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MIGRATION OF SALINIAN COMPOSITE BLOCK, CALIFORNIA, AND DISAPPEARANCE OF FRAGMENTS

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ABSTRACT. The Salinian composite block of California, comprising parts of the Cordilleran Cretaceous plutonic arc, is clearly out of place, being bordered on both sides by Franciscan-type assemblages which probably evolved along a subduction zone. Judging from the paleomagnetic findings of Champion, Grommé, and Howell (1980) and Wilson and others (in press), the block originated at the latitude of Mexico or Central America. The Franciscan-type rocks of the Sur-Obispo belt, which adjoins the southwest side of the Salinian block, probably originated somewhat south of the block. Apparently both terranes departed from their original locations in the Late Cretaceous or Paleogene, most probably 70 to 65 mybp, and traveled 2500 to 5600 km northwestward along the continental margin. Before or during the journey, the western flank of the Salinian block, together with a "foothills" belt analogous to that of the Sierra Nevada, and a forearc basin assemblage, were removed. These fragments have disappeared. The removal and disappearance was accomplished either by mega-transport to an unidentified destination at the Earth's surface or by subduction, the former perhaps being most plausible. Relative plate motions derived by Engebretson (1981, informal commun.) seem marginally adequate to account for the northwestward transport of the Salinian and Sur-Obispo terranes, the Kula and Farallon plates having converged obliquely with North America, producing a dextral component of motion if the continental margin had a favorable trend. The Salinian block and Sur-Obispo belt were joined side by side at some time between 80 and 55 mybp, probably, and they most likely arrived in California between 55 and 38 mybp. There is some likelihood that the northwest tip of the Salinian block was subsequently removed along the alignment of the present continental slope, perhaps by subduction erosion, between 40 and 20 mybp. Dextral strike-slip resulting from Pacific-North America transform interaction (Atwater, 1970) imparted the final 300 to 1000 km of coastwise motion to the Salinian and Sur-Obispo terranes after 29 mybp. This motion continues today, being mainly accommodated by slip on the San Andreas fault.

INTRODUCTION TO THE PROBLEM

The Salinian composite block (fig. 1) is an out-of-place terrane (or group of terranes) 40 to 70 km wide and at least 500 km long, in the California Coast Ranges. It extends northwestward from the Transverse Ranges of southern California to some uncertain point north of San Francisco, possibly reaching the vicinity of Point Arena, although this now seems unlikely. The northwest part of the terrane is largely offshore. Both onshore and offshore, the exposed parts of the Salinian basement consist mainly of Cretaceous granitic plutons and associated high temperature metamorphic rocks of unknown age. The block is of current interest because of divergent views about its origin and emplacement

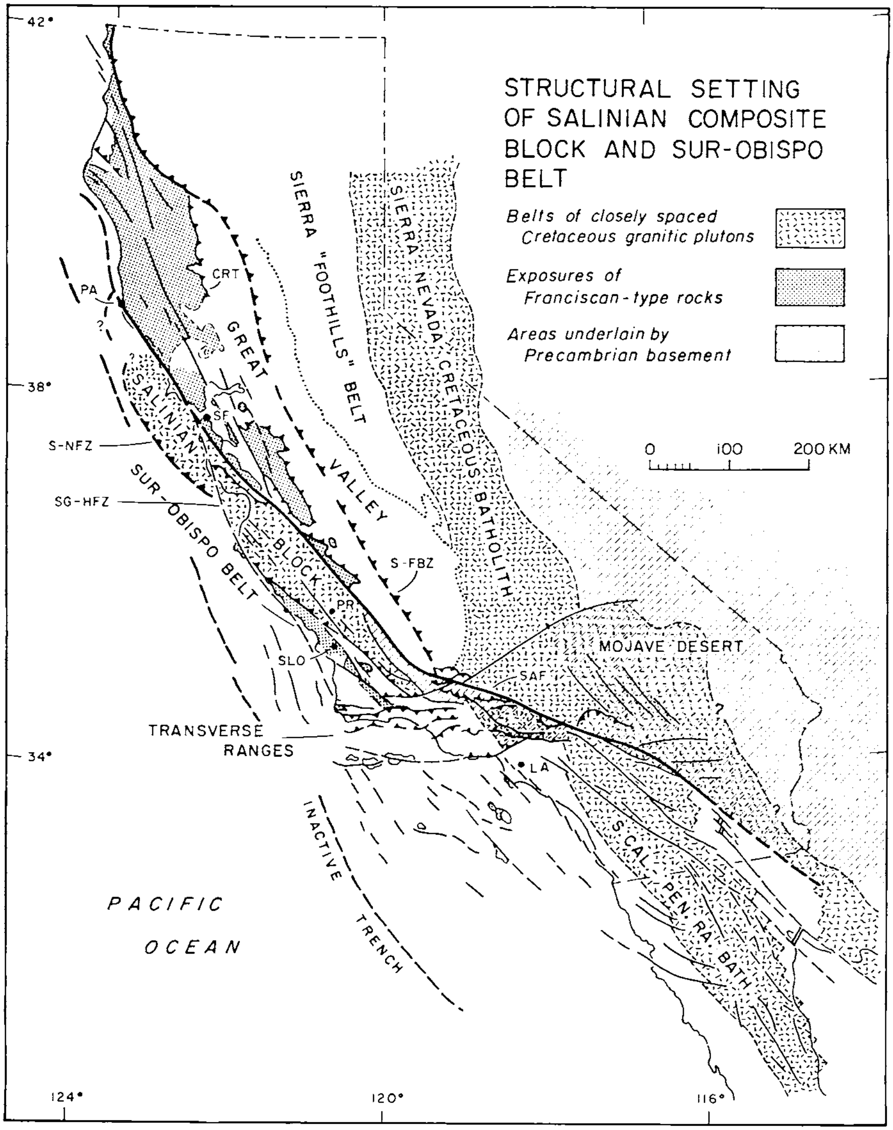

Fig. 1. Structural setting of Salinian composite block and Sur-Obispo belt. Abbreviations: BH, Bodega Head; CRT, Coast Range thrust; LA, Los Angeles; PA, Point Arena; PR, Paso Robles; SAF, San Andreas fault; SF, San Francisco; S-FBZ, Sierran-Franciscan boundary zone; SG-HFZ, San Gregorio-Hosgri fault zone; SLO, San Luis Obispo; S-NFZ, Sur-Nacimiento fault zone.

(for example, Johnson and Normark, 1974; Gastil and Phillips, 1974; Howell, 1975, 1976; Moore, 1976; Ross, 1978; Kistler, 1978; Beck and Plumley, 1979; Wilson, Schnapp, and Cox, in press; Champion, Grommé, and Howell, 1980; Vedder, Howell, and McLean, in press; McWilliams and Howell, in press) and because parts of it are missing (Page, 1970, 1981). The latter problem is addressed at this time, despite the lack of final solutions, in the hope of stimulating further research. My views concerning the original location of the block have changed in response to recent paleomagnetic results obtained by others; consequently, some opinions herein differ from those reported previously (Page, 1981).

The Salinian composite block is considered to represent displaced fragments of a late Mesozoic continental plutonic arc, but at present it is closely flanked by Franciscan-type complexes, which are regarded as allochthonous accreted subduction zone assemblages. This relationship exists on both sides of the block, but only the southwest side poses the enigma addressed here. The San Andreas fault bounds the Salinian block on the northeast, and its history of strike-slip, including 300 km of offset in the Neogene, largely explains the anomalous juxtapositions along that side of the displaced plutonic arc terrane. The southwest boundary is where the loss of part of the Salinian block is dramatically evident. This boundary lies in the Sur-Nacimiento fault zone — an ill-defined system of faults of various kinds and various ages (Page, 1970).

Along the Sur-Nacimiento fault zone (S-NFZ), the Franciscan-type rocks on the southwest constitute the "basement" of the Sur-Obispo belt, shown in figure 1. These rocks will be called Franciscan for expedience, although they may have been assembled far from the rocks of the type Franciscan region. The juxtaposition of the Franciscan against the Salinian arc rocks is startling. Some of the Franciscan sedimentary rocks are mid- and Upper Cretaceous, as are Salinian granitic plutons, so there is a partial contemporaneity, yet the contrasts are pronounced. Parts of the Franciscan are little metamorphosed, whereas other parts are in the high P/T blueschist metamorphic facies, but directly across the S-NFZ the wall rocks of the Salinian basement are in the high T/P amphibolite or even granulite facies. Much of the Franciscan consists of mélange, whereas none of the Salinian rocks resemble mélange. Fragments of oceanic crust and pelagic sedimentary rocks in the Franciscan are locally almost touching Salinian granite but are entirely unaffected by the intrusives.

Normally the axial zone of an active continental margin plutonic arc is 200 to 350 km distant from a coeval trench. However, in the present case, tracts such as the forearc basin, "foothills" belt, and western fringe of the plutonic arc are missing and have not been identified elsewhere.

Two different modes of disappearance of the missing fragments are considered here: (1) disappearance by mega-transport at the Earth's surface, and (2) destruction by piecemeal subduction.

GEOLOGY OF THE SALINIAN COMPOSITE BLOCK

Subdivisions of the block.—The Salinian block is sliced longitudinally (fig. 2), as emphasized by Johnson and Normark (1974). It is called the "Salinian composite terrane" by Vedder, Howell, and McLean (in press), and I have borrowed their adjective. Some of the slices differ petrologically from others, and on this basis Ross (1978) recognizes at least four sub-blocks, of which the central one includes the greater part of the on-land Salinian terrane, embracing much of the Santa Cruz Mountains, Gabilan Range, Santa Lucia Range, and La Panza Range. Ross' central sub-block is dominated by four large Cretaceous granitic units and contains many smaller ones. Although this central tract seems to lack very large internal displacements (Ross, 1978; John, 1981), it is nevertheless slivered by faults, one of which (the Rinconada; Dibblee, 1976) has undergone about 40 km of dextral slip (Graham, 1978). The central sub-block is terminated on the southeast by the Red Hills-San Juan-Chimeneas fault, east of which is a small Salinian sub-block — the Barrett Ridge slice, characterized by high grade Precambrian (?) gneiss and granitic material (Ross, 1978). The central sub-block is partially bordered on the west by a plutonic complex containing charnockitic tonalite (Compton, 1960), migmatite, and granulite. This western sliver is separated from the central sub-block by the Palo Colorado fault. Ross' fourth sub-block encompasses all the Salinian terrane north of those just mentioned. If we modify his scheme slightly, we might subdivide the northern block along the San Gregorio-Hosgri fault zone, which has accrued 80 to 115 km of dextral slip (Silver, 1974; Hall, 1975; Graham and Dickinson, 1978). The northern region might be further divided, but it is largely covered by the ocean and by Cenozoic sediments. Interestingly, the thermal history of plutonic rocks at Bodega Head and Point Reyes apparently differs from that of plutons in the Santa Lucia Range (Mattinson, 1978), suggesting possible differences in tectonic background. Some geologists consider the central sub-block to be divisible into smaller components. Indeed, the number of subdivisions of the Salinian composite block is virtually indeterminate.

The relationship between the Salinian composite block and the Southern California batholith-Peninsular Range terranes is unknown. They may have belonged to the same, or different, allochthones at some time prior to the origin of the Transverse Ranges.

