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Rates of late Cenozoic tectonism in the Vallecito–Fish Creek basin, western Imperial Valley, California

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ABSTRACT

The kinetics of continental rifting are recorded in the late Neogene sediments of the western Imperial Valley, California. The Gulf of California opened in its present form about 4 m.y. ago, capturing the Colorado River. Some 5 km of deltaic and fluvial sediments accumulated in the Vallecito–Fish Creek area during the interval 4.3–0.9 m.y. ago. Initial sedimentation rates were 5.5 mm yr^{-1}, which diminished in an exponential fashion to 0.5 mm yr^{-1}. When isostatic adjustments are accounted for, this implies tectonic subsidence rates of 1.5 mm yr^{-1}, decreasing systematically to 0.1 mm yr^{-1}. After 0.9 m.y. ago, right-lateral shearing along the Elsinore fault zone cut across the basin, causing it to be tilted and uplifted at a mean rate of 5.9 mm yr^{-1}. The basin was concurrently rotated as a unit 35° clockwise. The dissected pediments and badlands that now characterize the area were formed and eroded in the past 0.9 m.y.

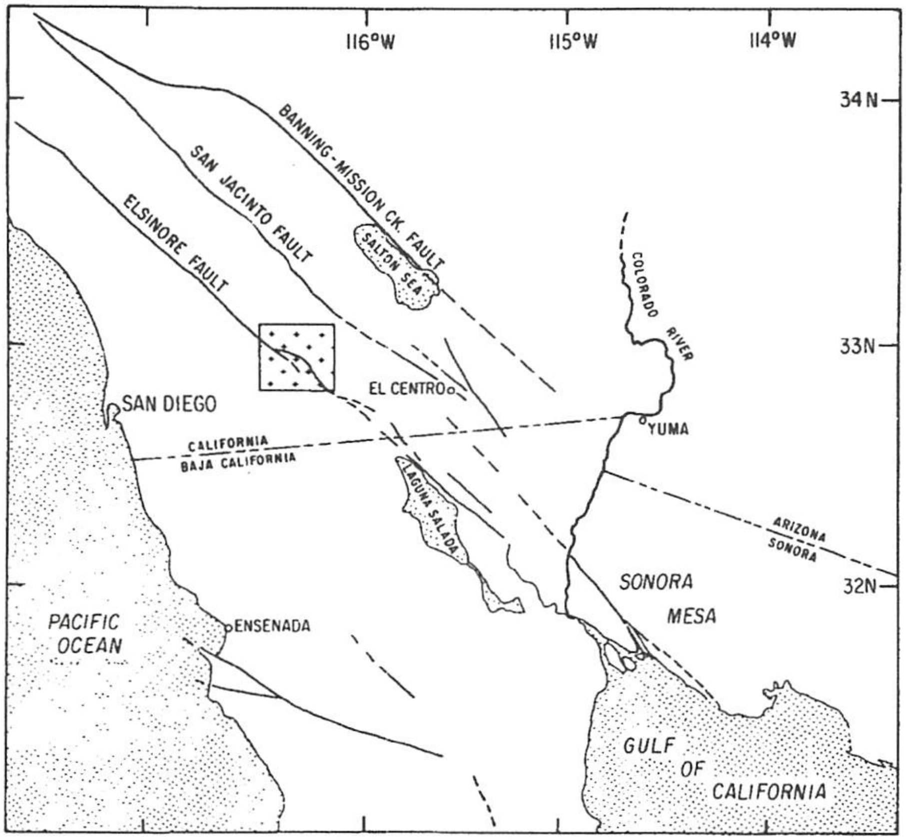

Figure 1. Location and structural setting of Vallecito–Fish Creek basin. Square with crosses = study area.

INTRODUCTION

We are concerned here with the rate and pattern of subsidence, uplift, and rotation associated with the rifting of continental crust. Our study area is the Vallecito–Fish Creek badlands situated in the western Imperial Valley of California (Fig. 1). Previous studies have established the structure (Woodard, 1974), paleontology (Downs and White, 1968; Ingle, 1974), and age (Opdyke et al., 1977) of the area. In this study we describe its tectonic history in terms of vertical displacement rates and the rotation associated with shearing.

