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The Measurement of Long Period and Secular Deformation with Deep Borehole Tiltmeters

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Abstract. Biaxial borehole tiltmeters have been or soon will be deployed in deep boreholes by groups in W. Germany, England, the United States, and Canada. Their purpose is to measure tidal loading and premonitory earthquake phenomena as well as long-period and secular deformations. Two clusters of instruments were emplaced in fractured bedrock in eastern Massachusetts in 1970 and 1975. The intra-site agreement at tidal periods was about two percent, but there is no agreement at longer periods. A strong temperature-induced annual component ranging from 3 to 15 urads was present on instruments installed at depths of 15-20m; it was not apparent on those at 100-120m. One instrument, in continuous operation for three years at 100m, showed a net drift of 0.3 urads down to the SW, with a maximum departure of 2.0 urads from the trend. Pore pressure variations, material corrosion and creep, and local movements are apparently the limiting factors to long-term measurements.

Deep Borehole Tiltmeter Experiments

Borehole instrumentation for the measurement of tilt (as well as strain and stress) has proved attractive for geophysical measurements because of the isolation from surface noise, such as that produced by meteorological and cultural sources, as well as the logistical advantage provided by the option of drilling at sites of interest as opposed to dependence upon mines and caves. Of even greater importance is the fact that borehole measurements should, in principle, be virtually immune to cavity effects [Harrison, 1976], which dominate the results from short-base tilt measurements made in niches carved in the walls of mines [Melchior, 1978]. Additionally, it is comparatively simple to deploy clusters of instruments to mitigate local perturbations.

Disadvantages include short baselength, cost, the lack of standardized instrumentation, and installation problems. Measurements from instruments installed at shallow depth (about 3m) in soils [Mortensen & Johnston, 1975], Lewcowicz & McConnell, 1977] have proved to be heavily contaminated by temperature and rainfall effects [Wood and King, 1977]. To avoid these the instruments must be placed at substantially greater depth. There we are confronted with groundwater problems, pore pressure changes, casing corrosion, etc. The short baselength means that very small vertical displacements and local tilting, which is not representative of the region under study, can dominate the measurements. Material creep, stress corrosion, stress release, and mineral weathering of the order of several atomic diameters, can produce significant spurious tilts. A number of long baseline instruments, which in essence measure the variations of height between two reservoirs and are free from effects of local tilt, have been developed (e.g., Beavan & Bilham [1977]). Definitive results at non-tidal periods have not yet been published.

There have been three types of deep borehole tiltmeters deployed: The Askania mechanical pendulum [Rosenbach & Jakoby, 1969], the Arthur D. Little diamagnetic suspension [Simon et al, 1968] and the servoed bubble flat [Hansen, 1968]. Two groups in West Germany, the Clausthal Technical University [Herbst, 1976] and Geophysical Institute at Kiel [J. Zschau, personal communication, 1978] have deployed a number of the Askania instruments in profiles across various geological structures. In England, the Institute for Coastal Oceanography and Tides has evaluated the Askania in a vault and is planning to deploy a Hughes sensor in a deep borehole [Baker, personal communication, 1977]. In North America, the Air Force Geophysics Laboratory (AFGL) operates two clusters of instruments in E. Massachusetts; details are presented in the next section. The University of Colorado plans to install about ten instruments in Colorado, Wyoming, and Montana [J. C. Harrison, personal communication, 1977]. The sensors are simple mechanical pendulums developed by Larry Burris of Instech, Inc.

The AFGL Tiltmeter Arrays

AFGL operates two deep borehole tiltmeter clusters (small arrays), as well as several shallow instruments, at two sites in eastern Massachusetts. The Bedford site is located on the north side of Hanscom (Air) Field in the town of Bedford, about 14 km WNW of Boston. Another 17 km to the WSW is the Maynard array, located on the Sudbury Annex of the Army Natick Laboratory in the town of Maynard.

