Curvature of the San Andreas fault, California

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ABSTRACT

The course of the San Andreas fault between Point Arena and San Bernardino undulates back and forth across a segment of a small circle with a radius of 9°. The pole of the circle is in southeastern Idaho, about 40 km (25 mi) south of Pocatello. This fault, associated with the great earthquakes of 1857 and 1906, is too curved to be a transform fault separating the rigid plates of North America and the Pacific.

INTRODUCTION

The northwest-southeast course of the San Andreas fault through the mountains near the California coast (Fig. 1) is known to millions of persons. In some places its trace seems to be a single straight line, but more commonly it is a broad zone containing two or more recent clean-cut breaks, either in alluvium or between strips and selvages of more or less crushed rock for a total width of several hundred metres to 15 km. The zone is an active fault. Creep and earthquakes occur along it. On April 18, 1906, the San Francisco earthquake resulted in measured right-lateral displacements of 1 to 6 m on its northern portion, from Point Arena to San Juan Bautista south of San Francisco. Similar displacements on a southern portion, between Cholame and Cajon Pass near San Bernardino, occurred in 1857 (Wallace, 1970; Sieh and Jahns, 1976). Creep and small earthquakes have since occurred on the short intervening portion. The fault extends northwest of Point Arena and southeast of San Bernardino; we have, however, limited our calculations to the active portion between those points, where displacements have been precisely measured.

For the purposes of this paper, we use plate tectonics. We assume that the lithosphere is made up chiefly of about a dozen major rigid plates, bounded by mobile belts that may include much smaller rigid plates. The big plates are in motion relative to each other, away from spreading zones of igneous upwelling and toward trenches or other sinks. Each plate is a segment of the Earth's spherical surface layer, whose motion can be described as rotation about an axis through the center of the Earth.

Where movement between two adjacent plates is parallel to the boundary between then, that boundary is called a transform fault. If the San Andreas is such a fault, its course should approximate a segment of a small circle whose radius may be used to locate the pole of relative movement between the Pacific and North American plates.

From the *Geologic Atlas of California* (1:250,000; Jennings and others, 1969), we prepared Table 1 showing the latitudes and longitudes of 27 points on the fault, between Point Arena and San Bernardino, together with the strike of a stretch through each point. We then obtained, using the least-squares criterion applied to the direction cosines, the circular arc best fitting the points. This arc on the spherical Earth can be described as the intersection with a cone whose apex is at the center of the Earth. The corresponding algorithm is given by the APL function (McIntyre, 1969; Iverson, 1972)

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    ∇ Z←CONE D
[1]   Z←(1×D[;1])⌹D
[2]   Z←(Z,1)÷(+/Z*2)*0.5
    ∇
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D is the matrix of direction cosines in three columns. Its rows correspond to the points on the sphere. *Z* is a vector of four components: the first three are the direction cosines of the axis of the least-squares cone, and the fourth is the cosine of the semiapical angle.

CURVATURES, POLES, AND RADII

The radius of the small circle that best fits the 27 points is 9.01°. The pole is at lat 42°21′N, long 112°27′W in southeastern Idaho about 40 km (25 mi) south of Pocatello. The fit, however, is not perfect. Inspection of Table 1 and Figure 1 or, better, the *Geologic Atlas of California* shows that the San Andreas fault zone is made up of two long sinuous stretches joined at a big bend. The northwestern stretch (points 1 through 17) has strikes varying about N40°W. Points 1 through 17 are best fitted by a small circle with radius of 14.08°, with a pole in southeastern Montana at lat 45°15′N, long 106°34′W. For essentially the same portion of the San Andreas fault, Morgan's selected points (Morgan, 1968) give 15.4°. Points 1 through 10, covering the stretch on which the 1906 displacements occurred, are best fitted by a small circle with a radius of 7.23° and a pole at lat 42°1′N, long 114°58′W, near the south Idaho border and due south of Boise. A long, smoothly curved stretch (points 7 through 15), however, is concave toward the southwest, with a radius of 10.28° and a pole in the Pacific Ocean at lat 29°10′N, long 129°40′W. The long southeastern stretch (points 19 through 27) has strikes varying about N66°W. It is concave toward the southwest, with a radius of 4.87° and a pole in the Pacific Ocean at lat 30°7′N, long 120°29′W. The big bend, in the San Emigdio Mountains and centered on point 19 southwest of Bakersfield, has a radius between points 14 and 22 of 2.2°, and the pole is at lat 36°51′N, long 117°59′W in the Inyo Mountains northeast of Owens Valley.

