NORDIC VOLCANOLOGICAL INSTITUTE 8203
UNIVERSITY OF ICELAND

THE N.V.I. MAGNETORESISTOR TILTMETER
RESULTS OF OBSERVATIONS 1977 - 1981

by

Eysteinn Tryggvason

Reykjavik
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ABSTRACT

A pendulum tiltmeter with magnetoresistor transducer has been designed at the Nordic Volcanological Institute. This instrument has been in continuous operation since August 1977 in the Krafla area, North Iceland, and since June 1978 in Vestmannaeyjar, South Iceland. The tiltmeter is normally installed about 2 m under the ground surface. This shallow depth results in rather large unwanted signals caused by temperature variations when the ground is frozed. Large annual tilt cycle is observed in Vestmannaeyjar. In spite of these problems, the N.V.I. tiltmeter has prooven very useful in monitoring active volcanoes.

A technical description of the N.V.I. magnetoresistor tiltmeter has been presented elsewhere (Sindrason & Ólafsson, 1978), but most of the results obtained through this instrument are here presented for the first time.

INTRODUCTION

The volcano-tectonic episode, which commenced in the Krafla area in 1975, was characterized by large scale ground movements as shown by repeated levelings in 1976 (Björnsson et al., 1977). As an example of the magnitude of the observed ground deformation, a leveling of the foundation of the Krafla power station in January 1976 showed that the north end of the 70 m long building, under construction at that time, had subsided about 5 cm relative to the south end since earlier leveling in November 1975. This represents about 700 μ-rad tilt. Later levelings of the same foundation showed that the north end of the power house started to rise relative to its south end in late February or early March 1976, and the rate of tilt during the following months was roughly 2 μ-rad/day.

The present author installed a water tube tiltmeter in the Krafla power house on August 20, 1976, to facilitate frequent tilt observations. This tiltmeter has been operated by the National Energy Authority, and readings are usually made once a day.

Subsidence events with brief but rapid reversal of tilt occurred on September 29 to October 4, 1976, October 31 to November 1, 1976 and January 20 to 21, 1977 (Tryggvason, 1980). These tilt reversals, or subsidence events, were early interpreted as caused by large scale underground magma movements (Björnsson et al., 1977).

Although the water tube tiltmeter in the Krafla power house gave rapid and reliable information on one component (N13°E) of tilt at one location, it did not show how the tilt progressed during the brief subsidence events, and it did not show when a tilt event started. Further, it gave no information on the ground tilt at other locations in the Krafla area, and the water tube tiltmeter is not easily operated in the field due to adverse weather conditions.

These shortcomings of the water tube tiltmeter made it desireable to construct and operate some other type of

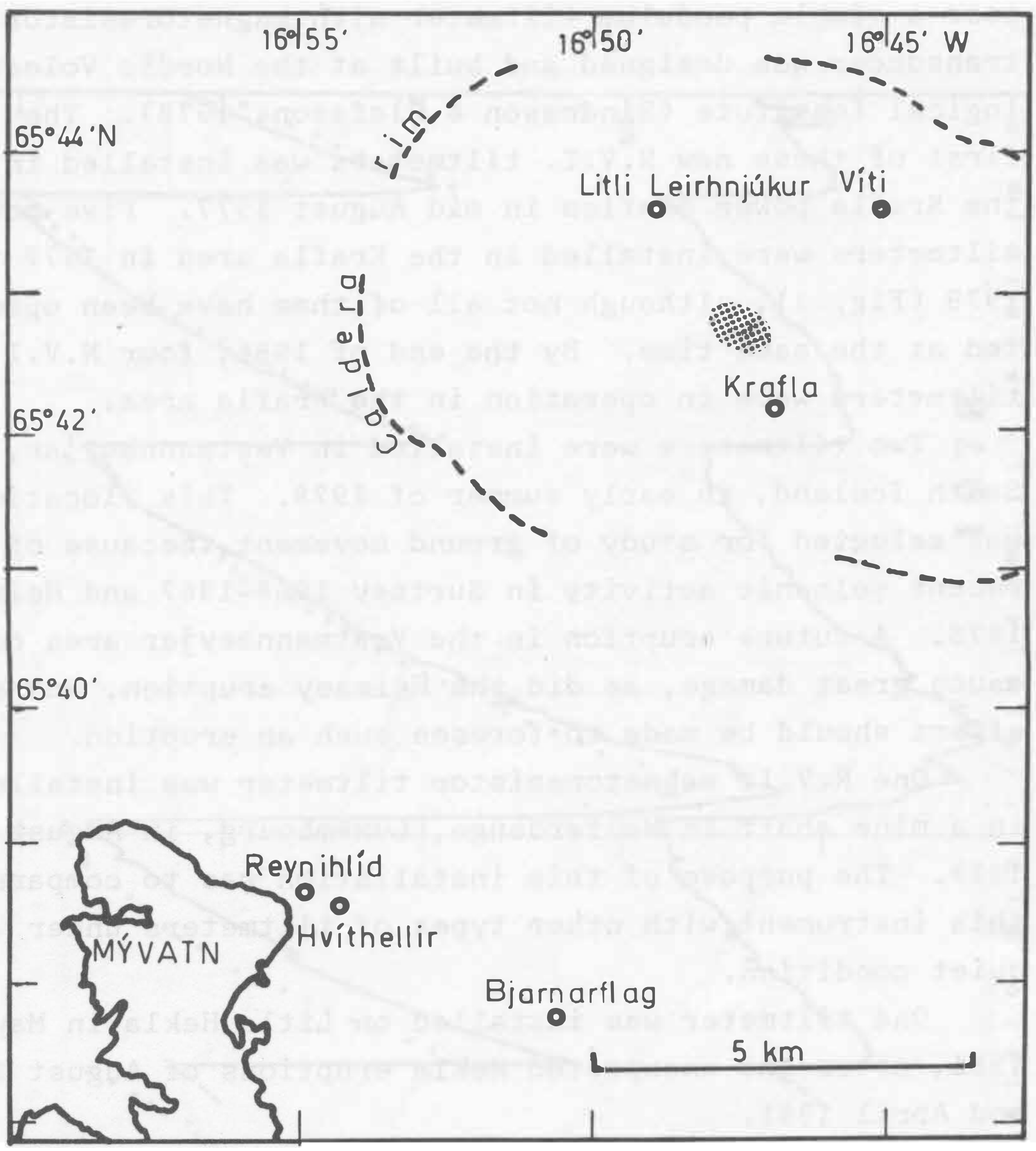


Fig. 1. Map of the Krafla area showing the location of the N.V.I. magnetoresistor tiltmeters. The tiltmeters at Reynihlíd and Hvíthellir were not in operation in 1981. The shaded area shows the center of ground movement during the present episode of activity of the Krafla central volcano.

tiltmeter that observed tilt variations continuously and could be operated at any desired location. For this purpose a simple pendulum tiltmeter with magnetoresistor transducer was designed and built at the Nordic Volcanological Institute (Sindrason & Ólafsson, 1978). The first of these new N.V.I. tiltmeters was installed in the Krafla power station in mid August 1977. Five more tiltmeters were installed in the Krafla area in 1977 to 1979 (Fig. 1), although not all of them have been operated at the same time. By the end of 1981, four N.V.I. tiltmeters were in operation in the Krafla area.

Two tiltmeters were installed in Vestmannaeyjar, South Iceland, in early summer of 1978. This location was selected for study of ground movement, because of the recent volcanic activity in Surtsey 1963-1967 and Heimaey 1973. A future eruption in the Vestmannaeyjar area could cause great damage, as did the Heimaey eruption, and any effort should be made to foresee such an eruption.

One N.V.I. magnetoresistor tiltmeter was installed in a mine shaft in Walferdange, Luxembourg, in August 1979. The purpose of this installation was to compare this instrument with other types of tiltmeters uncer very quiet condition.

