jurassic age that is unconformably

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[1]Andrews (1936) first introduced the name Pinnacles Formation for the sequence of volcanic rocks exposed in Pinnacles National Monument; he did not designate a type for the unit. Matthews (1973b) in a Ph. D. dissertation more fully described and mapped this unit which he called the Pinnacles Volcanic Formation. He described the unit as consisting of a sequence of calc-alkaline andesite, dacite, and rhyolite flows interbedded with pyroclastic and volcaniclastic rocks. He divided the formation into seven informal members with an overall thickness of at least 2,185 m. He noted that the unit occurs in several patches north of the Pinnacles National Monument (Matthews, 1973b, Fig. 18) and that it rests unconformably on Cretaceous granitic rocks and is overlain unconformably by unnamed middle Miocene shale. He cited K/Ar dates ranging from 23.9 ± 1.2 Ma to 21.5 ± 3.2 Ma as evidence for an early Miocene age. I accept Matthews' usage of the name Pinnacles and his suggested type section along High Peaks Trail in the Pinnacles National Monument (SW 1/4, SE 1/4, Sec. 35, to SW 1/4, SE 1/4, Sec. 34, T 16 S, R 4 E, North Chalone Peak 7.5 minute quadrangle). However, his term, Pinnacles Volcanic Formation, does not conform to the North American Stratigraphic Code (North American Commission on Stratigraphic Nomenclature, 1983) thus the unit is here renamed the Pinnacles Volcanics, a term also used by Huffman (1972). Although the Pinnacles Volcanics is not a widespread unit, its extremely important status in California regional geology justifies its retention as a formational rank unit. The retention of formational rank requires the designation of a type section.

[2]The Neenach Volcanic Formation (Dibblee, 1967) is here renamed Neenach Volcanics to conform with the recommendation of the North American Stratigraphic Code (North American Commission on Stratigraphic Nomenclature, 1983). The Neenach Volcanics is here considered to be early Miocene in age based on correlation with the Pinnacles Volcanics (Turner, 1968; Turner others, 1970; Matthews, 1973a, 1976).

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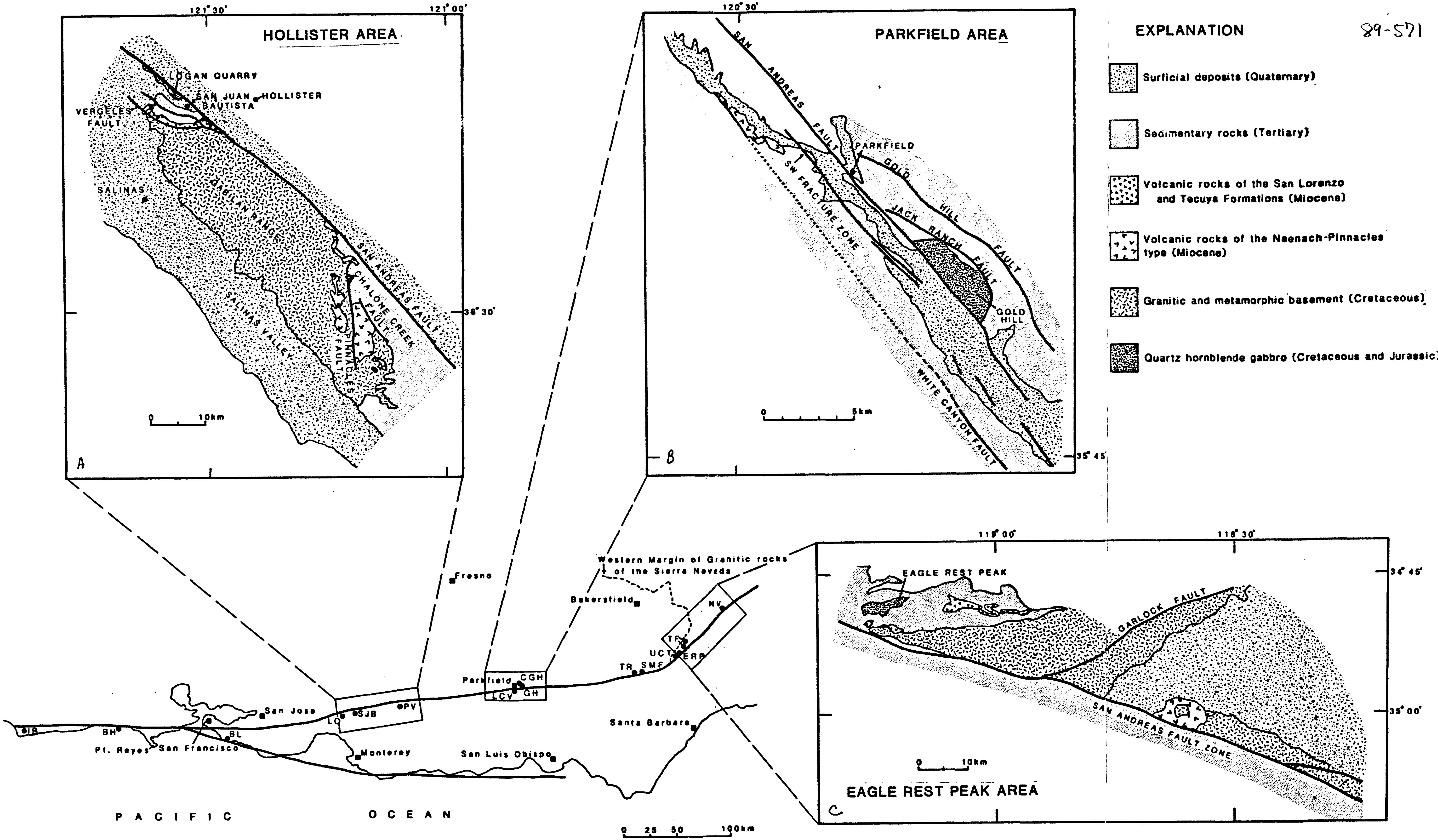

Figure 1. California and the location of the San Andreas fault and sites used to restore offset on the San Andreas and San Gregorio-Hosgri faults (see Table 1). Sites are keyed to Table 1 and from northwest to southeast are: IB - Iversen Basalt, BH - Bodega Head, BL - tonalite of Ben Lomond, LO -gabbro of Logan, SJB - rhyolite, andesite, and dacite of the San Juan Bautista area, PV - Pinnacles Volcanics, LCV - volcanic rocks of Lang Canyon, GH - hornblende quartz gabbro of Gold Hill, CGH - Eocene Uvas Conglomerate Member of Tejon Formation of the Gold Hill area (Sims, 1988), TR - Santa Margarita Formation bearing Sr-isotope dated Crasostrea in the southern Temblor Range, SMF - Volcanic clasts of Neenach-Pinnacles-type of the Santa Margarita Formation in southern Temblor Range, STR - volcanic-rich facies in the Temblor Formation of the southern Temblor Range, UCT - Uvas Conglomerate Member of the Tejon Formation, ERP - hornblende-quartz gabbro of Eagle Rest Peak, TF - volcanic rocks in the Tecuya Formation, NV - Neenach Volcanics.

A: Geologic map of the Gabilan Range and vicinity. Illustrates the spatial relationship of the gabbro of Logan (Ross, 1970), the Pinnacles Volcanics, and volcanic rocks of the San Lorenzo Formation. After Allen (1946), Dibblee (1971), and Dibblee and others (1979).

B: Geologic map of the Eagle Rest Peak-Neenach Volcanics area illustrating the spatial relationship between the gabbro of Eagle Rest Peak Eocene sedimentary rocks in the San Emigdio Mountains, and the Neenach Volcanics.

C: Geologic map of the Parkfield area illustrating the spatial relationship between the gabbro of Gold Hill, Eocene sedimentary rocks deposited on the Gold Hill body, and the volcanic rocks of Lang Canyon (Sims, 1988).

Table 1. Rock bodies and stratigraphic units that demonstrate offset along the San Andreas and the San Gregorio-Hosgri fault in post-late Miocene time. Ages and distances used in the palinspastic reconstruction of rock bodies across the San Andreas (see Fig. 1 for locations). Letters in parentheses refer to the designations on Figure 1D.

Name of Unit	Age (my)‡	Distance from Parent Body (km)	References
1 Neenach Volcanics (NV)	19.0 to 24.1†	Parent	1
2 Volcanic rocks of Lang Canyon (LCV)	22.3 to 23.6	220	2,4,9
3 Pinnacles Volcanics (PV)	24.2 ± 0.5	315	2
4 Volcanic clasts in Santa Margarita Formation, southern Temblor Range (SMF)	23.3 ± 0.7 to 24.2 ± 0.7	---	2
5 Sr age of Ostrea from Santa Margarita Formation, southern Temblor Range (STR)	13.6§	---	5
6 Dacite flow in Tecuya Formation (TF)	22.2 ± 0.3	Parent	3
7 Volcanic rocks near San Juan Bautista (SJB)	22.2 ± 0.7	315	2, 12
8 Gabbro of Eagle Rest Peak (ERP)	137 ± 4 to 212 ± 10	Parent	6
9 Gabbro of Gold Hill (GH)	147 ± 7	145	6, 8
10 Tejon Formation near Gold Hill (CGH)	Eocene "Tejon" stage	145	7, 8
11 Gabbro of Logan (LO)	159 ± 8	315	6
12 Uvas Conglomerate Member of Tejon Formation, San Emigdio Mountains (UC)	Eocene "Capay" to "Tejon" stage	Parent	10, 11

‡ Ages converted to conform to dates determined by new IUGS constants (Dalrymple, 1979)
† Minimum age, probable age is 23.7 Ma
§ No error stated

REFERENCES
1 D.L. Turner, unpublished data cited by Matthews (1973a)
2 Turner (1968, p. 67)
3 Turner (1970)
4 Matthews (1973a)
5 Hornafius (written commun. 1987)
6 Ross (1970)
7 Sims (1986)
8 Sims (1988)
9 Sims (in press)
10 Nilsen (1984)
11 Nilsen (1987)
12 Thomas (1986)

overlain by Eocene to Miocene sedimentary and volcanic rocks. These bodies, which are petrographically and geochemically similar (Ross, 1970; James and others, 1986), lie about 55 km northwest of the Pinnacles and Neenach Volcanics respectively. The two bodies, the gabbro of Logan near San Juan Bautista, and the gabbro of Eagle Rest Peak in the San Emigdio Mountains, and their overlying sedimentary rocks are separated by about 315 km along the San Andreas fault (Turner and others, 1970; Ross, 1970, 1984, Matthews, 1973a; Nilsen, 1984).

Slivers of rocks similar to the Neenach and Pinnacles Volcanics and the gabbros of Logan and Eagle Rest Peak also occur near Parkfield, an area intermediate between the offset pairs (Dickinson, 1966; Turner, 1968; Ross, 1970; Sims, 1988, in press). The displaced tectonic fragments of the Parkfield segment of the San Andreas fault lie just northwest of the 1-km right stepover of the fault in Cholame Valley and about 1.5 km northwest of the hamlet of Parkfield (Fig. 1B). Here, the volcanic rocks of Lang Canyon and the gabbro of Gold Hill are correlated with similar distinctive rocks 95 to 150 km to the northwest on the west side of the fault and 145 to 220 km to the southeast on the east side of the fault. The gabbro of Gold Hill is overlain by strata of early Eocene age and the volcanic rocks of Lang Canyon are unconformably overlain by sedimentary rocks of middle to late Miocene age. The relative positions of the volcanic and gabbro fragments are reversed compared to their correlatives to the northwest and southeast. The unusual reversed relative positions of the volcanic rocks of Lang Canyon and gabbro of Gold Hill suggests a more complex history of faulting along the San Andreas fault than has been previously proposed.

The correlations of the Pinnacles Volcanics with the Neenach volcanics and the gabbro of Logan with the gabbro of Eagle Rest Peak are generally accepted. However, several correlations of displaced rock units that support the correlation of the volcanics and gabbro are less well known, although no less well established. These additional correlations are crucial to the interpretation of the detailed movement history of the San Andreas fault and the palinspastic reconstruction I present. Therefore, I will first briefly describe pertinent correlations and their interrelationships.

SUMMARY OF CORRELATIVE ROCK UNITS

Gabbroic Rocks Overlain by Eocene Through lower Miocene Strata

Three bodies of distinctive and areally restricted gabbroic rocks lie along the San Andreas fault at Logan, near Eagle Rest Peak, and at Gold Hill (Fig. 1). Correlation of the gabbro of Gold Hill with other similar distinctive hornblende quartz gabbro bodies along the San Andreas fault was first suggested by Ross (1970). He correlated the gabbro of Gold Hill with the gabbro of Eagle Rest Peak, 145 km to the southeast, and with the gabbro of Logan, 170 km to the northwest (Ross, 1970). The gabbros of Logan and Eagle Rest Peak also have identical U/Pb zircon ages of 161 Ma and similar Pb and initial Sr ratios (James and others, 1986). Ross (1970, p. 3058) concluded, based on the petrographic and chemical characteristics of the rocks, "it seems virtually inescapable" that the Logan and Gold Hill masses were once a single body.