SEDIMENTARY HISTORY

The Gulf of California opened about 4 m.y. ago as the Baja peninsula was detached from the Pacific coast of Mexico (Larson, 1972). The Colorado River system quickly reacted to this event by emptying into the newly formed Gulf of California and depositing its sedimentary load there (Merriam and Bandy, 1965; Lucchitta, 1972). The deltaic and fluvial deposits of the Vallecito–Fish Creek area reflect these events (Woodard, 1974). Sea water had spread over some parts of the lower Colorado watershed as early as 5.5 m.y. ago (Lucchitta, 1979), probably in response to crustal thinning preceding the actual rifting of Baja.

The stratigraphy of the Vallecito–Fish Creek area has been divided into four conformable formations—Anza, Split Mountain, Imperial, and Palm Spring. The basal unit is the Anza Formation, which is a coarse conglomerate some 350 m thick. It is interpreted by Woodard (1974) as a subaerial alluvial fan deposit. The Split Mountain Formation, about 200 m thick, conformably overlies the Anza Formation. It consists of a sequence of conglomeratic deposits interbedded with sandstone and gypsum. The sandstone member of the Split Mountain Formation contains marine foraminifera, and the gypsum member indicates an evaporitic, marine environment (Ingle, 1974). The sandstone and gypsum together represent the first certain incursion of sea water into the Vallecito–Fish Creek basin.

The basal sand of the overlying Imperial Formation is also marine and contains a variety of invertebrate fossils. The benthic species of foraminifera indicate a paleo-

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depth of more than 100 m (Ingle, 1974). However, most of the Imperial Formation consists of deltaic sand, silt, and clay from a Colorado River source (Merriam and Bandy, 1965) and contains numerous biostromes of *Ostrea* and other brackish water invertebrates. The uppermost beds of the Imperial Formation contain terrestrial land mammals (Downs and White, 1968). Thus, during Imperial time progressive shoaling occurred, with sedimentation eventually reaching sea level. During the subsequent deposition of the Palm Spring Formation, the area was characterized by terrestrial sedimentation rich in mammalian fossils (Downs and White, 1968). Significantly, these terrestrial deposits are commonly interspersed with beds containing *Ostrea* (Downs and Woodard, 1961), a tidal or shallow-water marine mollusc. Evidently, deposition of the entire Palm Spring Formation, about 4,100 m of sediment, took place at or near sea level. This could happen only if the mean rate of sedimentation during this time period was just equal to the mean rate of basin subsidence.

MAGNETIC POLARITY STRATIGRAPHY

Opdyke et al. (1977) published the initial paleomagnetic and magnetic stratigraphy of the Imperial and Palm Spring Formations. However, Opdyke later recognized that the published data contained a significant secondary overprint that had not been removed by alternating field demagnetization. Therefore, after thermal demagnetization at 500 °C, the entire data set was remeasured. Data of substantially improved quality resulted. Figure 2 shows a plot of all the site means that remained statistically significant after thermal demagnetization. The circles of confidence for the reversed and normal sites overlap, as required by the reversal test for stability, a condition not met by the data first published by Opdyke et al. (1977).

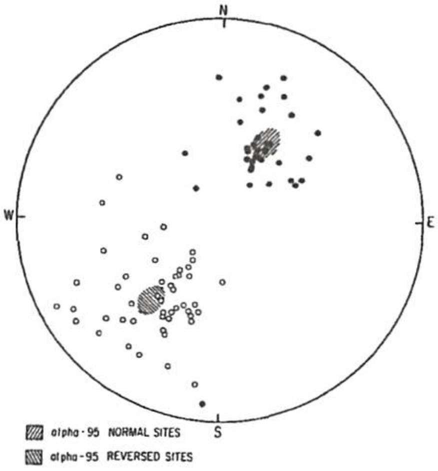

Figure 2. Distribution of polarity vectors for normal (solid dots) and reversed (open dots) paleomagnetic sites from Vallecito–Fish Creek basin. Only statistically significant sites ($k \geq 10$) after 509 °C thermal demagnetization are plotted. Mean vector for normal sites is declination 030.6°, inclination +41.6°, $\alpha_{95} = 7.4°$, $k = 13.1$; for reversed sites it is declination 219.4°, inclination -35.1°, $\alpha_{95} = 7.4°$, $k = 9.6$. Means of normal and reversed sites are antipodal given statistical uncertainty of means, so data represent positive reversal test. Note 35° clockwise rotation to data set relative to present geographic north-south.