One tiltmeter was installed on Litla Hekla in May 1981, after the unexpected Hekla eruptions of August 1980 and April 1981.

THE KRAFLA TILT STATION, N.V.I.-1

This tiltmeter is located in a concrete cellar below the transformer platform, about 20 m west of the west wall of the power house of the Krafla geothermal power station. The roof of this cellar is covered by a 1 m layer of volcanic scoria and the floor is 3.4 m below the ground surface. The tiltmeter is bolted to the west wall of this cellar, and oriented parallel to the walls of the power house and also parallel to the water tube tiltmeter,

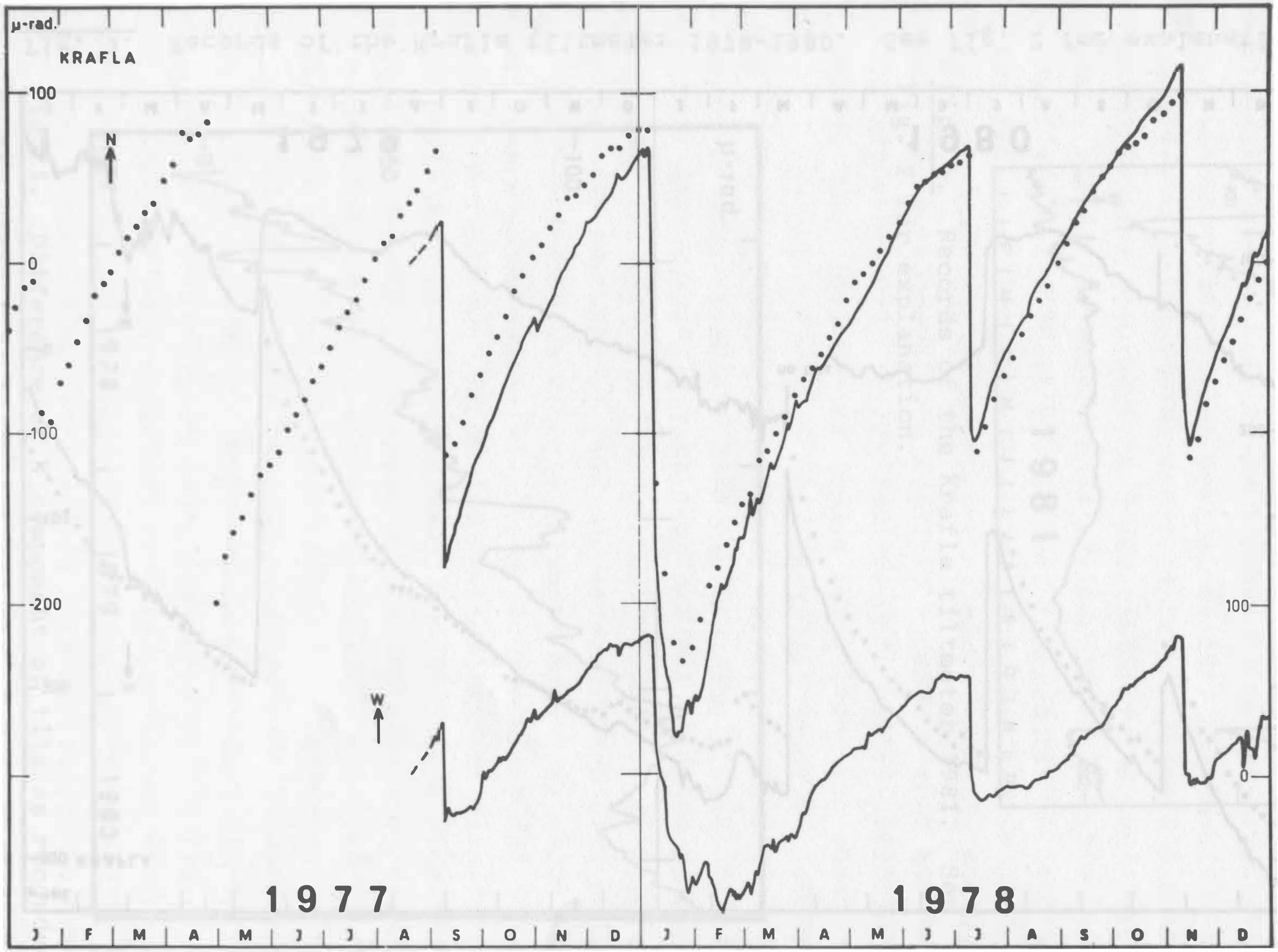
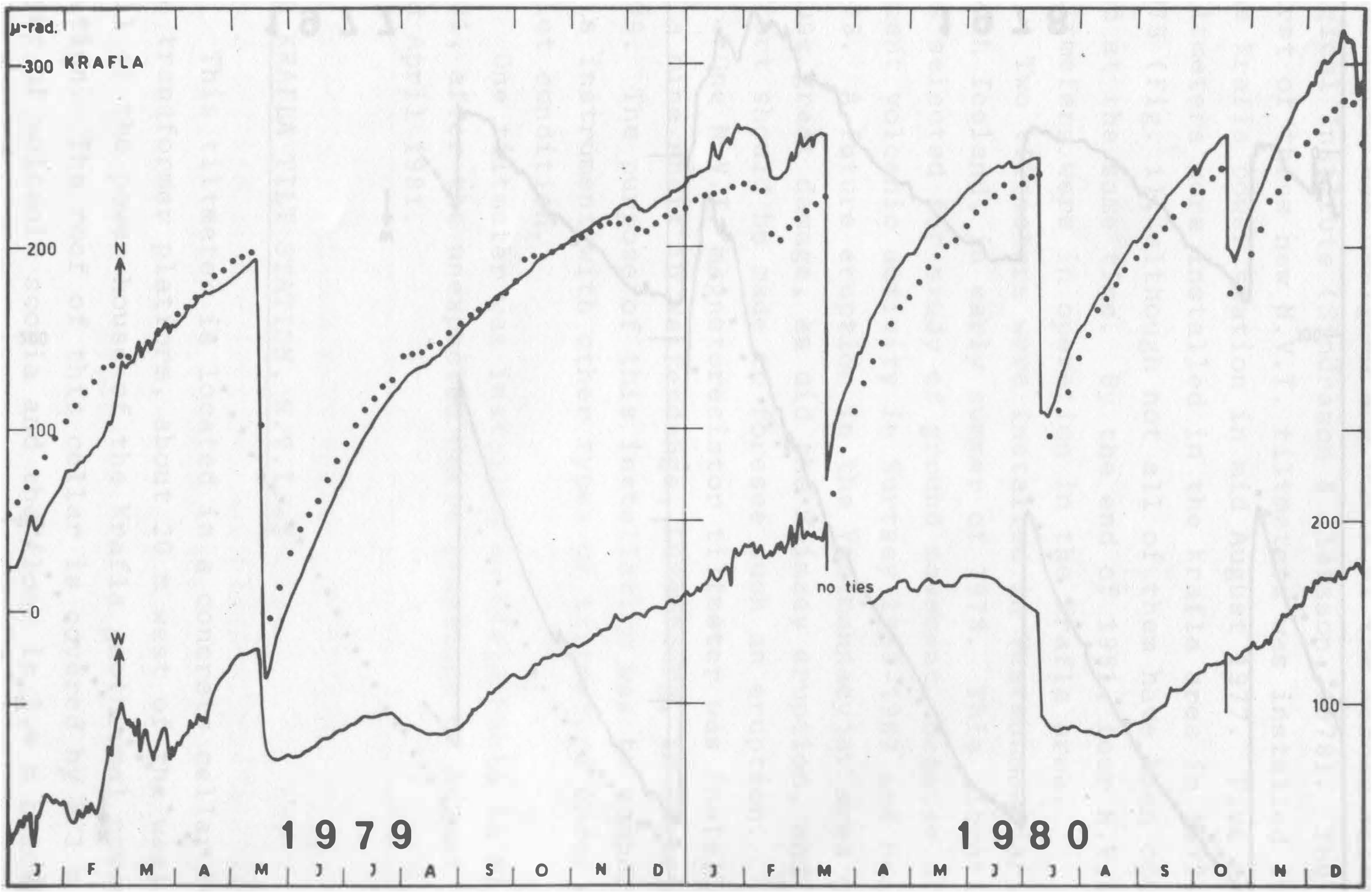


Fig. 2. Records of the Krafla (N.V.I.-1) magnetoresistor tiltmeter August 1977 to December 1978. The N-S component of the Krafla water tube tiltmeter is shown every 5th day as solid dots. Upper curve shows the N-S component of tilt, up is rising towards N13°E (left scale). Lower solid curve shows the E-W component of tilt, up is rising towards W13°N (right scale).