All three gabbro bodies are unconformably overlain by conglomerate of Eocene age; and distinctive and correlative Eocene to Miocene stratigraphic successions overlie the gabbroic bodies in the Logan and Eagle Rest Peak areas (Fig. 2). Strata younger than Eocene are

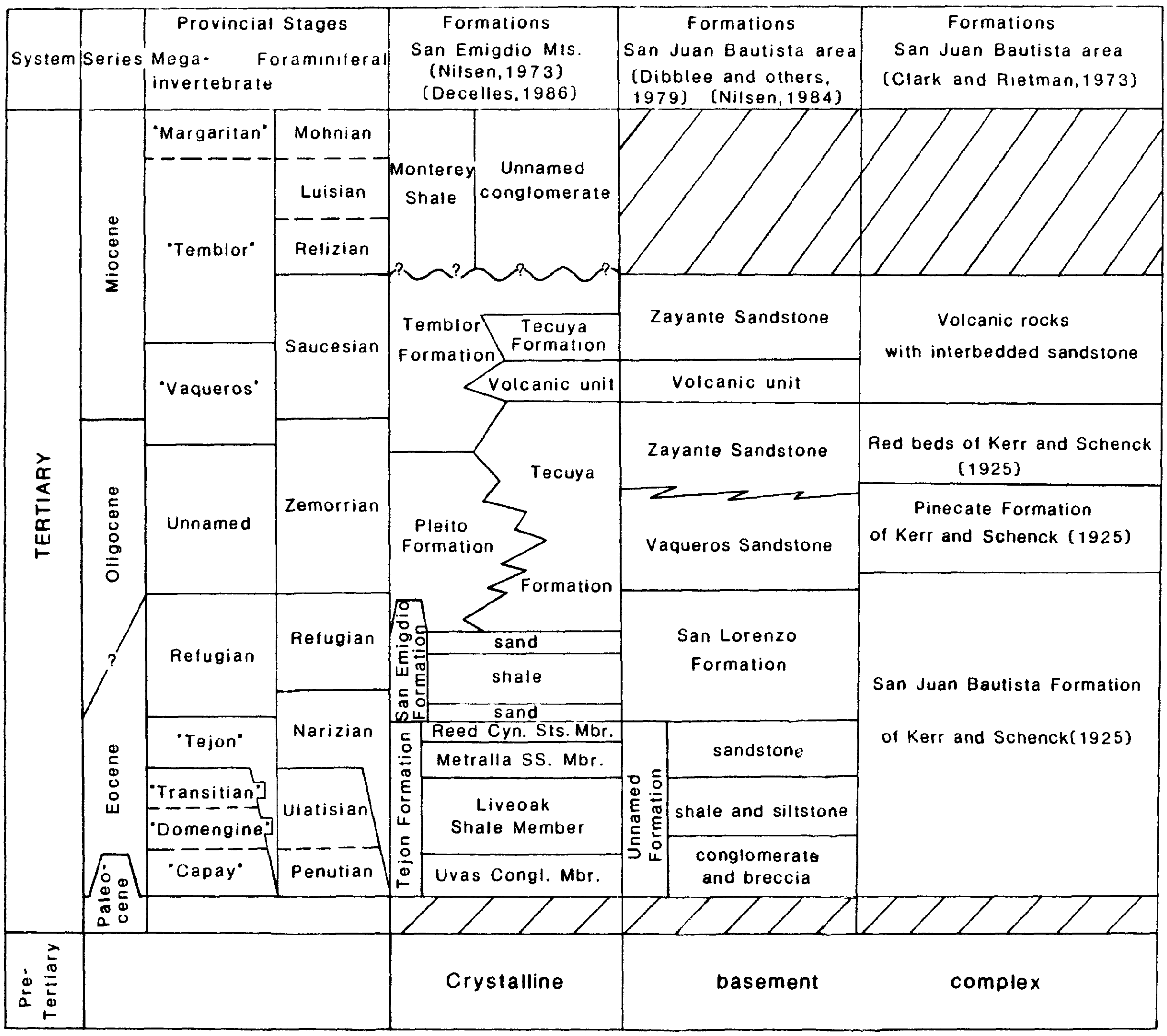

Figure 2. Stratigraphic correlation of Eocene strata in the San Emigdio Mountains with those near San Juan Bautista. Modified from Nilsen (1984).

absent at Gold Hill. The Eocene to Miocene sedimentary and volcanic rocks of the Logan and Eagle Rest Peak areas were first suggested to be correlative by Turner (1968). Later work the in San Emigdio Mountains (Nilsen and others, 1973; Nilsen 1987) and in the Juan Bautista area (Dibblee and others, 1979; Nilsen, 1984) support this correlation. The Miocene strata at Logan and Eagle Rest Peak contain andesite, dacite, and basalt flows interbedded with nearshore marine and continental sedimentary rocks. The Miocene volcanic rocks in both areas are petrographically and geochemically similar, and have similar stratigraphic positions and potassium/argon ages (Thomas, 1986). The three associations of petrographically similar gabbroic basement that is overlain by Eocene to Miocene strata and Miocene volcanic units are the basis of correlation of the three units.

Thus, units ranging in age from Jurassic to early Miocene are offset a constant amount -- 315 km. Younger rocks are offset lesser amounts. The correlation of the Neenach Volcanics with the Pinnacles Volcanics, in addition to the correlation of gabbroic basement rocks at Logan near with the gabbro of Eagle Rest Peak precisely and dramatically illustrate the magnitude of the total offset along the San Andreas fault in central California.

San Juan Bautista Area -- Near the town of San Juan Bautista lies a 10-km-long fault-bounded fragment of basement composed of hornblende quartz gabbro and anorthositic gabbro. This unit, the gabbro of Logan, is bounded on the east by the San Andreas fault (Ross, 1970). Aeromagnetic data suggests that the fragment, 1 to 2 km thick, has a vertical western boundary considered to be a fault (R.H. Jachens, oral commun., 1987). The gabbro is well exposed in Logan quarry, and is unconformably overlain by Eocene to Miocene sedimentary and volcanic rocks (Fig. 1A).

The Eocene strata that unconformably overlie the gabbro of Logan have been studied by a number of authors (Kerr and Schenck, 1925; Hill and Dibblee, 1953; Clark and Reitman, 1973; Nilsen 1984). These strata, considered to be equivalent to the lower part of the San Juan Bautista Formation of Kerr and Schenk (1925), are assigned to an unnamed formation by Dibblee and others (1979). The basal member of the unnamed formation consists of sandstone, conglomerate and breccia (Fig. 2). The cobbles, boulders, and blocks in the conglomerate have the same lithology as the underlying gabbroic basement rocks. The basal conglomerate member is laterally discontinuous and grades upward into a shaley section that contains foraminifers diagnostic of Ulatisian to Narizian age (Nilsen, 1984). Conformably overlying the unnamed formation are the deep-water fine-grained deposits of the upper part of the San Juan Bautista and Pinecate formations of Kerr and Schenk (1925), assigned by Dibblee and others (1979) to the San Lorenzo and Vaqueros Formations. These strata are correlated by Nilsen (1984) to the San Emigdio and lowermost Pleito Formations in the San Emigdio Mountains (Fig. 2).

The uppermost unit of the Cenozoic section in the San Juan Bautista area, assigned to the lower Miocene Zayante Sandstone by Dibblee and others (1979), is considered to be the equivalent of the "red beds" and the "volcanic rocks with interbedded sandstone" of Kerr and Schenck (1925). Interbedded with these strata is a volcanic member composed of andesite, dacite, and rhyolite (Thomas, 1986). Radiometric dates from the volcanic member range from 21.3 ± 1.3 to 23.5 ± 1.4 Ma and average 22.2 ± 0.6 Ma (Table 2, Appendix). This unit is correlated with the upper part of the Tecuya Formation of the San Emigdio Mountains (Nilsen 1984).

Table 2. Potassium-argon age dates of volcanic rocks offset by movement on the San Andreas fault in central California. All dates are corrected for the new IUGS constants (Dalrymple, 1979).

Analysis Number	Unit dated	Area	Age (Ma)	Reference
KA2215	Tecuya Formation	Eagle Rest Peak	18.1 ± 7.6	1, p. 16
KA2175	Tecuya Formation	Eagle Rest Peak	22.9 ± 0.7	1, p. 16
KA2166	Tecuya Formation	Eagle Rest Peak	22.4 ± 0.7	1, p. 15
KA2164	Tecuya Formation	Eagle Rest Peak	24.6 ± 7.2	1, p. 15
KA2162	Tecuya Formation	Eagle Rest Peak	25.2 ± 2.9	1, p. 15
KA2114	Tecuya Formation	Eagle Rest Peak	22.1 ± 0.6	1, p. 13
KA2115	Tecuya Formation	Eagle Rest Peak	22.5 ± 0.7	1, p. 13
	Pooled Mean Age		22.5 ± 0.1	*see* Appendix
KA2157	volcanic rocks near San Juan Bautista	Logan	22.2 ± 0.7	1, p. 60†
SJB-1	volcanic rocks near San Juan Bautista	Logan	23.5 ± 1.4	3
SJB-2	volcanic rocks near San Juan Bautista	Logan	21.3 ± 1.3	3
	Pooled Mean Age		22.2 ± 0.3	*see* Appendix
KA2079	Pinnacles Volcanics	Pinnacles	22.1 ± 3.2	1, p. 74
KA2087	Pinnacles Volcanics	Pinnacles	24.1 ± 0.7	1, p. 74
KA2091R	Pinnacles Volcanics	Pinnacles	24.3 ± 0.7	1, p. 74
KA2092	Pinnacles Volcanics	Pinnacles	24.5 ± 1.2	1, p. 74
	Pooled Mean Age		24.2 ± 0.2	*see* Appendix
KA2102	Volcanic rocks of Lang Canyon	Parkfield	23.6*	1, p. 74
KA2103	Volcanic rocks of Lang Canyon	Parkfield	22.3*	1, p. 74
------	Volcanic rocks of Lang Canyon	Parkfield	23.8 ± 0.7	2
------	Neenach Volcanics	Neenach	24.1*	4
------	Neenach Volcanics	Neenach	23.0*	4
------	Neenach Volcanics	Neenach	22.5*	4

References:

1 - Turner (1968)
2 - D.L. Turner (oral commun., 1987)
3 - Thomas (1986)
4 - D.L. Turner, unpublished data cited in Matthews (1973a)

* Minimum age

† Sample number is incorrectly stated as KA 2153 in Turner (1968, p. 60); however, KA 2153 is describned as the Modelo Tuff in the Appendix (p. 80). The correct sample number for the San Juan Bautista dacite is KA 2157 (Turner, 1968, p. 80).

Eagle Rest Peak Area -- The gabbro of Eagle Rest Peak and related rocks form the westernmost basement outcrops in the San Emigdio Mountains (Fig. 1C). These rocks are markedly different from the dominantly granitic and gneissic basement of the San Emigdio Mountains and are correlated with the gabbro of Eagle Rest Peak (Ross, 1970).

The Eocene Tejon Formation unconformably overlies the gabbro of Eagle Rest Peak. The Tejon Formation consists of four members in this area, the basal Uvas Conglomerate Member, the Liveoak Shale Member, the Metralla Sandstone Member, and the uppermost Reed Canyon Siltstone Member. The Uvas Conglomerate Member contains boulder conglomerate composed of clasts derived from the underlying basement, pebble and cobble conglomerate derived from more distant sources, and angular fragments formed in place by weathering of the gabbro (Nilsen, 1987). This unit is oldest in the western part of the San Emigdio Mountains and is progressively younger eastward.

The Eocene marine rocks in the San Emigdio Mountains are conformably overlain by continental sedimentary and volcanic rocks of the Eocene to Miocene Tecuya Formation (Nilsen and others, 1973; T.H. Nilsen, oral commun., 1987). The Tecuya interfingers westward with the marine Eocene and Oligocene Pleito Formation and the Oligocene and Miocene Temblor Formation (Fig. 2). The upper part of the Tecuya contains distinctive andesite and dacite flows overlain by basalt flows. Both volcanic subunits are laterally extensive and extend westward into the Temblor Formation (Nilsen and others, 1973). Radiometric dates from the dacites in the lower part of the volcanic member of the Tecuya Formation have an average potassium-argon age of 22.3 ± 0.6 Ma (Turner, 1970; Thomas, 1986). This section is similar in all respects to the one near San Juan Bautista (Fig. 2).

Gold Hill Area -- The gabbro of Gold Hill is composed of hornblende quartz gabbro that is surrounded by late Cenozoic strata near Parkfield (Ross, 1970). The gabbro of Gold Hill is bounded on the west by the generally straight trace of the San Andreas fault and on the east by the curving trace of the Jack Ranch fault (Fig. 1B). Aeromagnetic data suggests that the gabbro is about 1 to 2 km thick, 5 to 6 km long, and has vertical boundaries to at least 1 km depth (R.H. Jachens, oral commun., 1987). The gabbro of Gold Hill is unconformably overlain by strata of the Eocene Tejon Formation and locally derived Quaternary gravel (Sims, 1988). The gabbro and strata of the Tejon Formation together comprise a fault-bounded, lozenge-shaped, tectonic fragment that lies east of the San Andreas fault (Fig. 1B). A notable aspect of the geologic structure of the area east of the Gold Hill fragment is that the fold axes that lie between the Jack Ranch and Gold Hill faults all have a curvature similar to that of the Jack Ranch fault (Fig. 3).

The Eocene sedimentary rocks, correlated with the Tejon Formation of the San Emigdio Mountains (Sims, 1988), outcrop in a narrow band adjacent to the Jack Ranch fault on the northeast side of the fragment. This correlative of the Tejon Formation consists of sandstone and conglomerate that contain pebbles, cobbles and boulders of the gabbro of Gold Hill. Well preserved molluscan fossils are locally abundant in sandstone of the Tejon Formation north-northwest of Gold Hill (USGS locality M8901). These strata yield the gastropods *Turritella uvasana* sp. (cf. *T. u. sargenti*) and *Neverita globosa*, and the bivalves *Pitaria* sp. (cf. *P. uvasana*) and *Yoldia* sp. (cf. *Y. tenuissima*) which are diagnostic of the middle Eocene "Tejon" Stage (Sims, 1988). These Eocene rocks are correlated with the Uvas Conglomerate Member of the Tejon Formation which contains a larger fauna but includes *T. uvasana, P. uvasana,* and *Pitaria* sp.

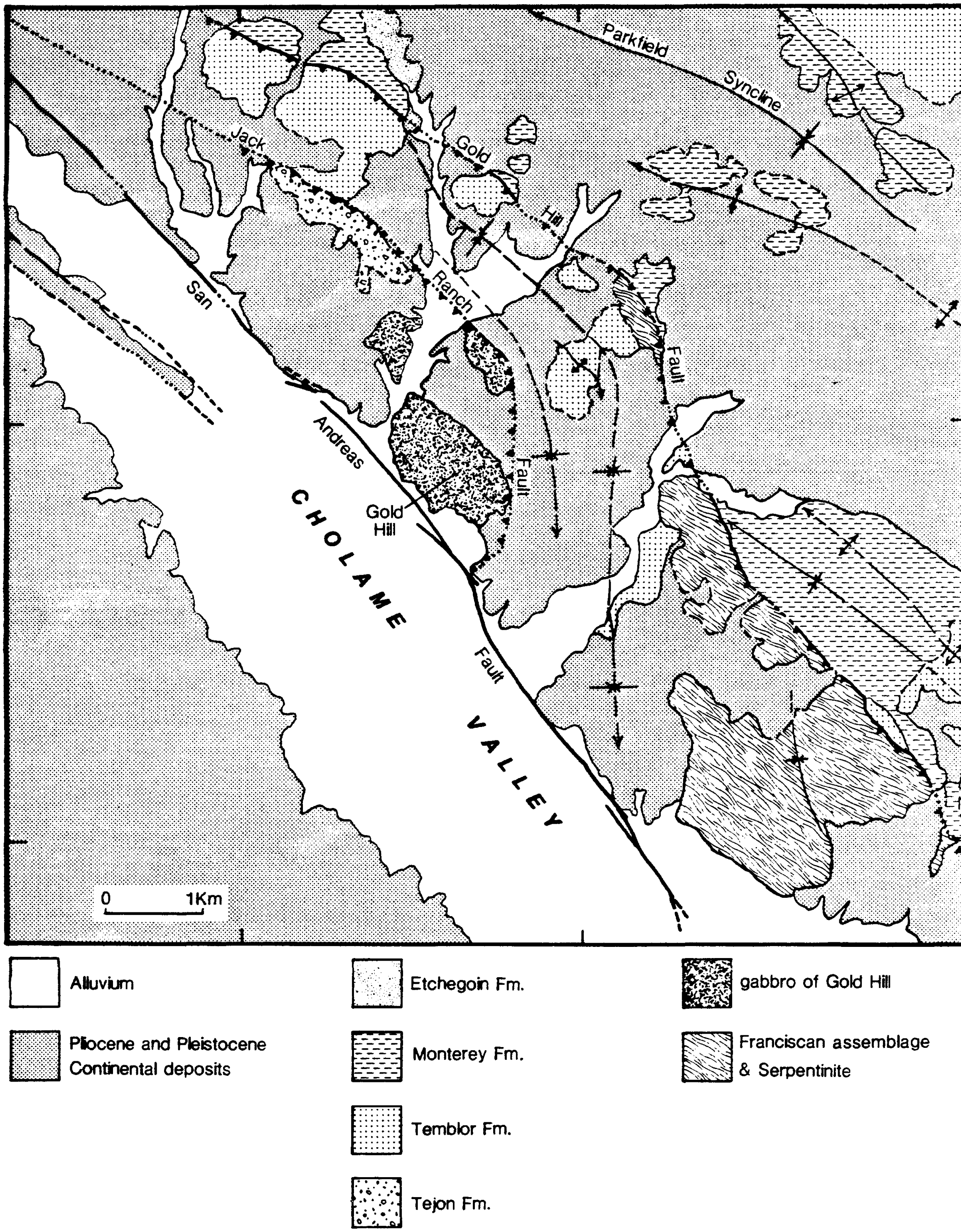

Figure 3. Geologic map of Gold Hill and vicinity showing relationships between Gold Hill fragment and concentric bending of fold axes in the Temblor Formation and the Gold Hill fault. Relationship of Tejon Formation to gabbro of Gold Hill also shown.

