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Deformation Of The Pacific Plate Near San Francisco, California

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Abstract. Observations of deformation on the margin of the Pacific plate opposite San Francisco, California, are yielding some new data concerning the distribution of relative motion along this section of the Pacific-North American plate boundary. Since 1978 three geodetic lines from the Farallon Islands to stations near the San Andreas fault have been measured. During this time, there has been very little deformation of the crust on the western side of the San Andreas fault. The observed distribution of relative motion is inconsistent with models of the plate boundary which have all of the displacement occurring on the San Andreas fault. The observations suggest that, in north-central California, the difference between the slip observed along the San Andreas fault (30± mm/yr) and the inferred plate motion rate (55± mm/yr) cannot be explained by slip west of the San Andreas fault as others have recently suggested. These observations are best fit by a dislocation model with no slip (±8 mm/yr) on the San Gregorio fault and 15 mm/yr (±2 mm/yr) below 8 km on the San Andreas fault. The absence of crustal deformation on the western side of the fault sharply contrasts to the eastern side of the fault.

Direct measurements of the rate of displacement across the San Andreas fault system in central California give a value of about 30 to 35 mm/yr for the rate of motion of the Pacific plate toward the northwest relative to the North American plate (1). On the other hand, global reconstructions of the relative motion of the Pacific and North American

plates suggest a rate of 55 mm/yr over the past few million years (2). The explanation for this apparent discrepancy has been a subject of discussion for many years. It has frequently been suggested that the balance of the relative motion occurs in the Basin and Range province (3). Recently, Minster and Jordan (4) concluded that the missing relative motion could not be accounted for by slip located east of the San Andreas fault and that the difference must be made up by relative motion occurring west of the San Andreas fault.

Because the San Andreas fault runs along the edge of the continent throughout much of central California, it is difficult to make direct geodetic measurements of the rate of deformation. The Farallon Islands, located 50 km west of the Golden Gate entrance to San Francisco bay (Fig. 1), provide a unique exception. The islands are not ideally suited for making geodetic measurements: Because of prevailing coastal fog, they are only visible from the coast a few days a year; in addition the presence of a wildlife sanctuary on the islands precludes helicopter access. In spite of these obstacles, the U.S. Geological Survey began trying to observe the distance to the Farallon Islands from three coastal stations in the mid 1970's. It was several years before we were able to make the first measurements of these lines, and it was only after the last round of measurements that we were able to obtain reliable estimates of the rates of change of line length, and consequently the rate of crustal deformation west of the San Andreas fault.

All of the stations shown in Fig. 1 and discussed in this paper are marked by standard survey monuments. The distances between the stations were measured with a Geodolite, a comercially manufactured laser surveying instrument. To determine the refractivity of the

intervening atmosphere with sufficient precision, the temperature and humidity of the air along the line of sight between station pairs was directly measured from a light aircraft at the same time that the distance was measured. The air pressure was measured at the endpoints of each survey line. These techniques have been used to measure a large number of lines during the past 15 years; experience indicates that the precision of the measurements is about 0.2 ppm for long lines, like those to the Farallon Islands (5). For all the lines shown in Fig. 1, one standard deviation uncertainty in the length is from 5 to 10 mm. All of the observations that we have been able to make are shown in Fig. 2. Observations made at the end of 1984 and at the beginning of 1985 appear anomalous and we believe they are incorrect; that is, we attribute these anomalies to survey error rather than to a real change in line length. Evidence to support this interpretation is the fact that for two lines (Farallon to Pt Reyes Head and Farallon to Tamalpais) remeasurement a few weeks later did not confirm the anomally but rather fell on the previously observed trend. The deviant observation of the line Farallon to Sweeney occurred on a day when only that line was measured. We were unable to repeat the observation until late 1984, at which time the distance was essentially the same as all of the earlier measurements. Given the small number of observations, the simplest interpretation of the data is that the changes have occurred as a linear function of time. With the exception of the three observations early in 1984, the data for all of the lines in Fig. 2 fit a least-squares straight line within one standard deviation. Fig. 2 also includes data for the remainder of the lines shown in Fig. 1. Best-fitting rates for all the lines are given in Table 1.

