Franciscan Complex limestone deposited at 17° South paleolatitude

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ABSTRACT

At Laytonville, California, about 230 km north-northwest of San Francisco, three blocks of pelagic limestone, each a few tens of metres long, are incorporated in the Franciscan melange. Bedding is well defined, but top indicators are lacking. Paleomagnetic study of two of the blocks (16 samples, 52 specimens) yielded directions of D: 183.9°, I: −22.6°, α_{95}: 21.6° (block 1), and D: 229.5°, I: −31.8°, α_{95}: 10.7° (block 2) relative to the present orientation of bedding. Inclinations were not significantly different, but the difference in declinations shows that magnetization preceded emplacement of the blocks in the melange. Study of foraminifera showed that the blocks are of Albian and Cenomanian age and were deposited during the Cretaceous Long Normal Polarity Interval. Details of the foraminiferal zonation show that both blocks are right side up. The observed inclinations imply deposition on the Farallon plate at 17° ± 7° *South* paleolatitude at about 96 m.y. B.P. (block 2; block 1 data agree but are less definitive). Consideration of reasonable paleolongitudes and possible times of incorporation of the blocks in the melange indicates a Farallon–North America convergence rate significantly higher than any observed today. The most commonly accepted emplacement time (latest Cretaceous) indicates convergence at about 38 cm/yr (range: 24 to 60 cm/yr). An alternate interpretation, that emplacement occurred at 30 ± 15 m.y. B.P., would indicate convergence at about 15 cm/yr (range: 9 to 24 cm/yr). The convergence rates obtained in the first case are astonishingly high, and they suggest that perhaps current ideas on the Franciscan should be re-evaluated, with consideration given to the possibility that tectonic mixing continued until the middle or late Tertiary. Even so, the Farallon–North American convergence rate was apparently higher than any convergence rate observed today. This rapid convergence coincides with the Cretaceous rapid spreading pulse, and it may be responsible for such features as the large volumes of Late Cretaceous batholiths and subduction complexes in western North America.

INTRODUCTION

Recent developments in paleomagnetic instrumentation have made it possible to measure weakly magnetic limestones on a routine basis, and pelagic limestones of Jurassic and Cretaceous age in the Umbrian Apennines have yielded excellent magnetic data (Alvarez and others, 1977: Lowrie and Alvarez, 1977a, 1977b, and references therein). Pelagic limestones somewhat similar to those of Umbria are a very rare component in melanges of the Franciscan Complex of California (Bailey and others, 1964; Wachs and Hein, 1975; Gucwa, 1975). We report here a paleomagnetic study of two limestone blocks from the Franciscan. Although the chaotic structure

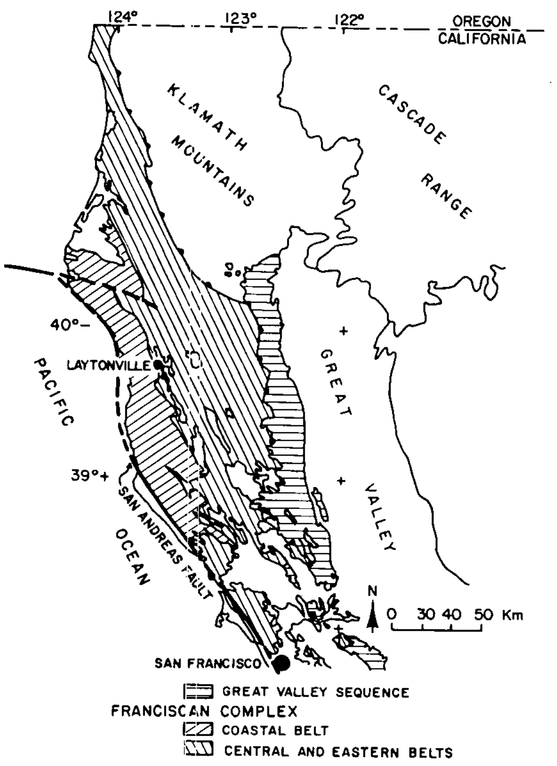

Figure 1. Sketch map of the Franciscan Complex in northern California. Modified from McLaughlin and Pessagno, 1978. Limestone blocks discussed here are located 1 to 3 km north of Laytonville.

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of the melange makes declination values useless, measurements of inclination with respect to bedding planes make it possible to determine the paleolatitude of the limestones at the time of deposition. This information is important in understanding plate motions in the Pacific and the sources of rocks accreted in subduction zones at the Pacific margin.