Bedford Site

The Bedford array has been described in detail by Simon [1971] and Cabaniss [1974], so a brief summary will suffice. Three holes 20 cm in diameter and 100 m apart were drilled about 18 m into a foliated granitic gneiss beneath 0-1m of overburden. The holes were cased to a depth of about 6 m; so water in the fracture system was free to enter. Each instrument was emplaced at the bottom of a hole, resting either on its own 5 cm flat base or on a 10 cm blunt spike screwed into the base. The tiltmeter was wedged into position with heavy bronze weights. Alignment was made to a known direction using a set of rods rigidly coupled to the top of the instrument but which could be removed afterwards. Several analyses for the M_2 tidal component showed that the three instruments agreed among themselves to within 2% in amplitude and 2° in azimuth and phase, although the discrepancy between the observed and calculated tides

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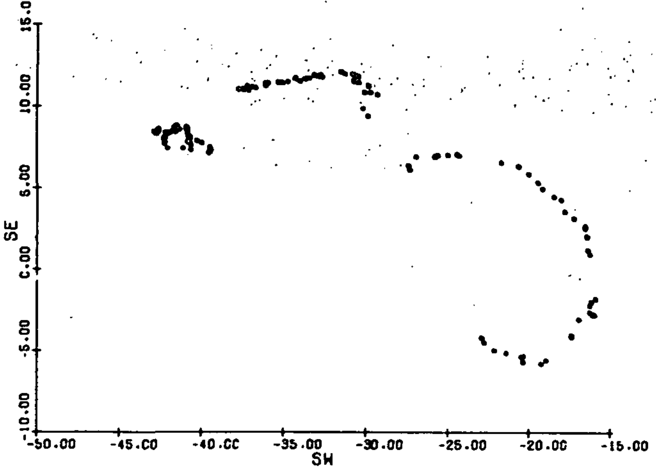

Fig. 1. Long-term tilt from Bedford Inst. 1. 1971-72 (left), 1972-73 (middle) and 1973-74 (right). Each set begins at the left in October, proceeds clockwise, and terminates in June. No connection between years is implied. Tilt is positive down to the SE and SW.

was considerably larger [McConnell, 1971; McConnell et al, 1973].

At periods greater than that of the diurnal tides, the coherence among the data from the three instruments approached zero. Although an annual term was apparent on each, its orientation and amplitude showed no apparent relationship to neighboring instruments. As an example of the annual behavior spot readings from an instrument oriented SE-SW (positive down), covering about three-quarters of three successive years are shown in Fig. 1. The 1971-72 and 1973-74 data show annual ellipses oriented in an E-W direction which can be explained by unequal temperature effects in the two orientations in response to the 0.1° C annual temperature variation at this depth. The data were interrupted in July of each year because of lightening damage; the instrument was removed and re-emplaced after repair by October. Thus any connection between the sets would be highly speculative. The differences from year to year were ascribed to slight changes in installation details [Cabaniss, 1974]. "Secular" drift has shown even greater disagreement and far exceeds the 4-15 nanoradians (down to the north) per year, as estimated from shoreline, geodetic re-leveling, and tide gage data [Cabaniss, 1974]. Those discrepancies are undoubtedly related to the problems outlined above.

Maynard Site

The Maynard tiltmeters were installed in cased holes (16 cm diameter) with a horizontal separation of about 100 m drilled 100 m into granitic gneiss beneath 20 m of overburden. The instruments were the Hughes servoed bubbles packaged by Earth Sciences Research, Inc. They were emplaced 5-15 m above the hole bottoms, each resting on a holelock which forces wedges against the casing wall with a heavy spring [McConnell, 1978]. They were aligned by sighting on incandescent lamps with a transit device. Preliminary results from tidal analyses showed inter-instrument and monthly variations reaching 10% in amplitude [McConnell, 1978]. These have been tentatively ascribed to local variations in scale factor caused by bubble flat topography [McConnell, personal communication, 1978; Cabaniss, in preparation].