Salinian basement rocks.—The basement complexes include metamorphic wallrocks and intrusive plutons with complicated relations (Compton, 1966b; Ross and McCulloch, 1979). Collectively, the wallrocks are said to differ somewhat from those of nearby areas in California (Ross, 1977a). The petrology has been discussed by Trask (1926), Compton (1960, 1966a, b), Wiebe (1970), and Ross (1976a, b, 1977a). The most extensive outcrops of the pre-intrusive rocks are in the Santa Lucia Range (fig. 2A), where the dominant varieties are biotite–feldspar quartzite, quartzo–feldspathic granofels, and quartzo–feldspathic gneiss and migmatite. There are lesser amounts of calc–silicate granofels, amphibolite,

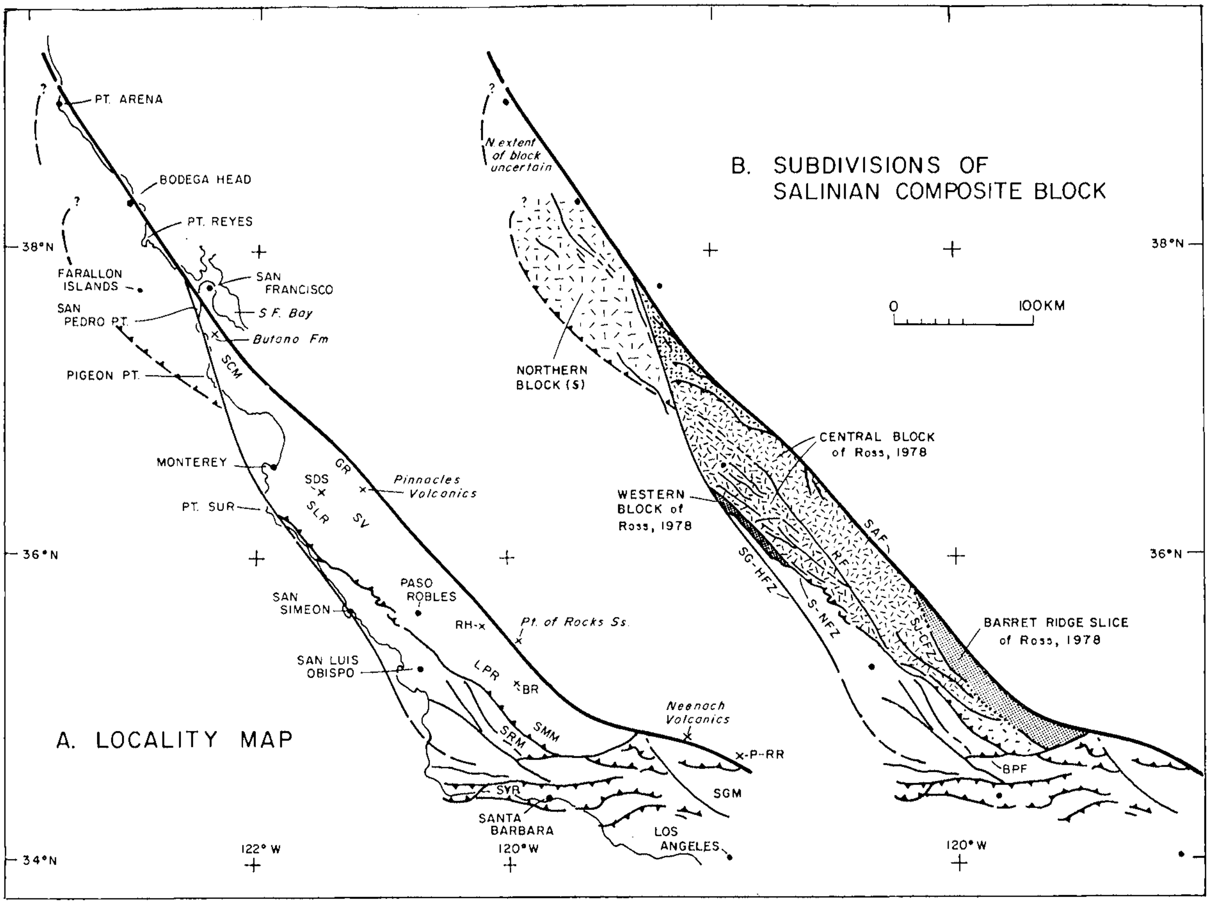

Fig. 2. (A) Locality map. Abbreviations: BR, Barrett Ridge; GR, Gabilan Range; LPR, La Panza Range; P-RR, Portal-Ritter Ridge; RH, Red Hills; SCM, Santa Cruz Mountains; SDS, Sierra de Salinas; SLR, Santa Lucia Range; SMM, Sierra Madre Mountains; SRM, San Rafael Mountains; SV, Salinas Valley; SYR, Santa Ynez Range. (B) Subdivisions of Salinian composite block. Abbreviations: BPF, Big Pine fault; RF, Rinconada fault; SAF, San Andreas fault; SG-HFZ, San Gregorio-Hosgri fault zone; SJ-CFZ, San Juan-Chimeneas fault zone; S-NFZ, Sur-Nacimiento fault zone.

aluminous schist, calcite marble, and metadolomite. It is believed (Compton, 1966a; Wiebe, 1970; Ross, 1977a) that most of the rocks are metasedimentary, and Ross concludes that they mainly represent a sequence of interbedded quartz-rich siltstone and impure sandstone, with smaller amounts of shaly, marly, and calcareous rocks. The age(s) could be anything from Precambrian to Mesozoic. Ross (1977a) has not found correlatives of the sequence as a whole in regions such as the Sierra Nevada or westernmost Mojave Desert, and he regards the Salinian block as an "orphan" of unknown parentage (Ross, 1978). However, he suggests (Ross, 1976b) that the schist of the Sierra de Salinas in the Santa Lucia Range of the central sub-block (fig. 2B) may match the schist of Portal-Ritter Ridge 300 km to the southeast on the opposite side of the San Andreas fault. Ross (1977a) finds one other possible match: a gneissic and granitic complex comprising the Barrett Ridge slice of the Salinian block (in the southeastern part of the latter, fig. 2B) resembles Precambrian metamorphic-igneous complexes in the San Gabriel Mountains of the Transverse Ranges.

The plutonic rocks of the Salinian basement have been described by Compton (1960, 1966a, b), and Ross (1972a, b, 1974, 1976a, 1977b, 1978). Most of the plutons are granodiorite, quartz monzonite (or granite, depending on definitions) and tonalite, the first two predominating. These rocks are extensively exposed in the La Panza, Gabilan, and northern Santa Lucia ranges (fig. 2A). Smaller exposures occur northwestward along the coast as far as Bodega Head 80 km beyond San Francisco, and subaerial and submarine outcrops are found west and northwest of San Francisco near the brink of the continental slope. The apparent ages of the plutons range from mid- to Late Cretaceous; this will be discussed later.

Most Salinian granitic rocks seem generally similar to some of those in the Sierra Nevada and other parts of the Cordillera, especially those near the axis of the main belt of Cretaceous intrusives, and the apparent ages are quite comparable. The reader may compare the mineralogic and chemical data of Ross (1977b) for plutons of the Santa Lucia Range with data from the Sierra (Bateman and Dodge, 1970). Kistler and Peterman (1973) find $^{87}Sr/^{86}Sr$ ratios of 0.706 or higher both in the Salinian block and in much of the High Sierra, whereas they note lower values in most plutons of the Sierran foothills. All things considered, it seems likely that the Salinian granitic rocks were once part of a distant (perhaps *very* distant) southward continuation of the main Cretaceous plutonic belt of which the Sierra Nevada is a member.

Sedimentary cover.—The Salinian basement is locally covered depositionally by Upper Cretaceous (Campanian and Maastrichtian) marine clastic sediments. Somewhat similar strata of Paleocene and Eocene age commonly overlie the Cretaceous deposits or rest unconformably directly on the basement. The Cretaceous, Paleocene, and Eocene deposits are predominantly of sub-sea fan facies, but shallow marine and nonmarine sediments occur in some localities. The succeeding Oligocene deposits are generally strikingly different from the older, predominantly turbiditic marine sediments. In many areas they are nonmarine, and locally they include indigenous volcanics. Many Miocene sequences are marine but are different from the Paleogene sediments, being generally more organic and less coarsely clastic except near paleo-shorelines. Pliocene marine deposits are restricted, and most Plio-Pleistocene sediments are of synorogenic fluvial/alluvial origin.

The sedimentary cover will be discussed more fully in a later section dealing with the tectonic record.

STRUCTURAL SETTING

San Andreas fault.—The northeast boundary of the Salinian composite block (figs. 1, 2) is the San Andreas fault (SAF), a dextral northwest-trending fault. The Neogene history of the SAF is presumably the Neogene history of movement of the Salinian block; it is, however, only the last chapter of a longer story.

The possibility of 500 km of displacement along the SAF was recognized by Hill and Dibblee (1953), who showed progressively greater offsets of sequentially older features. In west-central California, early movements took place in the Late Cretaceous or Paleocene. It has been interpreted that the Eocene was a quiescent interlude during which a subsea fan was built across the fault trace (Nilsen and Clarke, 1975). In the early or middle Miocene, the SAF in west-central California resumed activity; it eventually accrued a total Neogene displacement of about 305 km, according to several estimates. The evidence, with references, has been summarized by Dickinson, Cowan, and Schweickert (1972), who constructed a graph of displacement versus time. The slip accelerated dramatically in the Pliocene and Quaternary, for reasons reviewed below.

The SAF in southern California did not experience the two-stage activity just mentioned. South of the Transverse Ranges, the San Andreas, San Gabriel, and San Jacinto faults collectively show a total offset of about 330 km (Crowell, 1981), all acquired in the Neogene. Evidently the two segments of the SAF, respectively north and south of the Transverse Ranges, have only been integrated into a single fault zone since some time in the Miocene.

Sur-Nacimiento fault zone.—The Salinian Block is bounded on the southwest by the Sur-Nacimiento fault zone (S-NFZ, fig. 2B), which may include a displaced continuation of the Sierran-Franciscan boundary zone that lies beneath the sediments of the Great Valley. Evidently the SAF shifted said boundary zone from a point at the south end of the Great Valley to a point offshore somewhere north of Cordell Bank, possibly near Point Arena. Thence the S-NFZ extends southeastward, coming ashore at Point Sur and passing obliquely along the Southern Coast Ranges all the way to the Transverse Ranges. Although it may incorporate a prolongation of the Sierran-Franciscan boundary zone, the S-NFZ is not characterized by this alone. It is, in fact, a poorly defined assemblage of different kinds of faults of different ages (Page, 1970). Some of the faults are relatively old and of thrust-like aspect, perhaps being related indirectly to effects of subduction or suturing. Others are high-angle faults with reverse, strike-slip, or oblique displacement, and some of these affect Neogene formations. Some are arbitrarily included in the S-NFZ because they visibly bound the exposed Franciscan rocks of the Sur-Obispo Belt on the northeast; some are included because they bound the exposed Salinian basement on the southwest; still others lie in a "no man's land" between exposures of the two different basement complexes.

Sur-Obispo belt.—The Sur-Obispo belt (sometimes called the Nacimiento block) lies southwest of the S-NFZ alongside the Salinian composite block (fig. 1). It consists largely of highly deformed Franciscan-type rocks, including mélanges, of late Mesozoic age. Locally these are overlain tectonically by disrupted ophiolite, which forms the base of a superincumbent Great Valley-type clastic sedimentary sequence of Late Jurassic and Early Cretaceous age. In some areas these strata are in turn overthrust by Late Cretaceous (Campanian) Great Valley-type rocks (fig. 3). Tertiary sediments form an incomplete cover resting unconformably on any or all of the aforementioned assemblages. All the rocks, including the Tertiary cover, are strongly folded and are cut by northwest-trending high-angle faults which are sub-parallel with the Sur-Obispo belt itself.

The Franciscan rocks of the Sur-Obispo belt have been described by Bailey, Irwin, and Jones (1964), Hsü (1969), Page (1970 and 1981), Gilbert (1973, 1974), Cowan (1978), Ernst (1980), and others. A number of excellent map sheets have been published by Hall (1976, and Hall and others, 1979, for references). The Franciscan of this belt is largely mélange, but it includes some coherent sandstone-mudstone sequences in blocks

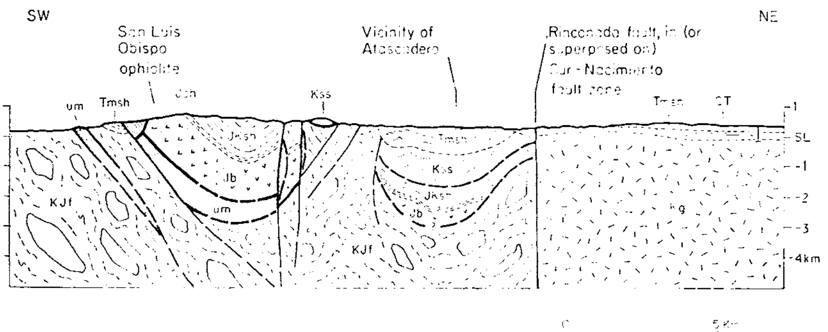

Fig. 3. Cross section across Sur-Obispo belt and part of Salinian block. Section shows juxtaposition of Franciscan-type subduction zone complex of Cretaceous age and Salinian plutonic arc, also of Cretaceous age. The section, which extends past San Luis Obispo and Atascadero, shows inferred truncation of post-Campanian thrust faults which underlie outliers of Great Valley-type ophiolite and sediments. The Rinconada fault where crossed by the section is either a rejuvenated element of the Sur-Nacimiento fault zone or is superposed on the zone. Abbreviations: KJf, Franciscan Complex; Kg, Cretaceous granodiorite/quartz monzonite; um, ultramafic rocks, chiefly of ophiolite suite; Jb, Upper Jurassic oceanic basalt and dike/sill complex of ophiolite; Jch, uppermost Jurassic (Tithonian) chert; JKsh, uppermost Jurassic and Lower Cretaceous shale; Kss, Upper Cretaceous (Campanian) sandstone; Tmsh, Miocene siliceous shale with sandstone at base; QT, Pliocene-Pleistocene nonmarine sediments.

or slabs measured in kilometers. Some of these bodies are interpreted to be trench-slope basin deposits (Smith, Howell, and Ingersoll, 1979). The mélanges have a highly sheared argillaceous matrix which encloses blocks of sandstone, greenstone, radiolarian chert, serpentinite, blueschist, conglomerate, and other rocks. The mélanges may be mainly tectonic or partly olistostromal in origin, but all have been strongly deformed, presumably in part by subduction, transpression, and other processes.

