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LAKE LEVEL OBSERVATIONS TO DETECT CRUSTAL TILT: SAN ANDREAS LAKE, CALIFORNIA, 1979-1989

R. J. Mueller, M. J. S. Johnston, G. D. Myren

U. S. Geological Survey, Menlo Park, California

T. Murray

Cascades Volcano Observatory, Vancouver, Washington

Abstract. A pair of precision lake level gauging stations, installed in 1978, have been monitoring differential crustal uplift (crustal tilt) at San Andreas lake, California, near the suspected epicenter on the San Andreas fault of the M=8.3, 1906 San Francisco earthquake. The stations are installed in the lake with a 4.2 km station separation parallel to the San Andreas fault. The gauging stations use quartz pressure transducers that are capable of detecting intermediate to long-term vertical displacements greater than 0.4 mm relative to a fluid surface. Differencing data from the two sites reduces the noise contributed by atmospheric pressure, temperature, and density changes, and isolates the relative elevation changes between the ends of the lake. At periods less than 20 minutes, the differenced data are dominated by lake seiches which have a fundamental mode at a period of 13±0.3 minutes. These seiche harmonics can be filtered or predicted and removed from the data. Wind shear, typically lasting several days, can generate apparent short term tilt of the lake and large seiche amplitudes. The tilt noise power spectrum obtained from these data decreases by about 15 dB/decade of frequency. Monthly averages of the data between 1979 - 1989 indicate a tilt rate of 0.02±0.08 microradians/yr (down S34°E). No measurable horizontal tilt has apparently occurred in this region of the San Andreas fault during the last decade, however, measurements of trilateration networks show this region to be undergoing a horizontal strain of 0.6±0.2 μstrain/yr.

Introduction

Large-scale ground tilting is expected to accompany moderate to large earthquakes and, as a consequence, many attempts have been made to use relative sea level measurements to monitor the earthquake process (*Yamaguti*, 1968; *Wyss*, 1976a,b; *Lagios and Wyss*, 1983; *Hurst and Beavan.*, 1987). This paper describes an experiment to monitor crustal deformation by measuring lake level changes near the San Andreas fault in California at a higher precision than can be attained in the open ocean. Two lake level gauging stations, operated since 1978, are installed in a man-made fresh water reservoir (San Andreas lake) 17 km south of San Francisco, California, Figure 1. San Andreas lake lies directly on the trace of the San Andreas fault and is part of the water system operated by the San Francisco Water Department.

The lake is located near the suspected epicenter of the M=8.3, April 18, 1906, San Francisco earthquake (*Boore*, 1977). Seismicity since this time has been relatively low except for two periods (in the late 1950's and in the early 1970's) when numerous earthquake swarms occurred and caused minor damage, most evident in Daly City, Figure 1 (*Bolt and Miller*, 1975).

If changes in vertical displacement of the earth's crust occur at opposite ends of the lake for tectonic (or other) reasons, these displacements will result in an apparent change in water level at the two gauging stations. The spatial averaged crustal tilt θ would be given by

$$\theta = \Delta h / L \tag{1}$$

where Δh is the apparent change in water level and L is the distance between gauging stations. Because San Andreas lake is long and narrow, tilt can be determined only in a direction parallel to the San Andreas fault (N34°W). This paper describes the installation of water level monitors in San Andreas lake, measurement limitations, and the apparent tilt observed in this critical location during the period 1978-1989.

Installation

The lake level gauges use absolute pressure transducers (0-45 psia) installed on benchmarks two to three meters below the lake surface. The benchmarks consist of a triangular baseplate bolted in each corner to three independent lengths of 1.2 cm diameter copper ground-

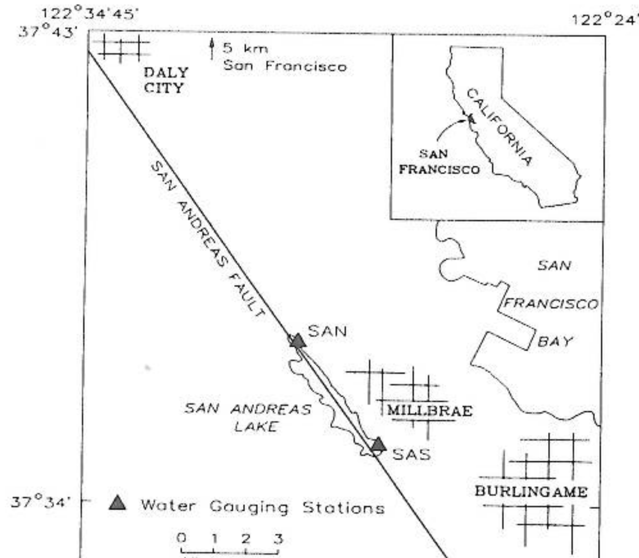

Fig. 1. Location of water level monitoring sites (triangles) in San Andreas lake, California. The line through the lake represents the trace of the San Andreas fault.