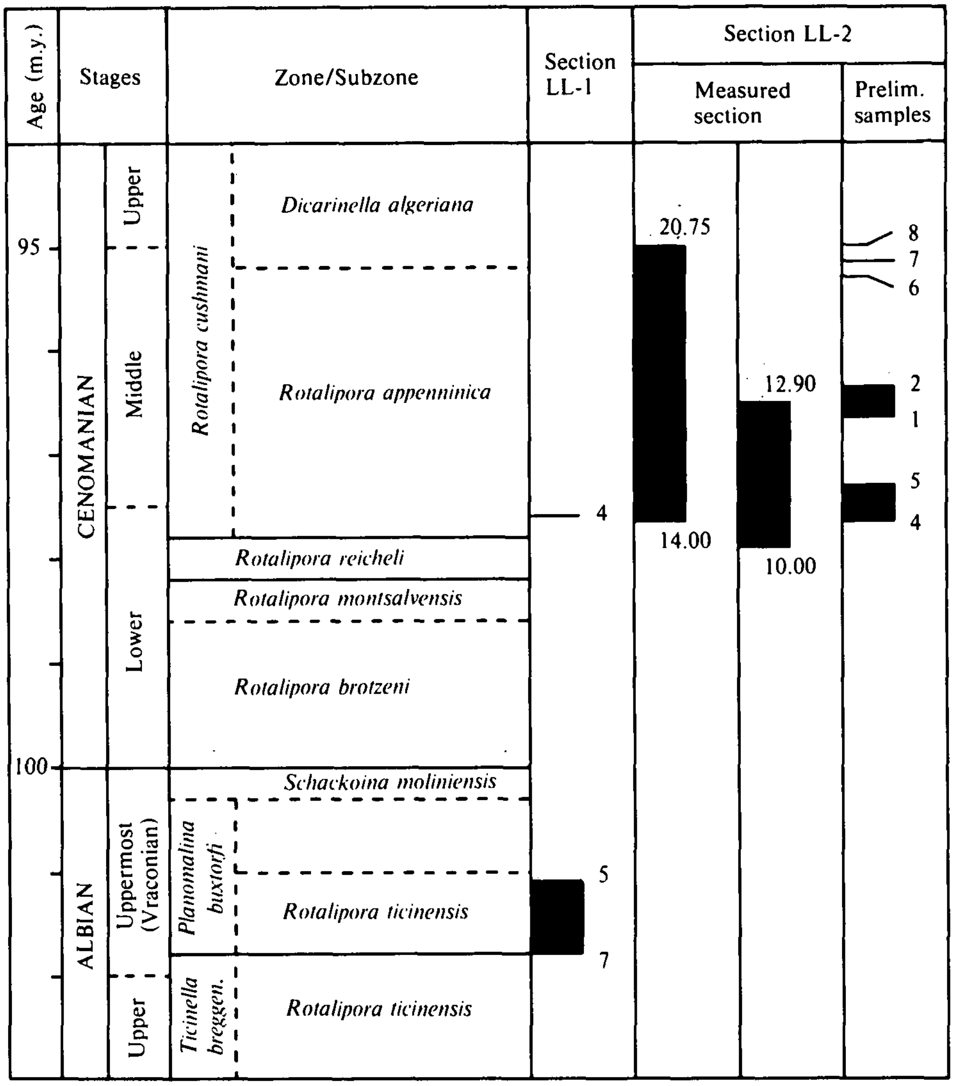

Figure 2. Stratigraphic positions of the two sections. Planktonic foraminiferal zonation scheme, stages, and absolute age after Sigal (1977) and Premoli Silva and Boersma (1977).

GEOLOGIC SETTING

At the latitude of Laytonville, California (39°41.5′N, 123°29′W), the Franciscan Complex is 75 km wide, extending from the Pacific Ocean on the west to the tectonically overlying Great Valley sequence on the east (Fig. 1). In the Central Belt Franciscan of the Laytonville area, Gucwa (1975) recognized a subunit, the Laytonville melange, formed of "sheared greywacke-shale matrix with large blocks of chert, pillowed volcanic rocks and blueschist" (Maxwell, 1974, p. 1197). The Laytonville melange contains the best known exposures of the pink, cherty, pelagic limestone that Bailey and others (1964) called "Laytonville-type limestone." This limestone consists of a micritic matrix sprinkled with abundant planktonic foraminifera. Electron micrographs from two other occurrences of Laytonville-type limestones show that the micritic matrix contains abundant coccoliths and coccolith fragments (Fischer and others, 1967, Figs. 38 through 41). Gucwa (1974) mapped three small blocks of this limestone, 1 to 4 km north of Laytonville [only the northern and central blocks are shown on Gucwa's (1975) sketch map], and a few other occurrences are known to exist elsewhere in the Franciscan (Bailey and others, 1964; Wachs and Hein, 1975).

For both paleomagnetic and micropaleontologic study, we sampled the southernmost and northernmost of the three blocks north of Laytonville. The southern block (sample locality LL-1; 39°42.0′N, 123°29.1′W) is apparently only a few tens of metres long and is exposed mainly in a road cut on Highway 101. The northern one (sample locality LL-2; 39°43.1′N, 123°29.4′W) is about one hundred metres in length. The contacts between these blocks and other parts of the Laytonville melange are not exposed, but the blocks are evidently enclosed within the melange matrix.

In the limestone bodies near Laytonville, bedding is very clearly displayed as a set of subparallel, anastomosing, stylolitic surfaces spaced one millimeter to several centimetres apart. These surfaces are parallel to elongate chert nodules, which demonstrates that they are bedding-parallel stylolites, rather than tectonic stylolites or solution cleavage at an angle to bedding (Alvarez and others, 1978). Unfortunately, no macroscopic or microscopic stratigraphic top indicators were found, leaving an ambiguity in interpreting the paleomagnetic results. Although the inclination value would give the depositional paleolatitude, it would not be possible to distinguish between the Northern and Southern Hemispheres. This problem would be compounded by a second ambiguity; we would not know whether the limestone was deposited during a normal or a reversed polarity interval. By good fortune both ambiguities were resolved through paleontological dating, which indicated upright bedding and deposition in the Albian-Cenomanian, during the Cretaceous Long Normal Polarity Interval.

LITHOLOGY AND BIOSTRATIGRAPHY

Fossils were identified in thin section, because the limestones, originally foram-coccolith oozes, are strongly indurated. Recognizable chert and siliceous material is limited to a few samples; in one chert sample examined, radiolarians are still visible as ghosts. Calcite veins are a common feature of all samples studied. The limestone commonly shows effects of irregular, partial dissolution. Solution seams are marked by dark red or rust-colored insoluble residues. Where solution seams are very close together and the micritic matrix has been largely removed, the forams give a false appearance of being mechanically concentrated.

Three sets of samples were available for paleontological study — preliminary samples from both blocks (LL-1 and LL-2) with relative stratigraphic positions measured only roughly, and follow-up samples from the northern block (LL-2), which were spaced about 1 m apart and referred to a measured stratigraphic section.