The disrupted ophiolites tectonically overlying the Franciscan are Middle Jurassic, about 160 ± 5 m.y. in age. They have been comprehensively described and interpreted by Hopson, Mattinson, and Pessagno (1981). Some ophiolitic igneous suites are overlain by Upper Jurassic radiolarian chert which is followed by a substantial sequence of Great Valley-type clastic marine sediments.

The Great Valley-type sediments of the Sur-Obispo belt have been summarized and interpreted by Howell and others (1977) and Vedder, Howell, and McLean (in press). Typically, the basal chert is overlain by mudstone with turbiditic sandstone interbeds; these deposits range from Tithonian (Upper Jurassic) to Valanginian (Lower Cretaceous) in age. Generally mid-Cretaceous sediments are scarce or absent, and at least locally, thrust faults intervene between Lower and Upper Cretaceous sections. However, a nearly intact Cretaceous column (including mid-Cretaceous) is reported in the San Rafael Mountains (fig. 2A; Vedder and others, in press). Elsewhere, thick Cretaceous sequences are common but apparently mainly represent the Campanian Stage, a few extending into the Maastrichtian. The Upper Cretaceous sandstones are largely arkosic and contain much granitic detritus. They and the interbedded mudstones mostly represent subsea fan deposits, but in the San Rafael Mountains Vedder, Howell, and McLean (1980 and in press) find tongues of shallow water and nonmarine sediments derived from a nearby granitic terrane east of the site of the Sur-Nacimiento fault zone. This could have important tectonic implications, as discussed later.

Oligocene nonmarine sediments occur in several areas. In places they give way upward to transgressive marine sandstones of late Oligocene-early Miocene age. Middle Miocene facies include characteristic siliceous organic-rich sediments which are virtually identical with those of the Salinian composite terrane, although none can be traced with continuity across the Sur-Nacimiento fault.

Transverse Ranges.—The east-west Transverse Ranges (fig. 1) terminate the Salinian composite block (in its present form) on the south, interrupting or modifying any former continuity between the block and the Southern California batholith and Peninsular Ranges. The origin and kinematics of the Transverse Ranges are not well understood.

The basement rocks of the Transverse Ranges north and east of Los Angeles have been described by Ehlig (1981) and Crowell (1981). Precambrian gneisses, migmatites, and plutonic igneous rocks are invaded by Mesozoic granitic intrusives. The Precambrian basement is locally seen to comprise the upper plate of a thrust of probable regional extent.

Beneath the thrust is the Mesozoic (?) Pelona Schist, which is recognized in southeastern California, in the western Mojave Desert, and possibly in part of the Salinian block (Ross, 1976b).

In contrast to the foregoing, the basement of the western Transverse Ranges (including the offshore area and islands, apparently) consists of Franciscan rocks. Hence the Sur-Nacimiento fault zone or its equivalent must transect the province, although it now has no surface exposure or expression. The western Transverse Ranges have an extensive cover of sedimentary rocks, ranging in age from latest Jurassic to Pleistocene (see, for example, Dibblee, 1950). Pre-Campanian rocks resemble those of the Sur-Obispo belt, whereas Upper Cretaceous and Eocene rocks resemble those of the Salinian block. All the strata (including those of Pleistocene age) are folded along east-west axes and are locally cut by similarly-trending reverse faults, some of which are seismogenic. Similar faults bound the eastern Transverse Ranges.

The Pliocene-Quaternary north-south compression which is manifested in the province may have entailed more crustal shortening than formerly supposed, as Miocene volcanic rocks to the south, on both sides of the San Andreas fault, contain paleomagnetic evidence of substantial northerly transport (Marshall and others, 1979; Erskine and Marshall, 1980), whereas rocks of comparable age in the southern Sierra Nevada show little or no movement (Kanter and McWilliams, 1982). An added complication is the marked clockwise rotation of most of the transported Miocene rocks and those of the western Transverse Ranges (Kamerling and Luyendyk, 1979). A recent model by Yeats (1981) postulates a subhorizontal surface of décollement beneath the province at a depth of some tens of kilometers. Much of the deformation and rotation within the province may have occurred above such a surface.

MOVEMENTS OF SALINIAN AND SUR-OBISPO TERRANES

The terranes that concern us have been transported apparently over great distances during a long span of time. The earlier, larger part of the story is poorly known. The later, more reliable part of the movement history is provided by the record of slip (versus time) along the San Andreas fault. The motion is on-going today, so we are privileged to witness the continuation of the long journey of the two terranes.

Cenozoic movements, based on San Andreas history

Atwater (1970) interpreted the history of the SAF in terms of plate interactions. Whatever the origin of the ancestral SAF may have been, the present fault is a transform whose modern role commenced after 29 mybp when the Pacific and North American plates first came into mutual contact (Atwater, 1970; Atwater and Molnar, 1973). The relative plate motion entailed horizontal northwest-southeast dextral shear. Although the principal shear was initially concentrated seaward of the SAF and seaward of the Salinian composite block, the motion migrated inland and the SAF (which had slumbered after earlier movements of possibly different origin) began to awaken about 15 mybp under this new influence. Between 6 and 3.5 mybp, apparently, the East Pacific Rise spreading system reached the mouth of the Gulf of California, and the main locus of relative plate motion shifted east. Spreading in the Gulf was linked to the SAF system in southern California. Baja California, southwestern California, the Salinian block, and the Sur-Obispo belt are now attached to the Pacific plate and share part of its motion relative to North America. Present-day relative motion of areas on opposite sides of the San Andreas fault is about 3.2 to 3.7 cm/yr in west-central California (Savage and Burford, 1973), whereas the relative plate motion is about 5.6 cm/yr (Minster and Jordan, 1978).

During the transform regime, the Salinian block has traveled about 305 km along the SAF, relative to the interior of North America. This has taken place mainly since the beginning of the Miocene. The distance is based largely on the strike separation of such features as an early Miocene shoreline and the 23.5 m.y.-old Pinnacles-Neenach Volcanics (Turner, 1969; Huffman, 1972; Matthews, 1973). Throughout the transform regime, the Sur-Obispo belt presumably accompanied the Salinian block, with which it was in contact, but at times it must have moved a bit faster and farther than the block, as some (strike-slip?) faulting occurred along the Sur-Nacimiento fault zone, offsetting Miocene and (locally) Pliocene rocks.

During the Neogene (and continuing in the Holocene), the northern part of the Salinian block moved somewhat farther than the remainder by virtue of the San Gregorio-Hosgri fault zone, which crosses the block at an acute angle and joins the SAF just north of San Francisco (fig. 1). Total displacement along the SG-HFZ is variously estimated in different places to be about 90 km (Silver, 1974), 80 km (Hall, 1975), 70 km (Greene, 1977), and 115 km (Graham and Dickinson, 1978). Thus the northern part of the Salinian block has probably moved 70 to 115 km farther than the southern part, more or less in the manner postulated by Johnson and Normark (1974). The Salinian block is not only sliced obliquely by the SG-HFZ, but it is slivered internally by a number of additional strike-slip faults. However, most of these have small to moderate displacements, and, being inland from the margin of the block, they have little bearing on the problems at hand.

If one imagines the Salinian block to be translated backward 305 km along the SAF in central California, some Eocene as well as Miocene features seem to match across the fault, but pre-Eocene rocks are still displaced. The two parts of the postulated Butano-Point of Rocks subsea fan of Eocene age rejoin one another, apparently forming an integrated fan straddling the SAF (Nilsen and Clarke, 1975). However, one part of the fan (the Butano Sandstone, fig. 2A) is underlain by Paleocene sediments and Salinian basement, whereas the other part (Point of Rocks Sandstone, fig. 2A) is underlain by Cretaceous and Upper Jurassic strata of the Great Valley sequence, tectonically beneath which is the Franciscan Complex. In other words, restoring the 305 km Neogene movement of the Salinian block leaves a residual mis-match in basement rocks, implying pre-Neogene movement (Nilsen and Clarke, 1975) prior to about 50 mybp.

If the foregoing restoration is supplemented by reversing 100 to 115 km of displacement on the San Gregorio-Hosgri fault zone (Graham and Dickinson, 1978), the net residual mis-match of basement rocks extends 100 to 200 km along the SAF, giving a deceptively small minimum for pre-Eocene movements of the Salinian block. The existence of pre-Eocene movements is supported by sedimentological and structural evidence in addition to that which is sketched above (Dickinson, Ingersoll, and Graham, 1979).

Although the foregoing geological clues are important, they fail to predict the magnitude of pre-Eocene movements indicated by paleomagnetic data, discussed below. Possible reasons for this discrepancy could include the following: (1) The farthest point reached by the Salinian block is in question. The northern tip may have been removed, as postulated farther on; this would affect the length of mis-match of basement rocks. (2) Much of the pre-Eocene movement involved both sides of the site of the SAF and thus is not registered by the fault. (3) The paleomagnetic results may be unreliable. However, it seems very unlikely that inaccuracies or errors could negate the overall qualitative conclusions.

Pre-Neogene Mega-Movements

Until recently, the writer supposed that the Salinian block was once end-to-end with the southern Sierra Nevada. Ross (1978) discounted this interpretation on petrologic grounds, and he is supported by recent findings. Paleomagnetic data indicate that the Southern California-Peninsular batholith has moved about 1000 km northward and rotated clockwise 23.5° sometime after the mid-Cretaceous (Teissere and Beck, 1973; Beck, 1976; Beck and Plumley, 1979; Erskine and Marshall, 1980). The Salinian composite block could hardly have avoided comparable translation, as it lies in the path of the above-mentioned terrane. Initial paleomagnetic results from Salinian plutons are permissive of large displacements but are difficult to evaluate (Lisa Kanter, 1980, oral commun.). However, Salinian sedimentary rocks have yielded persuasive paleomagnetic results. The Campanian-Maastrichtian(?) turbiditic Pigeon Point Formation (Hall and others, 1959) on the coastal flank of the Santa Cruz Mountains (fig. 2A) has been studied by two independent teams. Wilson and others (in press) concluded that the formation has moved 38° ± 13° toward the 70 m.y. Late Cretaceous pole, this being equivalent to 2700 to 5600 km of poleward translation. Champion, Grommé, and Howell (1980) deduced a poleward movement of about 27° ± 5°, implying 2500 to 3000 km of poleward transport. Apparently the sediments were deposited at a paleolatitude of 10° to 25° north instead of the expected 42° to 48° north. The basement beneath the sediments is not exposed but is presumed to be Salinian. The Pigeon Point Formation lies seaward of the San Gregorio-Hosgri fault zone (SG-HFZ), so it has moved farther (perhaps only 70-115 km) than the central part of the Salinian composite block. At San Pedro Point near San Francisco (fig. 2A), Paleocene turbiditic sediments, which are east of the SG-HFZ and which are clearly affiliated with Salinian basement, have given preliminary paleomagnetic indications of deposition at a paleolatitude of about 26°N instead of the expected 45°N, implying about 2100 km of poleward component of movement (Champion, 1981, oral commun.).

The foregoing findings are qualitatively compelling, although the exact distances of transport, the starting points, and the migration route(s) are necessarily uncertain. The resemblance of Salinian plutons to the axial part of the Cordilleran Cretaceous plutonic arc suggests that the Salinian allochthone(s) did not travel from remote parts of the Pacific but instead started from the Cordillera of Mexico or Central America and moved more or less coastwise.

The Franciscan rocks of the Sur-Obispo belt probably traveled even farther than the Salinian allochthone(s), although this has not been proved. They must have shared something of the same history as their counterparts in the northern Coast Ranges, prior to their dislocation by the San Andreas and perhaps by ancestral faults. The Franciscan north of San Francisco appears to be a collage of allochthonous terranes (Blake and Jones, 1981). The mid-Cretaceous Laytonville Limestone, now at lat 30°40′N may have been deposited at 17°S paleolatitude (Alvarez and others, 1980), based on paleomagnetism in conjunction with microfossils. Surely the limestone did not travel alone. A large mass of Franciscan pillow basalt near Nicasio, 43 km northwest of San Francisco, has apparently traveled more than 2000 km. Paleomagnetic data show that this mass has rotated 105° clockwise and has moved 19° closer to the paleomagnetic pole position since its origin (Grommé and Gluskoter, 1965; up-dated by Grommé, 1980, oral commun.). The basalt is Early Cretaceous, judging from associated radiolarian chert (D. L. Jones, 1980, oral commun.). Some Franciscan sandstones differ markedly from coeval Great Valley sandstones which are presently immediately landward, suggesting deposition at different latitudes (Blake and Jones, 1981).

