likely, is an active volcano. One of the difficulties associated with such an explanation is why a volcanic eruption would cause the balloon to sink. The more likely explanation is some form of mountain or lee wave. Such waves can produce intense perturbations in the terrestrial atmosphere well above the tropopause (*12*), and gravity waves forced by topography are important momentum sources in the stratosphere and mesosphere (*13*).

Although the appropriate calculations have not yet been done for Venus, Schubert and Walterscheid (*14*) have shown that for vertically dependent Venusian static stability and mean zonal wind profiles certain gravity waves forced at the surface are capable of reaching the atmosphere at or above cloud level. They did not consider waves that are stationary with respect to the surface, but their calculations did indicate that at a given wave frequency there were particular horizontal wave numbers for which amplitudes could be considerably amplified in the upper atmosphere relative to the surface forcing. There is no a priori reason to believe that such would not be the case as well for stationary waves.

An estimate of the terrain slope required to produce vertical winds of the magnitudes observed at the balloon float altitudes can be obtained as follows. The vertical wind at the surface is the product of the surface horizontal wind, u, and the terrain slope, α, which is the ratio of terrain height to horizontal scale. Suppose that there are particular gravity waves for which $R_w = 1$, where R_w is the ratio of the quantity $\rho^{1/2}|w|$ at the balloon float altitude to that at the surface. Values of R_w up to order 10 were computed under certain conditions by Schubert and Walterscheid (*14*). Using R_w we can estimate what terrain slope is required at a given value of the surface wind in order that vertical winds at the balloon altitude are of the order of 2 to 3 m $\sec^{-1}$. Choosing $u = 1$ m $\sec^{-1}$ (*15, 16*) and $R_w = 1$ gives a value for α of about 0.3, which is equivalent to a 1-km rise in 3 km. This is a slope much steeper than that indicated by the topography envelope given in Fig. 1 but one that is realized over horizontal distances of several miles in rugged terrestrial mountain ranges. A value for R_w of 10 gives a value for α of about 0.03, which is a modest slope for high mountain ranges. Thus mountain forcing of the cloud level atmosphere appears to be feasible, but obviously more work needs to be done before we can be confident that such an effect actually exists.

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Southern Hemisphere Origin of the Cretaceous Laytonville Limestone of California

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New paleomagnetic, paleontologic, and stratigraphic data from outcrops of the Laytonville Limestone (101 to 88 million years old) support a Southern Hemisphere origin. A paleomagnetic megaconglomerate test is statistically significant and suggests magnetization at 14° ± 5° south, predating Late Cretaceous to Eocene (70 to 50 million years ago) accretion. Rapid Kula plate movement or the existence and demise of a now vanished oceanic plate (or both) are required to accommodate the greater than 50° of poleward displacement implied by the paleomagnetic data. This rapid motion brings into question the validity of a "speed limit" for absolute plate velocity based on present-day plate motions.

PIONEERING WORK OF ALVAREZ *et al.* (*1*) centered on a paleomagnetic and paleontologic study of two blocks of red pelagic limestone contained in the Franciscan central mélange belt near Laytonville, California. Study of the abundant foraminifera of the Laytonville Limestone determined that the northern LL-2 block is middle Cenomanian in age [97 to 95 million years old (Ma)] (*2*) whereas the southern LL-1 block is latest Albian in age (101 Ma). Evolutionary trends in the foraminiferal species within the LL-2 section were thought to be distinctive enough to determine stratigraphic polarity. The 101- to 95-Ma interval is entirely contained within the Cretaceous normal polarity superchron; therefore, the paleolatitude of Laytonville Limestone deposition could be determined specifically by paleomagnetic analysis, assuming magnetization shortly after deposition. In their paleomagnetic analysis, Alvarez *et al.* concluded that the Laytonville Limestone acquired its magnetization at 17° ± 7° (95 percent confidence interval) *south* paleolatitude.