Lower Miocene Volcanic Rocks and Derivative Strata of the Upper Miocene Santa Margarita Formation

Three bodies of distinctive lower Miocene volcanic rocks lie along and near the San Andreas fault at the Pinnacles, the Neenach Volcanics in the northwestern Mojave desert, and in Lang Canyon near Parkfield (Fig.1). Each unit is unconformably overlain by middle to upper Miocene strata assigned to the Santa Margarita Formation. The sedimentary strata consist of conglomerate and sandstone derived from similar volcanic and granitic sources. Similar sedimentary strata, not now associated with volcanic and granitic basement rocks, crop out in the western Temblor Range northeast of the San Andreas fault (Fig. 1).

Both the Pinnacles and Neenach Volcanics are complex assemblages of flow-banded rhyolite, andesite, dacite, and pyroclastic deposits that overlie granitic basement rocks (Matthews, 1973a; Ross, 1984). These volcanic rocks have similar stratigraphic successions and major- and trace-element chemistry. The Neenach Volcnaics have no reliable potasium-argon dates; however those given for the Neenach are compatible with dates from the the Pinnacles and its correlatives (Matthews, 1973a, 1973b, 1976; Turner 1968). In some sections both the volcanic and basement rocks are unconformably overlain by marine and nonmarine conglomeratic rocks of the Santa Margarita Formation which were derived in part from the underlying volcanic and basement rocks (Fletcher, 1967; Weise, 1950; Sims, 1986). A sliver of similar volcanic rocks and overlying early Miocene conglomeratic strata is also present in the Lang Canyon area 95 km southeast of the Pinnacles (Fig. 1). A fourth occurrence of conglomeratic Santa Margarita Formation, not now associated with lower Miocene volcanic rocks or granitic basement, lies east of the San Andreas fault in the southern Temblor Range (Ryder and Thompson, 1989).

Strata of the Santa Margarita Formation in the southwestern Temblor Range as well as those that overlie the Pinnacles and Neenach Volcanics have similar sources of granitic and Miocene volcanic rocks (Huffman, 1972). In addition Ross (1984) demonstrated the similarity of the granitic and tonalitic basement rocks of the Gabilan Range and in the Western Mojave, on which the volcanic rocks rest. This evidence supports the conclusion that the middle Miocene conglomeratic rocks, commonly assigned to the Santa Margarita Formation in central California, were derived from debris eroded from the Neenach and Pinnacles Volcanics and their underlying granitic basement. The volcanic rocks west of the San Andreas fault, the Pinnacles Volcanics and the volcanic rocks of Lang Canyon, are tectonically transported fragments of the same initial volcanic field. The relationships between these volcanics and the sedimentary strata derived from them suggests that the initial volcanic field, which includes the Neenach Volcanics, was repeatedly cut by the evolving San Andreas fault system to produce these fragments.

Pinnacles Area -- The Pinnacles Volcanics are exposed in and near the Pinnacles National Monument in the Gabilan Range (Fig. 1A). This formation consists of rhyolite, dacite, andesite, rhyolite agglomerate, rhyolite breccia, and pumice lapilli-tuff. The formation rests unconformably on the granitic basement of the Gabilan Range and is unconformably overlain by upper Miocene strata assigned to the Santa Margarita Formation (Matthews, 1973a). Potassium/argon ages from rocks of the Pinnacles Volcanics range from 25.2 ± 2.9 to 22.1 ± 0.6 m.y. (Turner, 1969) and average 24.2 ± 0.5 m.y. (Table 2). The Miocene strata that unconformably overlie the granitic basement and Pinnacles Volcanics consist of boulder conglomerate and interbedded lithic-feldspathic arenites, diatomaceous shale, and pyroclastic breccia assigned to the Santa Margarita Formation (Fletcher, 1967). Basal conglomerate that lacks rhyolite clasts unconformably rests on diatomaceous shale of the Monterey Formation and granitic basement. The basal conglomerate is overlain by conglomerate that contains clasts of granite and flow-banded rhyolite which is interbedded with agglomerate of the Pinnacles Volcanics (Fletcher, 1967, p. 79).

Neenach Area --The Neenach Volcanics crop out in a 40 km^2 area adjacent to and east of the San Andreas fault along the western edge of the Mojave Desert (Fig. 1C). The formation consists of rhyolite, dacite, andesite, rhyolite agglomerate, and pumice lapilli-tuff. The formation rests unconformably on the Cretaceous granitic basement and is unconformably overlain by upper Miocene strata assigned to the Santa Margarita Formation (Weise, 1950). Potassium/argon analyses of rocks from the Neenach Volcanics yield minimum ages that range from 22.5 to 24.1 Ma. (Turner, 1969 cited in Matthews, 1973b). The upper age limit is preferred owing to the similarity of these rocks with those of the Pinnacles Volcanics (Matthews, 1973b).

The Miocene strata, here assigned to the Santa Margarita Formation[3], are of two facies; maroon sandstone, conglomerate, and mudstone and gray to buff sandstone and conglomerate. The maroon facies overlies and is in part conformable with the Neenach Volcanics (Weise, 1950). The maroon strata interfinger with light gray arkosic facies of the Santa Margarita Formation (Weise, 1950, p. 34). The light-gray arkosic facies of the more typical Santa Margarita Formation is largely composed of granitic debris that is similar in composition to the granitic rocks present in the San Emigdio Mountains and on Portal Ritter Ridge. Volcanic material is rare in the lower part of the light-gray facies but increases in the upper one-half of the unit. In the uppermost part of the light-gray facies of the Santa Margarita volcanic debris is about equal to the granitic debris. Volcanic clasts in the Santa Margarita are identical to rocks of the Neenach Volcanics and attest to local derivation (Weise, 1950, p. 32-33).

Lang Canyon Area -- The volcanic rocks that crop out in Lang Canyon near Parkfield were first correlated with the Pinnacles Volcanics on the basis of similar K/Ar dates and field petrographic relationships (Turner, 1968). The volcanics of Lang Canyon were later correlated with the Neenach Volcanics (Turner and others, 1970; Huffman, 1972; Matthews, 1973b). The volcanic rocks of Lang Canyon (Sims, 1988), a body of flow-banded rhyolite, obsidian, and volcanic breccia, lie 16 km northwest of Gold Hill (Fig. 1B). The volcanic rocks crop out in a narrow northwest-southeast elongated belt about 6 km long and 1 km wide about 2 km west of the main trace of the San Andreas fault, but are best exposed in Lang Canyon 4 km northwest of Parkfield. The volcanic rocks dip steeply to the northeast in contrast with the gently southwest-dipping Santa Margarita Formation which unconformably overlies the fragment on the southwest. The fragment is considered to be fault bounded

[3]Gray to buff conglomerate and sandstone that bear fossils and outcrop in the Neenach and Lebec quadrangles, Los Angeles and Kern Counties, California were referred to the Santa Margarita Formation by Wiese (1950). An unnamed unit of Miocene(?) continental deposits of similar composition but maroon in color was also described by Wiese (1950) and Crowell (1952). These strata were reassigned to the Quail Lake Formation and the Oso Canyon Formation respectively by Dibblee (1967). A comparison of clast types between the two units and with the Santa Margarita Formation at its type locality and in the southern Temblor Range (J.G. Vedder, oral commun., 1987) and near Parkfield and in the Gabilan Range shows that all these strata strikingly similar in clast lithology. Strata exposed in the excavation for the West Branch of the California Aqueduct near Quail Lake shows that lentils of gray conglomerate and sandstone of Santa Margarita-type occur in the maroon conglomerate and sandstone; thus suggesting that the two colors of sandstone and conglomerate are facies of the same formation. Therefore, Quail Lake Formation and the Oso Canyon Formation are both hereby abandoned and their strata are reassigned to the Santa Margarita Formation.

although the bounding faults are poorly exposed (Sims, in press). The southwest bounding fault is in part covered by strata of the late Miocene Santa Margarita Formation. The northeast boundary of the fragment is overlapped by alluvial deposits of Cholame Creek. Sedimentary rocks of the upper Miocene Santa Margarita Formation are of two distinct types in the Parkfield area. The upper Santa Margarita consists of light-colored, well-sorted, fossiliferous sandstone. The lower Santa Margarita Formation consists of conglomerate and conglomeratic sandstone that is dominantly composed of coarse granitic debris. Sandstone of the upper Santa Margarita unconformably overlaps the west edge of the volcanic rocks of Lang Canyon. These white to pale gray, coarse grained, fossiliferous sandstone strata represent a shallow, nearshore, marine environment. Well-sorted, calcareous and fossiliferous arenites lap onto the volcanic rocks of Lang Canyon in sections 20 and 29, T. 23 S., R. 14 E. in the Parkfield 7½-minute quadrangle. Megafossils collected from the white calcareous sandstone suggest a late Miocene age for the rocks (J.W. Durham, written commun., 1985). Strata of this type are not present in the Santa Margarita of the Neenach and Pinnacles area, but are similar to the Santa Margarita in its type area (Sims, in press).

The lower Santa Margarita outcrops principally about 1 km west of the volcanic rocks of Lang Canyon and is unconformably(?) overlain by sandstone of the upper Santa Margarita. The lower Santa Margarita consists of interbedded granitic debris, boulder conglomerate, and interbedded quartzose arenite, mudstone, and claystone. The conglomerate contains volcanic clasts composed of andesite, flow-banded rhyolite and rare purple amygdaloidal andesite (Sims, in press). The andesite and purple andesite clasts, common in the Neenach Volcanics, are not present in the volcanic rocks of Lang Canyon (Wiese, 1950, p. 31; Crowell, 1952, p. 11-12; Matthews, 1973b, p. 43). The presence of purple amygdaloidal andesite clasts in the lower part of the Santa Margarita Formation suggests that these strata were, in part, derived from the Neenach or Pinnacles Volcanics.

Granitic and Metamorphic Basement Rocks

Basement rocks which underlie the Neenach and Pinnacles Volcanics and the sedimentary rocks derived from them also show striking similarities to each other (Ross, 1984). Correlations of these granitic and metamorphic rocks together with correlations of late Cenozoic volcanic and sedimentary rocks suggests that the Gabilan Range lay opposite the tail of the Sierra and the western Mojave Desert prior to initiation of movement on the San Andreas fault.

The granodiorite of Natividad in the Gabilan Range closely resembles the granodiorite of Lebec in the San Emigdio Mountains (Fig. 4). Both are medium grained, and contain distinctive coarse biotite flakes and scattered hornblende crystals with red cores of skeletal clinopyroxene crystals. Coarse-grained biotite granite, the granites of Fremont Peak and Brush Mountain, typical and common "low melting trough"-type granites, are also associated with both the granodiorite of Natividad and Lebec (Ross, 1984). The tonalite and granodiorite of Johnson Canyon, which crops out near the Pinnacles Volcanics in the Gabilan Range, are similar lithologically, modally and chemically to the granodiorite of Fairmont Reservoir which crops out near the Neenach Volcanics (Fig. 4). Both the Johnson Canyon and Fairmont Reservoir bodies contain distinctive, euhedral sphene crystals(Ross, 1984, p. 13 and 33). The Johnson Canyon, Bickmore Canyon, Burnt Peak and Fairmont Reservoir bodies are also noteworthy for the presence of small pink K-feldspar phenocrysts, as much as 2 cm long, in

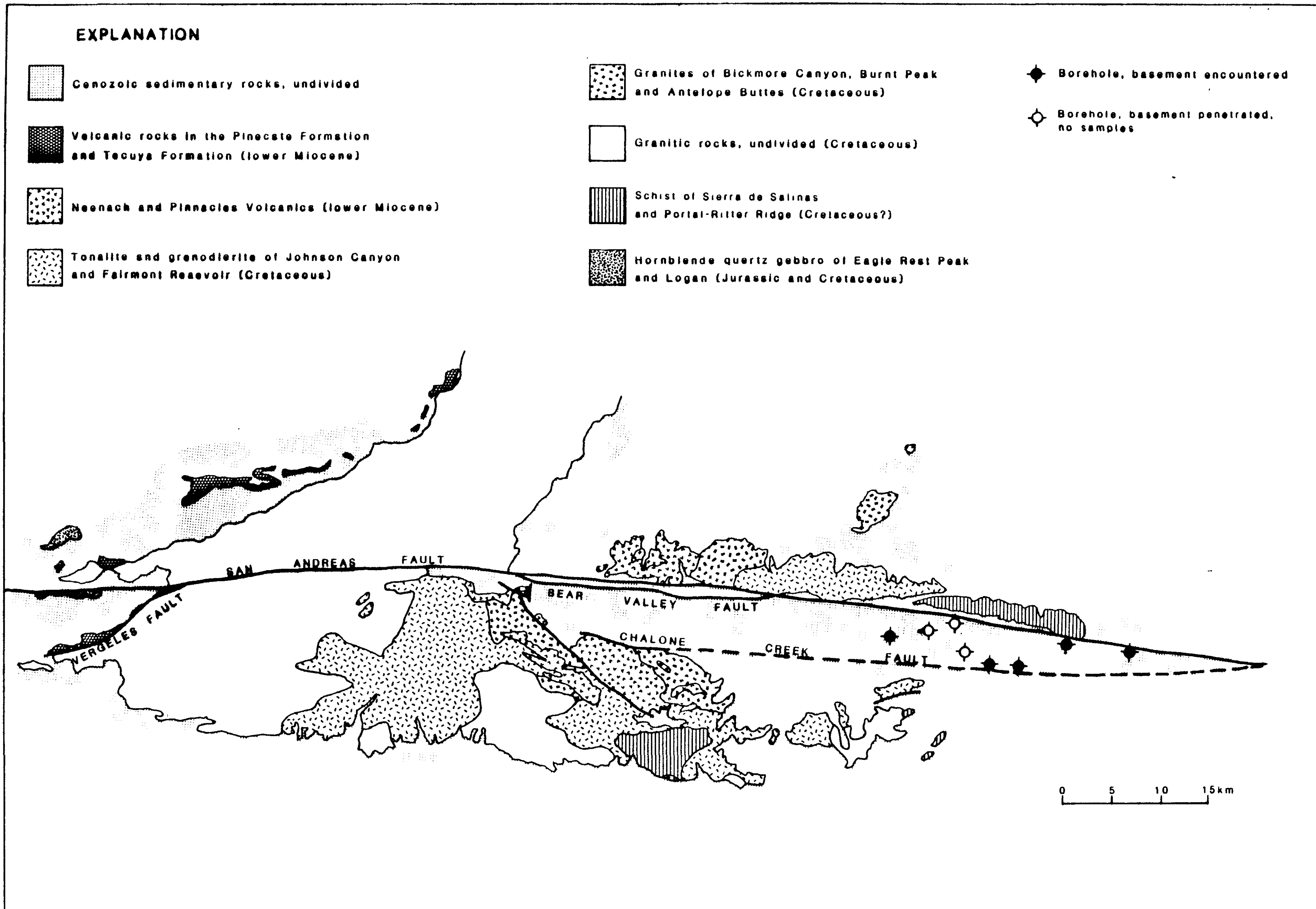

Figure 4. Geologic map showing palinspastic reconstruction of the Neenach and Pinnacles Volcanics. The main mass of the Pinnacles is placed opposite the Neenach Volcanics. Crystalline basement rocks of the Johnson Canyon, Burnt Peak, and Fairmont Reservoir bodies which bear distinctive sphene crystals are correlated. Granitic rocks that bear salmon-pink K-feldspar phenocrysts, the Bickmore Canyon and parts of the Burnt Peak and Fairmont Reservoir bodies are also correlated (Ross, 1984). Modified from Ross (1984, figs. 8, 19, and 20).