The Sur-Obispo belt itself has yielded a few clues indicating a distant point of origin. Blocks of conglomerate in Franciscan mélanges in the belt contain pebbles of Triassic chert (Seiders, Pessagno, and Harris, 1979) unlike anything *in situ* in California. The Cambria slab of Upper Cretaceous sandstone north of San Simeon bears a remanent magnetism that suggest more than 2000 km of poleward movement (Champion, 1981, oral commun.). This unit is partially enveloped in a Franciscan mélange. Jurassic ophiolites, structurally overlying the Franciscan Complex, have given preliminary paleomagnetic data indicating poleward transport over distances at least as great as those mentioned above.

In summary, parts (or all) of the Salinian block and Sur-Obispo belt have probably been transported from the vicinity of Mexico or Central America. If tentative paleomagnetic results are taken literally, the Salinian and Sur-Obispo terranes may have traveled more than twice as far as their present southern neighbor(s), the Southern California batholith and Peninsular Ranges, but of course this is unconfirmed.

A complication is posed by the possibility that the Southern California batholith and Peninsular Ranges traveled about 1000 km northward in the last 15 m.y. Miocene volcanics as well as the Cretaceous plutons have apparently moved that distance (Marshall and others, 1979; Erskine and Marshall, 1981). Thus there is an implication that the main journey of the Salinian block and Sur-Obispo belt was earlier and longer than that of the Southern California batholith and Peninsular terranes, and that the latter traveled far in the last 15 m.y. — much farther than predicted solely from the opening of the Gulf of California and the slip on the San Andreas fault. If this is true, regions along *both* sides of the Gulf and the SAF were carried concurrently; the SAF, being transported bodily, failed to record the event.

A schematic representation of the mega-movements is attempted in figure 4, but this is likely to become obsolete as more data are acquired.

Time and circumstances of major events

The inferred time intervals during which the Salinian composite block and Sur-Obispo belt were transported, joined together, and accreted to California are summarized in table 1. The time of removal of parts of the Salinian flank is included, although poorly constrained. Evidence bearing on the timing of major tectonic events is discussed below.

Age of truncated plutons.—Clearly, the Salinian block departed from its place of origin and lost its southwest flank after the plutons were emplaced. Hence the age of emplacement is critical.

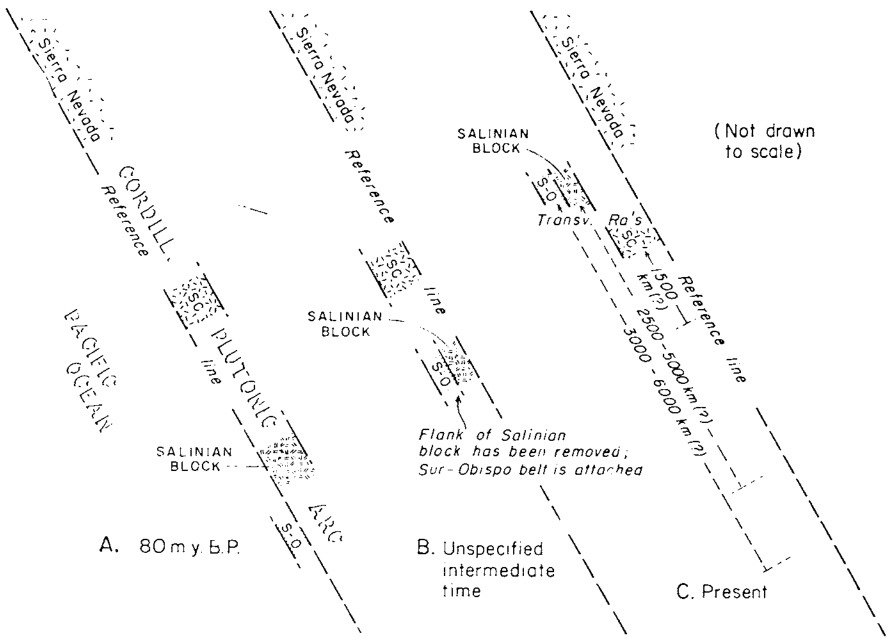

Fig. 4. Speculative diagram of mega-transport of Salinian and Sur-Obispo terranes. Based on preliminary paleomagnetic findings of Teissere and Beck (1973), Beck (1976), Champion, Grommé, and Howell (1980), Wilson, Schnapp, and Cox (in press), and McWilliams (1981, informal commun.). Abbreviations: SC, Southern California-Peninsular Ranges batholith; S-O, Sur-Obispo belt.

TABLE 1
Time of major events

Event	Time (mybp)	Constraints and comments
A. Departure of Sur-Obispo belt (S-O) from distant site	Between 88(?) and 55; most probably *between 70 and 65*	Post-development of Franciscan-type rocks. Microfossils include Upper Cretaceous (Evitt*). Blueschist facies metamorphism reportedly 88, 74, 70 m.y. (Suppe and Armstrong, 1972). Pre-Eocene, based on plate motions of Engebretson*.
B. Departure of Salinian block (SB) from distant site	Between 82 and 55; most probably *between 70 and 65*	Post-plutonism (hence post-82 to 89 m.y.: Mattinson*). Large transport since Pigeon Point deposition (Champion, Grommé, and Howell, in press), hence since 73 mybp. Pre-Eocene, based on plate motions of Engebretson.
C. Removal of fragments (now lost) from southwest flank of SB	Between 82 and 23; most probably *between 80 and 55*	Post-plutonism (see above). Pre-Miocene; upper Oligocene-lower Miocene sediments are similar on both sides of Sur-Nacimiento fault zone, and although not continuous across it, overlap basement on both sides. (See other arguments under (A) and (B).)
D. Joining of S-O and SB	Between 82 and 23; most probably *between 80 and 55*	Most of the above arguments apply. Additional evidence is conflicting. Vedder, Howell, and McLean (1980, in press) find sedimentary evidence for Campanian tie. All Campanian sediments in S-O are involved in thrust-like sheets/plates. Some thrust complexes involve Jurassic rocks not found in SB.
E. Arrival of SB (with S-O?) in California	Between 60 and 23; most probably *between 55 and 38*	Post-Point San Pedro sediments (Paleocene), if paleomagnetic interpretation is valid (Champion and others*, 1981). Pre-Eocene, if Butano-Point of Rocks match across San Andreas is valid and Point of Rocks autochthonous. Pre-Miocene, accepting Pinnacles-Neenach match et cetera across San Andreas.
F. Removal of Northwest tip of SB	If separate event from (C), most probably *between 40 and 20*	Apparent truncation is along continental slope, which post-dates 28 m.y.-old sea floor.
G. Movement of SB and S-O in response to Pacific-North America transform interaction	Post-29 (Atwater, 1970); *approx 15 to 0*	Locus of main transform motion shifted from vicinity of continental slope to Northeast side of SB, along SAF, after beginning of Miocene, allowing SB to move with Pacific plate.

* Informal communication

Radiometric determinations of several kinds have given a wide range of results, some representing emplacement ages and some probably representing thermal histories. The subject is treated comprehensively by Mattinson (1978, 1982), who cites earlier literature and who presents his own U-Pb measurements on zircon, sphene, apatite, and feldspar from plutons at Bodega Head, Point Reyes, Santa Lucia Range, and Gabilan Range (fig. 2A). Mattinson concludes that most of the sampled plutons, except those in the Gabilan Range, were emplaced 100 to 107 mybp, but five Gabilan intrusives probably were formed 82 to 89 mybp. He suggests that most Bodega Head, Point Reyes, and Gabilan plutons were emplaced at intermediate depths and cooled within 5 to 15 m.y., judging from the moderate differences between U-Pb ages from minerals with various "blocking" temperatures, fisson-track results, and K-Ar "ages." On the other hand, plutons in the Santa Lucia Range formed at greater depths, remained hot for about 25 m.y., then quickly cooled, probably as a result of rapid uplift and erosion (Mattinson, 1978). The inferred delayed, rapid cooling could signify a tectonic event about 80 to 85 mybp.

Age of Franciscan in Sur-Obispo belt.—The age of the Franciscan-type assemblage of the Sur-Obispo belt is relevant to the timing of transport and suturing. A few blocks and slabs of marine clastic sedimentary rocks have been dated as Lower Cretaceous and others as Upper Cretaceous on the basis of dinoflagellates, spores, and pollen by W. R. Evitt (cited in Page, 1970), and the large Cambria sandstone slab (fragments of which appear to be incorporated in mélange) was dated by Evitt as Upper Cretaceous, probably Campanian (cited by Hsü, 1969; Evitt, 1981, oral commun.). Whole-rock samples of blueschist-facies rocks near the S-NFZ 6 to 11 km north of Cape San Martin gave K-Ar dates of 88, 74, and 70 m.y. (Suppe, 1972). Evidently part, or all, of the on-land Sur-Obispo Belt was assembled after some time in the Early Cretaceous — but when? It seems likely that the on-land part of the complex was assembled in the Late Cretaceous rather than in Paleogene time, based on comparisons with the Franciscan Coastal Belt of Tertiary age in northern California. The Sur-Obispo Belt, like the pre-Tertiary Franciscan terranes of northern California, contains relatively plentiful greenstone, red chert, serpentinite, and blueschist facies rocks, whereas these types are very rare in the Coastal Belt. The 135 km width of accreted terrane between the Salinian Block and the relict deep-sea trench west of San Luis Obispo (Page and others, 1979) is much greater than the width (less than 50 km) of the Coastal Belt of northern California. Probably an analog of the Coastal belt is present off central California, but it is well offshore — west of the East Santa Lucia Bank fault, judging from magnetic data (Page and others, 1979). Thus, the on-land Franciscan terrane southwest of the Salinian Block is probably post-Early Cretaceous and pre-Coastal Belt in age; in other words, it is Late Cretaceous. The adjacent Salinian plutonic arc is mid-to-Late Cretaceous, so there is a marked chronologic as well as spatial parallelism.

Evidence from Salinian Cretaceous sediments.—Sediments of late Campanian (Late Cretaceous) age unconformably overlie the La Panza quartz monzonite and some other Salinian plutons and are followed by clastic sediments of Maastrichtian, Paleocene, and Eocene ages (Howell and others, 1977; Vedder, Howell, and McLean, in press). Many of these are submarine fan deposits which in a general way resemble the Great Valley sequence. (The latter has been described by many, including Dickinson and Rich, 1972; Ingersoll, 1979.) The sediments are largely derived from continental calc–alkaline plutonic and volcanic source terranes and lack Franciscan detritus.

Parts of the Upper Cretaceous sedimentary pile in the Salinian Block differ in detail from the type Great Valley sequence, despite the general resemblance. Some units show rapid facies changes, local anomalous current directions, and overall indications of deposition along a deeply embayed coast. Nilsen (1978) and Howell and Vedder (1978) believe that borderland basins are indicated, probably denoting wrench tectonics in late Campanian and Paleogene time. This would be consistent with the disappearance of part of the Salinian Block during the same interval, if the event involved strike-slip. However, Vedder, Howell, and McLean (1980 and in press) suggest that the Salinian block and Sur-Obispo belt had already been sutured together before the late Campanian sediments were deposited. If this suggestion is correct, the removal of the flank of the Salinian block must have occurred prior to the late Campanian, as it necessarily preceded the suturing.

The Salinian Cretaceous and Paleogene sediments, as well as the plutons, are cut by the S-NFZ. It is not certain whether the sediments have been offset a great amount or a small amount, but whereas the displaced parts of the plutons have never been found, some geologists believe that the Campanian sediments on the two sides of the S-NFZ could be parts of a once-continuous deposit.

Conflicting evidence in the Sur-Obispo belt.—An unresolved chronologic and tectonic dilemma is posed by the following conflicting lines of evidence: (1) The petrologic and physical features of upper Campanian-Maastrichtian sediments in the Sur-Obispo belt are so similar to those of coeval rocks of the Salinian block as to suggest that the two terranes were joined prior to the deposition of these sediments. (2) Locally, Campanian alluvial deposits containing granitic boulders occur in the Sur-Obispo belt near the Salinian block (Vedder, Howell, and McLean, 1980). (3) On the other hand, Campanian sediments of the Sur-Obispo belt typically rest tectonically on the basement (Franciscan), whereas those of the Salinian block invariably rest depositionally on the basement (Salinian plutons and wallrocks). Furthermore, detritus from Sur-Obispo Franciscan rocks is lacking in Campanian sediments of both terranes. Thus the two terranes may or may not have been in mutual contact during Campanian deposition, despite the implications of item (1). (4) Thrust-like plates structurally overlying Franciscan rocks in the Sur-Obispo belt seem incompatible with a nearby Salinian presence prior to the Paleocene, as explained below, and imply that the two terranes could have remained separate until the early Tertiary.

