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MEASUREMENTS OF TILT USING A BOREHOLE TILTMETER

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This paper describes a borehole tiltmeter based on a pair of horizontal pendulums. We have used the tiltmeter to study the elastic properties of the Yellowstone National Park region by measuring the amplitude and phase of the earth tides there. We are currently operating several of these instruments in seismically active regions of Southern California to study the usefulness of borehole tilt measurements in earthquake prediction and in measuring the distortion of the near-surface material near a fault zone.

Although many different kinds of tilt-sensors have been developed, they are often not suitable for measuring the small, long-period distortions of the earth. Tidal tilts, for example, have amplitudes of about 200 nanoradians (0.04") and periods of 12 hours or longer; secular distortions rarely exceed 1 micro-radian per year, and are often considerably smaller than this value. These effects must be measured at remote, inaccessible sites in an environment where ambient temperature and pressure cannot be controlled, where power consumption must be minimized, and where the mean time between failures must be several months or longer.

Borehole Design

We have minimized the sensitivity to environmental perturbations by installing the sensors in boreholes as shown in Figure 1. The boreholes are nominally 15 cm in diameter and 30 m deep. A carbon steel casing, 135 mm in diameter with 6-mm walls is pressed into the hole. The casing is welded into a continuous, water-tight pipe as it is inserted. The casing terminates at the bottom in a stainless steel section used to hold the tiltmeter capsule. This bottom section is 2.4 m long and 115 mm in outside diameter. It is sealed by a plate welded across the bottom. A hemispherical knob is welded to the inside of the bottom plate to support the weight of the tiltmeter capsule. At some sites we also used a second, larger diameter casing to keep the top portion of the borehole from collapsing after the drill was removed and before the primary casing could be inserted. This larger casing was 210 mm in diameter. The length of this casing varied depending on local conditions.

The casing is sealed in place by means of cement poured down to the bottom of the hole before the casing is inserted and around the sides of the casing after it is in place.

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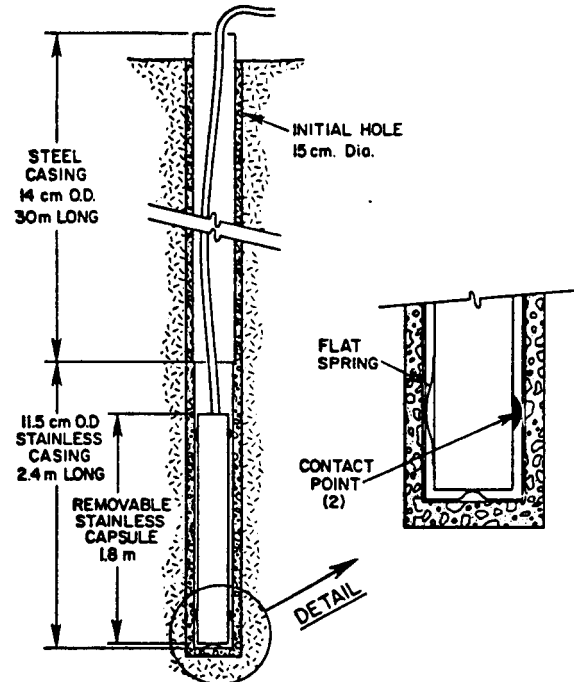


Fig. 1. Schematic diagram of the tiltmeter capsule installed in a cased borehole. All dimensions are nominal and the figure is not to scale. The detail shows one of the springs that is used to press the capsule against the side of the borehole to minimize the effect of strain-tilt coupling.

Ordinary cement can be used for 30-m boreholes. The cement is mixed somewhat thinner than normal, and can be poured around the casing by hand. This technique will not work for deeper boreholes, however, and the cement must be pumped to the bottom of the hole. Special mixes must be used to prevent the cement from separating and clogging the pipe used to carry the mixture to the bottom of the hole. The most important consideration is the balance between fine and coarse constituents of the mixture, and mixes that are easily pumped may be somewhat brittle when cured.

Although we have installed instruments in boreholes that were only 15 m deep, these instruments showed quite marked response to surface perturbations produced by changes in temperature or by rainfall. In Figure 2, we compare the response to rainfall of sensors

that are installed at a depth of 15 m (VP1 and VP2) with data from an adjacent 30-m deep installation. The periodic tilts on both instruments are the earth tides; note the larger secular effects on the shallower instrument and the pronounced effect coincident with the rain.