them. The granite of Bickmore Canyon is also strikingly similar to the felsic variant of the Fairmont Reservoir body. Another similarity between the basement rocks that underlie the Pinnacles and Neenach Volcanics is the abundance of alaskite, aplite, and pegmatite. Ross (1984) further suggested the correlation of the schist of Sierra de Salinas, in the Gabilan Range, to the schist of Portal-Ritter Ridge (Fig. 4). The strong physical and chemical similarity of these two schists is well established (Ross, 1976).

REGIONAL PATTERN OF CORRELATIVE ROCKS
North to South Arrangement

Fragments of gabbroic basement, lower Miocene volcanic rocks, and Eocene to upper Miocene sedimentary rocks are arrayed on both sides of the San Andreas fault over a distance of about 370 km from near San Juan Bautista in the north to the western Mojave Desert in the south (Fig. 1). The gabbro of Logan, the northernmost fragment, lies 55 km northwest of the Pinnacles Volcanics on the west side of the San Andreas fault. The gabbro of Logan is adjacent to the San Andreas, but the Pinnacles lie about 2 km west of the San Andreas. The volcanic rocks of Lang Canyon lie 95 km southeast of the Pinnacles and 16 km northwest of the Gold Hill fragment. The Lang Canyon fragment lies about 2 km west of the San Andreas, and the Gold Hill fragment is adjacent to the San Andreas but on the east side of it. The gabbro of Eagle Rest Peak lies 145 km southeast of Gold Hill and 55 km northwest of the Neenach Volcanics, the southernmost fragment. The Eagle Rest Peak fragment lies about 3 km east of the San Andreas, and the Neenach Volcanics lies adjacent to and east of the San Andreas.

The gabbro and volcanic rocks of both the Logan and Pinnacles and Eagle Rest Peak and Neenach fragments are 55 km apart. The volcanic rocks lie to the southeast in both cases. However, the Lang Canyon and Gold Hill fragments are 16 km apart and the volcanic rocks lie to the northwest (Sims, 1988, in press). This anomaly provides the clue to how these bodies attained their present positions.

Reversed Positions of Fragments near Parkfield

The relative positions of the volcanics and gabbro in the Parkfield area are reversed with respect to their correlative rock bodies because they lie only 16 km apart, not 55 km as the correlations with their parent bodies predict. Both the Lang Canyon and Gold Hill fragments are fault bounded (Sims; 1988, in press). The reversed positions of these two fragments requires a complex series of movements on their respective bounding faults to achieve their present locations.

The present position of the Lang Canyon fragment, intermediate between its correlative bodies, is best explained by slivering it from the Neenach Volcanics after the slivering off of the Pinnacles. A two-stage sequence of slivering the original Neenach/Pinnacles body explains the present position of the Lang Canyon fragment as well as the presence of east and west bounding faults.

The position of the Gold Hill fragment east of the San Andreas fault and just north of the 1-km right step in the San Andreas is anomalous because its parent mass is also on the east side of the San Andreas. The Gold Hill fragment is bounded on the southwest by the

San Andreas and on the northeast by the arcuate Jack Ranch fault. Arcuate fold axes in the Temblor Formation are nearly parallel to the Jack Ranch fault. Further eastward the arcuate trace of the Gold Hill fault also parallels the Jack Ranch but to a lesser degree. This unusual family of arcuate structures coincides with a similarly curved topographic configuration of Cholame Valley. The similar curvature of the faults, folds and the broadening of Cholame Valley around Gold Hill has prompted speculation that the Jack Ranch fault is a warped and abandoned older trace of the San Andreas fault (R.W. Simpson, written commun., 1986). Highly sheared Franciscan melange and serpentinite basement outcrops to the east of the Jack Ranch fault in a wedge-shaped mass bounded on the east by the Gold Hill fault. South of Gold Hill, Franciscan melange and serpentinite are less abundant and are unknown more than about 10 to 15 km to the south (Dibblee, 1971). This evidence suggests that as the parent mass of the Gold Hill fragment, the Logan block, approached the latitude of Gold Hill the easily deformable Franciscan melange gave way and a bend in the San Andreas fault developed. As the Logan block moved closer to the present position of Gold Hill the curvature of the San Andreas increased to a point that configuration of the fault was no longer stable (Fig. 5). The unstable configuration was resolved by formation of a new straight segment that cut through the Logan fragment. The reason the new straight segment of the San Andreas passed through the gabbro body rather than around it is unclear. The straightened segment may have occupied previously formed shear planes or other zones of weakness in the gabbro. Formation of the new fault segment resulted in the slivering off of the Gold Hill block and freed the remainder of the Logan fragment to be transported to its present position. Further eastward bending of the San Andreas fault after slivering off of the Gold Hill fragment probably did not occur because of the buttressing effect of the steeply dipping Parkfield syncline, west directed thrusting on the Table Mountain thrust fault (Sims, 1988, in press), and convergence across the San Andreas fault.

PALINSPASTIC RECONSTRUCTION

Palinspastic reconstruction of rock bodies cut and displaced by the San Andreas fault in central California is largely constrained by the location and relative position of the various fragments of tectonically transported exotic rock bodies that now lie between the San Juan Bautista and Neenach areas. The reversed fragments of exotic rocks in the Parkfield area are critical to this reconstruction. Correlation of the fault-bounded fragments near Parkfield with rocks that lie adjacent to or near the San Andreas to the northwest and southeast is well established. It is their relative position in the Parkfield area that implies a time sequence for tectonic transport and emplacement.

Simple removal of the 315 km of accumulated slip on the San Andreas fault places the gabbro of Logan, the Pinnacles Volcanics, and the overlying Eocene to Miocene strata opposite the gabbro of Eagle Rest Peak, Neenach Volcanics, and overlying Eocene to Miocene strata. Reconstruction of these bodies also juxtaposes the basement rocks on which they lie, the tonalite of Johnson Canyon and the granite of Bickmore Canyon with the granodiorites of Fairmont Reservoir and Burnt Peak. The reconstruction also places the Schist of Sierra de Salinas opposite the schist of Portal Ritter Ridge (Ross, 1984) (Fig. 2). No time history for the San Andreas, other than that determined from the ages of the rocks that are cut, can be implied.

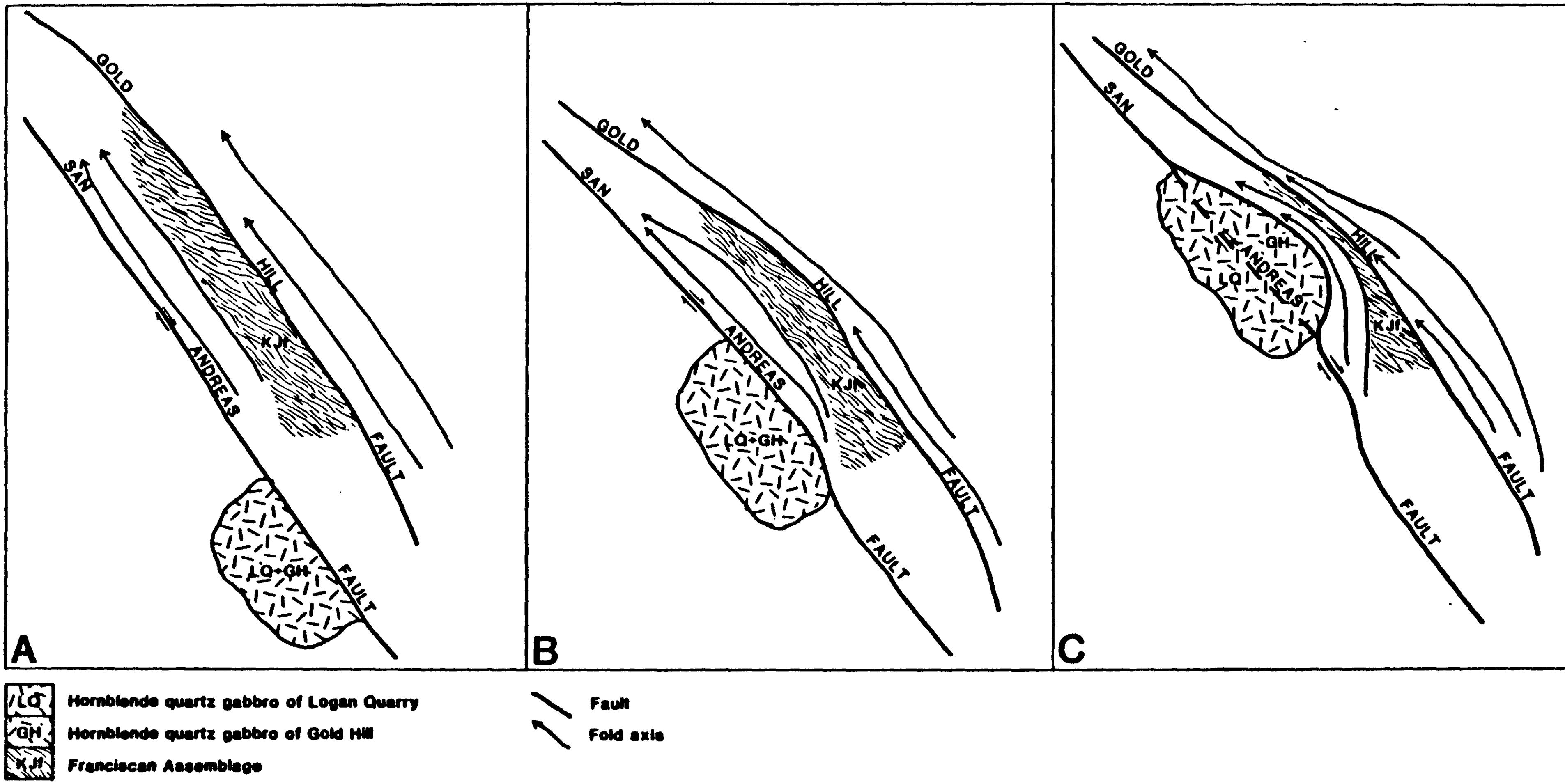

Figure 5. Development of the Jack Ranch fault and Gold Hill Fragment. See Figure 3 for geologic map of Gold Hill and vicinity.

Restoration of the exotic blocks of the Parkfield area to their respective parent blocks requires a more complicated sequence of movements. These movements must both remove the reversed relative positions and restore the Gold Hill block to the west side of the San Andreas fault. Reconstruction of these fragments and with their basement rocks, and associated derivative sedimentary rocks is accomplished in three phases (Fig. 6). Ultimately these phases of movement are related to the movement of the Pacific and North American plates and the migration of the two triple junctions that developed following the subduction of the Farallon plate (Atwater, 1970).

The present positions of the northernmost fragments suggest that they were separated from the parent masses first and those that now lie in the Parkfield area were separated later (Fig. 7A). The sequence of motions required to restore all of the exotic blocks to their initial positions is constrained to begin with the reversal of slip that has accumulated on the most recent trace of the San Andreas fault. I assume that in the first step of this sequence of reverse motions that the Logan, Pinnacles and Lang Canyon fragments remain fixed with respect to each other on the Salinian block.

1) Reverse movement of 165 km of the Logan fragment from its present position places it opposite the Gold Hill fragment. The Pinnacles and Lang Canyon fragments, having moved the same amount, then lie 55 and 140 km respectively to the southeast of Gold Hill (Fig. 7B). The Logan and Gold Hill bodies are joined and in further movements they will move together .
2) Strike-slip movement is transferred to the Jack Ranch fault, and strike-slip movement and the east directed compressional deformation of the fold axes to the east of Gold Hill is removed. The position of the amalgamated Logan and Gold Hill fragments fixes their position with respect to the Pinnacles and Lang Canyon fragments.
3) Reverse movement of an additional 55 km carries the Lang Canyon fragment to a position opposite the Neenach (Fig. 7C). The volcanic rocks of Lang Canyon are joined to the Neenach Volcanics fragment.
4) Following the amalgamation of the Lang Canyon fragment with the Neenach fragment strike slip motion is transferred to the White Canyon-Red Hills-San Juan-Chimineas fault zone. The remaining 95 km of deformation is removed along this western boundary fault of the Lang Canyon fragment (Fig. 7D). Movement along this fault zone joins the Pinnacles with the previously amalgamated Neenach and Lang Canyon body. This final movement also joins the Logan and Gold Hill fragments with the Eagle Rest Peak fragment.