<u>Fig. 3.</u> Records of the Krafla tiltmeter 1979-1980. See Fig. 2 for explanation.

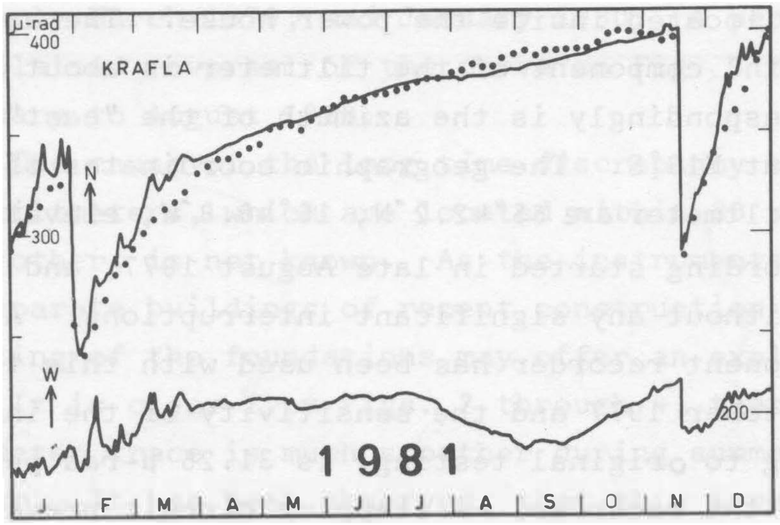


Fig. 4. Records of the Krafla tiltmeter 1981. See Fig. 2 for explanation.

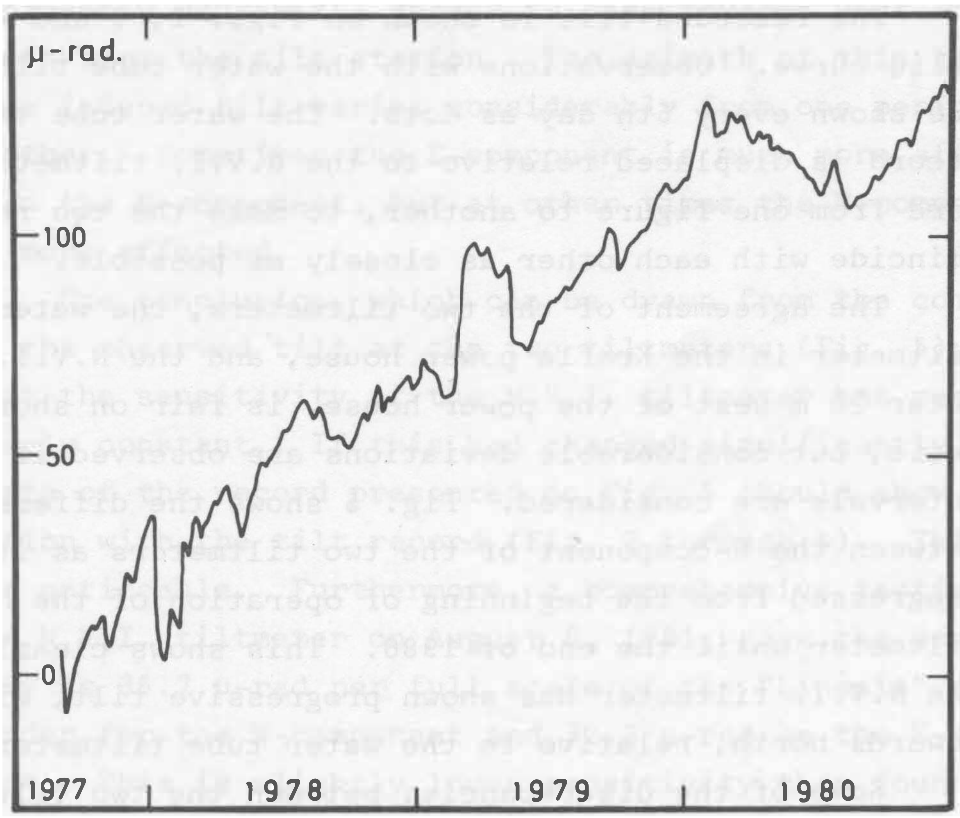


Fig. 5. Difference of N component of tilt as recorded by the water tube tiltmeter and the N.V.I. magnetoresistor tiltmeter at the Krafla power station. Increasing number mean that the magnetoresistor tiltmeter shows more tilt, up towards north, than the water tube tiltmeter.

which is located inside the power house. The azimuth of the "north" component of the tiltmeter is about N13°E, and correspondingly is the azimuth of the "east" component about E13°S. The geographic coordinates of the Krafla tiltmeter are 65°42.2´N, 16°46.8´W, elevation 413 m.

Recording started in late August 1977, and has continued without any significant interruptions. A "Linseis" two component recorder has been used with this tiltmeter since October 1977 and the sensitivity of the instrument, according to original testing, is 31.25 μ-rad per full scale on the recorder. A stepping circuit prevents the record to go off scale. A failure in the electrical part of the east component during a subsidence event on March 16, 1980, caused loss of continuity. Otherwise the tilt records are continuous, except for several short breaks caused by power failures.

The recorded tilt is shown on Figs. 2, 3 and 4 as solid curve. Observations with the water tube tiltmeter are shown every 5th day as dots. The water tube tilt record is displaced relative to the N.V.I. tiltmeter record from one figure to another, to make the two records coincide with each other as closely as possible.

The agreement of the two tiltmeters, the water tube tiltmeter in the Krafla power house, and the N.V.I. tiltmeter 20 m west of the power house, is fair on short time basis, but considerable deviations are observed if longer intervals are considered. Fig. 5 shows the difference between the N-component of the two tiltmeters as it has progressed from the beginning of operation of the N.V.I. tiltmeter until the end of 1980. This shows clearly that the N.V.I. tiltmeter has shown progressive tilt, rising towards north, relative to the water tube tiltmeter.

Some of the discrepancies between the two tiltmeters can be correlated with tilt events, as the subsidence events of September 1977, January 1978 and May 1979, while similar events of July 1978, November 1978 and March 1980 show conformance between the tiltmeters. Further, hard freeze causes sometimes discrepancies, as in late February to early March 1979, and January 1980. A peculiar and unexplained reversal of the curve on Fig. 5 occurs in February to August 1980.

The cause of the long time discrepancy between the two tiltmeters, which are located within 30 m distance of each other, is not known. As the instruments are placed in separate buildings of recent construction (1975-1976), settling of the foundations may offer an explanation.

It is clear from Figs. 2 through 4, that the N.V.I. tiltmeter trace is much smoother during summer than during winter. It has been observed, that this irregular behaviour of the tiltmeter during winter is only observed if the air temperature is below 0°C and if the ground is frozen. It is most pronounced if the ground is not or only partly covered by snow.