The long-term tilt variations are presented as a series of spot readings spanning a period of three years (Figure 2 and Figure 3). The two instrument components have been computationally rotated to North/East coordinates, and relevels have been removed, except those that occurred during the first eight months for Inst. 1 and two months for Inst. 3. Tides have not been removed and reach an amplitude of 0.25 urads (p-p) in the East component and 0.07 urads in the North. As at Bedford, there is little agreement among the data from the three instruments. No. 1 drifted back and forth, often in a well-defined direction; No. 2, after a stabilization period of about a year, moved in a very linear fashion until Day 740, when both instrument components drifted rapidly about the same amount but in opposite directions for about 45 days, after which the previous rate resumed. The direction of the rapid excursion was associated with that of one of the holelock wedges; so it has been surmised that casing corrosion might have been the cause of the event. Inst. 3 displayed remarkable stability over the same period. The first year was marked by decaying exponentials on both channels but the maximum rate was on the East component. The second year was characterized by roughly equal motion on both channels at the beginning but finished with accelerated movement on the North component. The last 18 months of the record are shown vectorially in Figure 4. There has been little motion during that period except for a counter-clockwise elliptical movement, equally partitioned between both instrument axes, which may have an annual periodicity. The net drift over three years on Inst. 3 was 0.3 urads, with a maximum excursion of 2.0 urads from the trend.

Discussion

Our results show that the annual components generally decrease in amplitude with depth but are highly dependent on the installation epoch. Herbst [1976], however, reported annual ellipse amplitude (semi-major axes) of 0.9 and 0.1 urads at depths of 15 and 30 m, respectively, which can be explained by thermoelastic effects caused by the coupling of the annual temperature wave with the topography.

The long-term records from the Bedford and Maynard arrays show drifts that vary widely in both rate and direction. If it is assumed that a low-drift record is "best", Maynard #3 shows a mean rate of 0.1 urads per year to the SW, compared to the tide gage and geodetic re-leveling estimates of about 0.01 urads per year down to the north. The disturbing result so far from

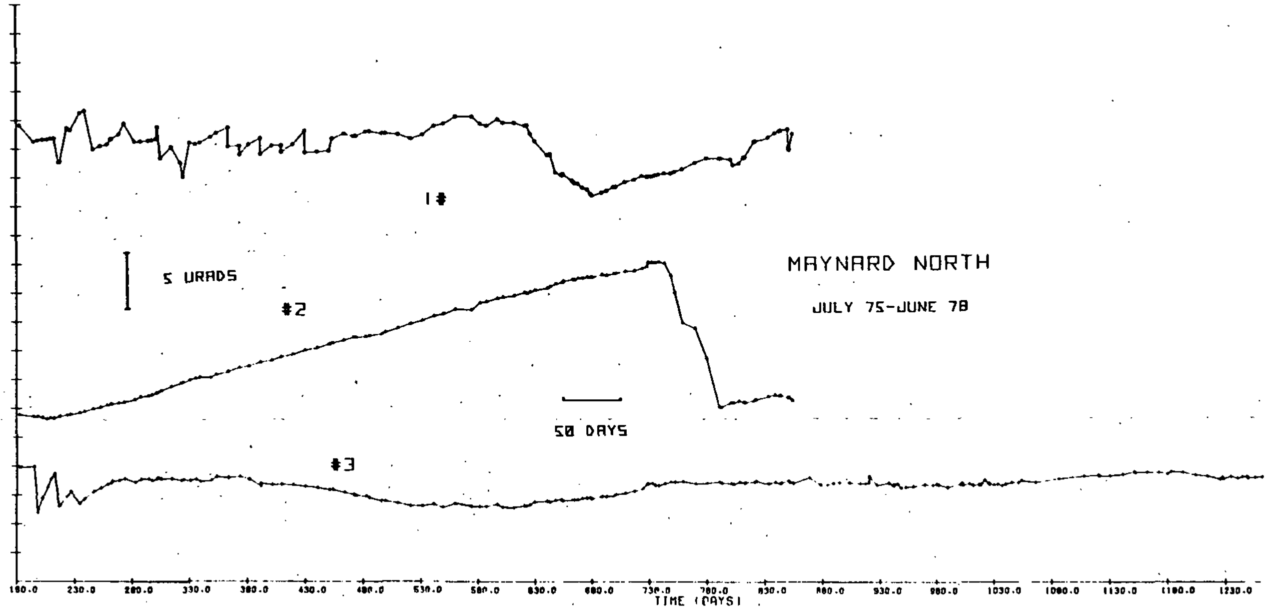

Fig. 2. North component of the long-term tilt from the Maynard array from readings taken at intervals of about 10 days. Data have been rotated from the azimuths of the instrument axes (#1, 294° - 24°; #2, 35° - 125°; #3, 2° -92°). Tilt is positive up to the north and east. The time axis is in days since 0 Jan 75.