Some workers expressed doubt as to whether the foraminiferal trends visible in the sections were distinct enough to permit determination of stratigraphic polarity (*3*). At the heart of the debate was the assumption that the implied convergence rates of 24 to 60 cm per year between the plate carrying the Laytonville Limestone and North America were unrealistically high. This was especially so because if it is arbitrarily assumed that the Laytonville Limestone outcrop LL-2 is overturned, the results of Alvarez *et al.* can be neatly incorporated into extant northern Pacific basin plate models (*3*).

We report new paleomagnetic and paleontologic data from previously unstudied outcrops of Laytonville Limestone. The new outcrops occur as blocks containing as much as 25 m of continuous section enclosed in mélange, and are located close to the outcrops studied by Alvarez *et al.* (Fig. 1B). Several distinct biozone boundaries are crossed within individual continuous blocks, providing unambiguous facing directions. Together with new data from the outcrops originally studied by Alvarez *et al.*, these new studies confirm a Southern Hemisphere origin for the Laytonville Limestone.

The Franciscan Complex in northern California consists of three major tectonic belts

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(Fig. 1A) that have been further subdivided into tectonostratigraphic terranes (*4*). The eastern belt contains metasedimentary and metavolcanic rocks of the blueschist facies (Yolla Bolly and Pickett Peak terranes) that were accreted to the continental margin during two collision events at about 125 and 90 Ma (*5*). The central belt is a tectonic mélange consisting of oceanic terranes plus numerous smaller blocks of altered basalt (greenstone), radiolarian chert, pelagic limestone, and high-grade blueschist in a sheared matrix of argillite, lithic graywacke, and radiolarian tuff. The structure of the central belt is dominated by high-angle, strike-slip faults and is interpreted to be a right-lateral transform mélange that was active following the 90-Ma collision event and before deposition of early Eocene strata (50 Ma) that overlap the eastern and central belts in southwest Oregon (*6*). The coastal belt consists of deformed graywacke and mudstone, contains fossils as young as upper Eocene, and is believed to represent an accretionary complex formed above a subduction zone between 40 and 24 Ma (*5*).

The Laytonville Limestone blocks occur along the western margin of the central belt, a few kilometers north of the hamlet of Laytonville (Fig. 1B). To date, seven large blocks of Laytonville Limestone have been mapped. Most of these consist entirely of limestone; however, one locality (LL-5) consists of vesicular basalt (greenstone), limestone, and arkosic graywacke.

Study of foraminifera from five additional outcrops of Laytonville Limestone (LL-4, LL-5a, LL-5b, LL-6, and LL-7), extends the age range (*7, 8*) of the original study by Alvarez *et al.* (Fig. 2). Locality LL-5 shows the maximum range in age and thus serves as a comparative standard for the other sections. The locality consists of two linear outcrops, LL-5a and LL-5b (Fig. 1B). Locality LL-5b is a continuous section that ranges from late Albian to middle Cenomanian in age. The section begins in the lower part of the *Planomalina buxtorfi* zone and extends to the *Rotalipora appenninica* subzone of the *R. cushmani* zone. Outcrop LL-5a consists of several sections separated by a covered interval. The lower section is late Albian to middle Cenomanian in age and ranges from a biostratigraphic position just below the boundary of the *P. buxtorfi* and *R. brotzeni* zones and extends just into the *R. appenninica* subzone. The upper sections range from the *Dicarinella algeriana* subzone and extend to the upper part of the *Marginotruncana schneeganzi* zone, for an age range of late Cenomanian to early Coniacian. Both LL-5a and LL-5b are overturned, based on the paleontological data.

Continuous sections at localities LL-4 and LL-6 range from latest Albian to Cenomanian in age; both are overturned. A fault is indicated at locality LL-6 by the biostratigraphic overlap that repeats a portion of the *R. reicheli* zone.