Measured Section, LL-2

This section was measured up the steep, western scarp of the east-dipping limestone block, from its base to its highest topographic point. The section was numbered from 10.00 m at the base to 20.75 m at the top. On the basis of species distribution, the samples may be divided into two groups: 10.00 to 12.90 m, and 14.00 to 20.75 m. Both parts are right side up, but they show a biostratigraphic overlap (Fig. 2). This suggests the presence of a fault between the samples at 12.90 and 14.00 m, although such a fault was not noted in the field when the samples were collected.[1] The sequence is mainly middle Cenomanian, with its base belonging to the uppermost part of the lower Cenomanian.

First Group (10.00 to 12.90 m). Sample 10.00 is the oldest in the measured section. The assemblage includes frequent large *Rotalipora* and *Praeglobotruncana.* Forms close to *Rotalipora reicheli* and *R. greenhornensis* are present, but *Rotalipora cushmani* and *Praeglobotruncana gibba* are apparently absent; this allows the assemblage to be attributed to the *Rotalipora reicheli* Zone or to the boundary between the *R. reicheli* and *R. cushmani* Zones. The overlying samples are definitely attributable to the *R. cushmani* Zone *(R. appenninica* Subzone). The increasing number of *R. cushmani,* the increasing size and increasingly conical shape of *Praeglobotruncana gibba,* and the gradually decreasing frequency of *R. appenninica and R. brotzeni* indicate that the sequence evolves upward relatively rapidly, although still within the *R. appenninica* Subzone.

Second Group (14.00 to 20.75 m). In sample 14.00, *R. appenninica* and *R. brotzeni* become abundant again, *R. gibba* is absent, and typical *R. cushmani* is very rare. The assemblage is very similar to that of sample 10.00, although sample 14.00 is probably a little younger than 10.00. The sequence evolves upward as described above. Sample 16.00 is closely similar to sample 12.90. Above 16.00, the assemblages gradually lose *R. appenninica, R. brotzeni,* and *P. delrioensis,* which are replaced by *P. gibba, R. cushmani,* and *R. greenhornensis,* showing that the sequence continues into the *R. appenninica* Subzone. In the last samples, 19.10 and 20.75, *Praeglobotruncana aumalensis* and *Dicarinella algeriana* (primitive double-keeled forms) appear, but *R. appenninica. R. brotzeni,* and *P. delrioensis* are missing. The boundary between the *R. appenninica* and *D. algeriana* Subzones falls between samples 18.05 and 19.10.

The preliminary samples from locality LL-2 cannot be accurately located in the measured section, but they show an evolutionary trend corresponding to that of the well-located samples. In summary, the limestones of LL-2 are entirely of Cenomanian age, and although the sequence is divided into two overlapping parts, both parts are right side up.

Preliminary Samples, LL-1

The limestone in the road cut of LL-1 is reasonably intact, but locally it is highly fractured and cleaved and contains some small faults subparallel to the cleavage. Samples were collected on the east side of the road, covering a stratigraphic interval of about 5 m.

The LL-1 section is of Albian age, with the exception of sample LL-1.4, which is of Cenomanian age and may have been incorporated into the sequence by late tectonic processes. The stratigraphic sequence of these samples is shown in Figure 2.

LL-1.4 is a red limestone of the Umbrian "Scaglia" type (Alvarez and others, 1977), very similar in lithology and fossil content to the Cenomanian samples of the LL-2 section. Fossils are condensed in some areas, possibly by burrowing and/or by very weak currents. Planktonic forams are abundant, with sparse benthics. The assemblage is indicative of the *Rotalipora cushmani* Zone (*R. appenninica* Subzone).

All of the other samples show a trend within the Albian *Planomalina buxtorfi* Zone. In the lowest samples (LL-1.6, 1.7), *P. buxtorfi* is represented by primitive specimens with a poorly developed keel, along with *P. praebuxtorfi* and with rare individuals still related to *Ticinella breggiensis* (the marker of the underlying zone). In samples 1.3 and 1.5, another evolutionary lineage, *Praeglobotruncana delrioensis – P. stephani,* is detectable, with the latter species first occurring in sample 1.3. Because of the occurrence of *Rotalipora ticinensis* up to the top, all of the section is attributable to the *Planomalina buxtorfi* Zone, *Rotalipora ticinensis* Subzone. The age is latest Albian, early Vraconian (Sigal, 1977), and the section is right side up.

In these late Albian samples, well-developed Rotaliporids (including the species *ticinensis* and *appenninica*) and, in

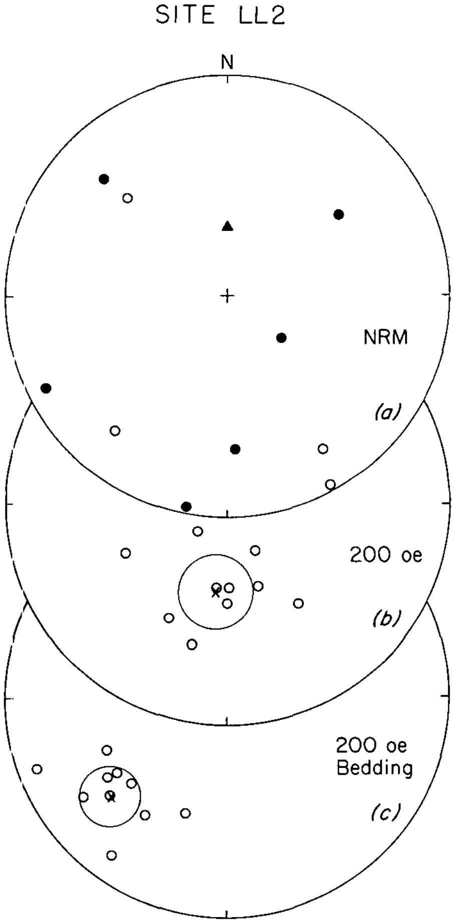

Figure 3. Paleomagnetic results from site LL-2. Solid circles are in lower hemisphere, open circles in upper hemisphere. (a) NRM directions; triangle is dipole field direction for this latitude. (b, c) After demagnetization in 200 oe, before and after bedding correction, showing mean (X) and α_{95} circle.

