areas are determined and they are found to correspond to low-pressure regions on the weather map. At longer periods, microseisms consist of fundamental and higher-mode Rayleigh and Love waves. At LASA a greater portion of microseismic energy arrives from east and northeast directions compared to westerly directions.

NOTICE OF THE 40TH ANNUAL MEETING
17-19 October 1968
Massachusetts Institute of Technology
Cambridge, Massachusetts

The Fortieth Annual Meeting of the Eastern Section of the Seismological Society of America will be held on 17, 18, and 19 October 1968 at Cambridge, Massachusetts. The Department of Geology and Geophysics of the Massachusetts Institute of Technology will act as the host and the organizer.

A special feature of this meeting will be a one-day symposium on theoretical seismology in honor of Dr. Norman A. Haskell and his many contributions to modern seismology. Invited papers on new developments in theoretical seismology will be presented at the symposium.

Those who wish to present papers at the annual meeting should send the abstracts to:

M. Nafi Toksoz
94-518
Department of Geology and Geophysics
Massachusetts Institute of Technology
Cambridge, Massachusetts 02139

The deadline for abstracts is 1 August 1968.

ABSTRACT
Evidence for correlation between earth surface tilt and subsequent local earthquakes has been observed at the Inertial Test Facility of the Marietta Corporation, Waterton, Colorado. The facility is located about 30 miles southwest of the apparent epicenters of the "Derby earthquakes" in the Denver area. During the period April-November 1967, eighteen local earthquakes were recorded at Waterton. Fifteen of these earthquakes were preceded by a measurable unidirectional tilt from 7 to 48 hours before the earthquake occurred. Magnitude of the earthquakes ranged from less than 1.0 to 5.4 on the Richter scale. Highest rate of tilt was 0.05 arcsec per hour and greatest amount of tilt was 1.15 arcsec. With one exception, each instance of sustained tilt for periods of more than 10 to 15 hours was followed by an earthquake. The exception was for a period of 62 hours following an earthquake of 5.4 magnitude. Instrumentation used consists of Talyvel Electronic Level Sensors, Honeywell precision bubble levels, and Benioff short-period seismometers. It appears that correlation between tilt in the Waterton area and the occurrence of earthquakes in the Derby area is sufficient to warrant the establishment of additional tilt measuring stations in the Derby area.

Introduction
The Martin Marietta Corporation, Denver Division, maintains a Flight Controls Development Laboratory which is equipped with precision instrumentation for measuring orientation of the stable test piers located within the laboratory. In the course of monitoring the stability of the inertial test pad, Mr. G. E. Marshall of the Flight Controls Development Laboratory has observed an apparent correlation between test pad tilt (rotation about horizontal axes) and the occurrence of earthquakes in the Denver area.

In recent years, the Denver area has experienced a series of earthquakes with an apparent epicenter in the vicinity of Derby, a community located 7 to 8 miles northeast of downtown Denver (fig. 1). During the period April-November 1967, eighteen local earthquakes were recorded at the
Martin Marietta Waterton facility, about 20 miles southwest of downtown Denver, and most were preceded by a recorded tilt of the inertial test pad. Four of these earthquakes were of magnitude 4.0 or greater on the Richter scale. Three were of magnitude 2.0, one of magnitude 1.7, and the remainder of magnitude less than 1.0. Prior to all four of the earthquakes greater than magnitude 4.0, prolonged tilts of the inertial test pad in one or both of the N-S and E-W planes were recorded by level sensors on the inertial test pad. The same effect was noted in connection with the smaller earthquakes, although the duration of tilt prior to the earthquakes was shorter, and the total angular displacement was, in general, less than in the case of the more severe earthquakes. The angular displacements were on the order of one arc second or less, but were significant deviations from normal test pad behavior.

These observations suggest that the stresses culminating in the Derby earthquakes are directly related to the measurable tilt of the inertial test pad in such a way that the Derby earthquakes may be predicted.

Geologic Setting

The Martin-Denver test facility is situated on an eroded hogback of arkosic sandstone in the upper part of the Fountain formation. This formation, about 2000 feet thick, is the oldest sedimentary formation in the vicinity and unconformably overlies the crystalline, pre-Cambrian core of the Colorado Front Range. The outcrop strikes approximately north 35° west and dips 50° to 60° northeast. The test pad is closely aligned with the strike of the outcropping hogback.