During periods of hard freeze, decreasing temperature apparently causes the ground to rise towards west and north from the tilt station. The azimuth of this temperature induced tilt varies considerably from one period to another. Sometimes the E-component is much more affected than the N-component, but at other times the N-component is more affected.

One conclusion, which can be drawn from the comparison of the observed tilt at the two tiltmeters (Fig. 5), is that the sensitivity of the N.V.I. tiltmeter has remained nearly constant. If this had changed significantly, parts of the record presented on Fig. 5 should show correlation with the tilt record (Fig. 2 through 4). This is not noticeable. Furthermore, a comprehensive testing of the N.V.I. tiltmeter on August 6, 1981, gave the sensitivity as 35.7 μ-rad per full scale of the "Linseis" recorder for the N-component and 32.3 μ-rad on the E-component. This is slightly lower sensitivity than found earlier, but the difference is hardly significant, as the first testing was of inferior quality.

The signal from the Krafla tiltmeter is frequency modulated and transmitted per telephone line to Reynihlíd, where a secondary recording is made for civil defence

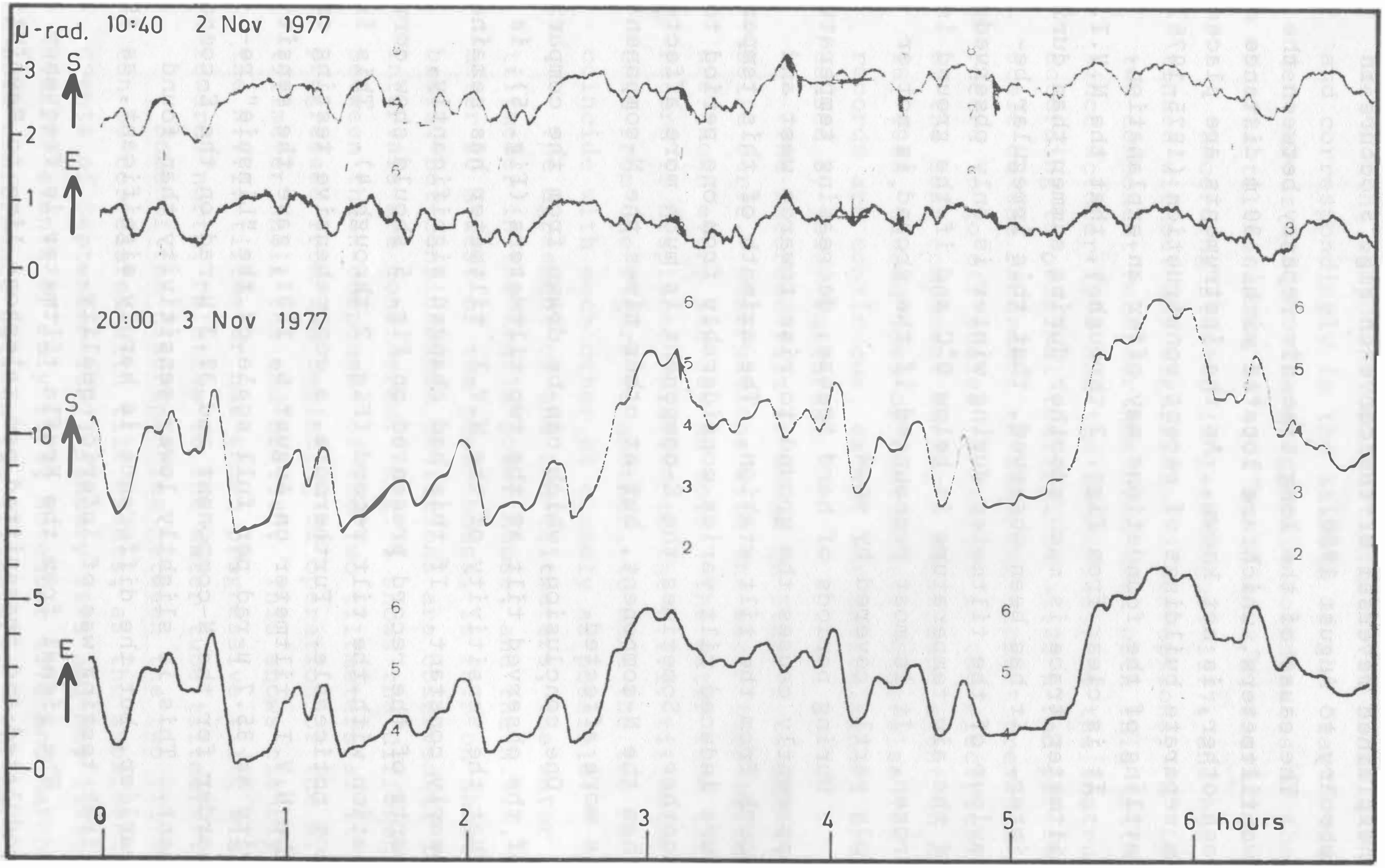


Fig. 6. Sample records of the Reynihlíd magnetoresistor tiltmeter. Arrows show direction of uplift. The unexplained irregular variations of apparent tilt have a stable azimuth of NW-SE.

purpose. The recorder is connected to an automatic alarm system, which gives a sound alarm if tilt rate, down towards north, indicates that subsidence event is starting. In case of eruptions, the tiltmeter alarm has sounded 1 to 4 hours before each eruption.

THE REYNIHLÍD TILT STATION, N.V.I.-2

This tiltmeter was installed in the fall of 1977, and recording started on October 28, 1977. The installation is in semiconsolidated morainic material. A hole was dug to 2 m depth and a vertical pipe placed in the hole and supported by concrete and gravel fill. The tiltmeter is placed inside this pipe and packed with dry sand.

The geographic coordinates are 65°38.7´N, 16°54.9´W, elevation 316 m.

The electrical signal from the tiltmeter was transmitted without any modulation over a 300 m cable to Reynihlíd,, where recording was made. Power for the tiltmeter (12 V DC) was transmitted from Reynihlíd through the same cable.

Recording was nearly continuous for almost two years, but it was terminated in September 1979. The record shows irregular tilt oscillations, especially in winter (Fig. 6), but clear tectonic tilt was observed only during a few subsidence events, most clearly in July 1978 (Tryggvason, 1980).

Only small sections of the Reynihlíd tilt record have been analysed and very little is known of the causes of irregular tilt waves, which make the record of limited use in studying tectonic tilt.

THE VÍTI TILT STATION, N.V.I.-5

The tiltmeter was installed in September 1978 in a 2 m hole dug in recent volcanic mixing of lava and scoria. The geographic coordinates are 65°43.6´N, 16°45.1´W, elevation 574 m. This location was chosen to be at similar distance from the Krafla volcano center of inflation/deflation as the tiltmeter in the Krafla power house.

The location of this tiltmeter, far away from electric power lines, required a local electric power supply.

The power problem was solved by installing a wind generator, which charges a 12 volt battery. A fully charged battery should last for three weeks of calm weather. This arrangement has prooven satisfactory although prolonged periods of calm weather have required replacement of battery once or twice a year.

Recording is with a "Rust Rack" recorder on pressure sensitive paper. The recorder, battery, and electronics box are placed in a wooden box, which is placed above the tiltmeter. The sensitivity of the recorded output is 65 μ-rad per full scale on the north component and 43 μ-rad per full scale on the east component, based on tests made during installation of the instrument. Another and more thorough test was made on July 2, 1981, and then the sensivity was found to be 51.5 μ-rad per full scale on the north component and 43.5 μ-rad per full scale on the east component. The discrepancy of the north component sensitivity is caused by nonlinearity of the relation between pendulum displacement and turning of adjustment screws, used for testing, and the first testing is based on too small displacements. Therefore, significant error may appear in the first test, and the latter test is considered more reliable. There is no reason to take the different sensitivity values as indication of decreasing sensitivity with time.