Instrument Capsule

The instrument capsule is a 1.8 m length of stainless-steel tubing closed at the bottom and having a pair of contact points and a flat spring welded on near its top and a second pair with a second flat spring near its bottom. The top of the capsule is sealed with a cap attached by screws and containing an O-ring.

The springs press the capsule against the casing; the weight of the instrument is supported by the hemispherical knob at the bottom of the casing, but this knob does not constrain the capsule. This design is intended to minimize tilt-strain coupling due to cavity effects. When the material that was in the borehole is removed by drilling, the elastic properties of the region are modified since the edge of the borehole is now a stress-free surface. Strains in the surrounding material deform the sides of the borehole, and this deformation varies with position, especially near the bottom of the hole where there is a transition region between the modified and unmodified zones of elastic parameters. This differential motion results in apparent tilts, as points that were directly above each other are displaced by different amounts as a result of the applied strain. It can be shown that there is no cavity effect if the side of the

borehole is used as a vertical reference axis for the tiltmeter, provided that the reference points are more than about one hole-diameter above the bottom. (These cavity effects are much more difficult to eliminate if the borehole is not vertical. In particular, tilt measurements in railway tunnels or mine drifts present special problems that are not easily overcome.)

The cables connecting the capsule with the surface are left slack; their weight is supported by a bracket fastened to the top of the casing.

Capsule Orientation

The capsule is usually not visible from the surface and its orientation cannot be determined by direct sighting. We use a system of light rods instead. A post is welded to the top cap of the tiltmeter with a flat side aligned with the axis of one of the sensors. A rod can be fastened to the post and is held in place by means of a trapped ball. As the capsule is lowered, additional sections of rod are added. Each section is notched and can only be attached in one orientation using a small screw. After the orientation of the top-most notch is determined using a compass and a transit, the entire series of rods is removed from the capsule by pulling upwards, thereby disconnecting the bottom rod from the post.

This method can be used to determine the azimuth of the sensors to within a few degrees. An uncertainty of only one degree is possible if great care is used and conditions are very favorable.

NBS Tilt and Rainfall

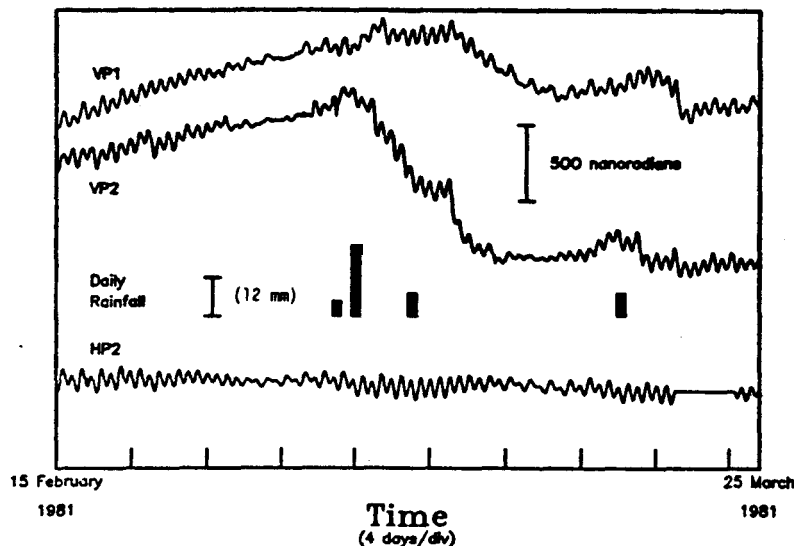


Fig. 2. Tiltmeters VP1 and VP2 are installed in a 15-m borehole and tiltmeter HP is in a 30 m borehole. The response of the instruments to rainfall is shown. The periodic signal of all of the plots is the earth tide.