these experiments is the wide disagreement among instruments spaced less than 100 m apart. Herbst [1976], for example, reported annual drift rates of 1.8 and 0.75 urads for instruments at depths of 15 and 30 m, respectively, spaced several meters apart. The drift directions varied by 15°. The question is whether this type of measurement is limited by the length scale of the phenomena, by the installation techniques, or by the inherent stability of the instruments. Parenthetically, no "events", including tilt steps associated with magnitude 7.7 teleseisms, have been detected on all instruments within a cluster.

The AFGL experiments suggest that improvements might be made by emplacing the instruments in sections of stainless steel casing at depths greater than 30 m at the bottoms of sealed holes. Installation in comparatively fracture-free material and at close spacing might also prove efficacious.

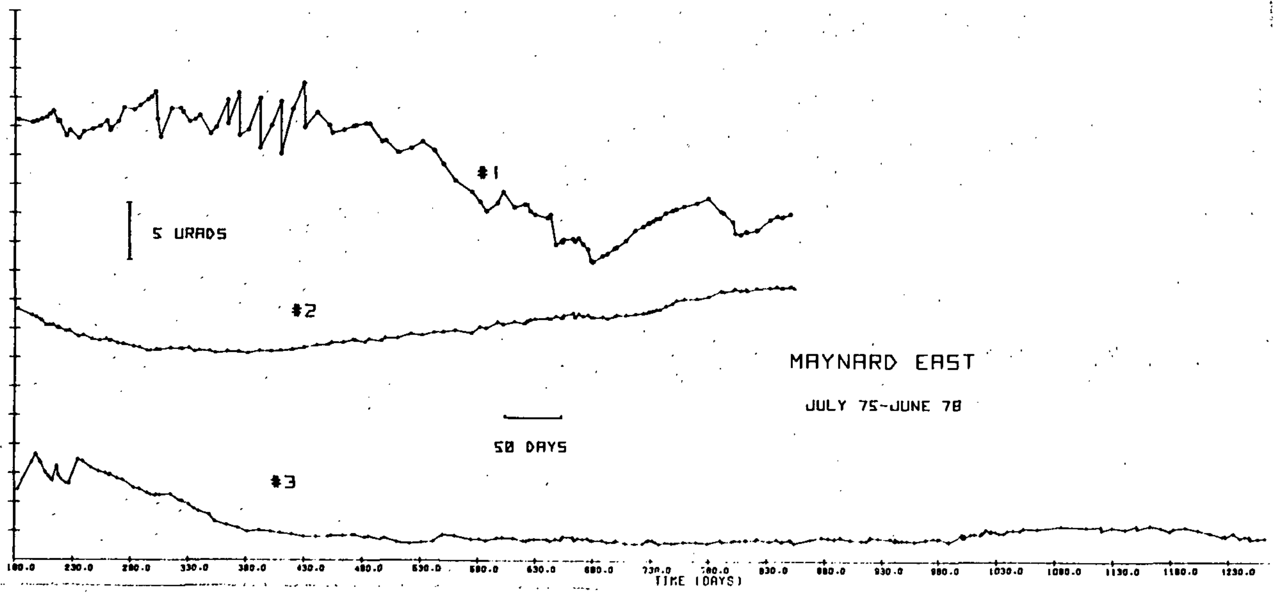

Fig. 3. East component of the long-term tilt from the Maynard Array. (See Fig. 2 legend.)