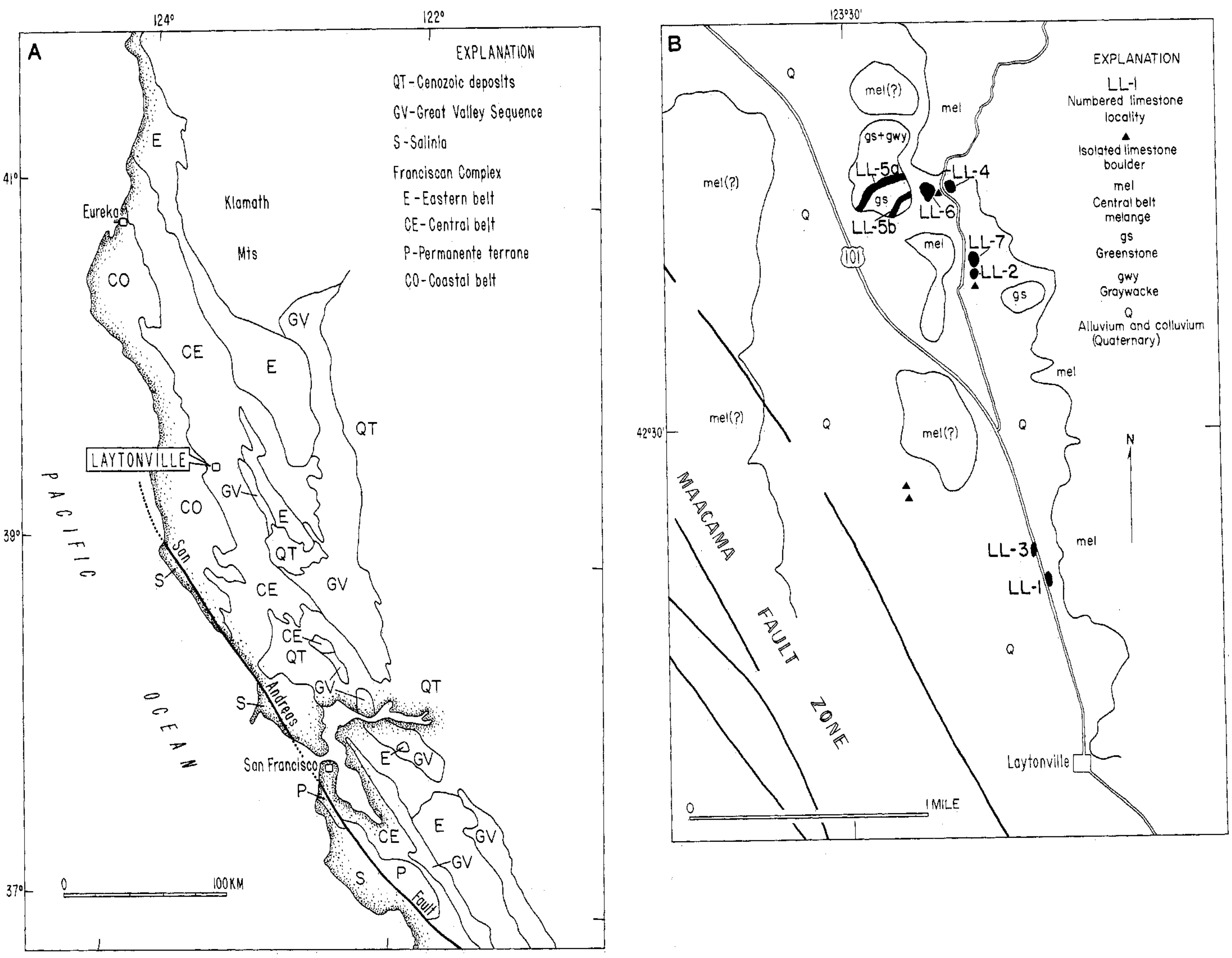


Fig. 1. (A) Geologic map of California showing the three major tectonic belts of Franciscan rocks of the northern Coast Ranges that have been further subdivided into tectonostratigraphic terranes, Salinia, and the Great Valley sequence. (B) Geologic map of the Laytonville Limestone localities.