If the implications of (1) and (2), above, are accepted, the disappearance of parts of the Salinian flank and the subsequent joining of the Sur-Obispo and Salinian terranes both occurred between the time of emplacement of the youngest Salinian plutons, perhaps 82 mybp, and the late Campanian, say 75 mybp. The time window would be constrained to a duration of about 7 m.y. However, evidence such as that of (3) or (4), above, might allow the occurrence of these events any time after 82 mybp in the latest Cretaceous or early Tertiary.

Vedder, Howell, and McLean (1980, and in press) lend support to items (1) and (2). They described a thick section of Campanian-Maastrichtian submarine fan sediments in the San Rafael Mountains (part of the Sur-Obispo belt not far from the Salinian block) which is interrupted by an interval of shallow marine and nonmarine alluvial deposits containing granitic cobbles, pebbles, and boulders. The granitic clasts came from a northeast source, that is, ostensibly from the nearby Salinian block (Vedder, Howell and McLean, 1980). This suggests that the loss of part of the Salinian block and the suturing of the block and Sur-Obispo belt pre-dated 75 mybp. However, because of the great length of the Cordilleran Cretaceous plutonic arc and the inherent similarity of sediments deposited at different latitudes along its flank, it is difficult to tell whether the granitic clasts came from the Salinian block or from some other part of the arc.

The thrust sheets mentioned in item (4), above, are significant. Evidently all Great Valley-type rocks in the Sur-Obispo belt, except possible trench-slope basin deposits such as the Cambria slab, are incorporated in tectonic sheets which are in thrust contact with underlying Franciscan rocks. A number of thrusts involve Campanian strata, and one such fault (near Santa Margarita, west of the Salinian Block) is overlapped unconformably by lower Miocene sediments, thus giving a time bracket for the thrusting (Page, 1981). No low-angle thrust and, specifically, no post-Campanian, pre-Miocene thrusts have been recognized in the Salinian block, to the best of my knowledge. Some thrusts in the Sur-Obispo belt, including an imbricated sequence between San Luis Obispo and Atascadero (fig. 3), involve unmetamorphosed Upper Jurassic as well as Campanian Great Valley-type rocks. The Jurassic sequence includes land-derived sediment overlying ophiolite, which rests tectonically on a Franciscan melange. The terrigenous sediment and thrust plates must have come from a landward (easterly) direction, but the unmetamorphosed Jurassic rocks could not have come from the Salinian block, which is now there, as the Salinian plutonic intrusions strongly transformed all pre-Cretaceous rocks that were nearby. Possibly, as suggested by Vedder (1980, oral commun.), there may have been two thrusting episodes, respectively pre-suture and post-suture in age, so that the Campanian rocks were emplaced long after the unmetamorphosed Jurassic sediments, and after the Sur-Obispo belt was joined to the Salinian block.

The thrust faults seem to be beheaded, and unaffected rocks of the Salinian block are situated where the thrusts should be rooted. However, this might be explained by Neogene displacements of modest magnitude along the S-NFZ.

From the above, it is seen that certain sedimentary/stratigraphic evidence and structural/stratigraphic evidence seem to favor different time windows for the joining of the Sur-Obispo belt and Salinian block and for the disappearance of part of the latter. The Tertiary record adds several important clues but does not clearly resolve the problem.

Tertiary sedimentary record.—The Paleogene record differs on the two sides of the S-NFZ, inasmuch as Paleocene and Eocene rocks are lacking in the Sur-Obispo belt except in the southern San Rafael Mountains but are prominent in the Salinian block. This difference is subject to a number of different interpretations. One possibility is that the Sur-Obispo belt came from a site where Paleogene sediments were not extensively deposited and was traveling during part of that time interval — an interval in which the flank of the Salinian block was departing. Another interpretation is that after partial destruction of the Salinian block in the Campanian, the Sur-Obispo belt was sutured to the block, and Paleocene and Eocene sediments were deposited on both terranes but were subsequently eroded from the western one. However, Salinian Paleocene and Eocene sediments commonly extend to the suture zone (the S-NFZ), where they are terminated abruptly. If they once extended across the boundary and were later removed from the western side, erosion must have been inexplicably restricted to the Sur-Obispo belt. Eocene marine sediments do occur on both sides of the extrapolated S-NFZ in the Transverse Ranges, supporting the opinion of Vedder, Howell, and McLean (in press) that mega-movements between terranes were completed by Eocene time. However, these sediments do not extend unbroken across the extrapolated suture, so there is still uncertainty as to former continuity.

Oligocene rocks in parts of the Salinian composite block, Sur-Obispo belt, and Transverse Ranges include more nonmarine sediments and local volcanics than are found in the Cretaceous, Paleocene, and Eocene sections. Perhaps unusual worldwide conditions are reflected in these deposits (Ingle, Graham, and Dickinson, 1976). Alternatively, the abrupt change from subsea fan environment to alluvial and local volcanic conditions could mean that the Sur-Obispo belt had just arrived, either soon after or long after the removal of parts of the Salinian block. The Oligocene Sespe Formation of the western Transverse Ranges contains Franciscan as well as granitic clasts (McCracken, 1972). Although the paleoposition of the Sespe Formation is difficult to establish, the mixed clasts show that Franciscan and plutonic arc terranes were juxtaposed by Oligocene time, at some undetermined location along the continental margin.

Finally, upper Oligocene-lower Miocene shallow marine sediments locally overlap all older rocks and structures that might be associated with the evolution and accretion of the Sur-Obispo belt, except the S-NFZ itself. West of the S-NFZ, these transgressive sediments contain both Franciscan and sialic detritus, implying that suturing had surely taken place by 25 mybp, if not before. This is confirmed by the similarity of upper Oligocene-lower Miocene sedimentary columns on the two sides of the S-NFZ in the southernmost Coast Ranges. In the region of the San Rafael, Sierra Madre, and Caliente Mountains, more than 200 m of upper Oligocene-lower Miocene sandstone rests on nonmarine strata in areas only a few kilometers apart on both sides of the S-NFZ.

Conclusions from sedimentary and structural record.—The stratigraphic data summarized above offer important clues as to some major events but do not indicate the time when the Salinian and Sur-Obispo terranes departed from their sites of origin. The Cretaceous and Paleogene sediments were largely derived from a continental arc provenance, but apparently they do not tell us whether the site of deposition was stationary during sedimentation or was being transported coastwise alongside the arc. Paleomagnetic characteristics of the Pigeon Point sediments indicate mega-transport since a time of Late Cretaceous magnetic reversals which probably correlate with known reversals at about 72 mybp on the time scale of Harland and others (in press). This may constrain the starting time of the entire journey of the Salinian block, or it may merely mark a particular moment en route, but in either case it is an important date.

The stratigraphic record suggests that the joining of the Sur-Obispo and Salinian terranes, and by implication the earlier disappearance of the Salinian flank, probably occurred in the Late Cretaceous or Paleocene, and structural relations favor the latter. The record is permissive of Eocene or early Oligocene for these events, but the Oligocene is perhaps more appropriate for some unusual occurrence relatively late in the tectonic sequence. The abrupt change in sedimentation in the early Oligocene certainly signals a major happening — perhaps a culmination in the accretion of the combined Sur-Obispo and Salinian terranes to the continent. This might be interpreted as the arrival of the joined allochthones in California.

All the above-mentioned events must have been completed by the beginning of the Miocene, in view of the overlapping of many structures by late Oligocene-early Miocene transgressive sediments and in view of the marked similarity of (offset) Miocene rocks on the two sides of the S-NFZ and SAF. The inception of transform motion and semi-pervasive northwest-southeast shear has been summarized in the section dealing with Cenozoic movements, based on San Andreas history.

Capability of Known Plate Motions

General.—Plate motions are the only known means of propulsion of migrant terranes. Thus if known plate motions were clearly adequate for postulated mega-transport, both the transport and the deduced plate motions would be more credible. Only a preliminary appraisal is attempted here, and unfortunately it yields only marginal encouragement.

There are several possible modes of transport by plate motions: (1) Terranes might have been carried piggy-back by an oceanic plate in a circuitous trajectory, eventually arriving at a site of convergence and accretion. However, the Salinian basement started from a continental margin, and all its superincumbent sediments are terrigenous, suggesting continuous proximity to land. (2) Transform motion parallel with the margin is an obvious option. (3) Oblique convergence with a dextral coastwise component could have nudged the terranes along the continental margin, as in Sumatra today. Known plate motions and relations favor the second mode for the Neogene and the third mode for earlier transport.

Plate motions for the last 29 m.y.—Atwater (1970) demonstrated the inception, about 29 mybp, of transform motion between the Pacific and North American plates. Spreading at the mouth of the Gulf of California and other observations fix the relative plate motion at 5.5 to 6.0 cm/yr for the last few millions of years. Apparently the total coastwise motion during the last 29 m.y. has been 1000 to possibly 1600 km — the maximum distance migrant terranes could have traveled under this influence. The Salinian and Sur-Obispo terranes moved 300 km, and possibly more, under this regime, but even if they had taken full advantage of the maximum relative plate motion, this would not satisfy the paleomagnetic requirements for mega-transport. Therefore these terranes must have traveled under some earlier plate interaction also.

Plate motions prior to 29 mybp.—The capability of known pre-29 mybp plate motions depends on: (1) the initial location of the Salinian and Sur-Obispo terranes, (2) the time interval during which they moved, (3) the trend of the continental margin at that time, (4) the geometry and extent of relevant plates and the location of triple junctions at the continental margin, and (5) plate motion vectors and sense of any coastwise relative motion component. Most of these conditions are poorly known, but adjustment of the several variables may someday yield an optimized result that best fits geologic and paleomagnetic observations.

In scanning the possibilities, we will simply make expedient assumptions and will note the consequences. Let us assume that part of the Salinian composite block, bearing the Pigeon Point Formation, moved to its present location from a 70 mybp paleolatitude of 15°N, which is between the estimates of Wilson, Schnapp, and Cox (in press) and Champion, Grommé, and Howell (1980). The location would be somewhere between Nicaragua and Acapulco, Mexico, in terms of present geography, judging from Morgan's (1980) and Engebretson's (1981, informal commun.) paleo-positions of North America. The 15°N paleolatitude would be close to 10°N in present coordinates in Engebretson's (1981) reconstructions. Probably the Sur-Obispo belt was farther south during some part of its history, but for simplicity we will deal only with the Salinian block.

The timing of transport is uncertain (table 1), but we will assume that the Salinian block departed at 70 mybp. At that time, the margin of Central America could have trended more northerly than at present (Morgan, 1980), which would facilitate matters. Hence the departing terrane could have started from about lat 10°N and long 260°E in present coordinates. For expedience, we will affiliate Central America with the North American plate.

The known plates of possible relevance are the Kula, Farallon, Pacific, and North American plates. Their relative motions have been re-determined by Engebretson and others (in press) using sea-floor spreading isochrons and transforms and hot spots in the Atlantic and Pacific. The hot spots are assumed to have remained fixed relative to each other, although not necessarily with respect to the spin axis. The following discussion relies entirely on Engebretson's findings, which he generously made available. Figure 5 is based on his data for 70 mybp.

A major obstacle is that the former southward limit of the Kula plate is unknown, as is the paleo-location of the Kula–Farallon–North America triple junction. However, relative plate motions can be determined for chosen locations whether or not the plates were actually there, and it may be useful to see if the motions were adequate. According to

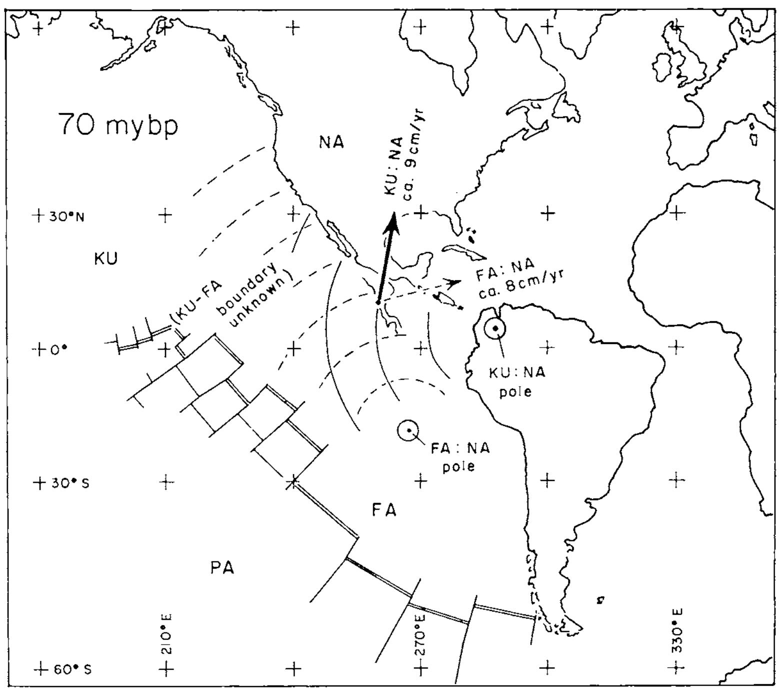

Fig. 5. Major plates, 70 mybp: FA, Farallon; KU, Kula; NA, North American; PA, Pacific. KU plate may or may not have extended to Central America. Its motion relative to NA shown by solid arrow. FA-NA relative motion shown by dashed arrow. Note poles of rotation, KU:NA and FA:NA. Coordinates are those of today, affixed to North American continent, shown in its present position. Other continents, plate boundaries, and poles shown in paleo-positions relative to present coordinates. (Data from Engebretson, 1982, informal commun.).