While some right lateral shear is occurring near the San Andreas fault, as indicated by three lines from Tamalpais (to Pt. Reyes, to Pt. Reyes Head, and to Sweeney) little deformation is occurring at greater distances from the fault. In fact, the previously reported (6) high strain rates near the San Andreas fault are sufficient to account for all of the observed changes in the two low angle fault crossing lines to station Tamalpais. The absence of extension in the Farallon to Sweeney line or contraction in the Farallon to Pt. Reyes Head line places some constraints on the location of slip along the plate boundary.

To determine the rate and location of fault slip most consistent with the observed rates of change of line length, we modeled the interseismic faulting process with a screw dislocation embedded in an infinite elastic half space (7). A slip discontinuity extended from a specified locking depth to infinite depth. The model parameters are the locking depth above which there is no slip and below which there is uniform slip, and the slip rate below the locking depth. Initially two faults were considered: the San Andreas, which was approximated as infinite in length, and the San Gregorio, which was semi-infinite with one end in the middle of the network. The geometry of the faults and the location of the slipping surfaces were specified and the observations were used to determine the slip rates. None of the solutions for the San Gregorio fault differed significantly from zero. For example, a model that allowed slip below 10 km on both faults had a significant slip rate on the the San Andreas fault, but left lateral slip of 3 ± 8 mm/yr on the San Gregorio fault. Consequently the San Gregorio fault was omitted from subsequent models. We examined models with locking depths ranging from 1 to 30 km (Table 2). The least-squares best-fitting model

included right lateral strike slip at a rate of 14.8 ± 1.9 mm/yr below a depth of 7.8 km on the San Andreas fault. The data suggest a locking depth between 5 and 10 km with corresponding slip rates of 11.1 and 17.6 mm/yr (Table 2). This range is probably a more realistic estimate of the uncertainty in the determination of slip rate than the 1.9 mm/yr quoted above, a figure that came from a solution with the depth of locking specified. Table 1 compares the rates of change of line length implied by the model with the observed rates of change. The agreement is excellent in all cases except for the line Farallon to Tamalpais. Extension of this line implies relative crustal motion normal to the trend of the faults. The model produces no significant normal motion of either station. An alternate way to examine these data is to solve for the relative motion of the stations directly. A variation of coordinates adjustment (8) of the observations produced the following results: Station Farallon is moving northwest at a rate of 3.0 mm/yr relative to Sweeney, Pt. Reyes Head, and Pt. Reyes. Tamalpais is moving southeast at a rate of 4.4 mm/yr relative to the same set of stations. Consequently the relative motion across the network is 7.4 ± 1.8 mm/yr. The model derived above predicts 9.2 mm/yr of relative motion between Tamalpais and Farallon, a reasonably good agreement. The near agreement between the two calculations is not surprising since they are based on the same data set, but it does serve to confirm that we are interpreting the results correctly. The displacement adjustment provides one new piece of information. From Table 1 it is apparent that the line Farallon to Tamalpais is lengthening, but it is not obvious whether this lengthening is due to motion of Farallon, to motion of Tamalpais, or to some combination. The displacement adjustment makes

it clear that it is Tamalpais that is moving away from the fault relative to the other stations. The normal motion of all four of the other stations is the same to within 0.5 mm/yr.

These results, when combined with earlier studies of this area provide a remarkably simple picture of the distribution of relative plate motion in north central coastal California. South of Hollister, California (Fig. 1), the relative motion between the Pacific and North American plates is concentrated on the San Andreas fault. Relative motion across the San Andreas fault occurs by aseismic creep at a rate of about 33 mm/yr with no evidence of strain in the adjacent crust (9). At Hollister the creep rate (i.e., aseismic slip at the surface on the fault trace) on the San Andreas fault drops from 33 mm/yr to about 12 mm/yr. Just east of Hollister, at San Juan Bautista, the creep rate drops to zero. The results of Prescott et al. (6) and the work discussed here suggest that slip at a rate near 12 mm/yr continues on the San Andreas fault north of the Hollister-San Juan Bautista area. North of San Juan Bautista the slip does not extend all the way to the surface but rather is only occurring at depth. Presumably, elastic strain is accumulating above the locking depth. It is probably not a coincidence that in addition to being the northern end of the creeping section of the San Andreas fault, San Juan Bautista is also the southern end of the surface rupture associated with the 1906 San Francisco Earthquake (10).