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ing rod, which were hammered into the lake bottom to the point of refusal. The lengths of copper grounding rod in the ground are typically more than four meters. Water pressure is measured with model 8020 Paroscientific Digiquartz pressure transducers mounted in sensor holders that are bolted to the benchmarks. The transducers were chosen for their long term stability, accuracy, range, and design for use in underwater marine environments. The quartz sensors generate a frequency which varies between 40 Khz and 36 Khz as the water depth increases from 0 m to 20 m.

Prior to 1984, data from the two individual transducers were transmitted to a microprocessor located between the two sites which converted the frequency to water depth, differenced the two measurements, and telemetered the difference every 10 minutes to U. S. Geological Survey computers located in Menlo Park, California. Since 1984, the frequency output at each gauging station was either recorded at each site or telemetered via GOES satellite telemetry (*Silverman et al.*, 1989) to Menlo Park where the data are processed and analyzed. Since 1988, water temperature, air temperature, atmospheric pressure, wind velocity, and wind direction are also monitored. The data collected since 1984 have been obtained by synchronously sampling the average transducer frequency output at each site (using a 30 second averaging interval). These mean frequency values were transmitted at intervals between 30 seconds and 5 minutes with the majority of data recorded at a 5 minute sampling interval. Additional meteorological parameters, such as water temperature and atmospheric pressure, are sampled every 20 minutes.

The stations were initially installed in 1978, but these early data are not continuous and are valid only during sporadic periods. After installation of satellite telemetery in 1988, the data set is more continuous, having only minor data gaps caused by equipment failures and low water levels in the lake. Six different pressure transducers have been operated at four different benchmark pairs between 1978 and 1989. Corrections relative to the north gauging station are made to each data set to account for these changes.

Data

The degree to which meaningful crustal tilt can be determined from differential lake level measurements depends on the pressure transducer's precision and stability and the distance between the monitoring sites. While the absolute pressure transducers are capable of resolving differential water level changes of short duration to less than 0.1 mm of water (i.e. less than 0.02 microradians for this installation), it was not clear initially that the transducers could maintain a stability equivalent to less than 0.5 mm of water per year. Wearn (1985) has measured the long term stability of five Paroscientific pressure transducers against a deadweight tester calibrated with a Schwien mercury manometer standard. The transducers were thermally cycled between 20°C and 85°C. The test results indicate a continuous decrease in pressure with time for all transducers. The differential output for all combinations of these transducers have drift rates that range from 0.003 mbars/yr to 0.041 mbars/yr. This range is equivalent to apparent change in water depth of 0.03 mm/yr to 0.41 mm/yr. Recalibration of the sensors used in this experiment indicates a differential drift of about 0.4 mm/yr. This corresponds to an apparent tilt rate of 0.1 microradians/yr. While the transducers at San Andreas lake are in a more uniform temperature environment and are not subjected to such sustained periods of high temperatures and large thermal cycles, their long term differential stability is probably still not greater than 0.4 mm/yr (0.1 microradians/yr).

Other considerations, such as benchmark stability and noise, could also affect the accuracy of the experiment. Single benchmarks, similar to those we use at San Andreas lake, are installed throughout California to measure long-term horizontal strain and tilt and appear to have r.m.s. stability less than 0.25 mm (*Savage et al.,* 1979). Wyatt (1989) found that systematic vertical motions of 0.5 mm/yr can occur in single shallow 3 m deep benchmarks. The benchmarks used in this study extend to greater depths (> 4 m) and have three (rather than one) support rods to provide some spatial averaging of crustal noise. Since, as discussed below, the total tilt during the 10 year period is less than 0.2 microradians, ascribing all of this to vertical motion of the benchmarks would give a differential uplift rate of 0.07 mm/yr.

The data collected prior to 1984 were corrected for water temperature using temperature at only one of the transducers (i.e., the temperature was assumed to be the same at each site). As a consequence, scatter in the earlier data due to temperature differences between sites could be as much as 0.7 microradians. Since 1984, the output from each pressure transducer is individually corrected for thermal sensitivity using manufacturer-supplied thermal calibrations.

All data have been corrected for sensor recalibration, changes in benchmark reference points, and all data are smoothed with 3-day running means. Erroneous data due to telemetry malfunctions, sensor failure, and other reasons have been removed. The most common data sets used for display of apparent long term crustal tilting at San Andreas lake between 1979 and 1989 are 30 day averages of differential level.