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[1] The suspected fault was subsequently located; see "NOTE ADDED" following acknowledgments.

part, Praeglobotruncanids, are poorly represented, whereas their frequent occurrence might already be expected (I. Premoli Silva, unpub. data). This fact could be interpreted as a consequence (1) of a non-tropical environment (water masses were impoverished in these warm-water species); (2) of dissolution at depth (these species are rather sensitive to solution), or (3) of dissolution during diagenesis. In the light of the available data, the environmental control may be the most important factor.

TABLE 1. LAYTONVILLE LIMESTONE, LOCALITY LL2

Sample	Specimens	Geographic		Bedding	
		Decl.(°)	Incl.(°)	Decl.(°)	Incl.(°)
LL2-M	6	149.4	−70.1	235.6	−39.5
N	(6)	weakly magnetized			
O	4	194.1	−34.9	215.5	−12.3
P	10	180.3	−52.8	230.2	−31.2
Q	2	144.8	−44.1	199.6	−43.8
R	4	178.9	−59.2	215.2	−35.0
S	6	244.0	−47.9	249.2	−8.9
1	2	185.4	−58.5	236.3	−35.0
2	2	159.5	−57.9	228.0	−41.8
3	(2)	weakly magnetized			
4	2	207.0	−41.5	235.0	−22.0
6	(2)	weakly magnetized			
7	2	228.0	−75.0	246.1	−40.2
10(13)	40(50)	186.9	−57.8	229.5	−31.8
		[K = 14.2, α_{95} = 13.2°]		[K = 21.0, α_{95} = 10.7°]	

Note: sample mean directions after 200 oe AF.

PALEOMAGNETISM

Sample Locality LL-2

Thirteen oriented hand samples, yielding 50 specimens for magnetic measurement, were collected over a stratigraphic interval of about 10 m. Three samples (ten specimens), consisting of veined and fractured material, gave very weak, inconsistent magnetizations, and were excluded from further consideration. The mean directions of natural remanent magnetization (NRM) of the remaining ten samples are scattered but generally away from the present direction of the geomagnetic field at the locality (Fig. 3). The NRM intensity was typically weak and averaged 4.5 × 10^{-7} Gauss (N = 40 specimens).

Progressive alternating field (AF) demagnetization of the NRM of one or more specimens per sample typically showed behavior similar to that illustrated in Figure 4.

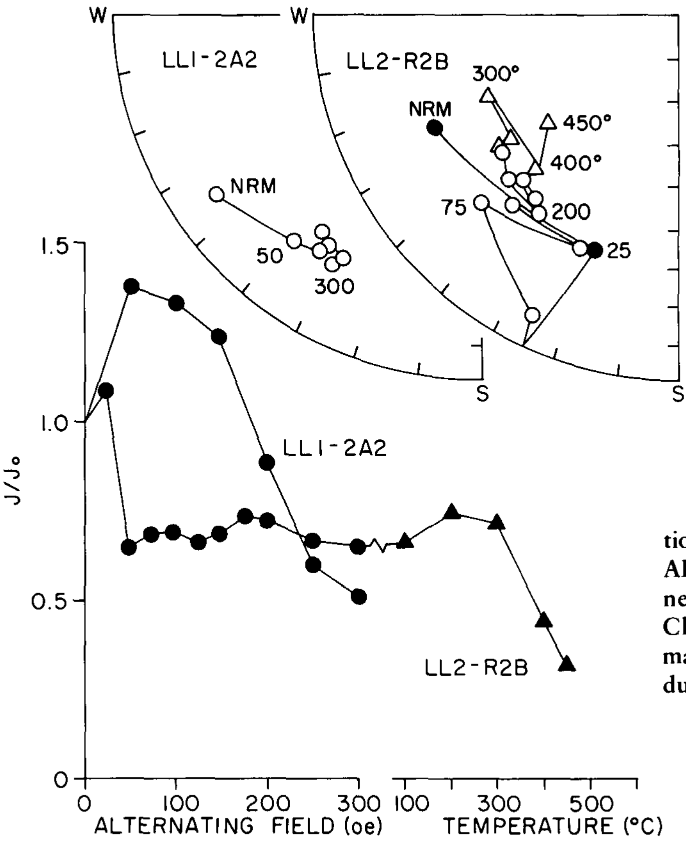

Figure 4. (top) Directional behavior during AF and thermal demagnetization. (bottom) Changes in remanent magnetic intensity (J/Jo) during demagnetization.

A low coercivity component is invariably present whose removal in AF of usually less than 150 oe results in large changes in NRM direction and intensity (decrease or increase) of the specimen. Demagnetization at higher AF to 300 oe results in little further change in direction, and in many specimens, in remanent intensity as well. Subsequent thermal demagnetization of the specimen shows that the stable direction of magnetization obtained after AF treatment persists to high temperatures as the remanent intensity decays and the magnetization is eventually reduced to below reproducible levels above about 450 °C (Fig. 4). This behavior argues for the presence of a single, characteristic magnetization in these rocks, apparently carried by magnetite or titanomagnetite. As the secondary magnetization is readily removed by AF treatment, all specimens were demagnetized in 200 oe for direction analysis of the stable magnetization.

The sample mean directions after 200 oe AF are plotted in Figure 3b, and the relevant statistics are listed in Table 1. All samples (N = 10) are of the same polarity, and they cluster around a mean direction of D = 186.9°, I = −57.8°, α_{95} = 13.2°. After correcting for the bedding tilt associated with each sample, the mean direction becomes D = 229.5°, I = −31.8°, α_{95} = 10.7°. The value of Fisher's precision parameter, K, increases after bedding correction (K_2/K_1 = 1.5), indicating that the directions have become more closely grouped, although it should be noted that the improvement in K is not statistically significant at the 95% confidence level (McElhinny, 1964). Nevertheless, the change in K is in the expected sense if the stable magnetizations were acquired prior to tectonic tilting; the lack of statistical significance at a high confidence level may be due to the fact that the bedding corrections for all samples were quite similar.