Engebretson's study, Kula-North America relative motion could have been favorable. The pole of rotation of the two plates was in northwest South America, so close to the region of interest that differences in location entail great differences in direction and velocity of relative motion. At 10°N and 260°E (in present coordinates), the Kula-North America relative motion at 70 mybp was approx 9 cm/yr in a N 10° E direction (fig. 5), which could produce 520 to 830 km of coastwise transport along a margin oriented N 15°-45° W, during a 10 m.y. period. Admittedly, the necessary stipulations require special pleading. At the same time and place, Farallon-North America convergence lacked a favorable coastwise dextral component.

Whether or not the Kula plate propelled the migrant terranes in the latest Cretaceous, probably the Farallon plate did so later. Apparently Farallon-North America relative motion was mildly favorable (that is, obliquely convergent) along the central and northern coast of Mexico from 53 to 29 mybp *if* the coast was oriented more northerly than at present. This relative motion could have provided 500 to 800 km of coastwise transport. Finally, after 29 mybp, Pacific-North America transform interaction brought the far-traveled terranes to their present position, contributing 300 to 1000 km of translation. Collectively, the foregoing interactions involving the Kula, Farallon, and Pacific plates might account for 1300 to 2600 km of transport, which may or may not be enough to satisfy tentative paleomagnetic requirements.

In summary, known plate motions *might* suffice to bring about the postulated events but not with overwhelming ease. Kula-North America relative motion would have been most effective if the Central American margin were oriented as nearly north-south as permissible, if the movement commenced as early as permissible, and if transport started as far south and west as permissible. However, the kinematic advantage of a southern location is offset by doubts as to the southern extent of the Kula plate. As improved knowledge imposes tighter constraints in the future, known plate motions may become inadequate. In that case, (1) the postulated events have been wrongly perceived, (2) inferred plate motions are incorrect, or (3) an unknown plate provided the required propulsion.

DISAPPEARANCE OF FLANK OF SALINIAN BLOCK

Missing fragments.—The collective width of missing fragments may be surmised by comparing the remaining Salinian composite block with more nearly intact segments of the Cordilleran belt, such as the Sierra Nevada (fig. 6). A transect westward from the vicinity of Reno crosses a Cretaceous plutonic arc 110 km wide, a "Foothills belt" 100 km wide, and a tract of forearc basin deposits (Great Valley sequence) 80 km wide, for a total width of about 290 km. In contrast, the Salinian composite block is only 32 to 65 km wide and lacks all but the axial part of the plutonic belt. Comparisons may also be made with presently active arc-trench systems. For instance, the width from the Juan de Fuca trench to the axis of the Cascades magmatic arc is 240 to 300 km.

With regard to the length of missing fragments, an absolute minimum of 400 km is given by a palinspastically corrected length of the remaining "deprived" Salinian composite block north of the Transverse Ranges. This is a deceptively small figure, if we ignore the Transverse Ranges and consider not only the Salinian block *sensu stricto* but also the more southerly allochthonous complexes which have lost their oceanward flanks. In southern California and Baja California the Cretaceous plutonic arc is bordered by remnants of a "foothills belt" which appears to be narrow and incomplete, suggesting that a tract more than 1000 km long and of varying width has been removed. The Sierra Nevada "Foothills belt" itself seems to have lost territory prior to the emplacement of the Salinian block, as the southern part becomes narrowed between the plutonic arc and the buried Sierran-Franciscan boundary zone (fig. 1). The Sierran-Franciscan boundary zone appears to lie along the site of removal of the missing "foothills belt."

These observations suggest that the same kinds of mechanisms or events that removed terranes adjoining the Salinian block *sensu stricto* affected other parts of the Cretaceous arc-trench system for a long distance to the northwest and southeast.

I conclude that the continental margin lost fragments 100 to 250 km in width and collectively more than 1000 km in length. Indeed, the affected zone probably extended northward from Central America (Karig and others, 1978; Moore, Watkins and others, 1979) to the flank of the Sierra Nevada. At the original site of the Salinian block, the "bite" that led to removal of fragments extended well inland.

Two alternative explanations for the disappearance of the crustal fragments are: (1) mega-transport at the Earth's surface, to a locality so remote or so concealed that the pieces have not been recognized; (2) destruction by piecemeal subduction. These two hypotheses are discussed below.

Loss by mega-transport at the Earth's surface.—The accretion of far-traveled terranes in southern Alaska and other parts of the Pacific margin (for example, Jones, Irwin, and Ovenshine, 1972; Coney, Jones, and Monger, 1980) implies the corresponding removal of such terranes from their distant sites of origin. The paleomagnetic evidence for large-scale transport of the Salinian composite block itself suggests that the missing parts of the block simply traveled farther than the remainder and ostensibly vanished. Although known relative plate motions are only marginally capable of accounting for the northwestward coastwise movement of the Salinian block and do not seem adequate for transport of crustal fragments from Central America to British Columbia or Alaska during the available time window, all such possibilities should be considered. Errors as to the starting place, timing of transport, and available plate motions may cause difficulties that are more apparent than real.

It should not be assumed that the lost fragments journeyed northwestward; in fact, they may have traveled southeastward under the influence of the Farallon plate. The Farallon-North America pole of

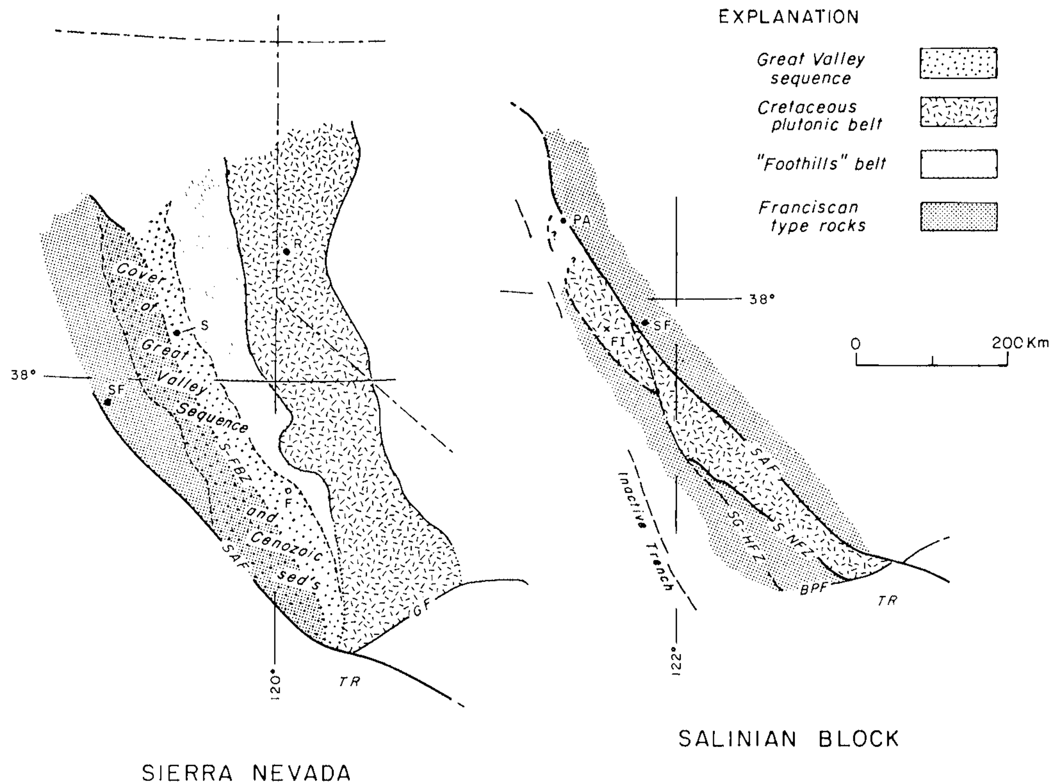

Fig. 6. Comparison between Salinian block and Sierra Nevada plutonic arc with its appurtenant assemblages ("Foothills" belt and Great Valley forearc basin deposits), suggesting that parts of Salinian flank are missing. Abbreviations: BPF, Big Pine fault; F, Fresno; FI, Farallon Islands; GF, Garlock fault; PA, Point Arena; R, Reno; S, Sacramento; SAF, San Andreas fault; SF, San Francisco; S-FBZ, Sierran-Franciscan boundary zone; SG-HFZ, San Gregorio-Hosgri fault zone; S-NFZ, Sur-Nacimiento fault zone; TR, Transverse Ranges.

rotation at 70 to 75 mybp was almost due south of Mexico and Central America (Engebretson, 1981, informal commun.), and the relative motion would have had a sinistral component on a northwest trending continental margin at the latitudes of Mexico, Central America, or northwestern South America (fig. 5). Perhaps the Kula–Farallon–North America triple junction was so located that rifting occurred at the margin and fragments moved northwest or southeast depending on which side of the junction they were on. Migration of the Kula-Farallon ridge, or the occurrence of ridge jumps, could have influenced the movement history.

An additional intriguing possibility is inherent in the history of the Caribbean plate. The latter is largely an errant fragment of the Farallon plate which migrated northeastward far beyond the alignment of trenches that existed along the west margins of Central and South America (Malfait and Dinkelman, 1972). Evidently the Caribbean plate moved more or less into its present position in the latest Cretaceous and/or early Tertiary, perhaps carrying with it a part of the Cordilleran Cretaceous plutonic arc, now lodged in Hispañiola and Cuba. Could parts of the Salinian and affiliated terranes have found their way into the Greater Antilles? I can only pose the question.

The quest for missing fragments.—If the missing terranes were carried away by horizontal mega-transport rather than by subduction, they are presumably still somewhere at the Earth's surface. What should one expect to find? The answer is unsatisfying in its broad permissiveness.

Somewhere there should be allochthonous granitic rocks resembling those of the remaining Salinian composite block, hopefully with similar Sr isotope ratios (Kistler and Peterman, 1973) and other geochemical clues. Wall rocks from the axial part of the plutonic arc might well include types in the remaining Salinian terrane, such as amphibolite-facies and granulite-facies metasediments, quartzo-feldspathic granofels, gneiss, and migmatite. However, the batholithic belt may have crossed the strike of the wallrocks obliquely, as in the case of the Sierra Nevada; hence the expectable types of wallrocks cannot be narrowly restricted. Only a small part of the Salinian basement is exposed today, so even the remaining composite block may include unfamiliar wallrocks.

Most likely some missing fragments would be assemblages roughly analogous to the "foothills belts" of the Sierra Nevada, southern California, and Baja California. It is almost impossible to predict the character of such assemblages. The Sierra Nevada foothills consist of accreted island arc assemblages, ophiolites, slate sequences, mélanges, and so forth (Schweickert and Cowan, 1975; Saleeby, 1979). It is unlikely that more southerly parts of the Cordillera acquired exactly the same accreted terranes, and indeed the "foothills" belt of Baja California is quite different from that of the Sierra Nevada. One can only presume that prolonged Mesozoic plate convergence likely swept island arcs, sea mounts, oceanic platforms, and possibly continental fragments against much of the American margin prior to mid- and Late Cretaceous batholithic intrusion.

Forearc basin deposits that were removed tectonically from the west side of the Salinian block might be expected to resemble the Great Valley sequence of California (Bailey, Irwin, and Jones, 1964; Dickinson and Rich, 1972; Ingersoll, 1979). The oldest sediments would be Upper Jurassic, and these would rest on ophiolite. There would be a great thickness of Lower to Upper Cretaceous turbiditic graywacke and arkosic sandstone, with associated mudstone. Rather extensive remnants of turbiditic Great Valley-type rocks are preserved on the Vizcaino Peninsula and Cedros Island, Baja California (Jones, Blake, and Rangin, 1976; Patterson, 1979; Boles and Hickey, 1979), bearing testimony to the former great extent of such rocks along the continental margin. One should bear in mind that Great Valley-type rocks might be somewhat transformed if transported far away, attached to some other part of North America, metamorposed, and perhaps invaded by Tertiary plutons.