The magnetic polarity zonation of the Imperial and Palm Spring Formations and its correlation with the magnetic polarity time scale is shown in Figure 3. Zircons from an air-fall tuff occurring at the 3.6 km stratigraphic level (Fig. 3), yield a fission-track date of 2.3 ± 0.4 m.y. (Table 1). The magnetic reversal that occurs at about the 3.6-km level was originally correlated (Opdyke et al., 1977) with the Gauss-Matuyama boundary (2.47 m.y. ago, according to Mankinen and Dalrymple, 1979) and the isotopic date (2.3 ± 0.4 m.y.) supports this original correlation.

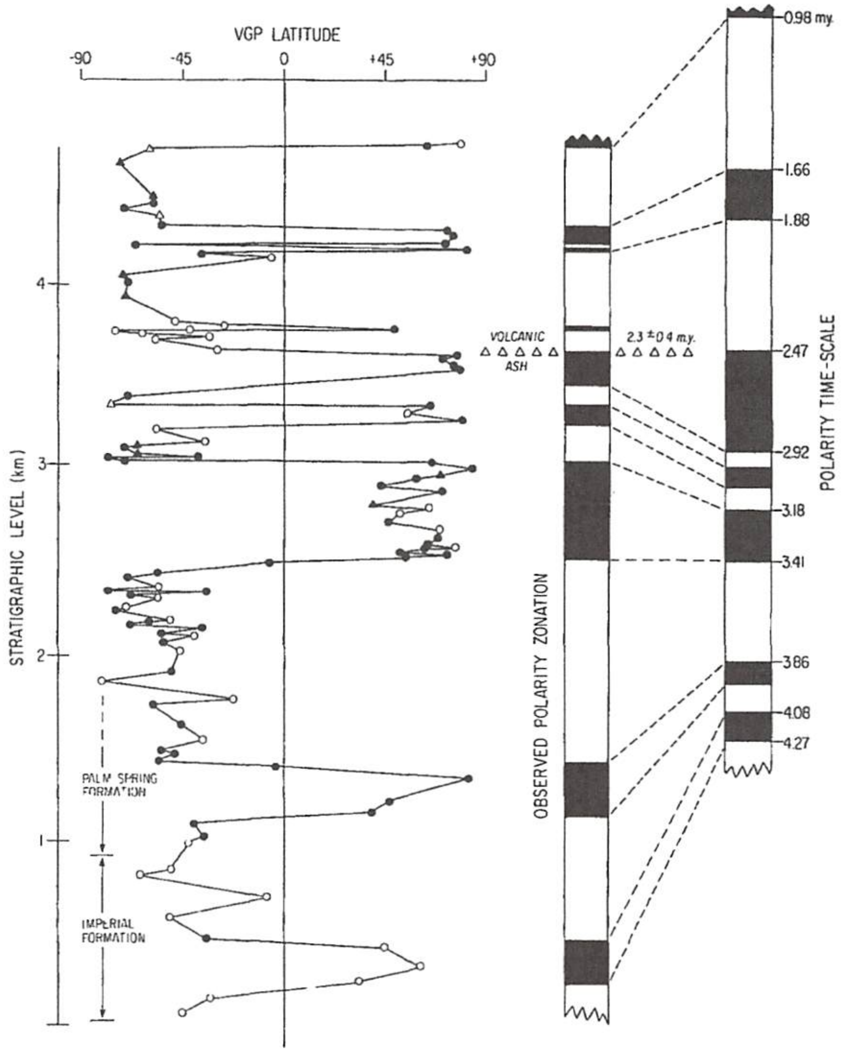

Figure 3. Magnetic polarity stratigraphy of Imperial and Palm Spring Formations of Vallecito–Fish Creek area. Circles indicate site means for samples thermally demagnetized at 509 °C. Triangles indicate site means for samples demagnetized by 200 Oe. Solid symbols mark site means whose *k* value exceeds 10. Open symbols represent data whose polarity is not in doubt, but which are not deemed statistically significant ($k < 10$). Ages for magnetic polarity time scale are taken from Mankinen and Dalrymple (1979). Note that observed polarity zonation is distorted compared with time scale, being compressed in its upper parts and expanded in its lower parts. This indicates differential sedimentation rates over time.

A statistical analysis of our paleomagnetic results also aids in this correlation (Table 2). The number of magnetic reversals that we found (17) with our given sampling program (107 sites) predicates that a 3.2-m.y. interval in the Neogene was most likely sampled (Table 2). Because we know both age (Table 1) and time span (Table 2) for the Vallecito–Fish Creek section, we are reasonably certain that our correlation of the magnetic stratigraphy with the magnetic time scale is correct (Fig. 3).

TABLE 1. FISSION-TRACK DATA FOR AIR-FALL ZIRCONS FROM 3.6 KM STRATIGRAPHIC LEVEL, VALLECITO-FISH CREEK SECTION

Age* (m.y.)	Fossil tracks No.	Fossil tracks Density (cm^{-1})	Induced tracks No.	Induced tracks Density (cm^{-1})	No. of grains	Correlation†	Neutron dose§ (cm^{-2})
2.3±0.4	63	7.06×10^{5}	378	8.48×10^{6}	10	0.91	4.64×10^{14}

*$\lambda_f = 7.03\times10^{-17}$ yr^{-1}; $\lambda_d = 1.55\times10^{-10}$ yr^{-1}; $\sigma_n = 5.80\times10^{-24}$ cm^2; $I = 0.00725$

†Isochron intercept not statistically different from zero. Error (2σ) calculated using method of McGee and Johnson (1979).