Sample Locality LL-1

Seven oriented hand samples, yielding 14 specimens for magnetic measurement, were collected over a stratigraphic interval of about 5 m. One sample (two specimens) was veined and fractured and proved unsuitable for further consideration. The remaining six samples have shallow and southerly NRM directions that are reasonably well grouped, in contrast with the samples from locality LL-2, which had scattered NRM directions before demagnetization.

Progressive AF demagnetization of NRM typically shows an initial increase in the remanent intensity in low fields followed by a gradual decay at high field which, however, is not accompanied by large directional changes (Fig. 4). Apparently the reddish pigment present in the rocks at locality LL-2 is related to the appreciable secondary magnetic components in those samples; the rocks at locality LL-1 are light in color, and secondary magnetizations appear to have a minor effect on the total magnetization directions of these samples.

The sample mean directions after treatment in 200 oe AF are given in Table 2 and plotted in Figure 5. They give a locality mean of D = 176.4°, I. = −16.5° α_{95} = 23.7°; similar directions were obtained after only 100 oe AF. Correcting for bedding tilt gives a mean direction of D = 183.9°, I = −22.6° but with essentially the same grouping (α_{95} = 21.6°), due to very similar bedding attitudes over the outcrop sampled. Note that all samples are again of the same magnetic polarity.

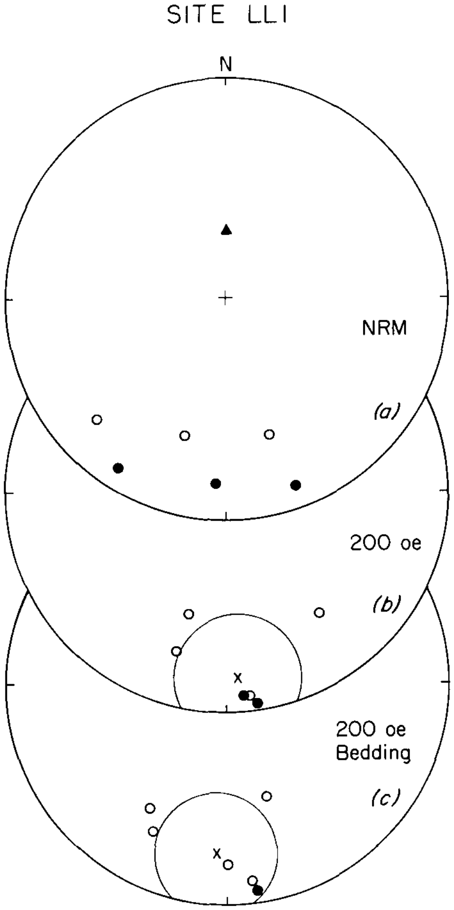

Figure 5. Paleomagnetic results from site LL-1, description as in Figure 3.

PALEOLATITUDE

The mean characteristic directions for localities LL-1 and LL-2 are significantly different at the 95% confidence level, both before and after correcting for bedding tilt. However, the difference in mean direction after correction for bedding tilt is due primarily to difference in declination, but the mean inclinations are not significantly different. This result is encouraging in that the limestone blocks have undoubtedly been rotated within the melange, and the amount of rotation is not expected to have been exactly the same for each block. The significant difference in mean directions for this tectonic setting can be considered a positive conglomerate test for stability of magnetization (Graham, 1949), and it also shows that the directions are not the result of a magnetic overprint uniformly affecting the entire terrain the blocks are now enclosed in. On the other hand, we interpret the consistency of the mean characteristic inclinations with respect to bedding at each locality as evidence that these limestones were deposited at nearly the same paleolatitude.

TABLE 2. LAYTONVILLE LIMESTONE, LOCALITY LL1

Sample	N	Geographic Decl.(°)	Geographic Incl.(°)	Bedding Decl.(°)	Bedding Incl.(°)
LL1-1	2	198.2	−41.6	211.9	−34.1
2	2	198.0	−24.9	206.3	−26.3
3	2	174.0	−6.9	179.7	−18.9
4	(2)	weakly magnetized			
5	2	171.7	3.4	173.4	−10.3
6	2	142.9	−32.7	160.9	−45.1
7	2	175.3	8.1	172.4	5.0
6(7)	12(14)	176.4	−16.5	183.9	−22.6
		[K = 8.9, α_{95} = 23.7°]		[K = 10.4, α_{95} = 21.6°]	

Note: sample mean directions after 200 oe AF.

Assuming that the mean locality directions (with respect to bedding) are a reasonable measure of a geocentric axial dipole field at the time of formation of the rocks, the paleolatitude at which they acquired their magnetization can be calculated from the dipole formula: tan I = 2 tan λ, where I is the measured remanent inclination and λ is the paleolatitude; the error, $\Delta\lambda$, in determining the paleolatitude from directions with a Fisherian distribution whose dispersion is given by α_{95} and is calculated by $\Delta\lambda = \frac{1}{2} \alpha_{95} (1 + 3 \sin^2\lambda)$. The calculated paleolatitudes and errors are 11.8° ± 12.2° for locality LL-1, and 17.2° ± 6.8° for locality LL-2. The paleontological data indicate that the beds are right side up at both localities; therefore, the sign of inclination as calculated is correctly referred to the paleohorizontal. Furthermore, the rocks at both localities correspond in age to the Cretaceous Long Normal Polarity Interval (Lowrie and others, 1980), and so we can reasonably assume that the uniform polarity of samples at each locality is in the normal direction. Consequently, the mean negative inclinations imply that the rocks at both localities were magnetized in Southern Hemisphere paleolatitudes, most likely between the equator and 24°S. The data from locality LL-2, however, give the best estimate of paleolatitude of formation as 17.2° ± 6.8° South latitude; data from locality LL-1 support this estimate.