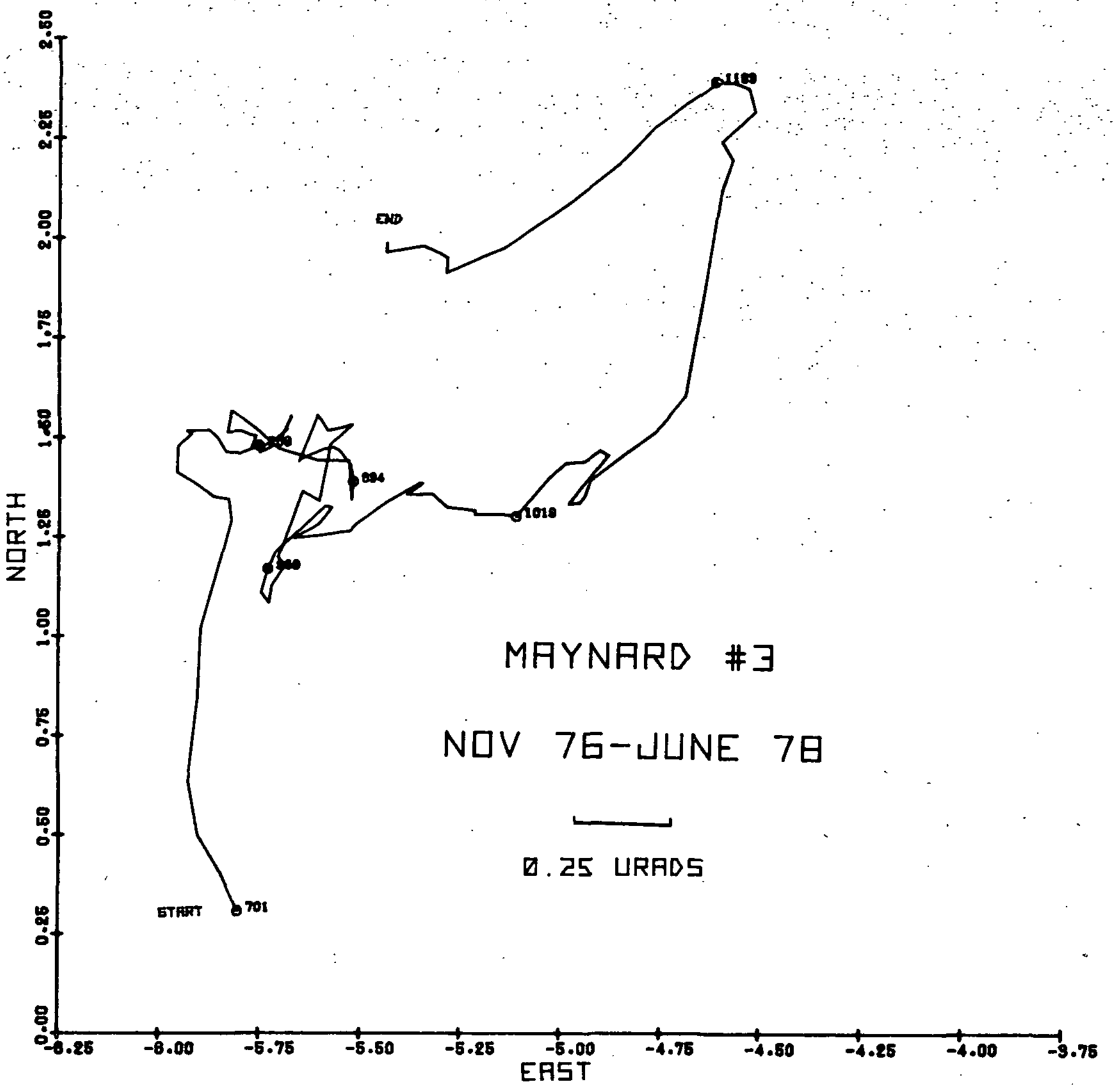

Fig. 4. Vector plot of a portion of the long-term data from Maynard Inst. 3. Symbols and numbers correspond to times indicated on Fig. 2 and 3. The last point is at Day 1250.

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