The distances of the 27 points from the computed pole near Pocatello and the deviations from the computed small circle are shown in the last two columns of Table 1. Radii shorter than the mean by 0.10° or more are in the long smooth stretch between points 9 and 14, which is concave to the southwest. Radii 0.10° or more longer than the mean are at points 1 and 2 near Point Arena and at points 17 through 19 in the big bend. The maximum deviations are 0.15° above the mean at points 1, 18, and 19, and 0.15° below the mean at point 11 (Fig. 1).

The uncertainties of location of the individual points probably range between ±0.5 and ±2.0 km. Charles W. Jennings, editor of the *Geologic Atlas of California*, estimated the probable errors of transcription from original field data at 025 km or less. The precision of our map measurements was probably ±1 km. The map projection was transverse Mercator, which preserves latitude and longitude. The makers of the topographic base maps stretched the spheroidal Earth to a sphere, but the resultant errors are insignificant. Where possible, we chose the 1906 earthquake trace or the straightest or most discordant geologic contact or, in alluvium, the probable hidden contact between such incompatible rocks as quartz plutonite and the Franciscan Formation. At San Bernardino we chose the fault branch at the mountain front; the other branch is 0.5 km farther north. In general, the range in the width of the fault zone and the uncertainties of location of the points are small enough so that measured deviations from circular of 4 km (0.04°) or more are quite surely real.