TECTONIC IMPLICATIONS

The principal conclusion based on the paleontological and paleomagnetic work described above is that the Laytonville limestone was deposited during the Albian-Cenomanian at a paleolatitude of 17.2° ± 6.8° South. In discussing the tectonic implications of this result, three questions are important: (1) where was the depositional site of the Laytonville limestone in the world paleogeography at that time, (2) where and when was the limestone emplaced in the Franciscan melange, and (3) at what rate did the Farallon plate move as it carried the limestone toward the margin of North America?

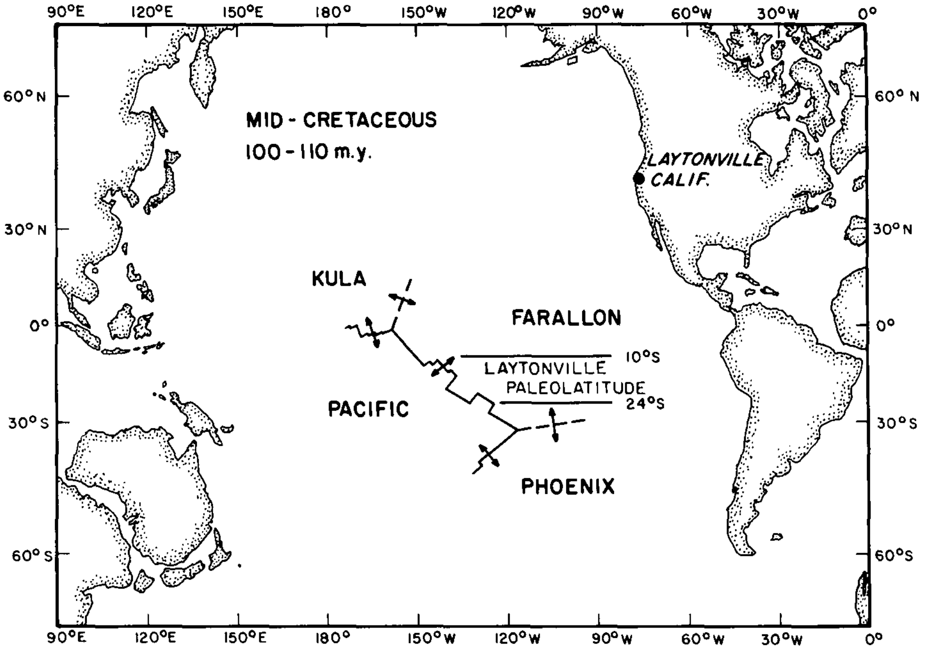

Figure 6. Reconstruction of the Pacific in the middle Cretaceous (see text). The results of this study indicate that the Laytonville limestone was deposited within the area marked, probably near its western end, at about 96 m.y. B.P., and emplaced in the Franciscan Complex at Laytonville, California, in the latest Cretaceous or the Tertiary.

Depositional Site

In the Early and middle Cretaceous, the Pacific plate and its associated system of spreading plate boundaries were generally located in the Southern Hemisphere (Lancelot and Larson, 1975). In Figure 6, the system of plates and plate boundaries is plotted on the mid-Cretaceous continental reconstruction of Smith and Briden (1977). This plate boundary configuration was achieved by first mapping the present-day locations of the M-1 magnetic anomaly lineation, assumed to be about Barremian (~113 m.y.) in age. This isochron was then rotated back into a paleolatitude framework, using the technique and assumptions of Lancelot and others (1974), Clague and Jarrard (1973), van Andel (1974), and Winterer (1973). These models generally assume that the "hot-spots" and associated island chains of the Pacific are fixed with respect to each other and to the spin axis of the Earth, and that motion of the Pacific plate can be deduced from the trends and ages of these island chains. Models involving the deep-sea sedimentary record also assume that the equatorial zone of high biological productivity is fixed with regard to the Earth's spin axis. The particular model used here is listed in Lancelot and Larson (1975) and is extended back into the Mesozoic with the sedimentary facies information gained on Deep Sea Drilling Project (DSDP) Leg 32 by drilling Mesozoic sediments in the northwestern Pacific.

This general plate boundary configuration and paleolatitude framework were also arrived at independently by Larson and Chase (1972) and Larson and Pitman (1972). They used the cross-sectional shape (skewness) and modeling techniques of Schouten (1971) and Schouten and McCamy (1972) to determine a paleomagnetic pole location for Early Cretaceous magnetic anomalies M-1 to M-10. This calculated pole yields a paleolatitude and orientation of the plate boundary network that is nearly identical to that shown in Figure 5, although the paleolongitude by this method is indeterminate. We point out that the assumption of a fixed hot-spot network allows the calculation of "absolute" motion so that the latitude, longitude, and orientation of the plate boundaries in Figure 6 are all determined. However, the less speculative assumption of a fixed equatorial zone of high biological productivity still allows the determination of paleolatitude. Both of these assumptions yield results in accord with the studies of magnetic anomaly skewness of Larson and Chase (1972).

Most of the mid-Cretaceous Pacific Basin has been subducted beneath the surrounding continents in the past 100 m.y. Thus it is possible that the Laytonville limestone was deposited near a spreading plate boundary that has been completely removed from the geological record by subduction. While this is possible, we point out that the Pacific-Farallon plate boundary was situated at a low southern latitude in the mid-Cretaceous (Fig. 6). Rocks accreted and deposited on the Pacific plate side of this spreading boundary now lie in the northwestern Pacific Ocean. It is our interpretation that the Laytonville limestone was deposited on the Farallon plate, subsequently transported thousands of kilometres to the north or northeast, and finally emplaced in the Franciscan Complex at the Farallon–North America trench.