Tilt Sensors

The tilt sensors are horizontal pendulums and the design is shown in Figure 3. A mass, M , is located at the end of a rigid beam, B . The beam is supported by three wires, W_1 , W_2 and W_3 . Two important features of the mechanical design are the small springs (S) incorporated into each of the wires to protect the suspension from damage due to shock or vibration and the pantograph arrangement of the suspension which makes the period and the mechanical sensitivity independent of temperature to first order. The wires are attached to the frame of the instrument at P_1 , P_2 and P_3 , but the diameter and stiffness of each wire are chosen so that displacements of the mass are with respect to the virtual hinge points V_1 , V_2 and V_3 . These hinge points lie along a line offset from the vertical by a small angle i . If the vertical axis tilts out of the plane of the paper by a small angle d , the pendulum swings out of the plane of the paper through an angle δ , where $\delta = d/i$. If the length of the beam is L , the mass moves a distance $L\delta = d(L/i)$. The time to reach the new equilibrium position is proportional to the period, which

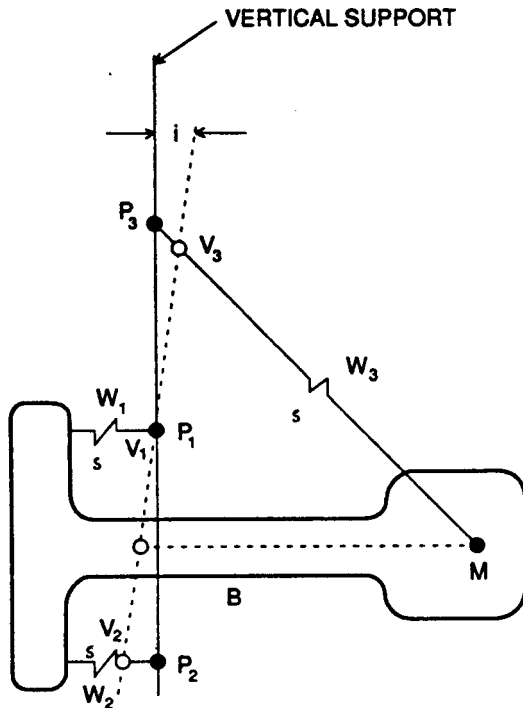


Fig. 3. A horizontal pendulum. A mass M is suspended at the end of a beam B using 3 wires W_1 , W_2 and W_3 . The wires are attached to the vertical support at points P_1 , P_2 and P_3 . The pendulum rotates about three virtual pivots V_1 , V_2 and V_3 which lie along a straight line offset from the vertical by a small angle i . The small springs (S) protect the suspension from damage due to shock or vibration.

depends on $(L/i)^{1/2}$. In our instruments, $L = 10$ mm and $i = 2.3^\circ$. The period is 1 second, the mass moves $0.24 \mu\text{m}/\mu\text{rad}$, and the displacement of the pendulum in response to a tilt is equivalent to a vertical pendulum that is 240 mm long. The mechanical amplification (relative to a simple vertical pendulum of the same length as the beam) is thus about 24.

Each instrument consists of two pendulums mounted so that their sensitive axes are perpendicular to each other. The pendulums are mounted on a small plate as shown in Figure 4, and are protected from air currents and dust by a sealed cylindrical cover. The mounting arrangement isolates the pendulums from the flexing of the hermetically sealed case due to changes in barometric pressure. The case is approximately 65 mm high and 70 mm in diameter.

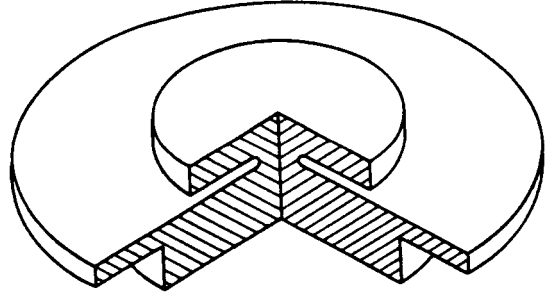


Fig. 4. The mounting plate. The pendulums are mounted on the raised inner plate so as to isolate them from the flexing of the base plate produced by atmospheric pressure changes acting on the sealed case.

The base-plate is supported on a three-point mount; two of the support points are motor-driven screws. These motors are used to level the instrument after the capsule is installed. The platform has a dynamic range of about 0.1 rad (5°), and the instruments can be zeroed to about $0.1 \mu\text{rad}$. See Figure 5.