The observed tilt is shown on Figs. 7 and 8. Tilt record is nearly continuous except for breaks caused by instrument and/or power failure from mid January to March 4, 1980 and from July 15 to September 7, 1980. Tilt during these intervals in unknown, and the plotted tilt stage on Fig. 7 after the breaks is at an arbitary level.

The large and irregular tilt variation during winter is observed only during freezing temperature, and when the

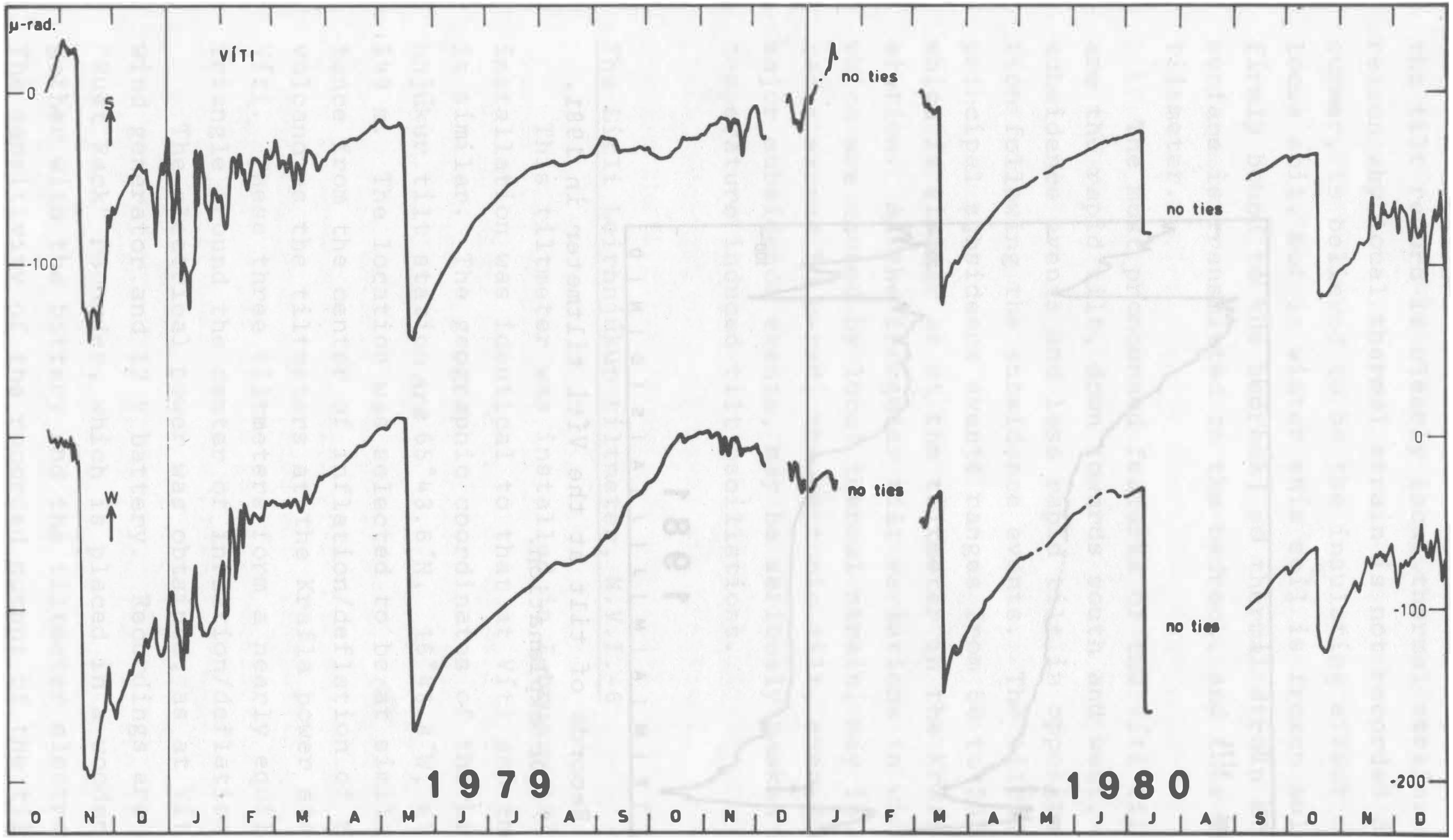


Fig. 7. Records of the Víti (N.V.I.-5) magnetoresistor tiltmeter, October 1978 to December 1980. The tilt stage in early March 1980 and early September 1980, are given arbitrary values after extended loss of records. Upper solid curve shows the N-S component of tilt, up is rising towards south (left scale). Lower curve is the E-W component of tilt, up is rising towards west (right scale).

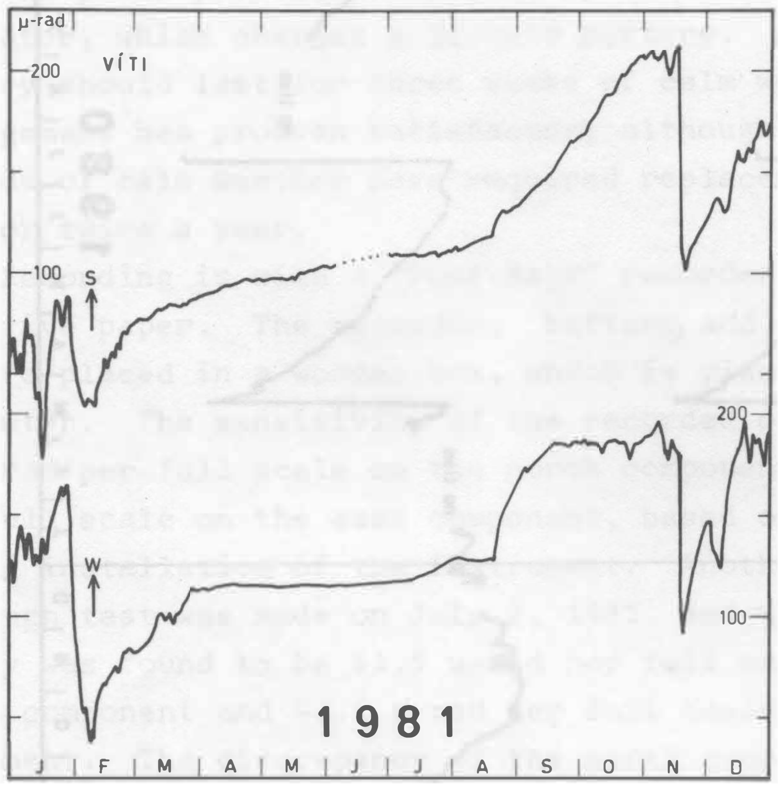


Fig. 8. Records of tilt at the Víti tiltmeter in 1981. See Fig. 7 for explanation.

ground is frozen. The cause of these irregularities in the tilt record is clearly local thermal strain. The reason why local thermal strain is not recorded during summer, is believed to be the insulating effect of the loose soil, but in winter this soil is frozen solid and firmly bound to the bedrock, so thermal strain at the surface is transmitted to the bedrock, and thus to the tiltmeter.

The most pronounced features of the Víti tilt records are the rapid tilt, down towards south and west, during subsidence events and less rapid tilt in opposite direction following the subsidence events. The tilt during the principal subsidence events ranges from 50 to 200 μ-rad, which is similar as at the tiltmeter in the Krafla power station. As the irregular tilt variations in winter, which are caused by local thermal strain, may in extreme cases exceed 50 μ-rad, the tectonic tilt, even during major subsidence events, may be seriously masked by these temperature induced tilt oscillations.