Time of Emplacement of the Laytonville Limestone

Determination of the velocity of the Farallon plate as it carried the Laytonville limestone is affected by uncertainties in four parameters: the time of deposition of the limestone, its location when deposited, its location when emplaced in the melange, and the time of emplacement. The first three parameters are known with acceptable accuracy, as discussed in the next section, but the time of emplacement presents a major difficulty.

Several geologists who have worked in the Franciscan terrane in the northern Coast Ranges believe that the Laytonville melange was already formed by the end of the Cretaceous (D. L. Jones, 1978, personal commun.). However, this has been very hard to prove, because the oldest post-deformation rocks that directly overlie the melange are of Quaternary age. All other arguments aimed at setting a minimum age for the deformation of the Laytonville melange are based on indirect evidence and uncertain stratigraphic and structural correlations. Articles that treat this question or contain relevant observations include Bailey and others (1964), Clark (1940), Evitt and Pierce (1975), Gucwa (1975), Maxwell (1974), McLaughlin and Pessagno (1978), and Swe and Dickinson (1970). After studying the relevant literature, we conclude that the stratigraphic evidence permits an emplacement time for the Laytonville limestone at some time from the Late Cretaceous to the late Tertiary. We do not believe that a detailed discussion is appropriate here, and we will deal with this ambiguity by calculating plate velocities for two extremes in a range of acceptable cases: (1) with emplacement occurring in the latest Cretaceous (70 ± 5 m.y.), and (2) with emplacement occurring in the middle of the Tertiary (30 ± 15 m.y.).

Transport Velocity of the Laytonville Limestone

The better determined of the two paleolatitudes comes from locality LL-2, with an age of 96 ± 1 m.y. (Fig. 2). If the Laytonville limestone was emplaced in the Franciscan Complex in the latest Cretaceous, in the range 70 ± 5 m.y., the duration of transport was 26 ± 6 m.y. If emplacement occurred in the middle Tertiary, in the range 30 ± 15 m.y., the duration of transport was 66 ± 16 m.y.

We consider first the northward component of motion of the Farallon plate as it carried the Laytonville limestone. Paleolatitudes of Laytonville were taken from the maps of Smith and Briden (1977). These maps are age calibrated using the magnetic anomaly time scale of Heritzler and others (1968; these dates are identified by quotation marks below), and we have revised the ages using the more recent time scale of Alvarez and others (1977) and LaBrecque and others (1977). Using this revision, an emplacement date of 70 m.y. B.P. corresponds closely to Smith and Briden's (1977) "80 m.y." map, on which the paleolatitude of Laytonville is 42° ± 6°N (uncertainty from the α_{95} of the mean paleomagnetic north pole reported by Smith and Briden, 1977). There is very little difference between the "80 m.y." and "100 m.y." maps of Smith and Briden (1977), and so we use the same value for the paleolatitude and uncertainty at the upper age limit on the time of emplacement, 75 m.y. The lower limit, 65 m.y., corresponds to a "70 m.y." map kindly prepared for us by A. G. Smith, on which the paleolatitude of Laytonville is 46° ± 6°N. Thus, for emplacement at 70 ± 5 m.y. B.P., our best estimate for the northward component of the velocity of the Laytonville limestone is 25 cm/yr, with a permissible range of 16 to 40 cm/yr (Table 3).

For a more recent emplacement, at 30 ± 15 m.y. B.P., we use Smith and Briden's (1977) maps for "20 m.y." and "40 m.y." These maps do not require an adjustment in age, and in both cases Laytonville falls in the latitude range of 42° ± 6°N. Thus, for emplacement at 30 ± 15 m.y. B.P., we estimate the northward component of the velocity of the Laytonville limestone at 10 cm/yr, with a permissible range of 6 to 16 cm/yr (Table 3).

It is unlikely that the Laytonville limestone moved due North. Figure 5 shows that the Farallon plate, now almost completely consumed beneath North America, must have moved northeast, and thus our preferred site for deposition of the limestone is toward the western end of the band of permissible paleolatitudes. Such a site of origin, near the Pacific-Farallon ridge, permits a path that avoids the Central America trench and offers suitable sites for deposition of limestone, above the calcite composition depth and out of the reach of abyssal plain turbidites (although the limestone could also have been deposited on a seamount farther east). A depositional site near the Pacific-Farallon ridge gives a northeastward velocity roughyly 1.5 times as fast as the northward component. We thus conclude that if emplacement of the limestone in the Laytonville melange occurred in the latest Cretaceous, the velocity of the Farallon plate relative to North America was in the range of 24 to 60 cm/yr, with a preferred estimate of about 38 cm/yr. If emplacement occurred in the middle Tertiary, the preferred estimate of the velocity is 15 cm/yr, with a permissible range of 9 to 24 cm/yr (Table 3.)

TABLE 3. CALCULATED FAR-PAC CONVERGENCE RATES (cm/yr)

Emplacement time of limestone in melange	Northward component			Convergence velocity		
	min	mean	max	min	mean	max
30 ± 15 m.y.	6	10	16	9	15	24
70 ± 5 m.y.	16	25	40	24	38	60

CONCLUSIONS

The most fundamental conclusion of this study is that the Laytonville limestone was deposited far to the south of its present location. This result is in good agreement with other lines of evidence that indicate a long history of northward motion of the plates of the Pacific Ocean.

It is difficult to draw a more specific conclusion because of the uncertainty in dating the emplacement time of the limestone. At this point, we will simply indicate the two extremes in a range of interpretations which are acceptable: (1) If one honors the widespread opinion that emplacement occurred by the end of the Cretaceous, one is forced to accept extremely fast convergence between the Farallon and North American plates (24 to 60 cm/yr). (2) On the other hand, if one prefers convergence rates that do not greatly exceed those observed today, our results would indicate that mixing of the Franciscan melange continued until the middle or late Tertiary.