Each pendulum is suspended between two plates separated by about 1 mm. The plates and the pendulum form two arms of a capacitance bridge; the other two arms are formed by the center-tapped secondary coil of a transformer. The area of each end-plate is about 1 cm^2 , so that the capacitance between the pendulum and each end-plate is about 1 pf. The primary of the transformer is driven by an a.c. signal and the amplitude and phase of the signal at the center plate are measured using a phase-sensitive detector. Since the voltages on the two outer plates are equal in amplitude and opposite in phase, the voltage between the center arm and the center-tap of the drive transformer has a magnitude that is proportional to the deviation of the pendulum from the electrical mid-point of the system; the phase gives the direction of the offset. The frequency of the drive is not critical and is usually about 10 kHz. Higher drive frequencies

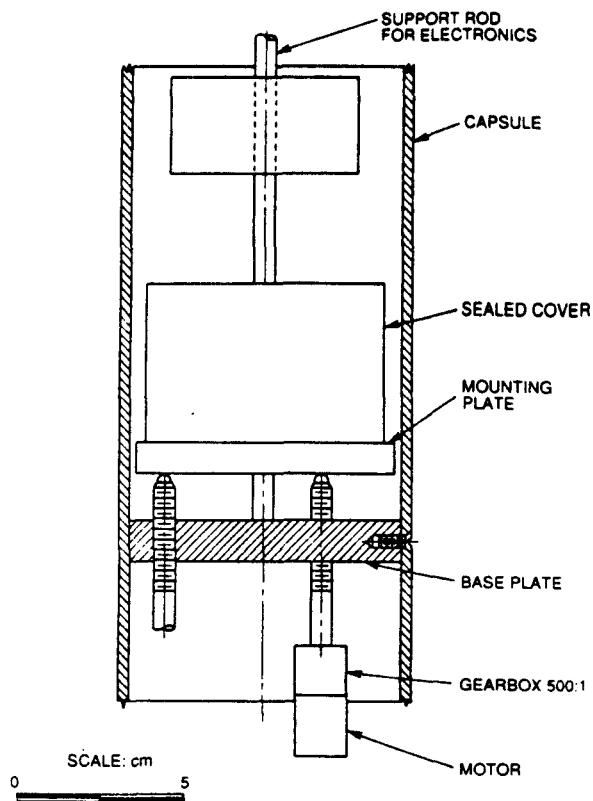


Fig. 5. The pendulums and the leveling system. The leveling screws have 4 threads/mm and are driven by small electric motors through 500:1 reducing gear boxes.

will produce larger signals for a given tilt since the capacitive reactance of the bridge decreases with frequency, but using these higher frequencies makes the circuit more sensitive to fluctuating stray capacitances which produce spurious "tilts" due to changes in the offset between the mechanical and electrical zero-points.

The capacitive reactance between the pendulum and either end-plate is about 10 M Ω , and a tilt of 1 μ rad decreases the reactance of one side by about 2400 Ω and increases the other arm by the same amount. The current flowing in the capacitance bridge is about 1 μ A, so that the inherent sensitivity of the pendulum is about 5 mV/ μ rad. The gain of the amplifier is about 400, resulting in an overall sensitivity of approximately 2 V/ μ rad. This gain is realized using two stages each of which has a gain of about 20, followed by a unity-gain phase-sensitive detector. The final stage is a unity-gain buffer amplifier that is used to drive the cable leading to the surface. The phase-sensitive detector and the amplifiers are located inside the capsule within a few centimeters of the pendulums. These circuits are totally self-contained, requiring only power from the surface.

The sensitivity of each pendulum is measured in our laboratory using a tilt table. Successive calibrations agree to within 1% even if they are performed several years apart. Once the mechanical sensitivity of each pendulum has been determined, the gain of its amplifier is adjusted to yield the nominal overall sensitivity discussed above, and successive calibrations are then performed on the sensor-amplifier pair.

Filters and Digitizer

The outputs of the two phase-sensitive detectors are transmitted to the top of the borehole where they are low-pass filtered with a low-frequency gain of unity and using a time constant of 200 s. The voltages are then digitized with a 12-bit digitizer having a full scale range of ± 10 V; the least count of the digitizer is equivalent to a tilt of about 2 nano-radians and the digitizing frequency is 10 times/hr. The data are stored in a small single-board computer at the top of the borehole and are transmitted to our laboratory once per day using dial-up telephone lines.