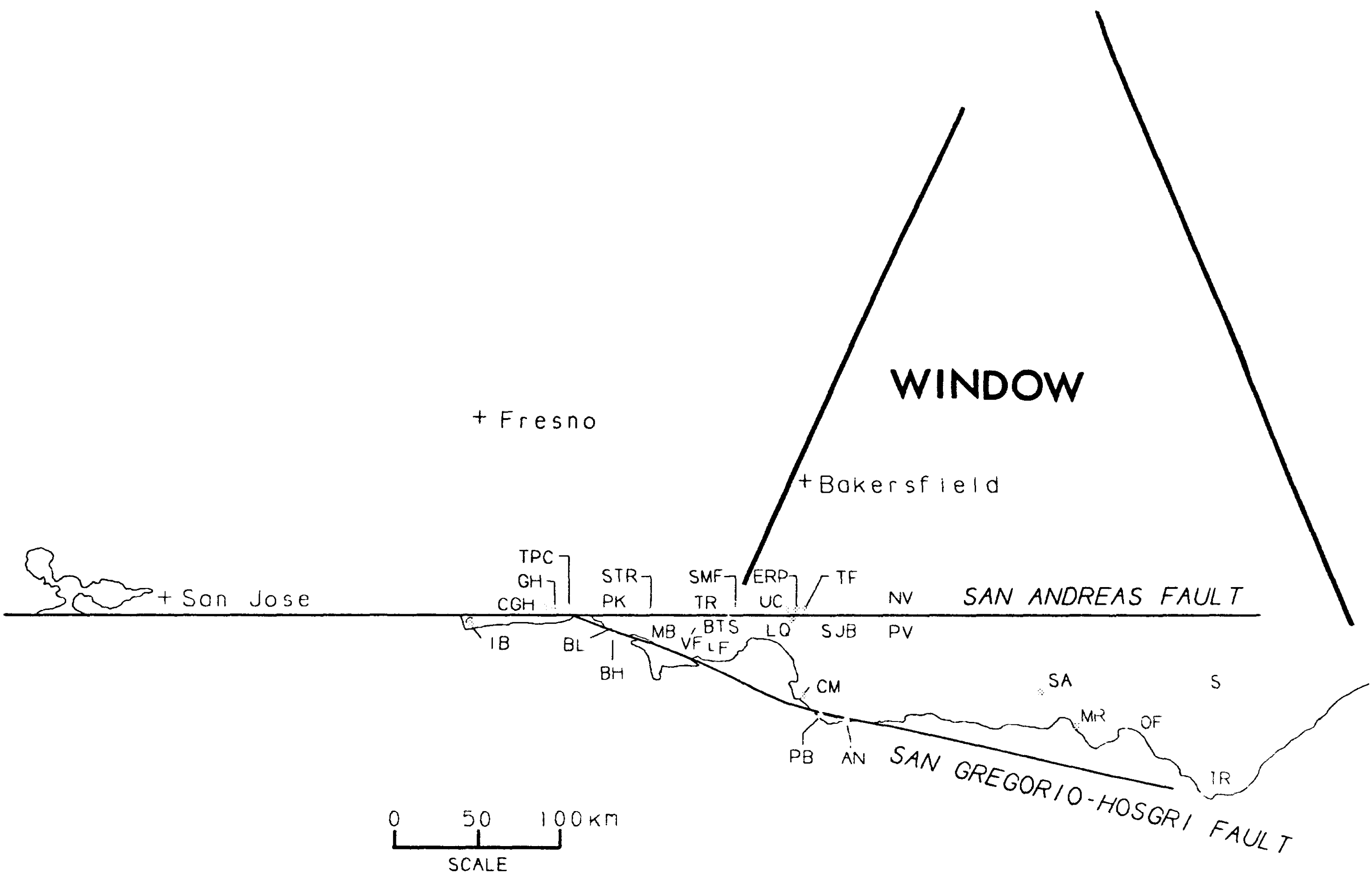

Figure 6. Palinspastic reconstruction of the positions of units offset by the San Andreas fault; modern coastline shown for reference. Map constructed by moving block bounded by San Andreas fault and San Gregorio-Hosgri fault 150 km southeast; rotation of the Tehachapi and San Emigdio mountains were proposed by McWilliams and Li (1986) and Plescia and Calderone (1986) and the restoration of left-lateral movement on the Garlock fault serves to straignten out the trace of the San Andreas. Sites are keyed to Table 1 and from northwest to southeast are: IB - Iversen Basalt, BH - Bodega Head, BL - tonalite of Ben Lomond, LO - gabbro of Logan, SJB - rhyolite, andesite, and dacite of the San Juan Bautista area, PV - Pinnacles Volcanics, LCV - volcanic rocks of Lang Canyon, GH - hornblende quartz gabbro of Gold Hill, CGH - Eocene Uvas Conglomerate Member of Tejon Formation of the Gold Hill area (Sims, 1988), TR - Santa Margarita Formation bearing Sr-isotope dated Crasostrea in the southern Temblor Range, SMF - Volcanic clasts of Neenach-Pinnacles-type of the Santa Margarita Formation in southern Temblor Range, STR - volcanic-rich facies in the Temblor Formation of the southern Temblor Range, UCT - Uvas Conglomerate Member of the Tejon Formation, ERP - hornblende-quartz gabbro of Eagle Rest Peak, TF - volcanic rocks in the Tecuya Formation, NV - Neenach Volcanics.

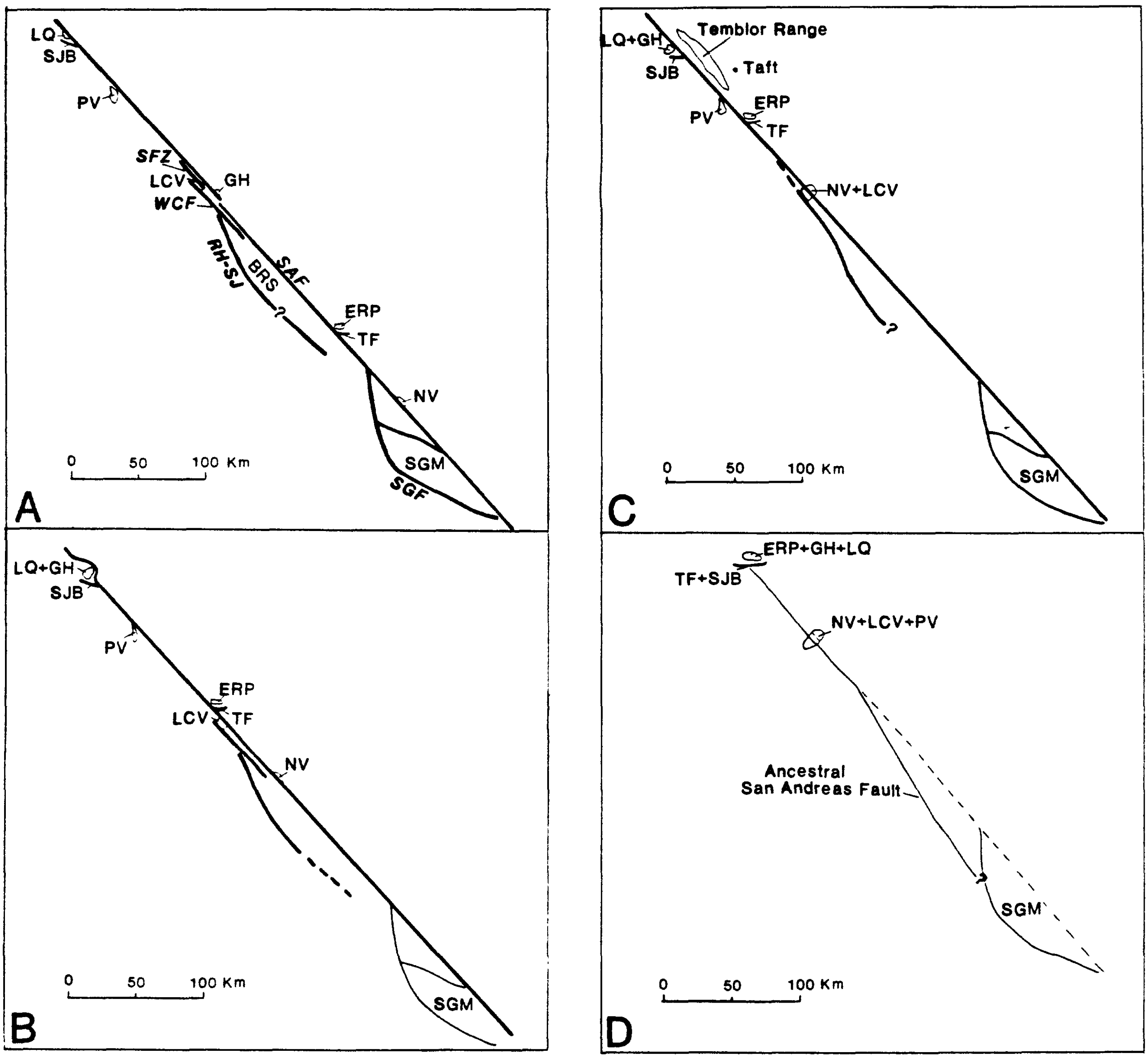

Figure 7. Stages of palinspastic reconstruction discussed in text. Symbols of offset fragments are, from northwest to southeast, LO - gabbro of Logan, SJB - volcanic rocks near San Juan Bautista, PV - Pinnacles Volcanics, LCV - volcanic rocks of Lang Canyon, GH - gabbro of Gold Hill, BRS - Barrett Ridge Slice, ERP - gabbro of Eagle Rest Peak, TF - volcanic member of Tecuya Formation, NV - Neenach Volcanics, SGM - San Gabriel Mountains. Faults (in italics) are *SAF* - San Andreas Fault, *SFZ* - Southwest Fracture zone, *WCF* - White Canyon fault, *RH-SJ* - Red Hills-San Juan-Chimineas fault, *SGF* - San Gabriel fault.

A. Present configuration of exotic Fragments along the San Andreas fault.

B. First stage of back slip. The slip removed is 165 km. The Gabbro of Gold Hill is moved along the present trace of the San Andreas fault to lie opposite the gabbro of Gold Hill.

C. Second stage of back slip. The slip removed is an additional 55 km. The volcanic rocks of Lang Canyon are moved to lie opposite the Neenach Volcanics.

D. Third stage of back slip. The amount of slip removed is an additional 95 km and completes the slip removal. The Pinnacles Volcanics are moved to lie opposite the Neenach Volcanics and the combined gabbros of Logan and Gold Hill lie opposite the Gabbro of Eagle Rest Peak.

DISPLACEMENT HISTORY ON THE SAN ANDREAS FAULT SYSTEM
Sequence, Magnitude, and Timing

Following subduction of the Farallon plate, the collision of the Pacific plate with the North American plate resulted in the formation of two triple junctions (Atwater, 1970). The northern, transform-transform-trench Mendocino triple junction, moved northwest with the Pacific plate and the southern, transform-ridge-trench Rivera triple junction, moved southeast. As the separation of the two triple junctions increased the San Andreas transform system formed. The San Andreas lengthened in response to migration of the triple junctions. As the San Andreas fault system developed volcanic rocks erupted along it to form a broad, nearly linear, northwest-trending belt of upper Tertiary to Quaternary volcanic rocks (Fox and others, 1985). Two volcanic centers, represented by the Neenach and Pinnacles Volcanics and thevolcanic member of the Tecuya and San Juan Bautista Formations, are among the oldest extrusive rocks thus formed. Both volcanic masses were cut and offset by the San Andreas fault in central California (Fig. 1).

The age of the Neenach and Pinnacles Volcanics is revealed by K/Ar dating to be 24.2 ± 0.5 Ma (Table 2) . Lower Miocene volcanic rocks of similar composition, the Tecuya Formation of the San Emigdio Mountains and their correlatives in the San Juan Bautista formation, are K/Ar dated at 22.6 ± 0.3 Ma and 22.2 ± 0.6 (Table 2). The Tecuya and San Juan Bautista units are offset the same amount as the Neenach and Pinnacles Volcanics -- 315 km. Thus, development of the San Andreas fault northwest of the San Emigdio Mountains postdates the eruption of both of these volcanic centers (Thomas, 1986; Peter Weigand, oral commun., 1987). The amount of time by which the establishment of the San Andreas fault postdates these volcanic units is imprecisely known. A minimum age of 18 Ma for initiation of movement on the San Andreas fault is based on evidence from basaltic volcanic debris deposited in the Temblor Formation of the western San Joaquin Valley (O'Day and Sims, 1986). An extensional tectonic regime is suggested between 24 and 20 Ma in western California from the Lahonda Basin in the northwest and the Diligencia Basin in the southeast (Tennyson, 1989). These suggestions are at variance with other suggestions that initial movement on the San Andreas fault occurred in late Oligocene time (Stanley, 1987; Addicott, 1968). On the basis of present information strike-slip movement on the San Andreas transform appears to have begun between 22 and 18 Ma.

The evolution of the San Andreas fault in central California is defined on the basis of the location of one or more exotic fragments along the trace of the fault system. I divide the evolution into three phases. The events that mark the begining and end of phases are: the eruption of the Neenach and Pinnacles Volcanics and the volcanic rocks in the Tecuya and San Juan Bautusta Formations, deposition of flow-banded rhyolite clasts in the Santa Margarita Formation of the southern Temblor Range, and slivering off of the gabbro of Gold Hill from the gabbro of Logan.