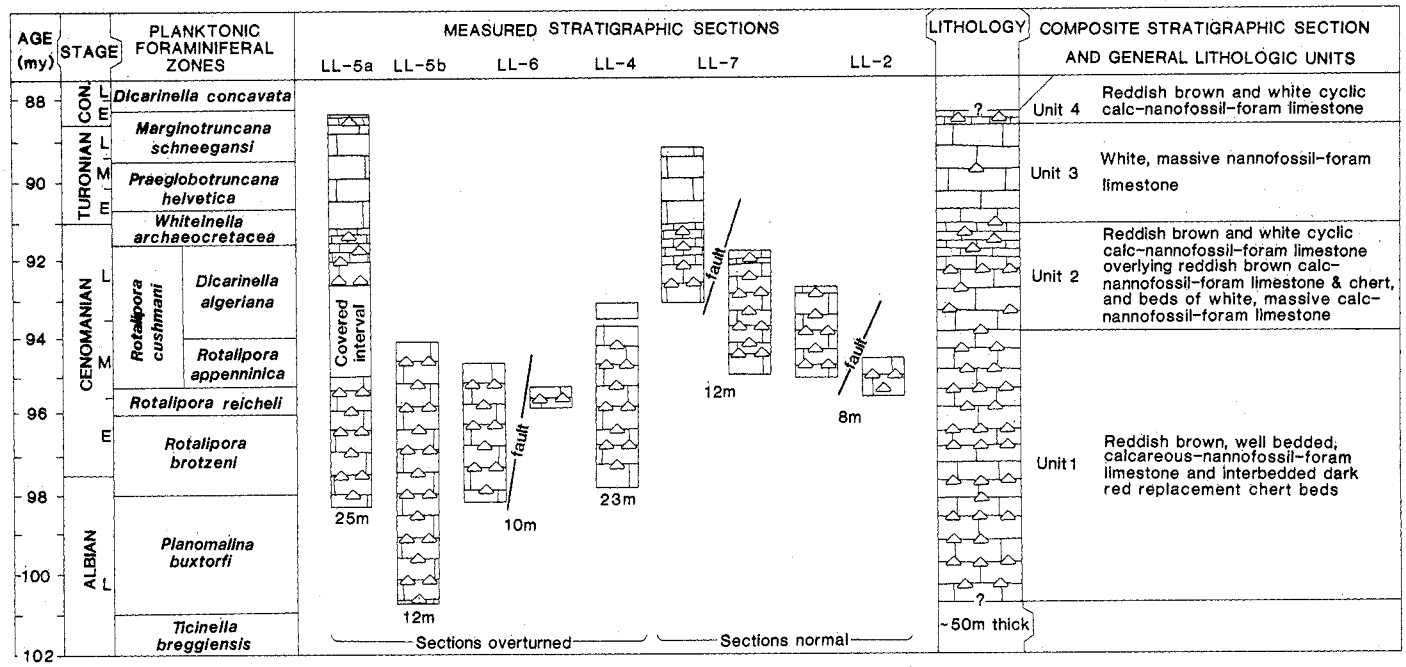


Fig. 2. Six measured stratigraphic sections of Laytonville Limestone with foraminiferal dating. LL-5a is a composite section. Foraminiferal dating is after Sliter (*7*) and Sigal (*8*). The geologic time scale is after Harland *et al.* (*9*).

Locality LL-7 is early Cenomanian to late Turonian in age. The oldest samples are from the lower part of the *R. appenninica* subzone, and the youngest samples fall within the *M. schneeganzi* zone. Faunal overlap within the *D. algeriana* subzone of the *R. cushmani* zone indicates the presence of a fault. The faunal succession from both faulted sequences shows locality LL-7 to be right side up.

The fauna indicates deposition in middle to lower bathyal depths (500 to 2000 m) above the calcite compensation depth. Rare benthic foraminifera consisting of calcareous and agglutinated species, such as *Osangularia, Gyroidinoides, Globorotalites, Dorothia,* and *Gaudryina*, thin-shelled bivalve fragments, rare aptychi, siliceous sponge spicules, and a lack of abyssal fauna are the basis of the bathyal interpretation. Reworking of age diagnostic forms is not observed.

A composite 50-m-thick stratigraphic sequence (Fig. 2) has been established for the Laytonville Limestone from six measured sections that exhibit stratigraphic and biostratigraphic overlap. This section can be divided into four lithologic units that are differentiated on the basis of their color, presence or absence of chert beds, bedding characteristics, and homotaxial position.