Power Supply

The entire tiltmeter system uses approximately 7 W. Most of this power is used by the digitizing and recording circuits. This power is provided by 12 V batteries that are continuously trickle-charged from commercial power lines. Great care is necessary to isolate the tiltmeter from the power-line ground if fluctuations in ground currents are not to be a problem. Power-line transients and large fluctuations in the input voltage are also a problem; these are quite common at remote sites and may be quite difficult to remove. At some sites, the power line transients are so large that any connection at all between the tiltmeter and the power line degrades the measurements by an unacceptably large amount. In these situations we have used a pair of batteries that are alternately charged by the power line and connected to the tiltmeter. The switch-over is made about once per hour by a series of switches that are actuated by a motor-driven cam.

Results and Discussion

A complete discussion of our results is beyond the scope of this paper, but some representative results are presented below. Since most of our work involves the measurement of long-period tilts, the diurnal and semi-diurnal components of the earth tides provide convenient signals to calibrate the instruments and to test various analysis procedures. Measurements of the amplitudes and phases of the larger tidal constituents can also provide information on the elastic parameters of the earth in the vicinity of the instrument, since they represent the elastic response of the region to a known driving potential. It is also possible that the amplitude or phase of the tides might change if a material became dilatant shortly before it fractured. This

effect, which has not been observed in field measurements, would provide a warning of imminent failure which might be useful in earthquake prediction.

Figure 6 shows a typical power spectrum obtained from a data set 28 days in length. The data were recorded using a horizontal pendulum installed at the bottom of a 30-m borehole in Boulder, Colorado. The dotted curve shows the residuals of a least-squares fit of the theoretical tidal potential to the measurements. The long-period and ter-diurnal tides were not estimated in the fitting process, and the two spectra are therefore identical at these frequencies.

The signal-to-noise ratio in the semidiurnal band, estimated by comparing the signal power to the residual power is about 35 dB or about 50:1 in amplitude. The signal-to-noise ratio in the diurnal band is only about 20 dB because of the sensitivity of the site to the diurnal pressure and temperature fluctuations acting both directly on the instrument and indirectly through thermoelastic effects in the earth.

Measurements of the secular tilt rate may also be useful in earthquake prediction. These data are particularly difficult to interpret, since the measurements cannot be unambiguously separated from spurious tilts due to drift in the instrument or in its immediate surroundings. These spurious effects often dominate long-period tilt records, with the result that long-period records obtained by two nearby nominally identical instruments often show little correlation.

In addition, many sites exhibit large annual (and 24-month period) tilts that are correlated with changes in the water table and the snow level. Figure 7, for example, shows a compari-

son between tilt measurements made near the Grand Canyon of the Yellowstone, the depth of the snow in the region and the height of nearby Lake Yellowstone. The annual cycle is asymmetric, showing a gradual accumulation during the fall and winter followed by a rapid decrease in the spring. The east-west component of the annual cycle is a regional effect; tiltmeters at Madison Junction, Yellowstone and near Lake Yellowstone (about 35 km apart) show the same annual cycle even though the tilts at shorter periods are quite different (See Figure 8).

Although our primary interest is in the measurement of long-period effects, we have also used our instruments to investigate more rapid changes in tilt. On 23 February 1982 a hydrofracture test was performed near our tiltmeter site at Erie, Colorado. The hydrofracture was intended to increase the production of a nearby oil well.

The experiment was performed on a 1480-m well which had a 120 mm diameter casing. The bottom 7 m of the casing was perforated. This perforation coincides with the Shannon formation, an oil-bearing relatively low-permeability Cretaceous sandstone.

A sand-laden water-gel was pumped into the well at a constant rate of 4000 l/min. The pumping continued for 84 min, after which the well was sealed. The seal-off pressure was $5.95 \times 10^6 \text{ N/m}^2$ (850 psi).