Phase 1 -- The event that marks the initiation of recognizable movement on the San Andreas fault in central California is the eruption of the Neenach and Pinnacles Volcanics, and the volcanic members of the Tecuya and the San Juan Bautista formations between 24.2 ± 0.5 and 22.2 ± 0.6 Ma (Fig. 7A). Eruption of these volcanics postdates the migration of the Menodicino triple junction through the area and is associated with expansion of the no-slab window as the subducted slab of Pacific Plate continued to pass beneath the North American plate (Fig. 8). Following eruption of the volcanics the San Andreas continued to

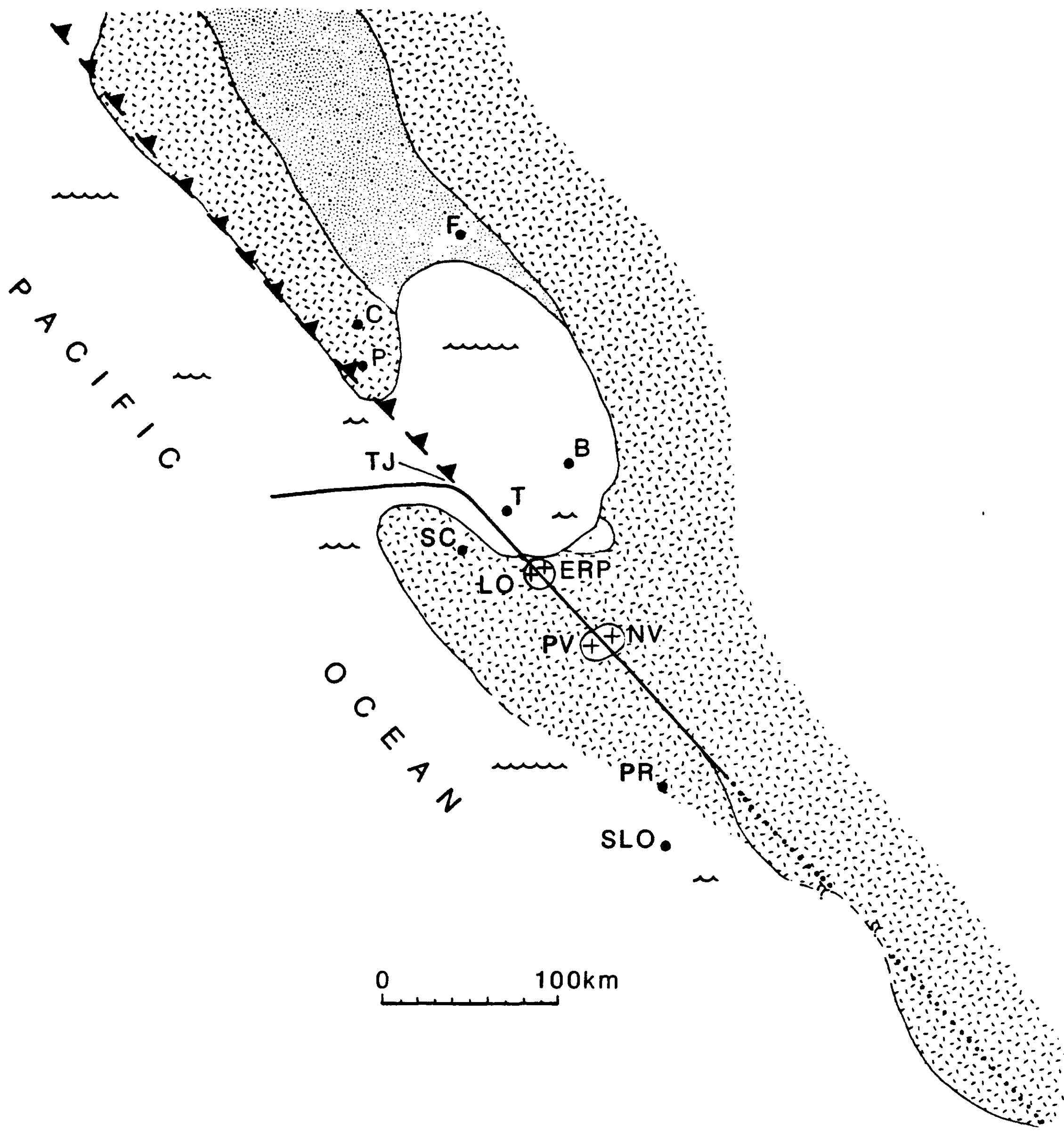

Figure 8. Paleogeographic map of central California for the early Miocene after the reuption of the Neenach/Pinnacles and Tecuya/San Juan Bautista Volcanics. Shorelines and depositional units taken from Bartow (1987), and Perkins (1987). C -Coalinga, B - Bakersfield, ERP - gabbro of Eagle Rest Peak, F - Fresno, LO - gabbro of Logan, NV - Neenach Volcanics, P - Parkfield, PR - Paso Robles, PV - Pinnacles Volcanics, QSV - Quien Sabe Volcanics, SC - Santa Cruz, SF - San Francisco, SLO -San Luis Obispo, SV - Sonoma Volcanics, TJ - Mendocino triple junction.

extend to cut the volcanic rocks, the gabbros of Logan and Eagle Rest Peak, the overlying Eocene to lower Miocene sedimentary rocks, and their associated basement. The precise time that the San Andreas cut the volcanic rocks is unknown but, for present purposes, tentatively is taken at less than 22 Ma. Right lateral movement continued durring this phase and the San Andreas transform system extended as the Mendocino triple junction migrated further northwest. The Salinian block, on which lay the Pinnacles and Logan fragments, moved northwestward away from the Neenach Volcanics and gabbro of Eagle Rest Peak until the Pinnacles fragment lay at the latitude of the southern Temblor range. (Fig. 9). Little or no deformation occurred on the Salinian block since the initiation of strike-slip movement on the San Andreas system. This is attested to by the fact that the distance between the Pinnacles and Logan fragments is the same as the Neenach and Eagle Rest Peak fragments.

Arrival of the Pinnacles Volcanics in the vicinity of the southern Temblor Range, about 95 km northwest of the Neenach Volcanics (Fig. 9), is marked by the presence of abundant clasts of flow-banded rhyolite in member C of the Santa Margarita Formation (Ryder andThompson, 1989). The rhyolite clasts have the same lithology and K/Ar age as the Pinnacles Volcanics (Fletcher, 1967; Turner, 1968). Members A, B, and D characterized by coarse detritus derived from granitic and metamorphic basement which is free of volcanic clasts. These units record the passage of the exposed northern and southern Gabilan Range through the latitude of the southern Temblor Range. The time of the passage is placed at about 14 Ma on the basis of Sr-isotope dating of fossil moluscan shells from member B of the Santa Margarita (Scott Hornafius, written commun. 1987). Member C, which carries the flow-banded rhyolite clasts, conformably overlies member B. Member D of the Santa Margarita Formation is overlain by latest Miocene and Pliocene strata. The time of first deposition of rhyolite clasts in member C cannot be directly determined. However, their deposition began after 14 Ma but before late Miocene time, about 10 Ma. Therefore, I suggest a tentative date of 12 Ma for the initiation of the deposition of flow-banded rhyolite clasts in the Santa Margarita Formation of the western Temblor Range.

The end of the first phase of movement of the Andreas fault is placed at the cessation of the deposition of rhyolite clasts in the upper part of the Santa Margarita Formation of the southern Temblor Range. Strike-slip movement up to this time occurred on a fault that is now represented by segments of the San Juan, Chimineas, Red Hills, and White Canyon faults. The northwestward extension of the White Canyon fault connects with the west boundary of the Lang Canyon fragment. Abandonment of this fault occured at the time the Lang Canyon fragment was slivered off of the Neenach fragment. Abandonment of the fault is chosen at the end of phase 1 because the Lang Canyon fragment lies 95 km southwest of the Pinnacles and the Pinnacles and Logan fragments have remained a constant distance apart since they were slivered off of their respective parent bodies at the begining of the phase. The reason for abandonment of the old fault and realignment of the San Andreas to sliver off another fragment of the Neenach Volcanics is unclear. The realignment may have resulted from the development of a bend in the fault that was an unstable configuration. The bend may have resulted from rotation in the tail of the Sierra Nevada (McWilliams and Li, 1986; Plescia and Calderone, 1986) and accompanying bending of the fault.

Phase 2 -- The beginning of phase 2 is marked by the end of deposition of flow-banded rhyolite clasts in the Santa Margarita Formation of the southern Temblor Range and an eastward jump in the location of the San Andreas fault (Fig. 9). The eastward realignment of the San Andreas fault resulted in a second fragment, the volcanic rocks of Lang

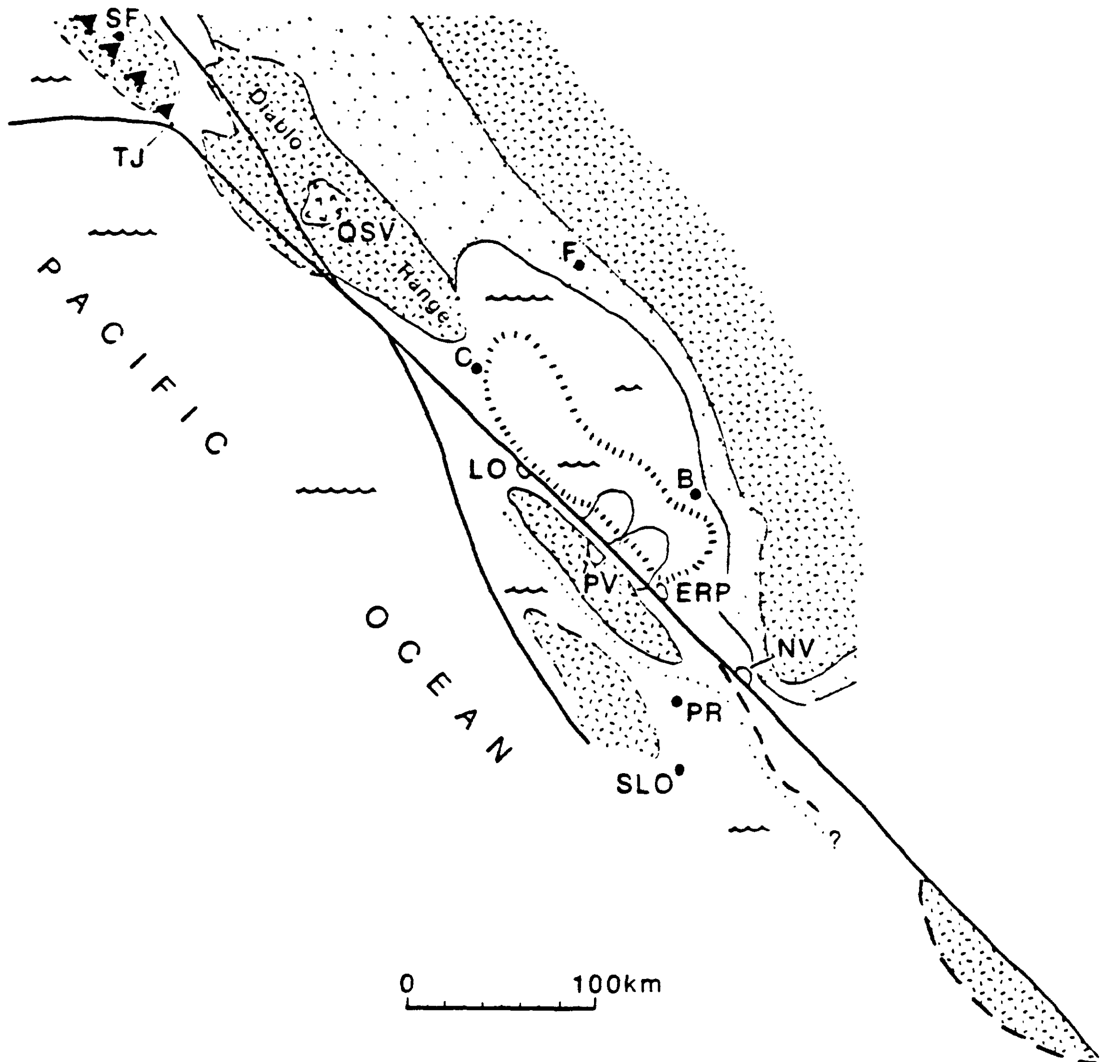

Figure 9. Paleogeographic map of central California for the early Miocene after the reuption of the Neenach/Pinnacles and Tecuya/San Juan Bautista Volcanics. Shorelines and depositional units taken from Bartow (1987), and Perkins (1987). C -Coalinga, B - Bakersfield, ERP - gabbro of Eagle Rest Peak, F - Fresno, LO - gabbro of Logan, NV - Neenach Volcanics, P - Parkfield, PR - Paso Robles, PV - Pinnacles Volcanics, QSV - Quien Sabe Volcanics, SC - Santa Cruz, SF - San Francisco, SLO -San Luis Obispo, SV - Sonoma Volcanics, TJ - Mendocino triple junction. Phase 1 of the evolution of the San Andreas fault began with strike slip movement following eruption of the (composite) Neenach-Pinnacles volcanics and the volcanic rocks in the Tecuya Formation. The end of Phase 1 is placed at the time flow-banded rhyolite clasts first occur in the Santa Margarita Formation in the southern Temblor Range. The age of the Santa Margarita is here considered to be ≈12 Ma. The time span of Phase 1 is about 10 m.y. The amount of slip is 95 km. Thus the minimum slip rate for Phase 1 is 9.5 mm/yr.

Canyon, being sliced from the Neenach Volcanics. The old trace of the San Andreas, represented by the San Juan-Chimineas-Red Hills-White Canyon fault zone, became wholly or largely inactive. The exact length of the abandoned trace of the San Andreas is in doubt. However, the fault segments that bound the Barrett Ridge slice including the fault segment that forms the west boundary of the Lang Canyon fragment were most likely abandoned (Fig. 10).

The precise length of the newly activated segment of the San Andreas fault in phase 2 is uncertain. The segment certainly extended at least from just northwest of the Lang Canyon body to some distance southeast of the Neenach Volcanics. This fault is now represented, in part, by the Southwest fracture zone near Parkfield (Sims, in press). The Southwest fracture zone is thought to connect with the west trace of the San Andreas fault which lies on the west side of Cholame Valley to the southwest (Fig. 1B). The northwest extension of the Southwest fracture zone is not clearly defined, but the trend of its en echelon segments suggests that it connects with the San Andreas on Middle Mountain (Sims, in press). The Chalone Creek fault which lies to the northwest of Middle Mountain, considered by Matthews (1973a) to be an old segment of the Andreas fault. Matthews hypothesized the that the Chalone Creek fault is connected to a fault that lies on the west side of Peachtree Valley, here refered to as the Peachtree Valley fault (Fig. 2). Matthews considered the combined Chalone and Peachtree Valley faults to predate tha San Andreas fault and to have a comparable amount of offset. Mathews' suggestion was later questioned by Ross (1984). Ross noted that the basement rocks that lie between the Chalone Creek fault and the San Andreas fault are similar to the granitic rocks and schist of the Gabilan Range. However, Ross (1984) also shows that the rocks of the Gabilan are strikingly similar to those of Portal-Ritter Ridge. Thus, Ross' argument that large-scale offset on the Chalone Creek fault comparable to the San Andreas cannot be demonstrated is not a convincing one. There is also abundant evidence that the active trace of the San Andreas has not remained fixed through time as shown here and by Matti and others (1986) and Powell (1986).

The end of phase 2 is marked by the separation of the Gold Hill fragment from the Logan fragment (Fig. 11). The location of the gabbro of Gold Hill constrains the amount of lateral offset that accumulated in phase 2 (Fig. 5). The timing of the split off of the Gold Hill fragment is poorly constrained but can be estimated by the age of associated late Cenozoic units involved in deformation that accompanied the positioning of Gold Hill. Units older than Pleistocene(?) and younger than Eocene are absent on the Gold Hill fragment (Fig 1B). The absence of the upper Miocene and Pliocene Etchegoin Formation on the Gold Hill fragment is significant; because these formations crop out within 2 km of exposures of the gabbro of Gold Hill (Sims, 1988). Fossil mollusks from these strata are all of late Miocene Relizian and younger age (E.M. Moore, written commun. 1985, 1986). Clasts in conglomerate of the Etchegoin Formation are composed only of Franciscan debris and clasts of basement rock derived from the Logan or Gold Hill fragments are absent. The Etchegoin Formation in the San Joaquin Valley ranges in age from about 4 to 10 Ma (Perkins, 1987). Additionally, remnant patches of upper Miocene sedimentary rocks of the Polonio Sandstone Tongue of the Monterey Formation of Marsh (1960) are also present throughout the area southeast of the Jack Ranch fault, but none of these rocks are present on the Gold Hill fragment (Sims, 1988). The absence of these rocks on the Gold Hill fragment suggersts that Gold Hill arrived after their deposition between about 5 and 10 Ma. Lastly, the average Holocene and late Pleistocene slip rate of the San Andreas fault is between 27 and 33 mm/yr (Sieh and Jahns, 1984; Sims, 1987). Such a rate may also be representative of the Pleistocene and Pliocene.