Faulting visible in the surface exposures in the area consists primarily of northwest-trending strike faults. The principal known fault is a branch of the Jarre Creek fault, a high-angle reverse fault, and its surface trace extends for a distance of at least 16 miles within the Fountain formation in a NW-SE direction, parallel to the mountain front, and passes within 500 yards west of the test facility. No known fault extends...
into the area from the vicinity of Derby, although much speculation has
centered on the unusual linearity expressed by the course of the South
Platte River between Derby and the site where the river leaves the moun-
tains, one-half mile from the test facility (fig. 1). No evidence of re-
cent movement on any of the faults has been observed, although streams on
the nearby plains are currently undergoing rejuvenation.

Laboratory Facility

The Flight Controls Development Laboratory is a part of the Research,
Development, and Engineering Laboratory complex of the Waterton Plant of
the Martin Marietta Corporation, Denver Division. The facility is located
at 39°30'09" N., 105°06'35" W., at an elevation of 5840 feet above sea
level. A primary function of the laboratory is the testing of inertial
sensors for use in the flight control systems of launch vehicles. In order
to obtain valid results in testing inertial sensors, test pad stabilities
must be determined to be below the threshold sensitivity of the sensors
being tested, or they must be measured and applied to the test data as
error corrections.

The test pad is formed of a concrete base 24 x 39 feet in area and 9
feet 8 inches in height. The test pad rests directly on the Fountain for-
mation bedrock. The bedrock was prepared for installation of the test pad
by scraping away the weathered surface rock, leaving fresh, unweathered
rock as a base for the concrete pad.

Projecting above the base of the test pad, and formed integrally with
it, are ten test equipment mounting piers and one central pier to support
stability monitoring instrumentation. The equipment mounting piers are
isolated from the laboratory floor, which is suspended from the building
foundation on springs. The building foundation is isolated from the test
pad by an air gap and from the bedrock by specially prepared rock-free
clay fill.

Instrumentation

Instrumentation used to monitor test pad stability consists of three
Benioff short-period seismometers (fig. 2), two modified Talyvel Electronic
Level Sensors, herein called "tiltmeters" (fig. 3), and, since November
1967, four Honeywell precision bubble levels.

The threshold sensitivity of the tilmeter is 0.05 arcsec or better.
The recorder scale factor is 0.5 arcsec per inch, and the record is easily
readable to 0.05 inch. The noise on the record from all sources is equi-
valent to approximately 0.1 arcsec peak-to-peak in the worst case. The in-
strumentation, which is somewhat sensitive to temperature, is operated in
a very stable temperature environment. Data from the tilmeter instrumen-
tation has been found to agree with readings of two pairs of precision bubble
levels which have a threshold sensitivity better than 0.25 arcsec and can
be read to 0.1 arcsec.

Because of the long time constant of the bubble levels, the bubble
level data does not show the short-period effects of earthquakes, but does
reveal long-period characteristics of the test pad behavior. The contin-
uous record of the tilmeters shows both effects. Data from the bubble
levels during the period of about one month during which these instruments
were in use shows good correlation with the tilmeter records. Bubble lev-
el records for the relatively short period of observations have not been
included in this report, but will be maintained in the future for correla-
tion with the electronic level data.

Tilmeter Data

The period during which a sustained tilt is observed prior to an
earthquake is measured from the onset of a definite identifiable trend on
either tilmeter to the time of the earthquake. The angular displacements
of the test pad during this period are measured from the readings at the
beginning of the tilt to the readings at the time of the earthquake.
Figure 2  Block Diagram - Seismometer System

Figure 3  Talyvel Tilt Instrumentation Electronic Level
The tiltmeters are designated N-S (North-South) and E-W (East-West) in accordance with the orientation of the sensitive axes, which are horizontal axes in the plane of motion of the tiltmeter pendulums. However, the instrument axes are rotated 30° counterclockwise from true N-S and true E-W to align with the major axis of the test pad and the strike of the rock outcrop. The N-S and E-W designations are used for convenience.

A polarity has been assigned to the tiltmeters based on the deflection of the tiltmeter recorder traces. For the N-S instrument, North-up is designated as the positive direction of tilt, and for the E-W instrument, West-up is positive.