Two of our instruments were located approximately 500 m away. The line from both of the tiltmeters to the well was along an azimuth of 168° . After the tides were removed from the tilt measurements, the residuals were combined to yield the tilt vector component along the axis to the well and perpendicular to that axis. These results are shown in Figures 9

Power Spectral Density

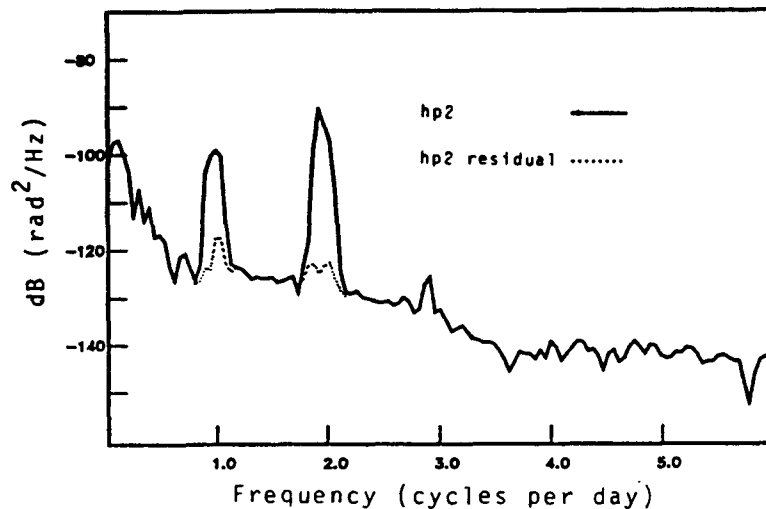


Fig. 6. The power spectrum of a data set 28 days long. The data were recorded using a pair of horizontal pendulums in a 30-m borehole in Boulder, Colorado. The dotted curve shows the residuals of a fit to remove the diurnal and semidiurnal tides. The long-period and ter-diurnal tides were not removed and the two spectra are therefore identical at these frequencies.

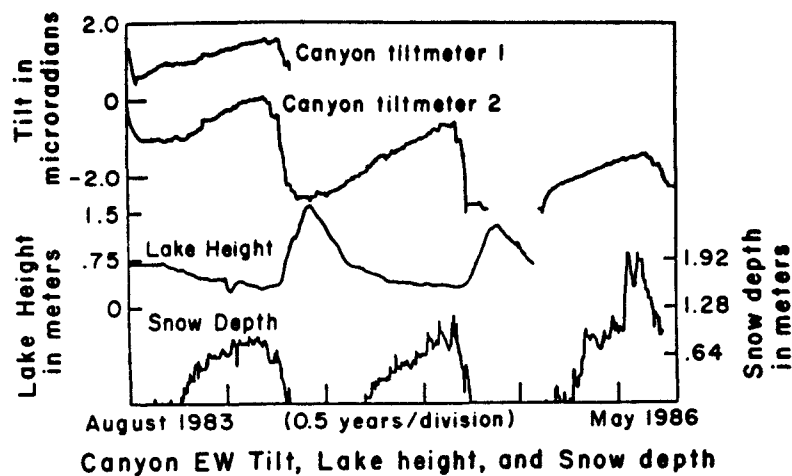


Fig. 7. A comparison between tilt measurements made at the Grand Canyon of the Yellowstone and at Lake Yellowstone with the height of the lake and the depth of the snow in the area.

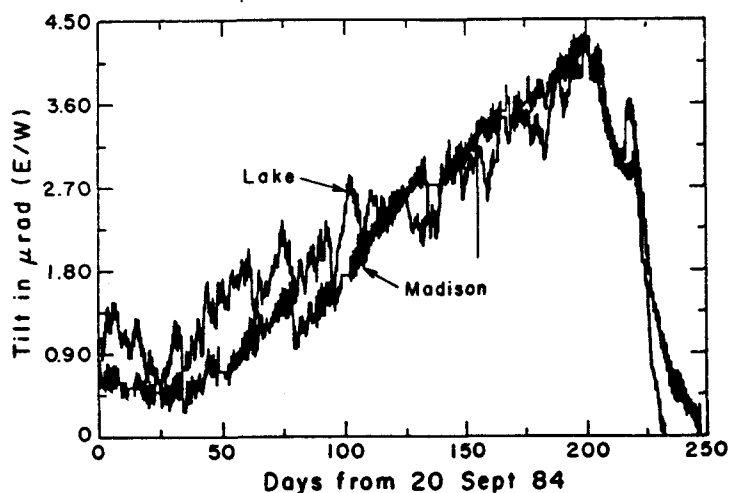


Fig. 8. Comparison of the east-west tilts at Lake Yellowstone and Madison Junction, which is about 35 km west of the lake.

and 10. On both tiltmeters, the components of the tilt along the axis to the well tilted toward the well during the fracture by about 25 nano-radians. The perpendicular components do not show any effect at that time.