Observations

Changes in water depth at periods less than 20 minutes are dominated by the natural modes of oscillation (seiches) in San Andreas lake, which are determined by the length, shape, and depth of the lake (*Defant*, 1958). The primary seiche is easily identified in the water level data (Figure 2, traces C, a, b, and c). The amplitudes of these seiches vary with time, and can reach the equivalent of 2-3 microradians in amplitude. Because the seiches are out of phase at opposite ends of the lake, differencing the data from the two gauging stations allows easy identification of these effects (Figure 2 - traces C and c). Simple smoothing techniques or predictive filtering can remove seiches from the record (Figure 2 - traces D and d). The periods of the fundamental seiche modes at San Andreas lake can be easily determined from the power spectral density of the differential lake level data (Figure 3). The fundamental mode has a period of 13.0 ± 0.3 minutes, with higher modes at periods of 7.3, 6.1, 4.6, and 2.5 minutes.

Changes in wind velocity and direction effect the short-term lake level data. These wind shear effects can be seen in individual and differenced water level records on March 25, 27, 28, and 29 in Figure 2 when the seiche amplitudes are dominant and water is temporarily piled up on the leeshore. These effects are usually evident for several days when strong winds blow continuously from one direction. While the seiche effects can be easily predicted and removed, the longer period wind effects seriously limit the resolution of crustal tilt at these times. Wiener filtering techniques

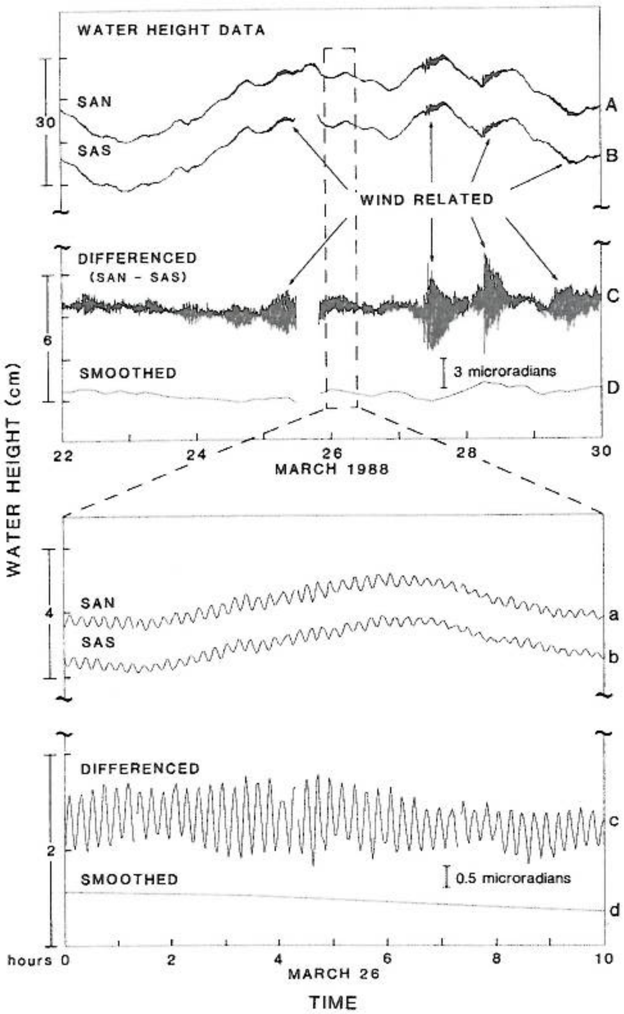

Fig. 2. Section of data taken at a 2 minute sample rate from the north (SAN) and south (SAS) sites in San Andreas lake (traces A and B), during the period March 22 to March 30, 1988. Differenced data and differenced data smoothed with a 180 point (3 hour) running mean are shown in traces C and D, respectively. An expanded section of data (traces a,b,c, and d) for 10 hours on March 26 is shown in the lower plot.

could minimize, but not eliminate, these effects. For this report, the water level data from San Andreas lake has only been differenced and smoothed.

The spatial averaging inherent in this technique is apparent in plots of noise power as a function of period, as shown in Figure 3. Noise power increases linearly with increasing period at about 15 dB/decade. This contrasts with the more rapid increase in noise power of about 20 dB/decade observed on shorter baseline tiltmeters (see, for example, the noise spectra in Wyatt *et al.,* 1984). This implies that, at periods greater than about six months, these differential lake level measurements will outperform higher precision short-baseline tiltmeters. A more complete discussion of comparative noise levels from long and short baseline instruments can be found in Agnew (1987). Hurst and Beavan (1987) have similarly concluded, after comparing data from mercury tube tiltmeters installed 20 m underground with data from differenced sea level measurements, that the sea level differenced data are