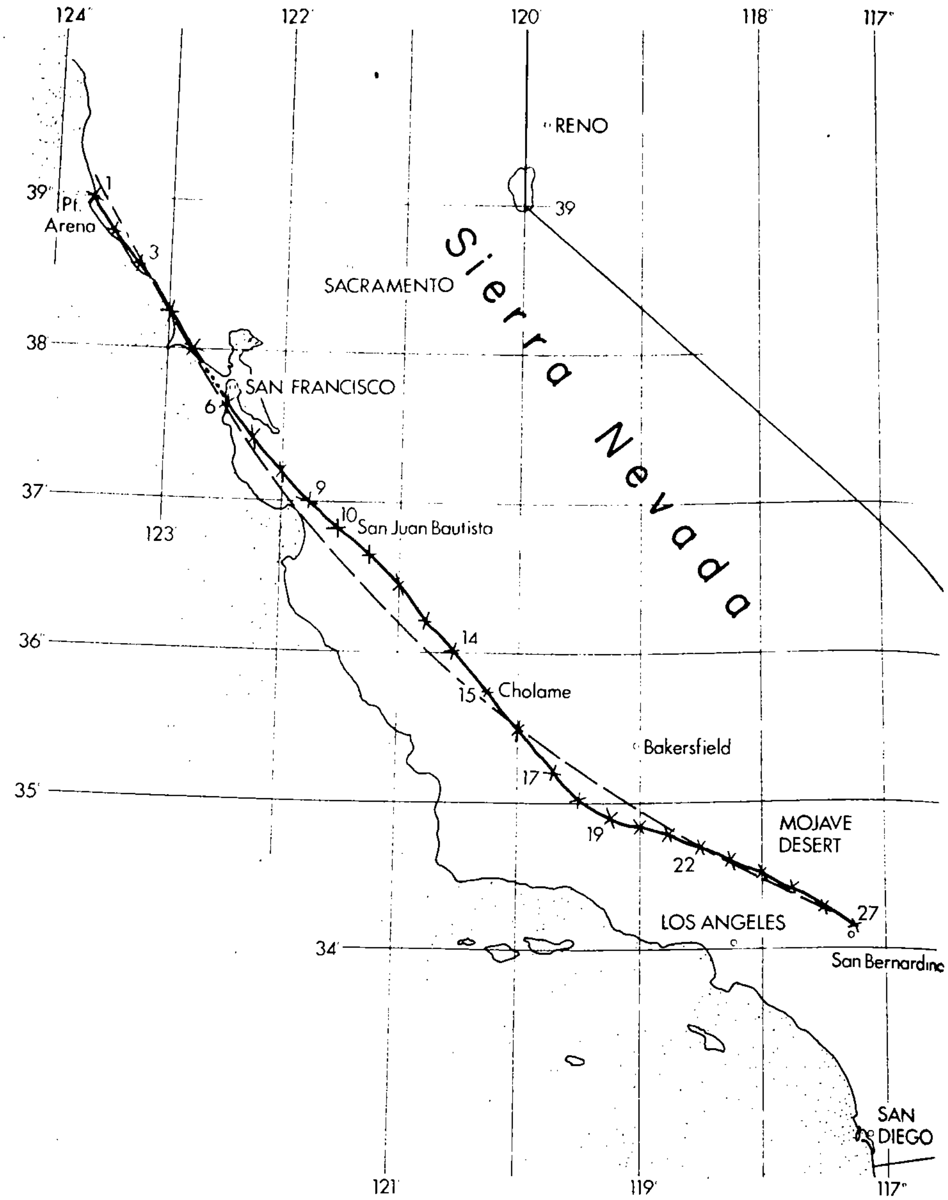

Figure 1. Map of part of California, showing 27 points on the San Andreas fault zone and the small circle (dashed line) that fits them best.

DISCUSSION

The sinuous course of the fault is perhaps what one should expect of a rotation that left a slice of the varied rocks at the west edge of the North American continent adhering to the Pacific plate. The surprising feature is the 9° radius. At the mouth of the Gulf of California, rotation on transform faults that may mark the boundary between the North American and Pacific plates or may involve accessory platelets seems to have been on a circle of about 40° radius (to the Gulf mouth), with a pole at lat 52°N, long 73°W, southeast of James Bay (Chase, 1972; Larson, 1972). The Chase pole gives radii to points on the San Andreas fault ranging from 36.165° (point 27) to 37.083° (point 7), a difference of 0.918° or 102 km. Two other proposed radii are to poles in the Atlantic Ocean (Morgan [1968]—lat 53°N, long 53°W, and Le Pichon [1968]—lat 53°N, long 47°W).

The San Andreas fault, if its 9° radius is usable throughout its course, cannot extend much south of lat 33°N, just south of the Chocolate Mountains in southeastern California. The Newport-Inglewood, San Jacinto, and other faults striking about N 50°W, southwest of the San Andreas curve, may belong to a pervasive system that includes faults with similar strike that extend from the Mojave Desert into the San Bernardino Mountains. Such a system would cross the San Andreas curve and might include some of the faults in or near the mouth of the Gulf of California.

The San Andreas fault, the Gulf of California, and the East Pacific Rise seem all to be on the same edge of the Pacific plate. If movements in or on all three have occurred simultaneously, the Pocatello pole may mark the axis on which the gulf has spread in the past few million years (see, however, Sharman and others, 1976). The mouth of the gulf is about 21° from the Pocatello pole, and its width, perpendicular to the East Pacific Rise, is about 300 km (Larson, 1972). At lat 31°N, opposite San Felipe in Baja California, 10.5° from the pole, the width of the gulf is 150 km and may be approximately the same as the gap between the peninsular siliceous crust and that of the main continental mass to the east. At lat 34°N, the Salton trough, the northern continuation of the gulf, is 30 km wide and ends abruptly against the southern San Bernardino Mountains. In these mountains the San Andreas fault splays out and may end. Detailed geologic mapping there and in the Little San Bernardino Mountains to the southeast is needed to test this possibility. A fault that extends southeast along the northeastern edge of the Salton trough seems to be the continuation of the