Lastly, it is likely that part of the late Mesozoic subduction zone complex was removed from the coastal flank of the ancestral Salinian block and disappeared with the other fragments. Thus the latter might include counterparts of the Franciscan Complex (Bailey, Irwin, and Jones, 1964; Blake and Jones, 1981; Page, 1981).

In summary, a broad spectrum of rock types might occur in displaced fragments, compounding the problem of knowing what to seek and how to correlate allochthones with the Salinian block and its former neighboring terranes. The ages of displaced assemblages, in conjunction with their petrology and chemistry, would narrow the options. Moreover, paleolatitudes based on magnetic properties could be indicative.

Regions which might harbor lost fragments.—Blake and Jayko (1980) report a collage of accreted tectonostratigraphic terranes in southwest Oregon. Nearly all these are Late Jurassic to Early Cretaceous, and they originated more or less concurrently in widely separated environments. Apparently these terranes were brought together by large-scale movements after the Early Cretaceous and prior to some time in the Eocene — a time interval that includes the major events that concern us. No Salinian-type basement rocks have been reported, but one or more of the allochthonous Great Valley-type assemblages (with basal ophiolite) might have been affiliated with the Salinian block.

Southern Alaska and western British Columbia have been pieced together by the accretion of far-traveled allochthones from remote southern regions (Jones, Irwin, and Ovenshine, 1972; Jones, Silberling, and Hillhouse, 1977; Berg, Jones, and Coney, 1978). Hence Alaska and western Canada would seem to be likely havens for the lost flank of the Salinian block, but such fragments have not been identified there. Probably the Tracy Arm terrane (see references in Berg, Jones, and Coney, 1978) is the only accreted assemblage in southeastern Alaska that could possibly be part of the Salinian basement, and it differs from the Salinian remnants in California. The Tracy Arm terrane includes paragneiss, pelitic schist, marble, hornblende schist, amphibolite, and ultramafic rocks (all of unknown age), partly affected by Cretaceous (?) amphibolite-grade metamorphism. It is likely that this terrane became attached to the Taku terrane, which adjoins it on the east, before some time in the mid-Cretaceous, as the presumed suture zone is occupied by an elongate tonalite sill of probably mid-Cretaceous age (Brew and Morrell, 1979). If the tentative dating is correct, the suturing was probably too early to have involved a Salinian fragment.

The Chugach terrane (Plafker, Jones, and Pessagno, 1977), which is an accreted Cretaceous flysch and mélange terrane of great coastwise extent in southern and southeastern Alaska, may consist of forearc basin and subduction zone complexes such as those that are postulated to have existed on the oceanward side of the Salinian block before disruption. Parts of the Chugach terrane may have come from the vicinity of Vancouver Island and Queen Charlotte Island (G. Plafker, 1980, oral commun.), but the full story has not been worked out. Outboard of the Chugach terrane there is no room for Salinian and associated assemblages, as the space is pre-empted by Paleogene rocks (G. Plafker, 1980, oral commun.).

Another possible resting place for Salinian fragments is central Washington. Beck, Burmester, and Schoonover (1981) report that the Mt. Stuart batholith of the Cascade Range may have moved from some region as distant as west-central Mexico, although the paleomagnetic inclination could have been affected by tilt. Beck (1980, oral commun.) wonders if the batholith could be a fragment of the Salinian block. Although at first this may seem far-fetched, the Late Cretaceous radiometric age of the batholith is appropriate, and the continental margin in Washington was probably suitably located east of the Cascades until subduction jumped westward in the Eocene. The main negative argument is based on the fact that the Mt. Stuart batholith intrudes wallrocks that are unknown in the Salinian block: the Chiwaukum Schist, which includes abundant quartz–feldspar–biotite schist, locally with staurolite, and the Ingalls Complex, a large Jurassic (?) ophiolitic body. Although these assemblages seem inappropriate, the full range of wallrocks in the ancestral Salinian terrane is unknown, so unfamiliar types do not conclusively disprove a Salinian affiliation.

Possible destruction by subduction. General arguments.—Tectonic erosion, rasping, or piecemeal plucking away of the upper plate during subduction has been postulated by several (Rutland, 1971; Katz, 1971; Page, 1970; Scholl and Vallier, 1979). Although unproved, this mechanism is a possible alternative to the disappearance of crustal fragments by mega-transport at the Earth's surface. The hypothesis is not widely favored and has been challenged with respect to truncation along the Middle America trench and the coast of Peru and Chile by Karig (1974, 1979), Karig and others (1978).

A common objection to the hypothesis of erosion by subduction is that low density material such as sialic crustal fragments "will not go down" because of buoyancy. Continental collision and continental-island arc collision (both made possible by subduction of intervening oceanic lithosphere) illustrate the reluctance of low-density terranes to be subducted. However, most such terranes are large, thickened crustal masses topographically higher than the sea floor. In colliding, they have met head-on. Perhaps smaller pieces of the same material could be plucked from the underside and carried down by subduction in defiance of buoyancy.

Evidently marine pelagic sediments are commonly (usually?) subducted, and terrigenous deposits may sometimes accompany them (Scholl, Marlow, and Cooper, 1977). The presence of blueschist facies mineral assemblages in Franciscan metagraywacke is evidence that sandstone was carried to depths of 10 to 30 km or more (for example, Ernst, 1973). Conglomerate and chert have been similarly metamorphosed. Perhaps blocks of sialic crust, incuding granite, could be carried down and eventually melted, although direct evidence is lacking.

The mechanics of removal of blocks from the underside or edge of a continental plate can only be conjectured, but one might envision plucking facilitated by pre-existing fractures and aided by high fluid pressure. Whether or not sialic blocks can be plucked, there is some evidence that fragments have been torn from the underside of ophiolite slabs.

Long-continued subduction along the western margin of North America during the time span relevant to this discussion is well established. Relative plate motions were convergent throughout the Late Cretaceous and Paleogene, from Central America to northern California (Engebretson, 1981, oral commun.), and were commonly accompanied by igneous activity onshore. Thus the plate tectonic setting was favorable for subduction erosion, if such a process is possible.

Local evidence pro and con subduction erosion.—The presence of the Franciscan Complex of the Sur-Obispo Belt adjacent to approximately coeval Salinian granitic plutons led Page (1970) to entertain the possibility of tectonic erosion during subduction. The idea was reinforced by an earlier suggestion by Stewart (1968), who noted a seismic amplitude attenuation at depths below about 10 km in the Salinian block. Stewart conjectured that this could indicate either elevated temperature or the presence of Franciscan rocks beneath the Salinian basement complex. However, a reinterpretation of Stewart's orginal seismic refraction data does not lend strong support for the presence of Franciscan rocks beneath the Salinian block (W. Mooney, 1980, oral commun.).

It seems increasingly doubtful that the Franciscan of the Sur-Obispo belt was in its present position alongside the Salinian block when part(s) of the block disappeared. It is more likely that the Sur-Obispo belt evolved elsewhere and was eventually brought into position as a completed package. If this is true, any role of subduction in the genesis of the Sur-Obispo Franciscan rocks would probably be irrelevant to the history of the Salinian block.

The physical nature and orientation of the Sur-Nacimiento fault zone (S-NFZ) might be expected to have a bearing on the matter of subduction erosion, especially if the zone itself were a direct result of subduction. Unfortunately, the S-NFZ is a composite of different kinds of faults of different ages. Near Point Sur, most of the faults within the zone are northeast-dipping and thrust-like (Gilbert, 1973), but rocks as young as Miocene are involved, so the faults are not original Cretaceous subduction structures that might be postulated along the contact between the Franciscan and Salinian basement rocks. Neogene folding may have determined the present dips of various parts of the fault zone. Strike-slip features are reported from a fault in the Point Sur area, but these features are probably related to the San Gregorio-Hosgri system of the present transform regime rather than earlier convergent tectonics. There seems to be no obvious clue here as to the manner in which the Franciscan Complex and the Salinian basement first came together. In the region of the Sierra Madre and San Rafael Mountains, the S-NFZ as presently understood, is again marked by a single fault or narrow zone. Here the feature mostly dips east, but this may not be the original attitude. The fault has a thrust-like aspect; however, generally younger rocks (Eocene and Oligocene) constitute the hanging wall, and Cretaceous rocks the footwall. Vedder and Brown (1968) interpreted a complex history. The relations are permissive of strike-slip, but the present dip of the fault and indications of drag suggest dip-slip (thrusting). Stratigraphic and spatial relations indicate successive changes, including reversals, in the mode of faulting. The record tells nothing about the loss of the flank of the Salinian block, which is presently next-door.

Information from Franciscan assemblage.—The features and relations of the Franciscan-type rocks of the Sur-Obispo belt must also be considered. If the missing Salinian fragments were carried away by horizontal mega-transport, the entire Sur-Obispo belt would have to be allochthonous with respect to the Salinian block, having arrived during or after the departure of the fragments. (This indeed is our favored interpretation). On the other hand, if the Salinian block were "eroded" by piecemeal subduction, the Sur-Obispo belt could have been more or less in its present relative position throughout the process, merely moving landward as the flank of the adjacent block was consumed. Both hypotheses are permissible as far as the geology of the Sur-Obispo belt is concerned.

Ernst (1980) summarized the following facts which, although cited for other purposes, relate to our subject: (A) The belt is characterized by a northwest-trending structural grain [semi-parallel with the Salinian block] and, at least locally, by an apparent imbricate structure dipping northeast [toward the block]. (B) Preserved bedding in the Franciscan commonly dips northeast and much (most ?) appears to be upright. (C) There is a rough, imperfect increase in Franciscan metamorphic grade toward the Salinian block. All these features are compatible with a subduction zone origin, but they do not prove that the Franciscan was subducted beneath the edge of the presently adjacent Salinian block and do not prove that subduction erosion occurred.

No blocks of sialic basement are demonstrably engulfed in the Franciscan near the Salinian Block in a way that would support subduction-related plucking or rasping. There is one 3 km block of Salinian rock in the Franciscan domain 23 km northwest of Cape San Martin, but Gilbert (1973) thinks it is bounded by orthodox high-angle faults. Gaps and inconsistencies in the distribution of metamorphism and the presence of local steeply dipping shear zones could possibly have resulted from rearrangement by strike-slip accompanying coastwise transport rather than subduction processes at a fixed latitude.

Summary of the case for destruction by subduction.—Although I now favor mega-transport as the means of disappearance of Salinian fragments, I have found no compelling evidence to either prove or disprove the alternative hypothesis. The provocative presence of a probable subduction zone complex (Sur-Obispo belt) alongside the Salinian plutonic remnants is not conclusively indicative. The geology along the contact (Sur-Nacimiento fault zone) between the Sur-Obispo belt and the Salinian block suggests that the Franciscan rocks were assembled elsewhere and arrived "ready made" alongside the plutonic arc, but it does not reveal the manner in which parts of the arc vanished. The Franciscan Complex does not contain pieces of the arc assemblage, except for a non-diagnostic fault block. Relative plate motions derived by Engebretson, Cox, and Gordon (in press) show prevalent convergence between North America and adjacent oceanic plates during the relevant time span. This would be permissive of subduction erosion. However, the same study shows that fragments of the continental margin could have been carried thousands of kilometers horizontally at the Earth's surface.

TRUNCATION OF NORTHWEST TIP OF SALINIAN BLOCK

The foregoing pages have dealt principally with the southwest flank of the Salinian block. The northwest part of the block is so situated that it merits special attention with regard to the manner of its truncation.

Relations at continental slope.—One of the most startling features of the offshore realm of California is the presence of Salinian granitic rocks at the extreme edge of the continent, on the brink of the continental slope (fig. 7). The area is west and northwest of San Francisco, and it may be near the northwest tip of the Salinian block, being only 45 km from the northernmost on-land exposure of Salinian basement rock at Bodega Head. However, it is nearly 120 km south of the commonly inferred terminus of the block near Point Arena.

Cordell Bank has yielded several dredge samples of quartz diorite, and the Farallon Islands consist of Cretaceous granodiorite (Ross, 1972b). The Bank is on the brink of the continental slope only 22 km from the deep ocean floor. The Farallons are also on the brink of the slope, within 45 km of the Pioneer Seamount below. Curray (1966, p. 340) published an interpreted seismic reflection profile showing granitic rock within 20 km of the foot of the slope.