The Laytonville limestones exhibit excellent preservation of foraminifera and contain abundant low amplitude bedding-parallel microstylolites and slightly compacted burrows. A comparison of these textures and diagenetic features with those of 700-m-thick pelagic limestone cores from the Deep Sea Drilling Project (*9*) suggests that the Laytonville Limestone was less than 400 m thick when it was accreted.

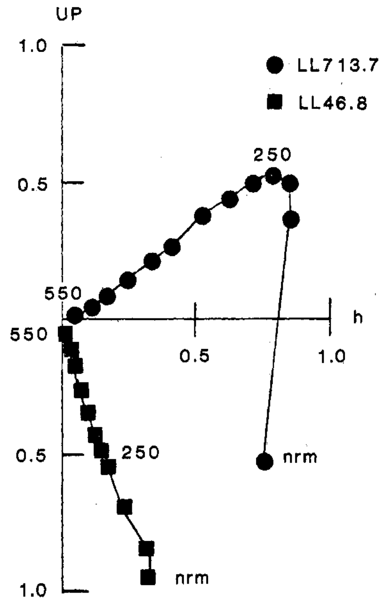
All four lithologic units resemble well-documented deep-sea pelagic carbonates typical of the equatorial Pacific region within 10° to 20° latitude (*9–11*). The Laytonville Limestone clearly does not resemble high-latitude, low-calcium carbonate-bearing pelagic clays or marls, and contains only trace amounts of terrestrial constituents. Thus, the lithology of the Laytonville Limestone is compatible with a low-latitude origin removed from a source of continental detritus. Net accumulation rates for the Laytonville Limestone are on the order of 2 to 6 m per million years. These rates are rather low for pelagic carbonates deposited in the equatorial zone of high productivity and above the calcite compensation depth (*12*). No adjustments, however, have been made for compaction, stylolitization, and chertification, which have undoubtedly reduced the thickness (*7*).

Forty-two independently oriented field-drilled paleomagnetic cores were collected from six of the Laytonville Limestone blocks. Stepwise thermal demagnetization isolated a stable magnetization having blocking temperatures ranging from 250° to 580°C, suggestive of a titanomagnetite remanence carrier (Fig. 3).

The Laytonville Limestone blocks may have rotated with respect to each other during emplacement in the mélange, and therefore the paleomagnetic inclinations are evaluated independently. Statistical analysis of the magnetizations using only inclination data (*13*) yields a positive "megaconglomerate" test ($P < 0.01$) (Fig. 4). These magnetizations show a 30-fold better grouping after tectonic correction, as compared with the in situ magnetic directions ($K_2/K_1 = 30$), indicating magnetization before Late Cretaceous–Eocene (*14*) accretion. Assuming magnetization shortly after deposition, these inclinations suggest that the Laytonville Limestone was deposited at a mean latitude of 14° ± 5° (95 percent confidence interval) south, over the depositional interval of 97 to 89 Ma.

Our paleomagnetic analysis makes a basic assumption concerning contemporaneous deposition and magnetization of the Laytonville Limestone. If the Laytonville Limestone was either magnetized after initial deposition during a reversed polarity chron, such as chron 33R (*2*), or remagnetized before incorporation into the mélange, the paleolatitude interpretation would be in error. Detailed paleomagnetic analysis of similar pelagic limestones (*15, 16*) has shown that magnetizations carried in titanomagnetite record the geomagnetic field present shortly after deposition. From this comparison, and since no evidence of remagnetization is present, magnetization long after initial deposition seems unlikely.