These results have several implications. If tectonic mixing, and hence perhaps subduction as well, continued at the site of the Franciscan Complex until late in the Tertiary, concepts of the tectonic history of western North America will require some revision.

The geology of the Franciscan Complex does not seem to indicate the presence of more than one subduction zone west of North America in the Cretaceous and Tertiary. Therefore, all of the convergence that brought the Laytonville limestone from its depositional site to its final resting place was apparently accommodated at a single Franciscan subduction zone. Convergence was probably not perpendicular to the trench, and so the straight-in velocity was probably somewhat less than the rate of convergence. The presence of any additional spreading ridge outboard of the trench would have markedly increased the convergence rate until that ridge was subducted.

Convergence rates at present-day consuming margins do not exceed 12.5 cm/yr, based on the new relative motion poles calculated by Minster and Jordan (1978). Convergence rates based on the present

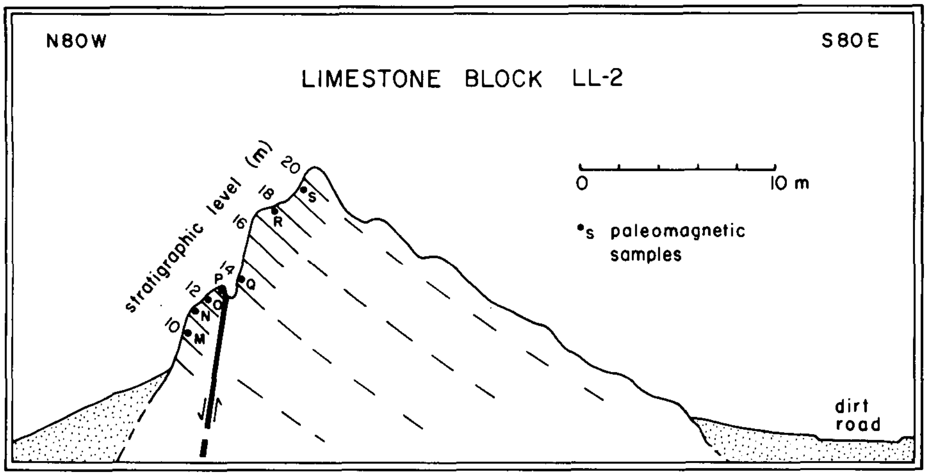

Figure 7. Cross section through the limestone block of LL-2, showing the fault passing between paleontological samples at 12.90 m and 14.00 m.

study (Table 3) show that Farallon–North America convergence during northeastward transport of the Laytonville limestone was almost certainly faster than present-day rates. If emplacement occurred in the latest Cretaceous, we obtain the astonishingly high convergence rate of 38 cm/yr, with a large margin of uncertainty. An Oligocene emplacement age gives a more reasonable estimate of 15 cm/yr for the convergence rate, which is still higher than the present maximum rate.

It is difficult to escape the conclusion that very rapid subduction occurred at the edge of North America in the Late Cretaceous, which we know was a time of high spreading rates (Larson and Pitman, 1972). These high convergence rates may have applied along much of the northeastern edge of the Pacific Ocean where the Farallon plate was subducted, and it is likely that somewhere northwest of California, where the continental margin curved westward, fast, straight-in subduction occurred. We call attention to the probability of high subduction rates in the Cretaceous northeast Pacific. This fast subduction is likely to have had a drastic effect on the structural development, volume of melange formed, thermal profile, and metamorphic and igneous characteristics of these subduction zones.

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NOTE ADDED

After this paper had been submitted to the *Bulletin* and had received critical review, we presented it at the Lopez Island Penrose Conference on Cenozoic and Mesozoic Microplate Tectonics in October 1979. At that time, some criticism was voiced as to whether it was really possible to determine stratigraphic sequence by foraminiferal zonation based on study of thin sections from such a short stratigraphic sequence. As a way of confirming the micropaleontological zonation, D. L. Jones suggested collecting the chert beds and extracting the radiolarians.

The chert beds at locality LL2 were subsequently collected by Alvarez, and the radiolarians were extracted by D. L. Jones, who stated (1979, personal commun.):

> Radiolarians extracted by HF acid leaching from chert substantiate a mid-Cenomanian age for the lower part of the LL-2 sequence. *Novixitus mclaughlini* Pessagno ranges from sample 10.35 to 12.20 m, and *Pseudodictyomitra pseudomacrocephala* (Squinabol) ranges from 10.35 to 11.38 m. Both species are diagnostic of the radiolarian *Cassideus riedeli* subzone of the *Rotaforma hessi* zone. According to Pessagno (1976, p. 4) this radiolarian subzone is equivalent to the upper part of the *Rotalipora appenninica* planktonic foraminiferal zone.

The chert beds also yielded abundant silicified foraminifera which are presently under study by Premoli Silva.

In addition to the new micropaleontological material, collection of the chert led to a striking confirmation of the validity of the previous foraminiferal zonation. This zonation indicated that the LL-2 section was repeated, with the lowest portion (10.00 to 12.90 m) corresponding to the portion from 14.00 to about 16.00 m. We had not revisited the locality since the foraminiferal zonation was completed, but examination of the outcrop during sampling of the chert beds immediately led to recognition of a steep fault passing between samples 12.90 and 14.00 m (Fig. 7). We had missed this fault during previous field work, but when one knows where to look, it is an unmistakable feature. There is some suggestion that a characteristic sequence of five chert beds between 9.75 and 11.38 m correlates with a similar sequence from 14.25 to 15.48 m, supporting the foraminiferal zonation, but variability in the thickness of chert beds makes this correlation uncertain. However, we feel that this recognition of a feature predicted by the foraminiferal studies should remove any doubts on the validity of the biozonation and the resulting determination of the original top direction.

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