The Litli Leirhnjúkur tiltmeter, N.V.I.-6

This tiltmeter was installed in February 1979. The installation was identical to that at Víti and the geology is similar. The geographic coordinates of the Litli Leirhnjúkur tilt station are 65°43.6´N, 16°48.8´W, elevation 549 m. The location was selected to be at similar distance from the center of inflation/deflation of the Krafla volcano as the tiltmeters at the Krafla power station and Víti. These three tiltmeters form a nearly equilateral triangle around the center of inflation/deflation.

The electrical power was obtained, as at Víti, through wind generator and 12 V battery. Recordings are made on "Rust Rack" recorder, which is placed in a wooden box together with the battery and the tiltmeter electronics. The sensitivity of the recorded output of the tiltmeter is 68 μ-rad per full scale of the "Rust Rack" recorder on the north component and 58 μ-rad per full scale on the east component. Several breaks in the records are caused by lack of power, and the remoteness of the station resulted in infrequent inspection. In order to improve the recording and especially to observe any recording failure, a signal transmission to Reynihlíd was designed. The tiltmeter signal was frequency modulated in the audio frequency range, with different frequency band for the two tiltmeter components. The same was done at the Víti tiltmeter. Radio transmitter at Litli Leirhnjúkur sent the signal over line of sight to the Víti tiltmeter station, where the signals of the two tilt components at Víti were mixed with the Litli Leirhnjúkur signal. Then all four signals were sent from Víti to relay station on Hlídarfjall, and from there to Reynihlíd. The four tilt components were separated at Reynihlíd and recorded on two 2-component "Linseis" pen recorders. This radio transmission of the tiltmeter signal from Litli Leirhnjúkur and Víti to Reynihlíd started in November 1979. The relay station at Hlídarfjall was taken down in September 1980, and replaced by receiving station at Kringla and cable from Kringla to Múlavegur 9, Reykjahlíd, where the Nordic Volcanological Institute had acquired housing facility.

The character of the Litli Leirhnjúkur tilt record is by and large similar to that at Víti (Figs. 9, 10). Irregular tilt oscillations in winter are very pronounced although of slightly smaller amplitudes than at Víti. Subsidence events are recorded with similar tilt as at Krafla power house and Víti, although some details of the records are different. The subsidence event of March 1980 produced surface fissures within 100 m from the Litli Leirhnjúkur tiltmeter, and the same fissures moved visibly during the October 1980 subsidence event. During both these events, extremely rapid tilt change was recorded at Litli Leirhnjúkur, supposedly as the nearby fissure moved. In October 1980 this movement was so rapid that continuity of the east component of tilt was lost.

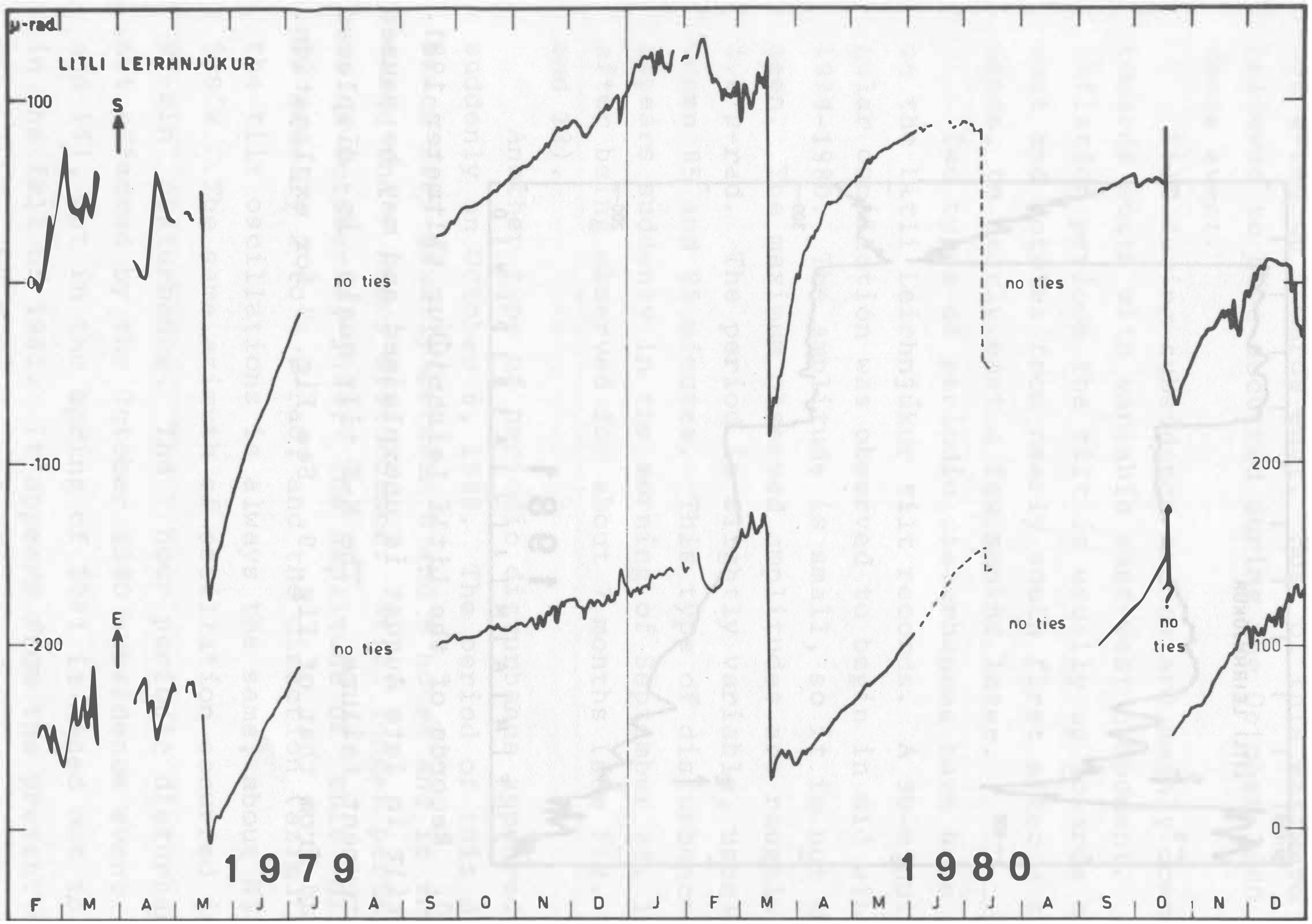


Fig. 9. Records of the Litli Leirhnjúkur (N.V.I.-6) magnetoresistor tiltmeter 1979-1980. Upper curve shows the N-S component of the tilt, up is rising towards south (left scale). Lower curve shows E-W component of tilt, up is rising towards east (right scale). Dashed parts of the curves are based on poor records of radio transmitted signals.