§Irradiated in U.S. Geological Survey TRIGA reactor. Dose monitored using muscovite detectors over NBS Glass SRM 962 (Cu calibration).

TABLE 2. EXPECTED TIME SPAN FOR OBSERVED MAGNETIC STRATIGRAPHY OF VALLECITO-FISH CREEK AREA

Given		Derived				
No. of paleomagnetic sites (N)	No. of reversals found (R)	Probability of finding reversal at given site ($p = R/(N-1)$)	Mean sample spacing* ($\bar{S} = f(p)$)	Expected time span§ ($\Delta t = \bar{S}\tau N$) (m.y.)	Sampling fluctuation ($\sigma = [p(1-p)(N-1)]^{\frac{1}{2}}$)	Coefficient of variance [(σ/R) 100] (%)
107	17	0.160	0.249±22%	3.2±22%	3.8	22

*From Johnson and McGee (1983, equation 7 ($p = \bar{S}/(2\bar{S}+1)$) and Fig. 3). Assuming samples are distributed with an exponential randomness over the stratigraphic section.

§Given mean polarity interval of the Neogene is 120,000 years.

SUBSIDENCE HISTORY

Figure 4 is a plot of sediment accumulation versus time for the Imperial and Palm Spring Formations. Each point in Figure 4 represents the age of a magnetic polarity reversal and the sediment thickness associated with it (Fig. 3). Figure 5 is a graph of sedimentation rate, as derived from Figure 4, versus time for the Imperial and Palm Spring Formations. During Imperial time (4.3–4.0 m.y. ago; Fig. 3) sedimentation rate was rapid (Fig. 5). It is noteworthy in this context that the Split Mountain and Anza Formations, which underlie the Imperial Formation, were also deposited rapidly as gravity deposits; boulder clasts 1–4 m in diameter are common in these formations (Woodard, 1974). The sedimentation rates depicted in Figure 5 are equivalent to total basin subsidence rates because the Imperial and Palm Spring Formations were deposited at or near sea level. To determine v', the tectonic subsidence rate component, the total subsidence rate, v, must be corrected for isostatic loading by the sediment column. The isostatic adjustment is time-dependent and is a function of the dimensions of the sedimentary basin. Using the relation given by Heiskanen and Vening Meinesz (1958, p. 369), the time constant for the Vallecito–Fish Creek basin is about 40,000 yr. Therefore, when considering the time scales of Figures 4 and 5, a 40,000-yr isostatic adjustment period is essentially instantaneous, and the steady-state relation $v' = [(\rho_m - \rho_s)/\rho_m]v$ may be used to determine v', where ρ_m is the mantle density and ρ_s the sediment density. When using values of $\rho_m = 3.3$ and $\rho_s = 2.4$, $v' = 0.27\ v$, giving the right-hand scale in Figure 5.