The only effect to steepen the measured paleolatitude that cannot be discarded is slope deposition. Carbonate sequences deposited on slopes as low as 2° to 4° commonly exhibit slides, slumps, sediment-gravity flow deposits, high sedimentation rates,



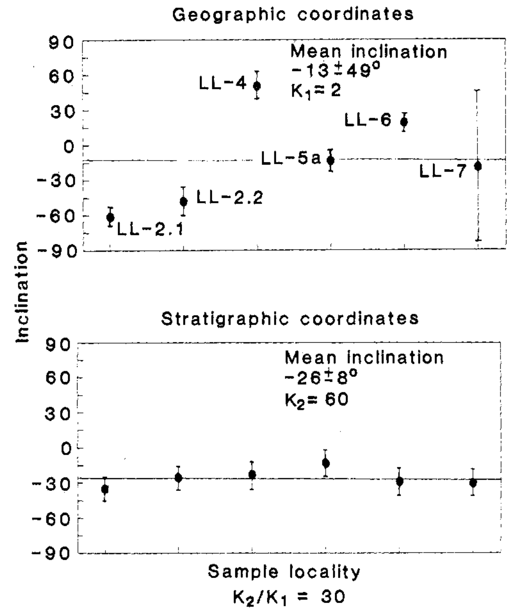


Fig. 3 (left). Plot of vertical versus horizontal component of magnetization in geographic coordinates from two specimens of Laytonville Limestone during thermal demagnetization. Sample LL46.8 is from an overturned block (LL4); sample LL713.7 is from a block that is right side up (LL7). Both samples are normalized to their respective maximum remanent magnetizations, which have intensities of approximately 10^6 emu/cm^3. A stable component of magnetization is located between 250° and 550°C. Abbreviations: nrm, natural remanent magnetization; h, horizontal. Fig. 4 (right). Paleomagnetic results from the Laytonville Limestone. Each data point represents a mean of four to ten paleomagnetic samples. In this analysis, LL-2 has been divided into two blocks, separated by the fault. Inclinations have a 30 times better grouping after tectonic correction to horizontal as compared with the in situ directions, comprising a positive megaconglomerate test. A mean paleolatitude of 14° ± 5° south is indicated by the data. Error bars show the 95 percent confidence interval.

and mixing of the age diagnostic foraminifera (*17–19*). Since such features are not observed in the Laytonville Limestone, we can assume that the depositional slope was low.

Paleomagnetic results from the Calera Limestone of the Franciscan Permanente terrane, presently located to the south of Laytonville (Fig. 1A), suggest deposition at 18° to 25° north during Albian to Turonian times (105 to 90 Ma) on the Farallon Plate (*3, 20*). When coupled with those of the coeval Calera Limestone, these new paleomagnetic results from the Laytonville Limestone require a complex history of accretion and postaccretionary translation in the formation of the Franciscan central mélange belt.

Using the apparent polar wander path of North America (*21, 22*), and assuming reasonable geologic accretion ages between 70 and 50 Ma (*14*), the Laytonville Limestone paleomagnetic data imply northward components of relative plate velocity of approximately 30 to 14 cm per year, respectively. These high minimum plate velocities suggest the Laytonville Limestone was carried on a plate other than the relatively slow-moving Farallon Plate. If the lower velocity estimate is correct, the Laytonville Limestone may have been carried on the Kula Plate, which has a large northward component of velocity during these times (*23*).

If the higher velocity estimates are correct and the modeled Kula Plate motions (*23*) are accurate, the paleomagnetic results from the Laytonville Limestone demand a modification of an exclusive Pacific-Farallon-Kula plate system. In this case, the Laytonville Limestone would have originated on a hidden plate that has subsequently subducted. Such a plate, which we call the Escondido Plate, would have had velocities higher than any observed or recorded plate. These high absolute plate velocities could be additional evidence for a decoupling of oceanic plates from the underlying mantle as inferred by intraplate stress studies (*24*). The observation that present-day plates do not move at such velocities is most likely a sampling problem (*25, 26*), since such rapid motions would only hasten the plate's demise. These rapid motions would also explain the relatively shallow burial depth interpreted for the Laytonville Limestone, since the plate would have resided in the equatorial zone of high productivity only for a very limited time.

In either plate scenario, we can only speculate that to drive the high minimum velocities, the plate that carried the Laytonville Limestone was attached to an old, dense subducting oceanic slab. The rapid northerly transport calls for highly oblique subduction relative to North America, which could have triggered coeval strike-slip faulting. This faulting may have played a major part in the transport of the numerous blocks and slabs of previously accreted Eastern Franciscan belt, Coast Range ophiolite, and Great Valley sequence to their present location within the Franciscan central belt mélange.

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