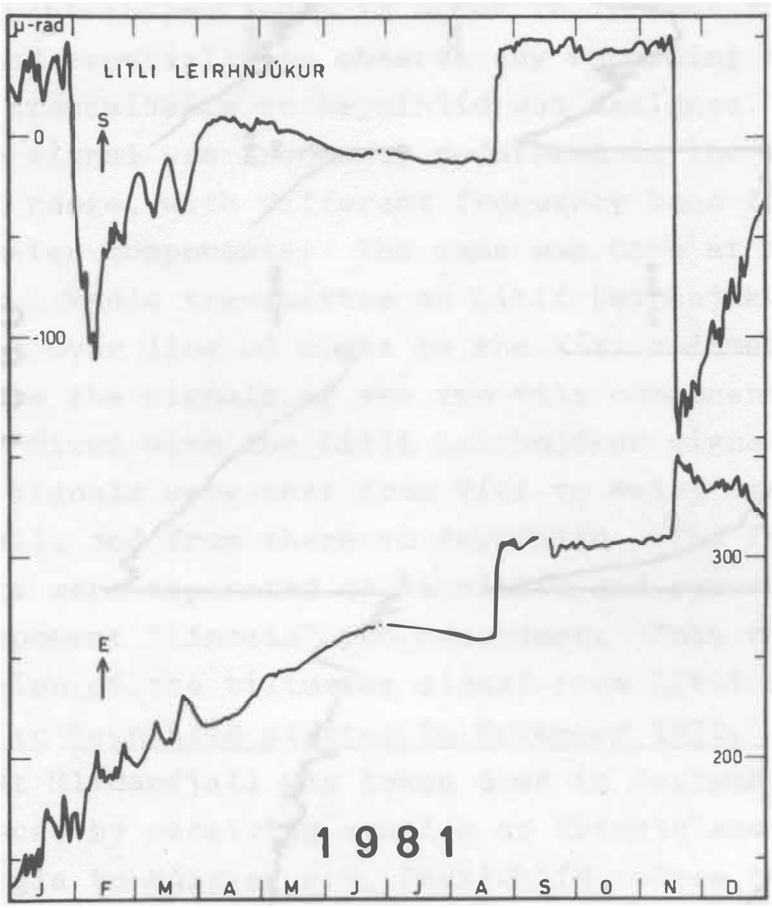


Fig. 10. Records of the Litli Leirhnjúkur tiltmeter 1981. Rapid tilt in late August is unexplained and may be caused by instrument failure. The N-S tilt scale is displaced 50 μ-rad from that of Fig. 9. See Fig. 9 for explanation.

Readings of the output of the tiltmeter transducer in June 1981, showed that the tilt since installation in September 1979 was about 155 μ-rad up towards north and 652 μ-rad up towards east. Most of this eastward tilt is believed to have occurred during the October 1980 subsidence event.

Tilt during subsidence events are mainly down towards south with variable east-west component. During inflation periods the tilt is usually up towards southeast and rotates from nearly south first after a subsidence, to nearly east a few months later.

Two types of periodic disturbances have been observed on the Litli Leirhnjúkur tilt records. A 90-minutes regular oscillation was observed to begin in mid winter 1979-1980. The amplitude is small, so it is not easily seen. The maximum observed amplitudes are roughly 0.5 to 1.0 μ-rad. The period is slightly variable, usually between 85 and 95 minutes. This type of disturbance disappears suddenly in the morning of September 28, 1980, after being observed for about 7 months (see Fig. 11, 12, and 13).

Another type of periodic disturbance appeared rather suddenly on October 8, 1980. The period of this disturbance lies usually between 6 and 8 hours and is therefore named the 7 hours disturbance. Still longer periods occur, as on October 8, 1980. The amplitude of this disturbance is usually 2 to 4 μ-rad, and the direction (azimuth) of the tilt oscillations is always the same, about N30°E to S30°W. The same azimuth of oscillation occurred in the 90-min disturbance. The 7 hour periodic disturbance was not affected by the October 1980 subsidence event (Fig. 14 and 15), but in the spring of 1981 it faded out to reappear in the fall of 1981. It appears from the present observation, that the 7 hour periodic disturbance at Litli Leirhnjúkur exists only during the winter. The cause of these periodic disturbances at Litli Leirhnjúkur is unknown, but it may be pointed out that an area, about 100 m to the

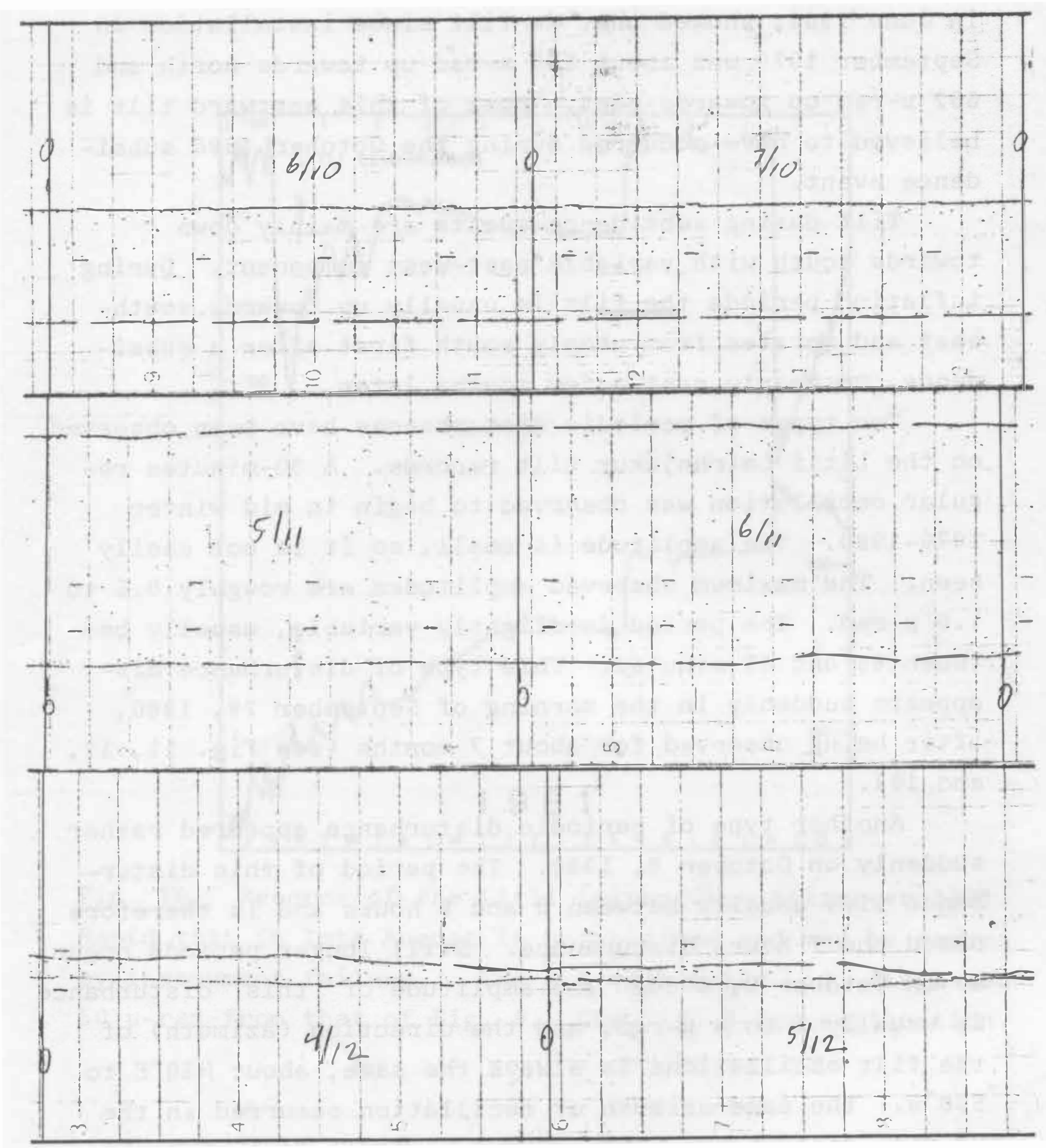


Fig. 11. Three 48 hours sections of tilt records from 1979 in Litli Leirhnjúkur. Record from October 6-7 is quite smooth, but irregularities on the records from November 5-6 and December 4-5 are caused by thermal strain in the frozen ground. The thicker of the two lines shows the N-component of tilt. Full scale represents about 60 μ-rad of tilt. Time signals are recorded every 6 hours.