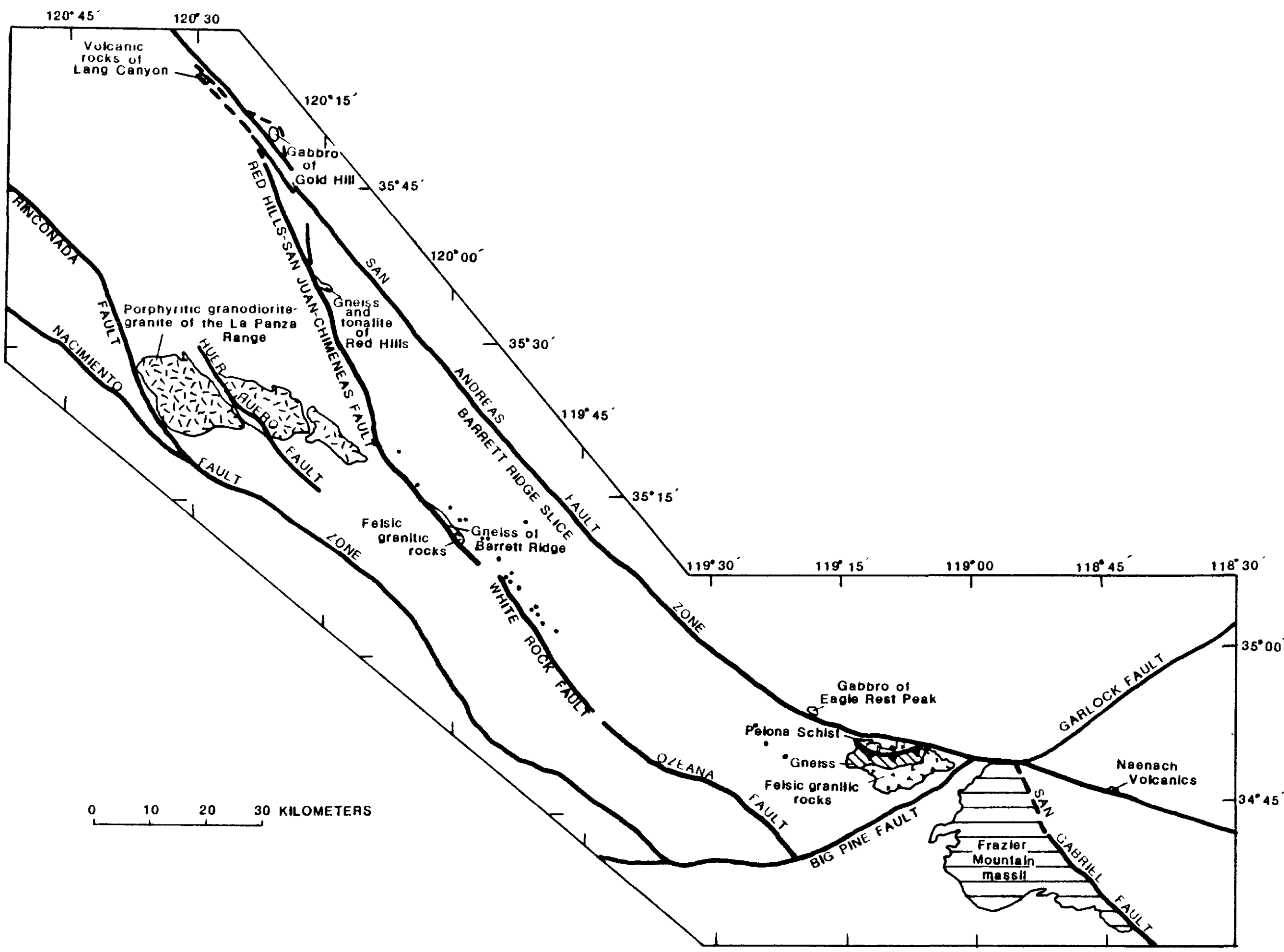

Figure 10. Map of faults that shows relationship between Salinian block, Barrett Ridge slice, and the sliver between the Chalone Creek fault and San Andreas fault. Wells that reach basement of the Barrett Ridge slice also shown.

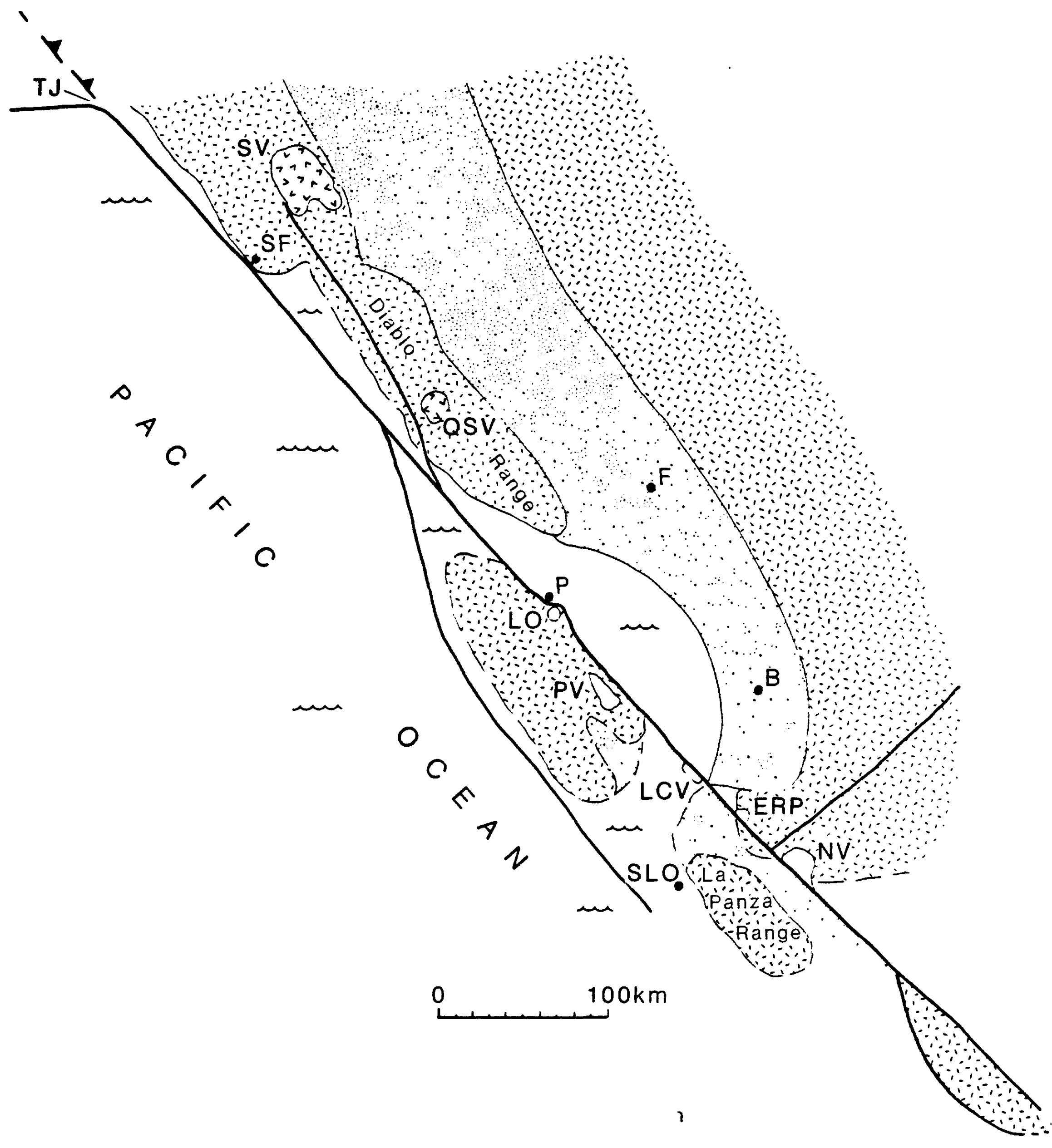

Figure 11. Paleogeographic map of central California for the early Miocene after the reuption of the Neenach/Pinnacles and Tecuya/San Juan Bautista Volcanics. Shorelines and depositional units taken from Bartow (1987), and Perkins (1987). C -Coalinga, B - Bakersfield, ERP - gabbro of Eagle Rest Peak, F - Fresno, LO - gabbro of Logan, NV - Neenach Volcanics, P - Parkfield, PR - Paso Robles, PV - Pinnacles Volcanics, QSV - Quien Sabe Volcanics, SC - Santa Cruz, SF - San Francisco, SLO -San Luis Obispo, SV - Sonoma Volcanics, TJ - Mendocino triple junction.

Phase 2--strike-slip movement is transferred to a new segment of the San Andreas and the older segment occupied during Stage 1 becomes inactive. The new segment severs the sliver composed of the now designated volcanic rocks of Lang Canyon from the Neenach Volcanics. The distance between the Pinnacles Volcanics and the volcanics of Lang Canyon remains constant. The end of Phase 2 is chosen as the time of slivering of the Gold Hill sliver from Logan body about 5 my ago. The distance between the Logan unit and Gold Hill unit at the end of stage 1 is 65 km. This stage is estimated a about 5 m.y. long. Thus the minimum slip-rate for Stage 2 is 13 mm/yr.

If this rate can be extended to the Pliocene then the 165 km of separation of the Gold Hill and Logan fragments could be accounted for in about 5 Ma (see discussion of phase 3 below). Thus, I tentatively place the end of phase 2, marked by the slivering off of the Gold Hill fragment, to be about 5 Ma.

Phase 3 -- The final phase of movement of the San Andreas follows the separation of the Gold Hill fragment from the Logan body, the abandonment of the Jack Ranch fault, and establishment of the present trace of the San Andreas in the Parkfield area (Fig. 11). At the begining of this phase the Pinnacles Volcanics lay about 55 km southeast of Gold Hill. Thus, the granitic and metamorphic basement of the Gabilan Range lay exposed from a point a few kilometers to more than 50 km southeast of Gold Hill. During this phase the distance between the Pinnacles Volcanics and the volcanic rocks of Lang Canyon continued to remain constant and the position of the San Andreas fault was probably similar to its present configuration. During phase 3 the Pinnacles Volcanics fragment was transported 160 km from about 55 km southeast of the Gold Hill fragment to its present position (Fig. 11). Passage of the Gabilan Range through the Parkfield area is recorded by the deposition of the Varian Ranch beds of Dickinson (1966). Debris was eroded off of the Gabilan Range and was deposited in a small basin now occupied by the Parkfield syncline. Formation of this basin and the subsequent Parkfield syncline may have been in response to the change in absolute motion of the Pacific plate and the associated noncollisional orogeny at about 4 Mm (Harbet and Cox, 1989). The Varian Ranch beds unit is restricted to the structural trough formed by the Parkfield Syncline. The unit is poorly exposed but does not contain flow-banded rhyolite clasts (Sims, in press). Thus, they were probably derived from the northern Gabilan Range prior to passage of the Pinnacles Volcanics through the Parkfield area (Fig. 12). A second indicator that the northern Gabilan Range passed through this area are allochthonous granite and marble slabs and large blocks along and near the northeast side of the San Andreas fault in the Parkfield area. These slabs and blocks overlie Late Miocene strata of the Monterey and Etchegoin Formations indicating late Miocene to early Pliocene deposition. The exact relationship of these allochtonous blocks with the Varian Ranch beds is largely obscured by younger surficial deposits. However, the lithology of the allochthons as well as that of the coarse detritus in the Varian Ranch beds strongly suggests derivation from basement rocks of the Gabilan Range. These basement rocks could not have arrived at the latitude of Parkfield until after the Gold Hill fragment was slivered off of the Logan fragment. The Varian Ranch beds overlie upper Miocene age strata of the Etchegoin Formation (E.M. Moore, written commun.; 1985, 1986. The Etchegoin Formation, as noted above, contains coarse detritus derived from the Franciscan assemblage and lacks debris derived from gabbroic or granitic basement.

Most of the slip during phase 3 occurred on the present day San Andreas fault although a lesser amount may have occurred on the Southwest fracture zone in the Parkfield area. However, there is little evidence for the amount of movement on the Southwest fracture zone because of the lack of distinctive offset markers. The southwest fracture zone is considered to be an extension of the San Andreas fault to the northwest of the right stepover in Cholame Valley (Sims, 1988) (Fig. 10). The segment of the San Andreas that on lies the west side of Cholame Valley may be extended through several young fault scarps on the northwest side of Cholame Valley to connect with the southernmost mapped exposure of the Southwest fracture zone (Sims, 1988).

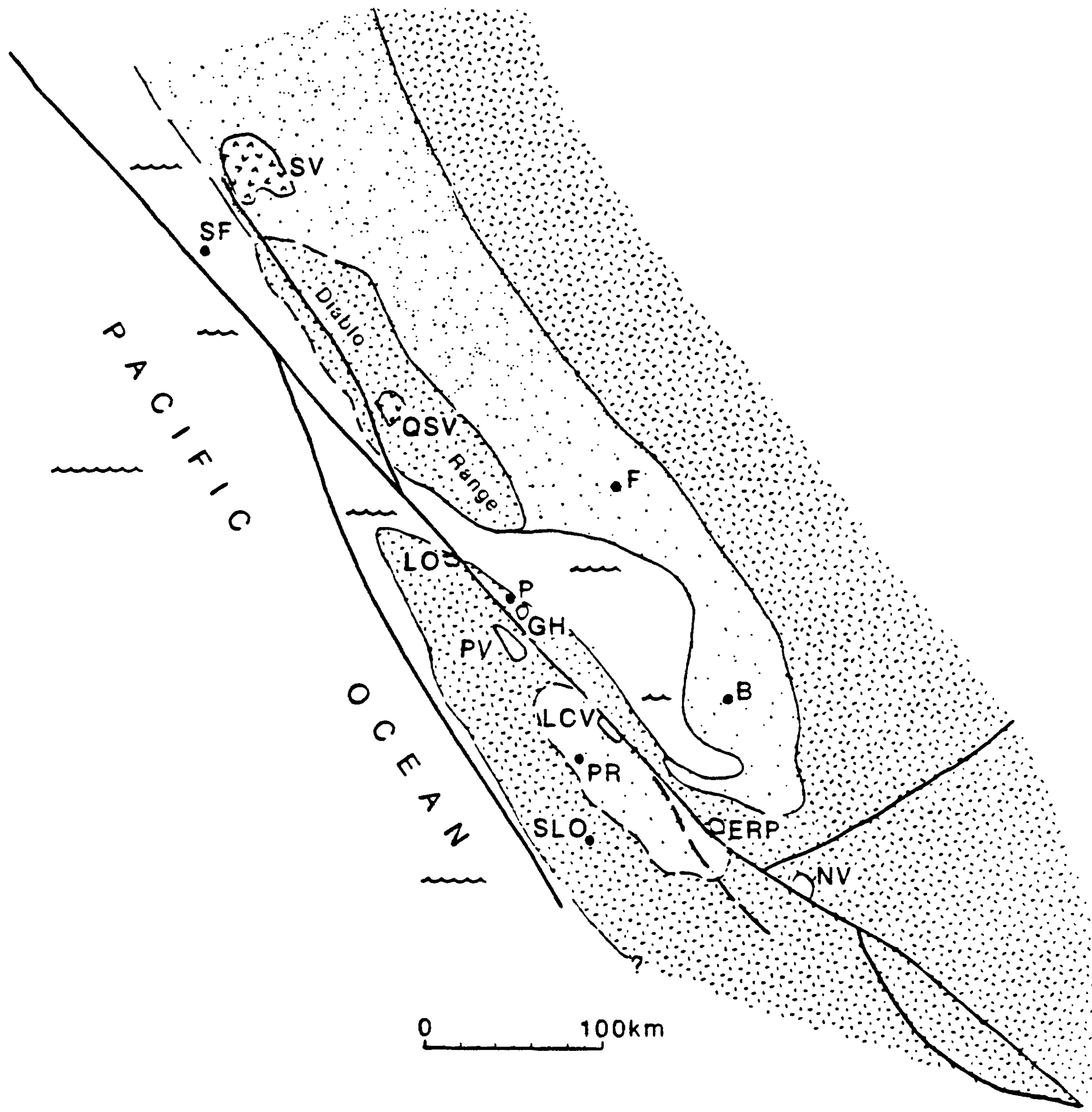

Figure 12. Paleogeographic map of central California for the early Miocene after the reuption of the Neenach/Pinnacles and Tecuya/San Juan Bautista Volcanics. Shorelines and depositional units taken from Bartow (1987), and Perkins (1987). C -Coalinga, B - Bakersfield, ERP - gabbro of Eagle Rest Peak, F - Fresno, LO - gabbro of Logan, NV - Neenach Volcanics, P - Parkfield, PR - Paso Robles, PV - Pinnacles Volcanics, QSV - Quien Sabe Volcanics, SC - Santa Cruz, SF - San Francisco, SLO -San Luis Obispo, SV - Sonoma Volcanics, TJ - Mendocino triple junction.