Sedimentation rates in the Vallecito–Fish Creek area decreased in a systematic manner from 5.5 mm yr^{-1} to less than 0.5 mm yr^{-1} over the period between 4.3 and 0.9 m.y. ago. The corresponding tectonic subsidence rates decreased from 1.5 mm yr^{-1} to about 0.1 mm yr^{-1}. These are substantial rates for the extended geologic time period covered (Mörner, 1980). The average tectonic subsidence rate over this time period is 0.4 mm yr^{-1}. This average subsidence rate can be checked by analyzing the present basement depth in the Gulf of California. The basement depth, h, is about 3,100 m (Larson, 1972). Using the relation $v' = [(\rho_m - \rho_w)/\rho_m]\ (h/t)$, with a value of $\rho_w = 1.0$ and $t = 4$ m.y., v' becomes 0.5 mm yr^{-1}. This value for subsidence of the gulf proper (0.5 mm yr^{-1}) is in good agreement with our average rate (0.4 mm yr^{-1}) for the Vallecito–Fish Creek basin.

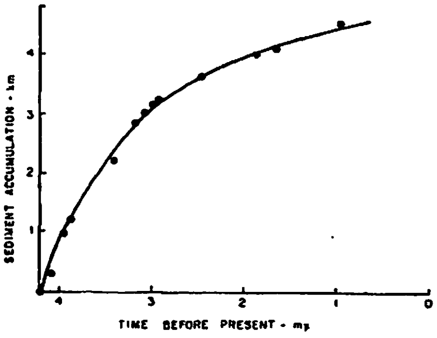

Figure 4. Sediment accumulation as function of time for Vallecito–Fish Creek basin. Data taken from Figure 3. Note that in this plot slope is equal to sedimentation rate.

UPLIFT AND ROTATION

The history of the Vallecito–Fish Creek area has changed radically from what it was 0.9 m.y. ago and has been dominated by a different set of geologic processes. The dissected pediments and the badlands found in the area today are the immediate evidence for these changes. Sediments that were buried 5.3 km below sea level 0.9 m.y. ago are exposed 100 m above sea level today, implying a mean uplift rate of 5.9 mm yr^{-1}. Correcting for the isostatic unloading of the eroded sediments gives a mean tectonic uplift rate of 1.6 mm yr^{-1}. Uplift rates for specific intervals may have

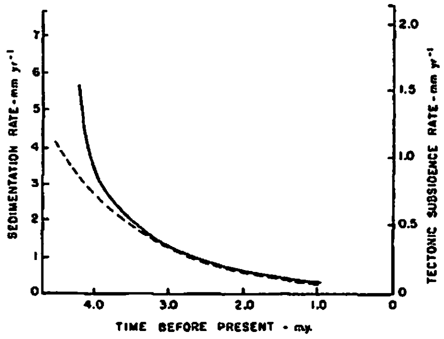

Figure 5. Sedimentation and tectonic subsidence rates (solid line) for Vallecito–Fish Creek basin. Data derived from Figure 4. Dashed line describes equation $s = s_0 \exp[-k(t_0 - t)]$ where $k = 1/1.27$ m.y. and $s_0 \exp(-kt_0) = 0.0341$ mm yr^{-1} (intercept parameter for tectonic subsidence rate). Note that theoretical curve is identical (although offset for illustration purposes) with observed curve over time interval 3.5 to 0.9 m.y. ago.

been well in excess of this mean value, as was the case for basin subsidence (Fig. 5).