North of Hollister, slip not occurring on the San Andreas is accounted for by the Calaveras fault and other faults to the east of the San Andreas fault (6). North of latitude 38° the slip is very broadly distributed, to the east of the San Andreas fault, with no evidence of any localization to a particular fault (11). Consequently, from San Juan

Bautista to Pt. Reyes the relative motion between the two plates is about 35 mm/yr and the San Andreas fault's share of the motion appears to be between 10 and 15 mm/yr.

South of Hollister, on the western side of the San Andreas fault, there are a number of subsidiary faults, some of which appear to have been active in Quaternary time (12). The westernmost of these is the San Gregorio-Hosgri fault, which joins the San Andreas fault near station Tamalpais. The Farallon Islands, located almost on the continental slope, are west of all the known active plate margin faults in California. Since the only deformation occurring between the San Andreas fault and the Farallon Islands is the small amount that is localized near the San Andreas fault, it follows that these faults of the western Coast Range province do not make a significant contribution to the relative plate motion at the present time.

On the eastern side of the San Andreas fault the situation is completely different. Perhaps 1/2 to 2/3 of the total relative motion (30-35 mm/yr) is occurring as slip distributed over a broad zone extending 30 km or more northeast of the San Andreas fault (11). An important question is whether this strain is elastic and will be released on faults other than the San Andreas during future earthquakes, or whether the strain is anelastic and represents permanent deformation of the crust on the eastern side of the San Andreas fault (13). The fact that there are neither historical records of very large earthquakes on these other faults nor is there geological evidence of large offsets on them suggests that the latter situation prevails.

Offset on the San Andreas fault during the 1906 earthquake was 2 m along the San Francisco peninsula and 4 m north of the Golden Gate (14).

Assuming uniform rates of strain accumulation and slip rates of 11 to 18 mm/yr (15), the next 1906-like event should occur in the interval 2017 to 2087 south of San Francisco and 2128 to 2269 north of San Francisco. However, there is some evidence to suggest that the rate of strain accumulation is not linear (16). If the rate of strain accumulation was indeed higher following the 1906 event, then the next earthquake might be expected earlier than indicated above.

Three studies (6, 9, 11) have estimated the total relative motion of the Pacific plate relative to North America at about 33 mm/yr for various parts of the region shown in Fig. 1. This rate is significantly lower than the 55 mm/yr derived from plate motion reconstructions (2). This discrepancy continues to be one of the major unresolved problems of western North American tectonics. Our measurements to the Farallon Islands make it very difficult to explain this discrepancy by placing the deficit on the western side of the San Andreas fault.

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15. In the simplest model, the recurrence interval between great earthquakes equals the slip during an event divided by the rate of slip at depth between events.

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17. We thank A. Lindh and C. Mortensen for their comments on the manuscript.

Table 1

Best fit rates of change of line length.

Line	Length (Km)	Azi	dl/dt (mm/yr)	Model (mm/yr)	Comparison (mm/yr)
Farallon-Pt Reyes Head	33.0	358.0	-1.9 ± 1.4	-0.5	-5.0
Farallon-Sweeney	49.0	101.5	+1.3 ± 2.1	+2.9	+7.5
Farallon-Tamalpais	43.4	55.1	+4.4 ± 1.6	+0.1	
Pt Reyes-Pt Reyes Head	15.9	234.2	+0.1 ± 0.7	+0.0	
Pt Reyes-Tamalpais	29.3	125.8	+5.1 ± 0.8	+4.7	
Pt Reyes Head-Tamalpais	37.5	102.3	+6.1 ± 1.8	+6.2	
Sweeney-Tamalpais	37.0	340.9	-3.7 ± 1.5	-4.8	

The column entitled **dl/dt** contains the slope of the linear least-square-fit to the observations of the individual lines; the column entitled **Model** contains the model fit to the observations for all of the lines; and the column entitled **Comparison** contains the rate at which a similarly oriented line located on the eastern side of the San Andreas fault would change based on the work described in (13).

Table 2

Best fitting models for slip on the San Andreas fault.

Locking Depth	$\dot{u}$	σ	σ_0
km	mm/yr		
30	40.1	5.6	1.704
20	29.5	4.0	1.510
15	23.8	3.2	1.397
10	17.6	2.3	1.301
7.8	14.8	1.9	1.278
5	11.1	1.5	1.283
1	6.3	0.8	1.396

$\dot{u}$ is the inferred slip rate;

σ is the standard error of the slip rate;

σ_0 is the standard error of an observation of unit weight, a measure of the model fit.