Using the above convention, a tilt or gradient vector can likewise be associated with the tiltmeter indications. A positive tilt vector directed along the positive axis of sensitivity of the instrument and of a length proportional to the angular displacement can be associated with each tiltmeter. From the two tilt vectors, which are directed along the N-S and E-W axes, a resultant tilt or gradient vector can be derived. This resultant tilt vector is directed along an axis of maximum tilt, since each tiltmeter measures the N-S or E-W component of the actual tilt. Similarly, a rotation vector can be associated with each tilt vector, with the positive rotation vector rotated 90° clockwise from the corresponding tilt vector in accordance with the right-hand rule governing rotation vectors. The concept of tilt vectors and rotation vectors is useful in determining the geographic and geologic significance of the tilt data.

Data Summary

Table I is a tabular summary of the significant features of the tilt data. The earthquakes recorded and identified in the figures are listed in the table in chronological order. In the column headed "Change of Tilt," the time at which a change in the tilt trend occurred is indicated in hours relative to the time of occurrence of the earthquake. A zero means that no change occurred.
change of slope of the tilt record occurred at the time of the earthquake; a negative number means a change of slope prior to the earthquake; and a positive number means a change after the earthquake.

Figure 4 is a polar plot of the resultant tilt from Table I. The directions of the gradient vectors are referred to true North. The numeral near the terminus of each gradient vector is the number assigned to the particular earthquake in Table I.

On the basis of the data in Table I, and figure 4, the following observations can be made:

1. Every occurrence of prolonged tilt in one or both axes, with one exception, has been followed by an earthquake. The one exception noted was the period of 52 hours following the 5.4 magnitude earthquake at 07:42 on August 9, 1967, in which both traces showed a fairly steady unidirectional tilt. This tilt may represent readjustment following the severe earthquake on August 9, 1967.

2. Fifteen of the eighteen earthquakes recorded were preceded by an identifiable tilt in one or both axes for periods ranging from 7 hours to 48 hours. Two of the three earthquakes in which no significant tilt trend was observed were of magnitude less than 1.0 on the Richter scale. The third, of magnitude 2.0, was an aftershock associated with the 5.4 magnitude earthquake at 07:42 on August 9, 1967.

3. A change of slope of one or both tiltmeter traces occurred in connection with fourteen of the fifteen earthquakes which were preceded by a definite tilt trend. In ten of the fifteen, including two of the four major earthquakes, the change of slope occurred one-half hour to four hours before the earthquake.

4. The average value of resultant angular displacements in the two measurement axes was 0.54 arcsec for the four earthquakes of magnitude greater than 4.0. The average resultant tilt for all earthquakes of magnitude less than 4.0 was 0.24 arcsec. Normal day-to-day variations are on the order of 0.1 arcsec or less.
5. The direction of the resultant tilt associated with most of the earthquakes recorded has predominantly E-W components. The resultant tilt vectors of two of the four earthquakes of magnitude greater than 4.0 are collinear, with the resultant vectors directed at 107° and 287° true. The resultant tilt vector of the third of the four major earthquakes is directed toward 114°. The resultant tilt vector of the fourth of the major earthquakes is directed at 065° true.

6. The average of the angular rates preceding the four major earthquakes was 0.017 arcsec per hour. The average angular rates for all of the fifteen earthquakes was 0.014 arcsec per hour. The highest angular rate observed was the 0.053 arcsec per hour recorded on the N-S axis prior to the 5.1 magnitude earthquake on April 10, 1967. The rates associated with the 4.1 magnitude earthquakes on November 15, 1967 were among the lowest recorded.

7. The period of tilt prior to the major earthquakes ranged from 22 hours to 48 hours with an average of 32.5 hours. The tilt periods preceding the minor earthquakes averaged 10 hours, with a range of 7 hours to 34 hours.

8. Prior to three of the four major earthquakes, both tilt traces showed negative deflections indicating North-down and West-down tilts. One of the three was preceded by a significant negative tilt in the E-W trace with very small negative tilt in the N-S trace. Prior to the fourth major earthquake, both traces showed a positive tilt. The tilts preceding the 11 minor earthquakes with which identifiable tilts were observed were distributed with respect to direction as follows:

<table>
<thead>
<tr>
<th>Type of Tilt Distribution</th>
<th>Number of Events</th>
</tr>
</thead>
<tbody>
<tr>
<td>Both negative</td>
<td>1</td>
</tr>
<tr>
<td>Both positive</td>
<td>2</td>
</tr>
<tr>
<td>One positive, one negative</td>
<td>4</td>
</tr>
<tr>
<td>Tilt on one trace only, positive</td>
<td>4</td>
</tr>
<tr>
<td>Tilt on one trace only, negative</td>
<td>0</td>
</tr>
</tbody>
</table>

Conclusions

1. The foregoing observations suggest the existence of a direct relationship between the tilt measured on the inertial test pad and the subsequent occurrence of earthquakes in the Derby area, about 30 miles away.