This was not a controlled experiment and we do not know the parameters that are needed to estimate the shape or extent of the fracture geometry from our measurements, although the size of the tilt step is consistent with approximate analytic models of the fracture zone. A simple model would suggest that the axis of the fracture should be roughly perpendicular to the axis of maximum tilt or along an azimuth of about 80°, but there is not enough information to construct a quantitative model of the event, and the data are presented primarily to demonstrate the sensitivity of near-surface tilt measurements to relatively small changes in the stress at depth.

Conclusion

We have constructed a borehole tiltmeter using a pair of small horizontal pendulums. The instrument is capable of resolving tilts with amplitudes of only a few nano-radians. It is totally self-contained, can be installed in 15 cm diameter boreholes, and can operate for long periods of time with little or no maintenance. We have used the instrument in several field investigations in Colorado and Wyoming. These investigations have concentrated on using the earth tides to estimate the elastic parameters of a region and on evaluating the secular performance of the instrument with a view toward measurements that might be useful for earthquake prediction. Additional experiments are currently under way in Southern California near the San Andreas Fault.

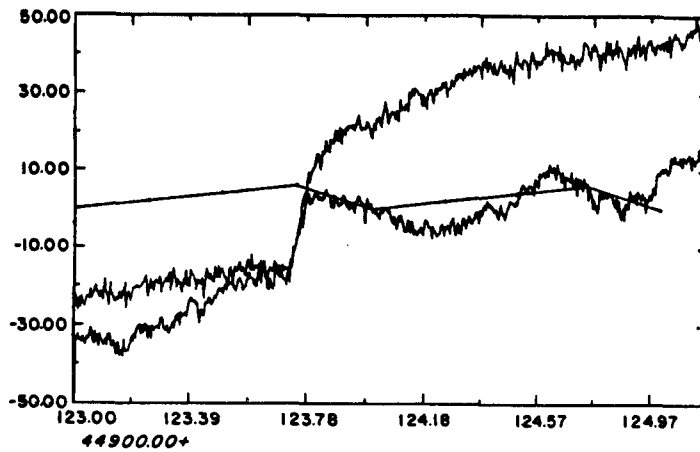


Fig. 9. Tilts recorded by two tiltmeters near Erie, Colorado. The tilts measured by the two pendulums in each borehole have been combined to yield the resultant tilt along an azimuth of 168° , which is the azimuth of the line joining the instruments to the well in which the hydrofracture was performed. The x-axis is in days, the y-axis is in nano-radians and the sawtooth curve in the center of the figure is a timing marker.

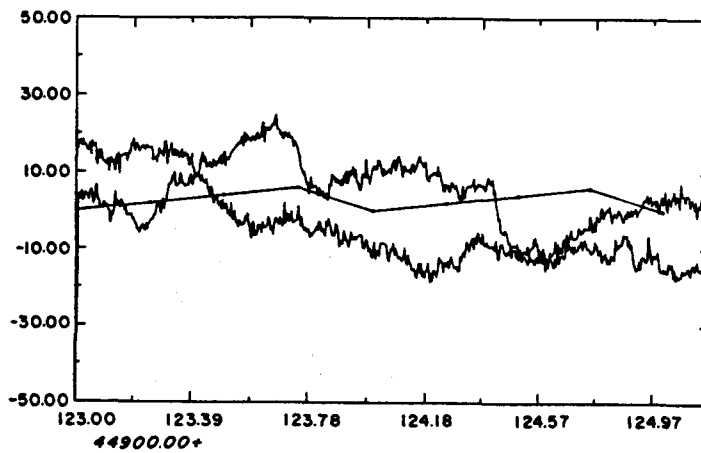


Fig. 10. The same as Figure 9, except that the data have been used to construct the tilt along an azimuth of 78° , which is perpendicular to the azimuth of the line between the instruments and the well in which the hydrofracture was performed.