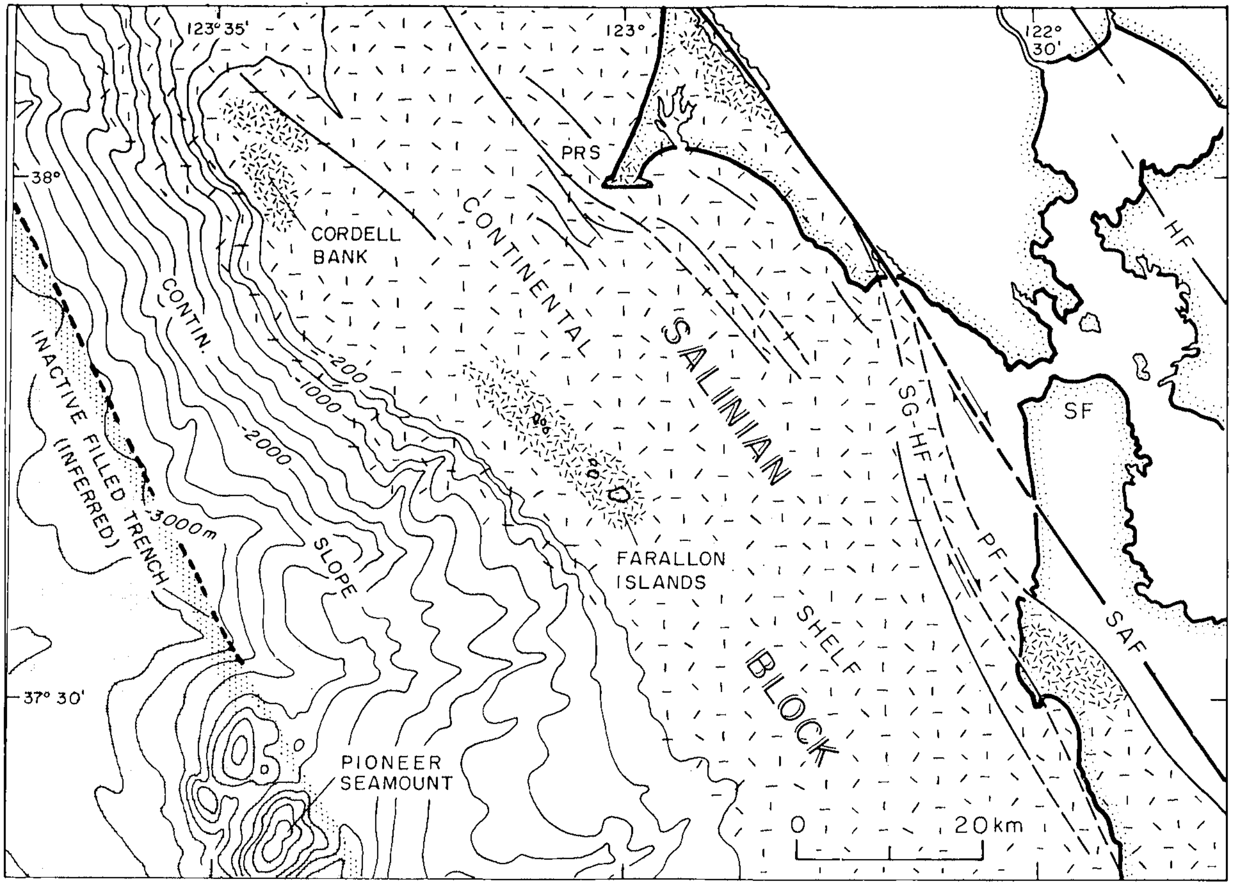

Fig. 7. Map showing northwest part of Salinian Block where it is apparently truncated by the continental slope and an inferred trench (now inactive) west of San Francisco. Offshore faults and granitic outcrops and shallow subcrops (patterned) from Hoskins and Griffiths (1971) and Howell, McCullough, and Vedder (1978). Submarine contours from Nat. Ocean Survey Bathymetric Map NOS 1307N-11B.

A relict deep sea subduction trench is believed to lie at the foot of the slope below the granitic outcrop. It is completely filled and concealed by sediment, but its presence is inferred from the linearity and relative steepness of extensive segments of the continental slope from Baja California almost to Cape Mendocino, by the deduced plate tectonic history (Atwater, 1970), and by the recognition of the relict trench in seismic reflection profiles near Point Sur (Ross and McCulloch, 1979) and off San Luis Obispo (Page and others, 1979).

The continental slope and relict trench not only transect the Salinian basement but also appear to truncate the accretionary terrane represented farther south by the Franciscan Complex in the Sur-Obispo belt. Of course, it is possible that there never was accreted material at the site in question, but wide accreted terranes occur to the north as well as to the south.

Circumstances of truncation.—Judging from appearances, the northwest part of the Salinian block may have been removed by processes involved in the origin or evolution of the continental slope, which transects the trend of the block and ostensibly terminates the latter. Otherwise, the block never extended beyond its present limit; it moved northwesterly as far as the site of the slope and stopped there.

The time and manner in which the continental slope acquired its present trend and location are difficult to determine. However, whether established by early Tertiary subduction or by subsequent strike-slip, the slope must be younger than the adjacent sea floor. A nearby part of the oceanic crust bears magnetic anomaly 8, which is about 28 m.y. in age and which necessarily predates the cessation of subduction in the vicinity, as the anomalies "young" eastward. Farther south, subduction perhaps continued until 23 or 24 mybp, when the oceanic crust that is now near Point Conception was generated. After the cessation of subduction, probably some segments of the defunct trench or some nearby zone of weakness accommodated dextral strike-slip before the transform motion was largely accepted by the San Andreas fault, commencing 10 to 15 mybp. Thus the location and trend of the continental slope could have been basically determined by subduction prior to 29 mybp, say, and could have been modified by strike-slip between that time and 15 mybp. However, at any given latitude transform strike-slip did not occur until the passage of the Mendocino Triple Junction, and the amount of such slip in or near the trench alongside Cordell Bank could not have exceeded the present distance to Cape Mendocino (about 300 km).

Discussion.—The spatial circumstances suggest one of the following: (1) The northwest part of the Salinian block and the adjoining accreted complex were removed by strike-slip along or near the site of the relict trench. (2) Subduction destroyed the northwest part of the Salinian block at a time when accretion was occurring elsewhere to the north and south. (3) The northwest edge of the Salinian block was shaped elsewhere before the block arrived in its present position. The arriving allochthone simply stopped at the site of the continental slope.

Regardless of the nature of the event, it may have taken place in Tertiary time, inasmuch as it was localized along the present trench-slope alignment. If the tip of the Salinian block vanished by strike-slip, it probably did so after most of the Coastal Belt was accreted, as this Belt is not present in the area of interest and presumably disappeared with Salinian fragment(s). Thus the event would have been post-Eocene, later than 40 mybp. Much of the transport would have preceded the initial juxtaposition of the Pacific and North American plates about 29 mybp (Atwater, 1970), because subsequent coastwise strike-slip along the defunct trench near the tip of the block was less than 300 km, as noted above. If the missing fragments had been carried away by post-29 mybp transform motion, they would still be south of the Mendocino Triple Junction, where they probably would have been discovered. Offshore studies to date have not revealed Salinian fragments south of the MTJ (see, for example, Curray, 1966; Silver, Curray, and Cooper, 1971; McCulloch and others, 1977). There appears to be insufficient room between the shoreline, the foot of the continental slope, and the MTJ to accommodate both the lost northwest part of the Salinian block and the missing accretionary terrane which (if indeed it was ever present) adjoined this part of the block on the west.

Relative motion between the Farallon and North American plates was convergent but quite oblique from 43 to 28 mybp (Engebretson, Cox, and Gordon, in press), with a total coastwide component on the order of 1150 km during this interval if the trend of the continental margin was about N 25 W. The oblique convergence could have carried crustal fragments as far as Oregon or Washington, or it could possibly have subducted them.

If the northwest part of the Salinian block disappeared by subduction rather than strike-slip, the timing is not a problem, as subduction was in progress during most of the required interval. The event could have occurred any time before the MTJ passed the sector that concerns us. The date of passage of the MTJ relative to the Farallon Islands and Cordell Bank depends upon the exact paleo-location of these areas. The location was at least 400 km farther south than at present, judging from Neogene displacement on the San Andreas (300 km) and San Gregorio-Hosgri fault zone (about 100 km), so probably the MTJ passed, and subduction was superseded by transform motion, about 15 to 20 mybp (see, for example, Dickinson and Snyder, 1979; Engebretson, Cox, and Gordon, in press).

Possibility of two separate events.—As pointed out above, it appears that the accretionary complex bordering the Salinian block may have been truncated along with the northwest part of the block. This would require two events, or two sets of events, because the accreted terrane had been emplaced during or after an earlier loss of part of the block along the site of the Sur-Nacimiento fault zone (S-NFZ). The Franciscan assemblage of the Sur-Obispo belt either arrived alongside the Salinian plutonic basement by mega-strike-slip after part of the basement had disappeared by the same process, or the Franciscan was accreted during or after the loss of Salinian basement rocks by subduction-erosion. In either case, the "rip-off" was localized along the site of the S-NFZ. However, the latter approaches the present continental slope and relict trench at angle and may itself be truncated (figs. 1, 7). Thus there may have been two separate events or two separate sequences if the processes were semi-continuous — one in Late Cretaceous or Paleogene time prior to 40 mybp and one later in the Tertiary some time between 40 and 20 mybp. The processes may or may not have been similar. If indeed there were two events, it seems to the writer that the first was likely the result of mega-transport at the Earth's surface, whereas the second can more readily be explained by subduction erosion.

TENTATIVE CONCLUSIONS

The foregoing considerations of field relations, plate tectonics, paleomagnetic data, temporal deductions, and various lines of reasoning lead to the following tentative conclusions:

1. The Salinian composite block is part of the Cordilleran Cretaceous plutonic arc. It originated near the latitude of Central America or Mexico, according to paleomagnetic findings of Wilson, Schnapp, and Cox (in press) and Champion, Grommé, and Howell (1980).

2. The Sur-Obispo belt is a coeval subduction zone complex which originated in the same arc-trench system as, but probably farther south than, the Salinian block.

3. The foregoing two terranes departed from their respective original locations between 88 and 55 mybp — most probably between 70 and 65 mybp.

4. Known relative plate motions (Engebretson, 1981, informal commun.) are apparently more or less adequate to explain subsequent mega-transport of the terranes, but there is room for doubt.

5. Before or during transport, parts of the Salinian block and adjoining assemblages were removed and have disappeared. Vanished terranes include fragments of the plutonic arc, forearc basin deposits, and perhaps parts of the associated subduction zone complex.

6. Two hypothetical modes of disappearance are: (A) mega-transport at the Earth's surface, to some undiscovered destination; or (B) destruction by subduction-erosion. Neither one has been conclusively proved or disproved for the case considered here, but mega-transport is now favored as the major cause of disappearance.

7. The major losses of territory took place along the eventual locus of the Sur-Nacimiento fault zone (S-NFZ), which lies along the boundary between the Salinian block and Sur-Obispo belt.

8. The most likely time window for removal of the Salinian flank along the site of the S-NFZ is poorly ascertained at 82 to 55 mybp.

9. The Sur-Obispo belt was joined to the southwest side of the Salinian composite block after event 5, sometime between 82 and 23 mybp — most probably 80 to 55 mybp.

10. The two joined (?) terranes traveled northwesterly along the continental margin, in response to dextral components of relative plate motion. The Kula (?) and Farallon plates successively moved the migrant terranes by means of oblique convergence with North America. After about 29 mybp (Atwater, 1970), the Pacific plate provided coastwise transform motion.

11. The two terranes arrived in California between 60 and 23 mybp — most probably 55 to 38 mybp.

12. Apparently (but not with certainty) the northwest tip of the Salinian block was removed along the alignment of the present continental slope 40 to 20 mybp, perhaps by subduction erosion.

13. Since about 29 mybp the Salinian composite block and adjoining Sur-Obispo belt have traveled together at least 300 km under the Pacific-North America transform regime. The San Andreas fault has accommodated most of this motion, which continues today. Modest displacements of a few tens of kilometers have occurred between the two terranes in the Neogene.

The foregoing interpretations depend in part on poorly established data which may have led to erroneous perceptions. The following types of future work would lead to a better understanding of the events discussed in this paper: (A) Further geological and geophysical work in coastal Mexico and Central America to establish the original locations of the Salinian block and Sur-Obispo belt. (B) Determination of the age of assembly of the Franciscan complex that is now adjacent to the Salinian block. (C) Further paleomagnetic and other research that would relate to the timing and amount of transport of the Sur-Obispo belt and Salinian block, the relative motion between the two, and the time of their suturing. (D) More detailed examination of non-Franciscan late Mesozoic and Paleogene sediments on both sides of the S-NFZ, to elucidate the record of tectonic events. (E) Continued attempts to find missing fragments of the Salinian and associated terranes. (F) Geological/geophysical search for a cryptic zone of Late Cretaceous-Paleogene mega-dislocation, other than the modern San Andreas fault. (G) Offshore seismic profiling and drilling on the continental slope west of San Francisco, to elucidate the tectonic history of the slope.

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