Figure Captions

Figure 1 - Map of central coast of California showing traces of the major faults (solid lines) and the geometry of the survey lines used in this report.

Figure 2 - Distance observations for the survey lines in Fig. 1. Error bars indicate one standard deviation either side of observed value.

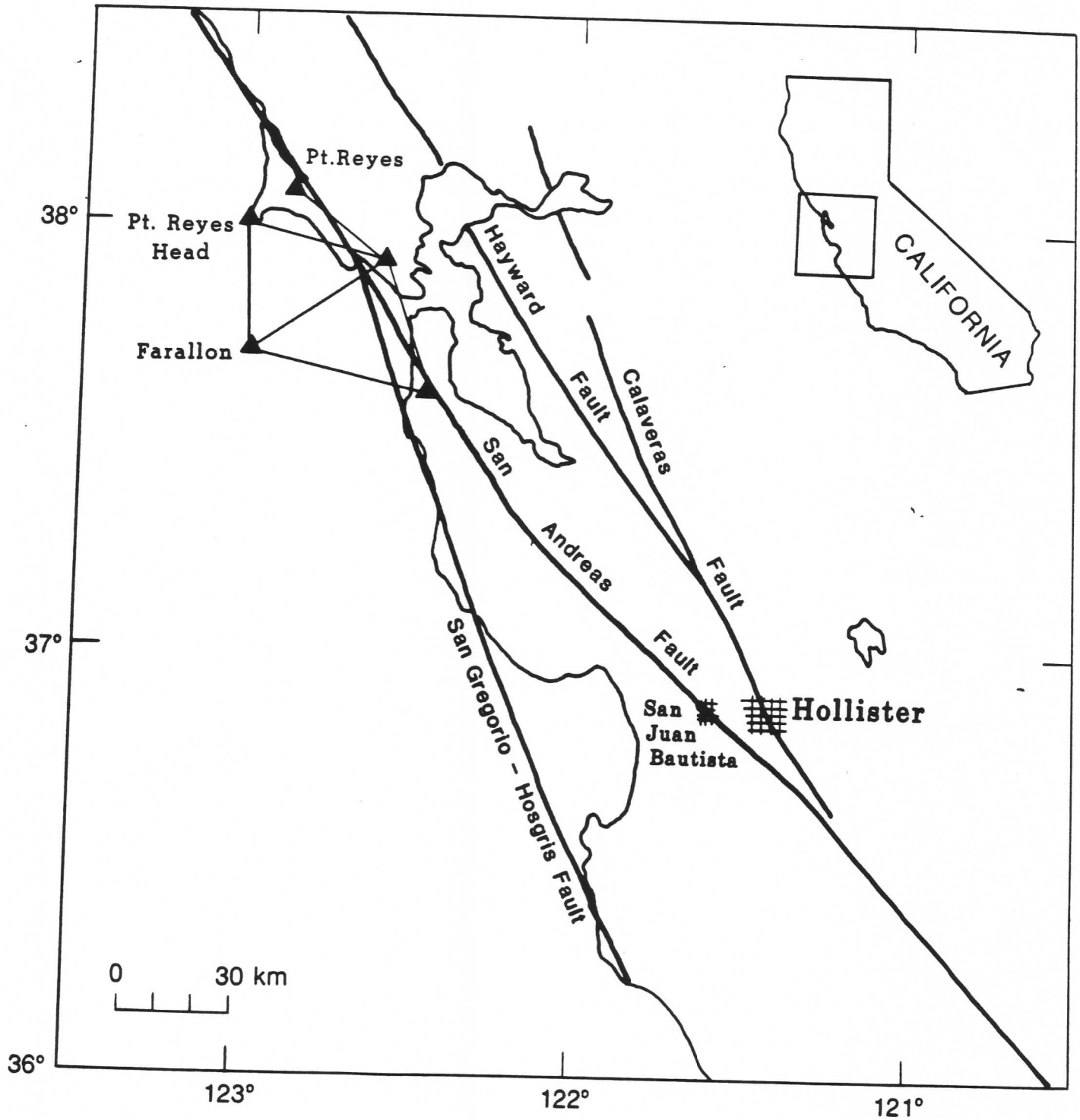

Pt.Reyes
38°
Pt. Reyes
Head
Farallon
Hayward
Fault
Calaveras
Fault
San
Andreas
Fault
San Gregorio - Hosgris Fault
37°
San
Juan
Bautista
Hollister
CALIFORNIA
0
30 km
36°
123°
122°
121°