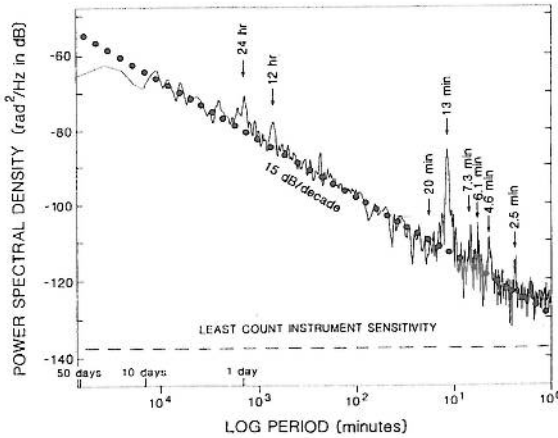

Fig. 3. Power density spectrum of differential water depth data from San Andreas lake. The dotted line indicates a least-square fit to these data while the dashed line represents the least-count noise level for these data.

more sensitive to tectonic signals at periods greater than about one month.

Long-Term Crustal Tilt

Thirty-day averages of differenced lake level data from San Andreas lake from 1979 to 1989 are shown in Figure 4. The long-term tilt rate at San Andreas lake calculated from these data is 0.02 $\pm$ 0.08 microradians/yr (down to the southeast). This means that, within measurement errors, no long term crustal tilting can be identified in this region over the last decade. Intermediate-term changes with amplitudes of 4-5 microradians can be seen in these data between 1979 - 1980 and during 1988. These changes are consistent with lake loading effects at the south site when the lake is filled, but these effects will not be calculated and removed from our data until they can be clearly

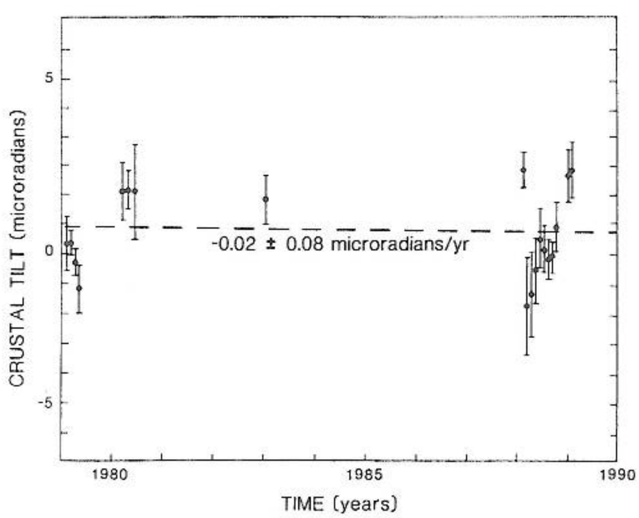

Fig. 4. 30-day averages of differential water level data converted to crustal tilt and plotted as a function of time from 1979 to 1989. Error bars represent two standard deviations for each monthly averages. The dashed line represents the least squares fit to these data.

identified in data during the next few years. In contrast, horizontal strain rates observed in this same region were 0.6±0.2 microstrain/yr (*Prescott et al.*, 1981).

Conclusions

The measurement precision achieved when Paroscientific quartz pressure transducers are used to monitor differential water level in San Andreas lake on the San Andreas fault in California without correction for wind shear or lake loading is approximately 4 mm. The net change in apparent lake level from 1979 to 1989, obtained by a least-squares fit to these data, amounts to 0.7 mm. This could have resulted from benchmark motion, transducer drift, or changes in vertical displacement along the San Andreas fault. Drift in the transducers could account for 4 mm and benchmark motion could be as much as 5 mm. Crustal displacements are of unknown amplitude. Because all expected changes are larger than actually observed, either we have overestimated these effects or somehow they have combined to fortuitously cancel. If all changes are ascribed to differential displacement generated by active crustal deformation, then the average long-term rate of crustal tilting over this 4.2 km baseline, is 0.02±0.08 microradians/yr down in a S34°E direction. This tilt rate is small compared to the horizontal strain rate (0.6±0.2 microstrain/yr) observed by *Prescott et al.*, (1981) for this region. Consistency between these two data sets depends on the deformation model used to relate them. Both of these data sets could support the simplest deformation models for which the region is assumed to be locked, uniformly sheared and homogeneous. However, for more realistic models of the region that include the observed geologically complexity and multiple faulting, the observed strain and tilt rates can only provide model constraints. A more continuous data set is needed to study changes at periods less than a year.

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R. J. Mueller, M. J. S. Johnston and G. D. Myren, U.S. Geological Survey, Menlo Park, CA 94025.

T. Murray, Cascades Volcano Observatory, Vancouver, Washington, 98661.

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