   If the geologic aspect of this relationship can be correctly interpreted, a valid basis for the prediction of local earthquakes, occurring under similar conditions, may be established.

2. The characteristics of the tilt measurements which may be of significance as indicators of earthquakes are: a) a sustained unidirectional tilt for a period of several hours; b) a definite change of tilt prior to the earthquake, both of which have shown a significant degree of correlation with the occurrence of local earthquakes. The rate of tilt does not appear to be significant. The rates observed prior to earthquakes are similar to rates which occur for short periods in the normal "undisturbed" behavior of the inertial test pad.

3. The data on which these observations are based are considered to be valid measurements of the angular displacements of the test pad about horizontal axes. Tilt displacements of several tenths of an arc second are characteristic of the extended periods of tilt prior to earthquakes.

4. The data contained in this report are not considered to be sufficient to support firm conclusions regarding the significance of tilt measurements relative to earthquakes. The limitations of this data are well recognized. All of the observations were made at a single site, and only eighteen earthquake events were recorded. Three of these were of such low magnitude as to show no significant effect on the tilt data.

   However, fifteen of these earthquakes occurred after several hours of definite, identifiable tilt in one or both directions of measurement. The tilt indications are consistent in form among the several
events, differing primarily in duration and total displacement. The high degree of correlation in the limited data sample is considered to be sufficient indication of the potential value of tilt measurements of this type for predicting earthquakes and would appear to justify continuing and augmenting the measurements and observations.

5. An extensive investigation will be necessary to evaluate the feasibility of basic earthquake predictions in the Denver area based on tilt measurements. The study should cover a time period of at least one year, and possibly much longer, depending upon the frequency of occurrence of earthquakes and the facilities available for observation. Several instrumentation sites, distributed over an area of several hundred square miles, should be used to increase the quantity of data obtained and to eliminate the effects of bias which may occur in a single observation site. Seismologists, geologists, geophysicists, and instrumentation specialists should participate in the definition of a program of investigation and in the review of the data.

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Editor's Note: Many members have notified us that they did not receive one or more of the recent issues. Some of these omissions are valid, but there is some confusion concerning the number and dates of publication. The last two published have been combined numbers which, unfortunately, have also been misnumbered. The March-June 1967 issue should be identified as Nos. 1-2, while the Sept.-Dec. 1967 issue which has an incorrect volume number should be designated Vol. XXXVIII, Nos. 3-4. We have attempted to catalog all of the valid requests and will include the missing numbers with the present bulletin in order to reduce mailing costs.

THE DENVER EARTHQUAKES, 1962-1967
Ruth B. Simon
Colorado School of Mines
Golden, Colorado

Studies of earthquakes, their numbers and magnitudes, azimuthal distribution and possible fault mechanism in the Denver-Derby area continue at the Colorado School of Mines. This is a report of recent work.

A comparison of the number of Derby (northeast Denver) events per month (observed at the Cecil H. Green Geophysical Observatory, 55 km west-southwest of the active zone) with the monthly volume of fluid injected in the RMA Deep Disposal well is shown in figure 1. The data for 1962 through 1965 show a positive correlation between pumping and seismic activity, and this was the basis for discontinuing pumping. Significant activity has continued since the well was shut down, thus the quality of the correlation is now noticeably reduced. The two largest shocks, April 10 and August 9, 1967, magnitude 5.0 and magnitude 5.3, will be reported in another paper.

Figure 2 is a map of the Denver area showing the active zone and Cecil H. Green Observatory (GOL). GOL and DEN are the only two stations to have run continuously the entire six years. All earthquakes exhibit (S-P) times of 5.2 ± 0.3 second at GOL. Thus the epicentral zone is limited to the area between the inner and outer arcs, corresponding to (S-P) times of 4.9 and 5.5 seconds, respectively. The numbered lines radial to GOL represent the azimuth determined by the P-wave N/E ratio, with the printed numbers indicating the appropriate ratio. The epicentral zone is less than 4 miles wide, along an arc swinging northwesterly about 10 to 15 miles from south of the arsenal well. The seismic activity is migrating northward with time, as determined from N/E ratios of P waves, which vary from 0.2 to 1.0. The S/P amplitude ratios vary also with time, from 1.0 to 7.0, with some much higher in 1967.