Fig. 1

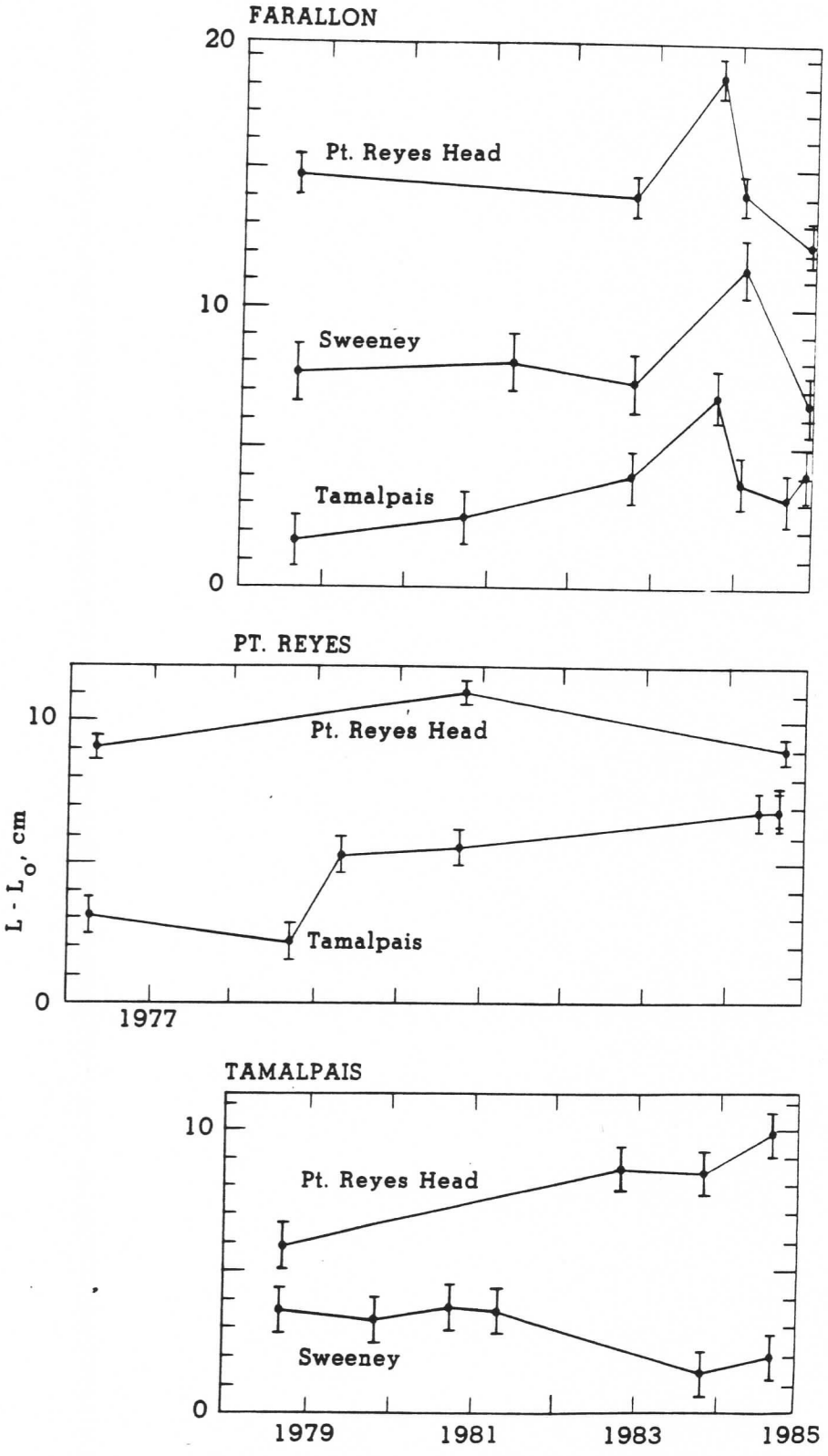

FARALLON
20
10
0
Pt. Reyes Head
Sweeney
Tamalpais
PT. REYES
10
0
L - L$_o$, cm
Pt. Reyes Head
Tamalpais
1977
TAMALPAIS
10
0
Pt. Reyes Head
Sweeney
1979
1981
1983
1985

Fig. 2