TABLE 1. DATA ON POINTS 1 THROUGH 27 ALONG SAN ANDREAS FAULT

Location*	Lat†	Long†	Strike§ (°)	Distance# (°)	Deviation** (°)
1 Just north of Point Arena	39 0.00	123 42	35.0	9.16	0.15
2 Gualala Point	38 47.00	123 30	36.00	9.11	0.10
3 Near Fort Ross	38 32.00	123 15	37.5	9.05	0.04
4 Bodega Bay	38 16.00	123 0	34.5	9.01	0.00
5 East of Point Reyes	37 59.00	122 45	33.0	8.99	–0.02
6 Mussel Rock	37 41.00	122 30	36.0	8.99	–0.02
7 West of Los Altos	37 23.00	122 15	37.0	9.00	–0.01
8 South of Saratoga	37 11.00	122 0	44.5	8.97	–0.04
9 West of Gilroy	37 1.00	121 45	36.5	8.92	–0.09
10 San Juan Bautista	36 49.00	121 30	50.0	8.89	–0.12
11 East of Salinas	36 39.00	121 15	47.0	8.86	–0.15
12 East of the Pinnacles	36 25.00	121 0	38.0	8.87	–0.14
13 East of King City	36 10.00	120 45	42.0	8.91	–0.10
14 West of Kettleman Hills, North Dome	36 0.00	120 33	43.0	8.92	–0.09
15 Cholame	35 42.00	120 15	38.0	8.99	–0.02
16 East of Santa Margarita	35 27.00	120 0	38.0	9.05	0.04
17 Carrizo Plain	35 12.00	119 45	42.5	9.13	0.12
18 Southwest of Taft	35 1.00	119 30	48.0	9.16	0.15
19 Southwest of Bakersfield	34 52.50	119 15	68.0	9.16	0.15
20 Cuddy Valley	34 49.50	119 0	74.0	9.09	0.08
21 Quail Lake	34 46.00	118 45	72.0	9.04	0.03
22 South of Neenach	34 41.75	118 30	70.0	8.99	–0.02
23 Southwest of Lancaster	34 36.25	118 15	65.5	8.97	–0.04
24 Pearland	34 31.00	118 0	63.5	8.95	–0.06
25 Northwest of Wrightwood	34 24.00	117 45	64.0	8.97	–0.04
26 Pine Canyon, Cajon Pass	34 17.00	117 30	59.5	8.98	–0.03
27 San Bernardino	34 9.00	117 15	61.0	9.02	0.01

* Locations shown in Figure 1.
† In degrees and minutes.
§ West of north.
\# Distance from the Pocatello pole.
** Deviation from 9.01° of the distance from Pocatello pole, with minus sign for short radii.

east-trending Banning fault that marks the north end of the Peninsular Ranges, although it is mapped by some as a continuation of the San Andreas fault.

The 9° radius of points 1 through 27 and the 14° radius of points 1 through 17 are within the range of radii of the many arcs in east and southeast Asia that were recognized as circular by Sollas (1903), considered the outcrops of planar thrusts by Lake (1903, 1931a, 1931b), and now called subduction zones. The San Andreas fault, however, is vertical or nearly so, and movement on it is mostly strike slip. The similarity in curvature of outcrop seems to be accidental.

A pole at Pocatello is too close to the border between North America and the Pacific to permit much relative movement on the San Andreas fault as a transform between these large plates. Atwater expressed the view that it is "almost certainly too simplistic" to view the San Andreas fault as a "simple boundary between 2 large, perfectly rigid plates" and suggested that western North America might be considered "a very wide, soft boundary between 2 rigid, moving plates" (Atwater, 1970, p. 3525). Actually, she based her interpretation of the geology of California on geometry derived by Morgan (1968), whose data included latitudes and longitudes of the San Andreas fault read from a map on the scale of 1:2,500,000 (California Div. Mines and Geology, Bull. 190, 1966, Pl. 1). We have shown above that Morgan's points indicate a radius close to our value for the same stretch of the San Andreas fault.

In order to create a manageable model of global tectonics, it may be convenient to treat as a unit, as Morgan did, a series of transform faults from Alaska to the Gulf of California. Because a long arc necessarily has a large radius, the implied axis of rotation of North America with reference to the Pacific plate is likely then to lie far to the east of Pocatello. But a theoretical transform fault, however appealing, must not be confused with the San Andreas fault mapped by geologists, which ruptured long segments of the surface in the great earthquakes of 1857 and 1906.

It is now apparent that caution is necessary in applying plate tectonics to the interpretation of California coastal geology. Details of local stratigraphy and structure should be taken into account. Then a geologic history may be discerned that will be useful in the solution of practical human problems and also significant for the understanding of the changes going on in the interior of the Earth.

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ACKNOWLEDGMENTS

Reviewed by Mason L. Hill.

We have gratefully incorporated in our manuscript suggestions made by A. K. Baird, A. F. Glazner, M. L. Hill, K. E. Iverson, T. H. McCulloh, D. M. Morton, and J. E. Schoellhamer.

MANUSCRIPT RECEIVED APRIL 26, 1976
MANUSCRIPT ACCEPTED JUNE 18, 1976