Phase 3--follows the slivering off of the Gold Hill block. Right-lateral movement continues to the present time. The distance between the Pinnacles Volcanics and the volcanic rocks of Lang Canyon remains the same as does the distance between the gabbro of Logan and the Pinnacles Volcanics. The distance from the Gold Hill unit to the present location the gabbro of Logan is 165 km which is also the distance required to bring the volcanic rocks of Lang Canyon to its present position. This phase is estimated as being about 5 my. Thus the slip rate for Phase 3 is 33 mm/y. See text for discussion.

Average Slip Rates

Incremental offset along the San Andreas fault since early Miocene time may be estimated from the positions of exotic fragments and sedimentary facies that contain clasts derived from these exotic rocks. Estimates of post-early Miocene average slip across the San Andreas fault zone have long been based on the 315-km offset the Pinnacles and Neenach Volcanics and on the assumption that slip began about the same time as the eruption of the Neenach and Pinnacles (Huffman, 1972; Matthews, 1973a). These data and assumptions yield an average slip rate of about 12 to 14 mm/yr on the San Andreas for the entire period from early Miocene time to present, a maximum of about 22 Ma. This rate is at variance with slip rates determined from offset Holocene and Pleistocene strata as well as geodetic measurements of rates of slip. Holocene and late Pleistocene slip rates range from 22 ± 4 mm/yr near Hollister (Perkins and others, in press), to 27 ± 4 mm/yr near Parkfield (Sims, 1987), to 33.9 ± 1.9 mm/yr on the Carrizo Plain (Sieh and Jahns, 1984). Geodetic rates are reported at 28-33 mm/yr for seismogenic depths in central California (Segal and Harris, 1986; Harris, 1986).

The reconstruction and slip history proposed here suggests varying slip rates for the three phases of post-early Miocene evolution of the San Andreas fault in central California. Each phase is characterized by the movement of specific exotic fragments along the fault, and by a different rate of average slip (Fig. 13). Evidence from transported tectonic fragments of crystalline basement, lower Miocene volcanic rocks, and displaced formations and facies of sedimentary rocks suggest that a more detailed sequence of events may be determined. This sequence of events suggests a step-like rate of movement on the San Andreas system since early Miocene time. Based on the data presented here, the minimum slip rate was about 9 mm/yr for phase 1, about 8 mm/yr for phase 2, and about equal to the present rate of 33 mm/yr for phase 3 (Table 3).

The slip rate for phase 1 is highly dependent on fixing the time of initiation of movement along the San Andreas fault. This is commonly assumed to be shortly after the eruption of the volcanic rocks. However, the relationship between the eruption of volcanic rocks, the passage and location of the triple junction, and the lengthening of the San Andreas transform fault is not precisely understood. Thus, placing the initiation of movement to before, during, or after eruption of the two volcanic units will change the slip rate slightly. The other constraint on the slip rate for phase 1 is the end of the phase. I place the end of phase 1 at the cessation of deposition of the flow-banded rhyolite clasts in the Santa Margarita Formation in the southern Temblor Range. Again, the age of this event is not well defined and may have occurred as much as 2 Ma on either side of the time here chosen.

The average slip rate for phase 2 is similarly dependent on the timing of the events that are used to define the phase. However, the beginning and end of phase 2 are perhaps better constrained by specific events -- the cessation of deposition of flow-banded rhyolite clasts in the southern Temblor Range and the slivering off of the Gold Hill fragment. The upper Miocene and lower Pliocene rocks east of the Gold Hill fragment. The time of start of phase 2, in sharing a common event with the end of phase 1 shares the uncertainty of that event. The end of phase 2, marked by the slivering off of Gold Hill, is further constrained by the distribution of, and the different style and degree of deformation of deformation of the upper Miocene and Pliocene strata in the Parkfield area carries an uncertainty of about 2 Ma (Sims, in press). However, the uncertainty in the endpoints of phase 2 does not produce a remarkable change in the overall slip rate (Fig. 10).

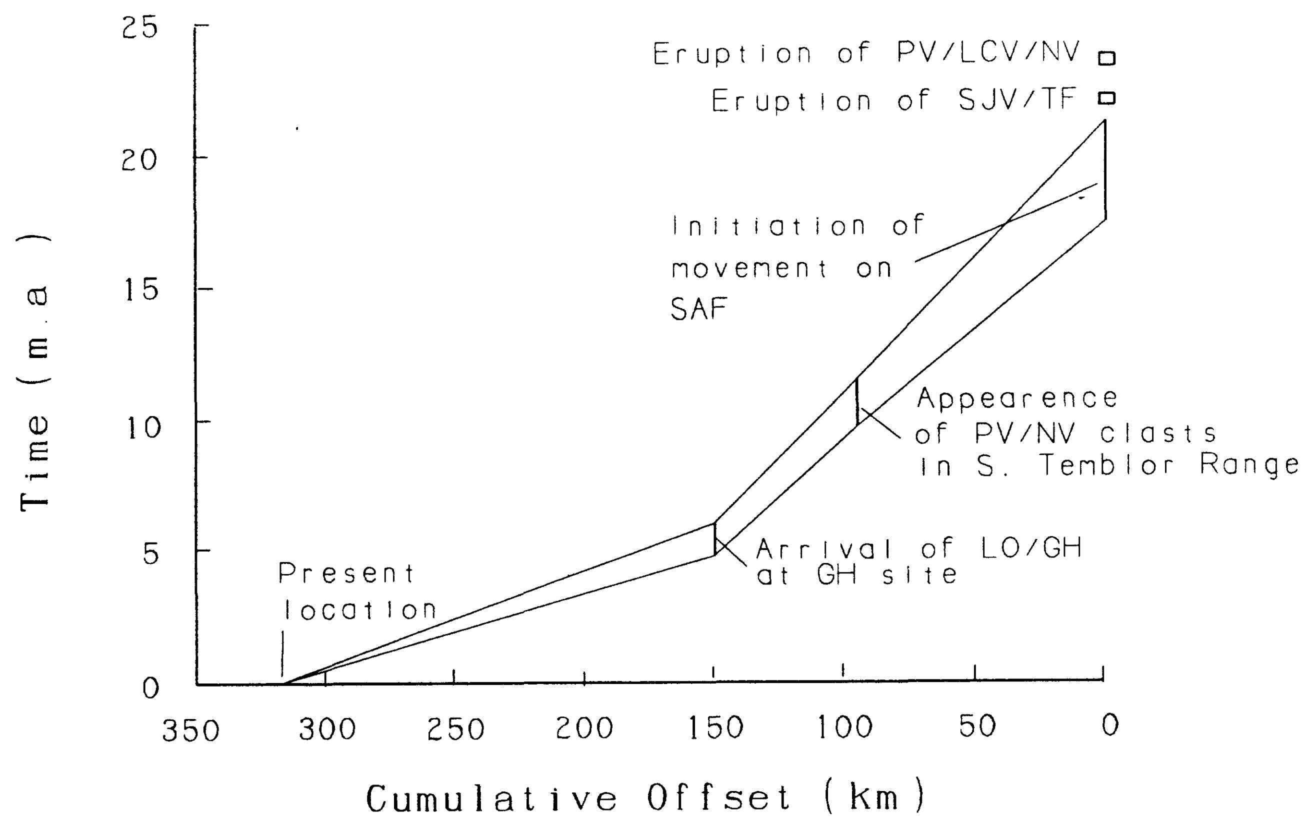

Figure 13. Slip history of the San Andreas transform system in central California since inception of strike slip movement less than 20 m.y. ago. The dates of eruption of the Neenach/Lang Canyon/Pinnacles Volcanics and the volcanic member of the San Juan Bautista/Tecuya Formation are shown for reference.

Table 3. Net incremental slip and average slip rate for each phase of the evolution of the San Andreas fault in central California. Three estimates of period of movement and the subsequent time length and average slip rate is given for each phase. The three estimates for each phase of movement are the maximum (upper value), prefered (middle value, and minimum (lower value).

Phase	Net slip (km)	Period of movement (Ma)	Period length (Ma)	Evidence*	Slip rate (mm/yr)
1	95	24 to 10	14	A	7
1	95	20 to 12	8	A	12
1	95	18 to 10	8	A	12
2	55	12 to 6	6	B	9
2	55	12 to 5	7	B	8
2	55	10 to 6	4	B	14
3	165	6 to present	6	C	27
3	165	5 to present	5	C	33
3	165	4 to present	4	C	41

* Evidence symbols:

A --- Clasts of flow-banded rhyolite in Santa Margarita Formation of southern Temblor Range.
Time of eruption of Neenach and Pinnacles Volcanics and the volcanic rocks near San Juan Bautista and in the Tecuya Formation.

B --- End of deposition of flow banded clasts in the Santa Margarita Formation in the southern Temblor Range. Slivering off of the volcanic rocks of Lang Canyon and the ancestral San Andreas fault is abandoned.

C --- Slivering off of gabbro of Gold Hill from gabbro of Logan and the Jack Ranch segment of the San Andreas fault system is abandoned. Etchegoin Formation widely distributed in the Gold Hill area but not present on Gold Hill.

Temblor Formation and Polonio Sandstone member of Monterey Formation widely distributed in Gold Hill area but not present on Gold Hill.

Varian Ranch "beds" of Dickinson (1966) contains eroded granitic debris similar to the basement rocks of the Gabilan Range but does not contain flow-banded rhyolite clasts derived from the Pinnacles Volcanics.

The uncertainty in the timing of phase 3, which ends at the present, is primarily in its starting time. The slip rate proposed for phase 3 is similar to the present rate and is similar to the rate for the last 5 Ma proposed by Weldon and Meisling (1986) for southern California. Most important, however, is that the rates proposed for phases 1 and 2 are similar and aboutone-third to one-fourth of those proposed for phase 3 -- the past 5 Ma. The start of phase 3 roughly coincides with the change in direction and speed of the Pacific plate at about 5 Ma (Minster and Jordan, 1973; Stock and Molnar, 1989). The realignment of the Pacific plate with respect to the North American plate resulted in transpression that deformed the rocks lying along the boundary between the two plates (Harbert and Cox, 1989). Deformationassociated with this episode of transpression in the Parkfield area resulted in folding and uplift of the Middle Mountain area, closure of the Parkfield Syncline, and eastward translation of the Gold Hill fragment (Sims, 1988, in press). This transpressional episode was accompanied by an increase in velocity of the Pacific plate and thus the San Andreas fault.

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APPENDIX

Method of Combining K/Ar Dates

The procedures of Wilson and Ward (1978) were used to examine the K/Ar age dates for the Pinnacles Volcanics, volcanic rocks in the Tecuya Formation of the San Emigdio Mountains, and the volcanic rocks in the San Jaun Bautista area. The procedure requires the calculation of a pooled mean date, A_p, from the following

$$A_p = \Sigma(A_i / E_i^2)/(\Sigma 1/E_i^2)$$

The pooled mean date A_p is then used in

$$T = \Sigma[(A_i - A_p)^2/E_i^2]$$

which has a χ^2 distribution on n-1 degrees of freedom. If $T < \chi^2$ the null hypothesis is accepted and the dates may be combined. If $T > \chi^2$ the null hypothesis is rejected and combination of the dates is not valid. When the null hypothesis is accepted the pooled standard deviation, σ_p, of A_p is calculated from

$$\sigma_p = 1/\Sigma(1/E_i^2)$$

The dates for the Pinnacles Volcanics are as follow:

22.1 ± 3.2 (KA 2079)
24.1 ± 0.7 (KA 2087)
24.3 ± 0.7 (KA 2091R)
24.5 ± 1.2 (KA 2192)

The calculated statistical values are $A_p = 24.2$, $T = 0.53$, df = 3, $\chi^2 = 7.81$ at $p = 0.05$, and $\sigma_p = 0.21$. Thus, the combined age date is 24.2 ± 0.2 Ma.

Dates for the volcanic member of the Tecuya Formation in the San Emigdio Mountains are:

22.9 ± 0.7 (KA 2175)
22.4 ± 0.7 (KA 2166)
24.6 ± 7.2 (KA 2169)
25.2 ± 2.9 (KA 2162)
22.1 ± 0.6 (KA 2114)
22.5 ± 0.7 (KA 2115)
18.1 ± 7.6 (KA 2215)

The calculated statistical values are $A_p = 22.5$, $T = 2.08$, df = 5, $\chi^2 = 11.07$ at $p = 0.05$, and $\sigma_p = 0.11$. Thus the combined date is 22.5 ± 0.1 Ma.

Dates for the volcanic member of the Zayante Sandstone of Dibblee (1979) near San Juan Bautista are

22.2 ± 0.7 (KA 2157)
23.5 ± 1.4 (SJB-1)
21.3 ± 1.3 (SJB-2)

The calculated statistical values are $A_p = 22.2$, $T = 1.35$, df = 2, $\chi^2 = 5.99$ at $p = 0.05$, and $\sigma_p = 0.32$. Thus the combined date is 22.2 ± 0.3 Ma.

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