The Vallecito–Fish Creek basin has been rotated clockwise about 35° since deposition ceased. This is shown by the orientation of the magnetic polarity vectors for the sediments with respect to present geographic north (Fig. 2). No rotation was manifested while the Imperial and Palm Spring sediments were being deposited, as indicated by their positive reversal test (Fig. 2). The clockwise rotation is consistent with the right-lateral motion of the Elsinore fault, which bounds the west side of the Vallecito–Fish Creek sediments (Gibson, 1983). Other structural features in the sediments are compatible with this northwest-southeast shear—folds indicating north-south compression, minor faults indicating antithetic northeast-southwest shear, and the fault-truncated sediments themselves abutting the Elsinore fault (Gibson, 1983).

CONCLUSIONS

On the basis of our interpretation of the magnetic polarity stratigraphy (Fig. 3), the age of the basal Imperial Formation is 4.3 m.y., which is essentially the same as the date given for the opening of the Gulf of California (Larson, 1972). It would appear, therefore, that the Vallecito–Fish Creek area was one of the earliest deltaic complexes for the Colorado River system in the newly formed gulf. Five km of marine, deltaic, and fluvial sediments accumulated over a 3.4-m.y. interval (4.3–0.9 m.y. ago). Sedimentation took place at or near sea level during the entire period, so that basin subsidence was equal to basin filling. Sedimentation rates decreased in a uniform manner from 5.5 mm yr^{-1} to less than 0.5 mm yr^{-1}. The corresponding tectonic subsidence rates decreased from 1.5 mm yr^{-1} to 0.1 mm yr^{-1}. The cause of the subsidence was most likely the thinning of continental crust associated with the rifting of Baja (Meidav and Howard, 1979).

We note also that the deposition of the Vallecito–Fish Creek delta was contemporaneous in part with the main downcutting of the Grand Canyon (>3.3 m.y. ago, according to Lucchitta, 1972). Thus, the Vallecito–Fish Creek delta is a repository for at least some of the material eroded from the Grand Canyon region.

Sedimentation in the Vallecito–Fish Creek basin ended abruptly some 0.9 m.y. ago; the basin was then deformed, uplifted, and truncated by pediment-forming erosion. A total uplift of 5.3 km took place at a mean overall rate of 5.9 mm yr^{-1}; the tectonic component is 1.6 mm yr^{-1}. During this phase the entire basin was rotated as a unit some 35° clockwise. The most likely cause of the uplift, rotation, and deformation is the right-lateral motion of the Elsinore fault acting on the pre-existing, undisturbed basin. At least 7 km of displacement along the Elsinore fault is required to account for the observed 35° rotation.

In summary, the tectonic history of the Vallecito–Fish Creek basin has two distinct phases. The first consists of crustal rifting and stretching that formed and maintained a sedimentary basin (4.3–0.9 m.y. ago); the second consists of shearing that deformed, uplifted, and rotated the basin (< 0.9 m.y. ago). The numerous pull-apart basins and grabens being formed today in the lower Imperial Valley (Aydin and Nur, 1982) probably represent the modern continuation of this shearing. It is appropriate to point out certain aspects of our data that must be accounted for by any prospective theoretical model (see, for example, Pálmason, 1982). Subsidence in the Vallecito–Fish Creek basin diminished exponentially with time during the latter stages of the basin's development (3.5–0.9 m.y. ago). However, before 3.5 m.y. ago, subsidence was considerably faster than would be predicted by the simple, exponential law (Fig. 5). If it were deemed necessary, the entire subsidence-rate curve for the Vallecito–Fish Creek basin (Fig. 5) could be fitted by a series of first-order decay components, or perhaps a single higher-order decay law. Nevertheless, the important feature is that for some 2.5 m.y., representing most of its history, the Vallecito–Fish Creek basin subsided according to a simple, exponential decay law with a time constant of 1/1.27 m.y. Any theoretical model explaining the origin of this basin must account for this form and rate of subsidence.

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