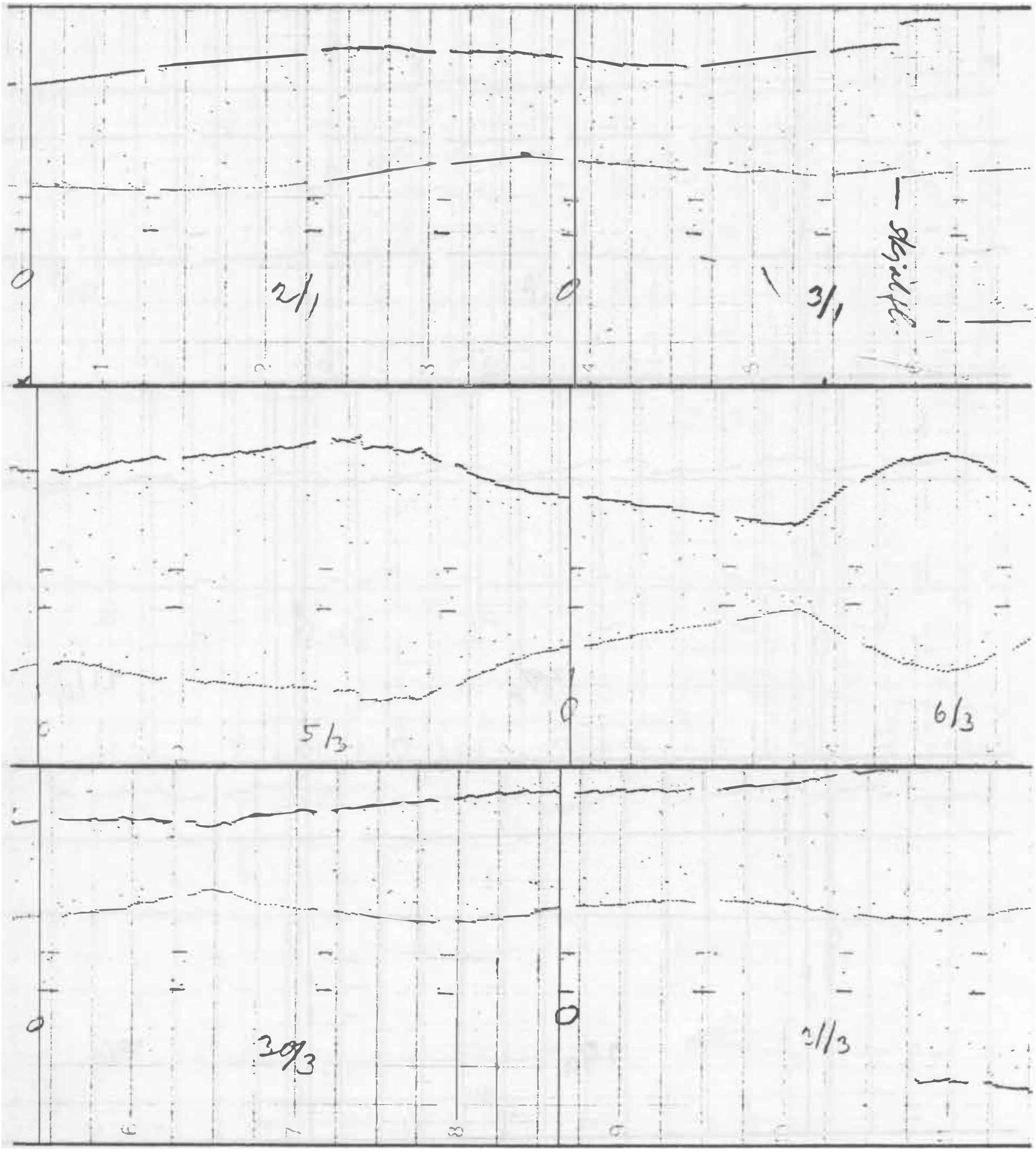


Fig. 12. Three 48 hours sections of tilt records from early 1980 in Litli Leirhnjúkur. The records are greatly disturbed by thermal strain, especially on March 5-6. Earthquake caused step in tilt record on January 3. The 90 min periodic disturbance is clearly visible on March 30-31, and also, but less clearly, on March 5-6.

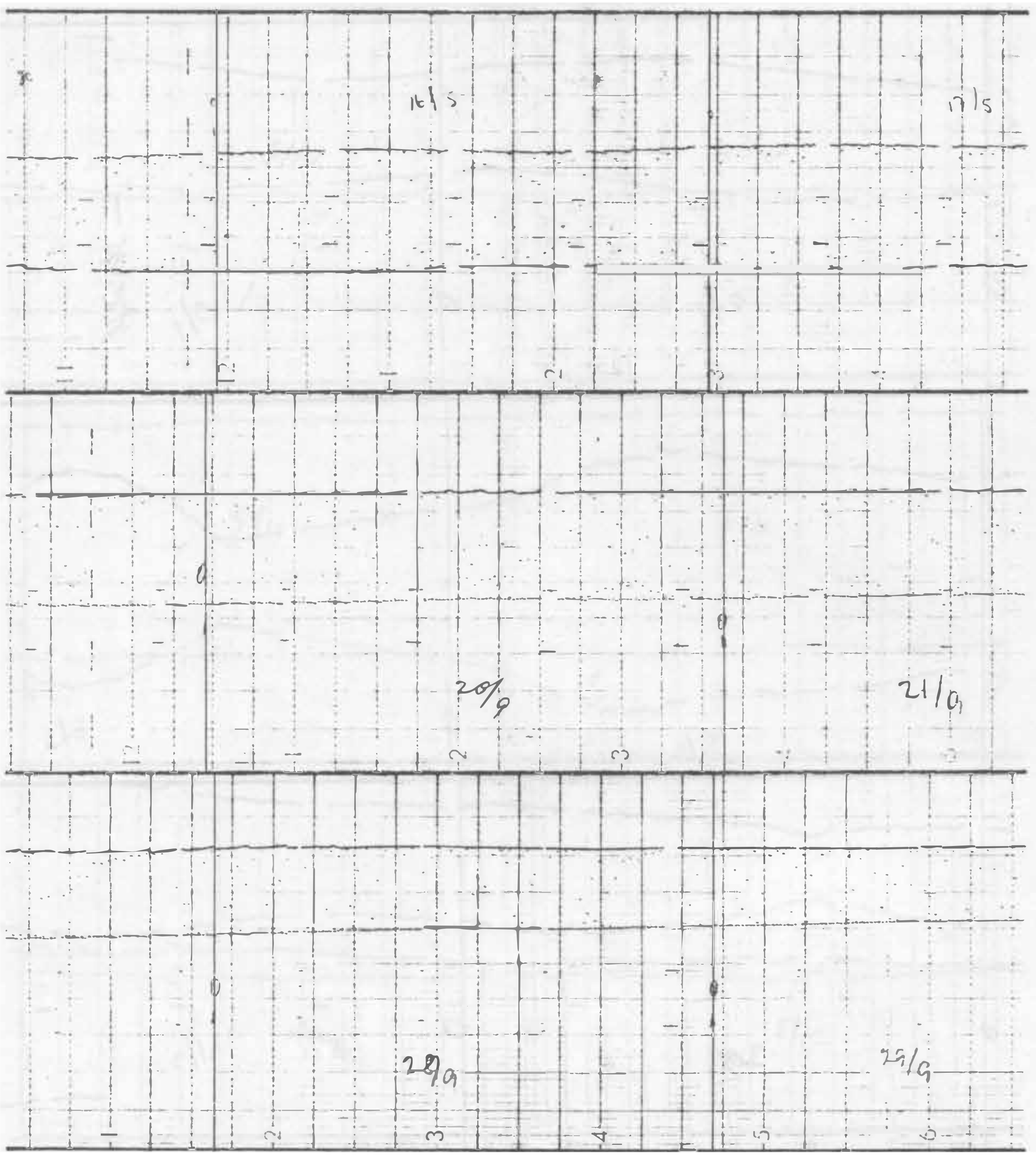


Fig. 13. Three 48 hours sections of tilt records from 1980 in Litli Leirhnjúkur. There is no thermal strain effect, but the 90 min periodic disturbance is seen on the records May 16-17 and September 20-21, but it disappeared on September 28.

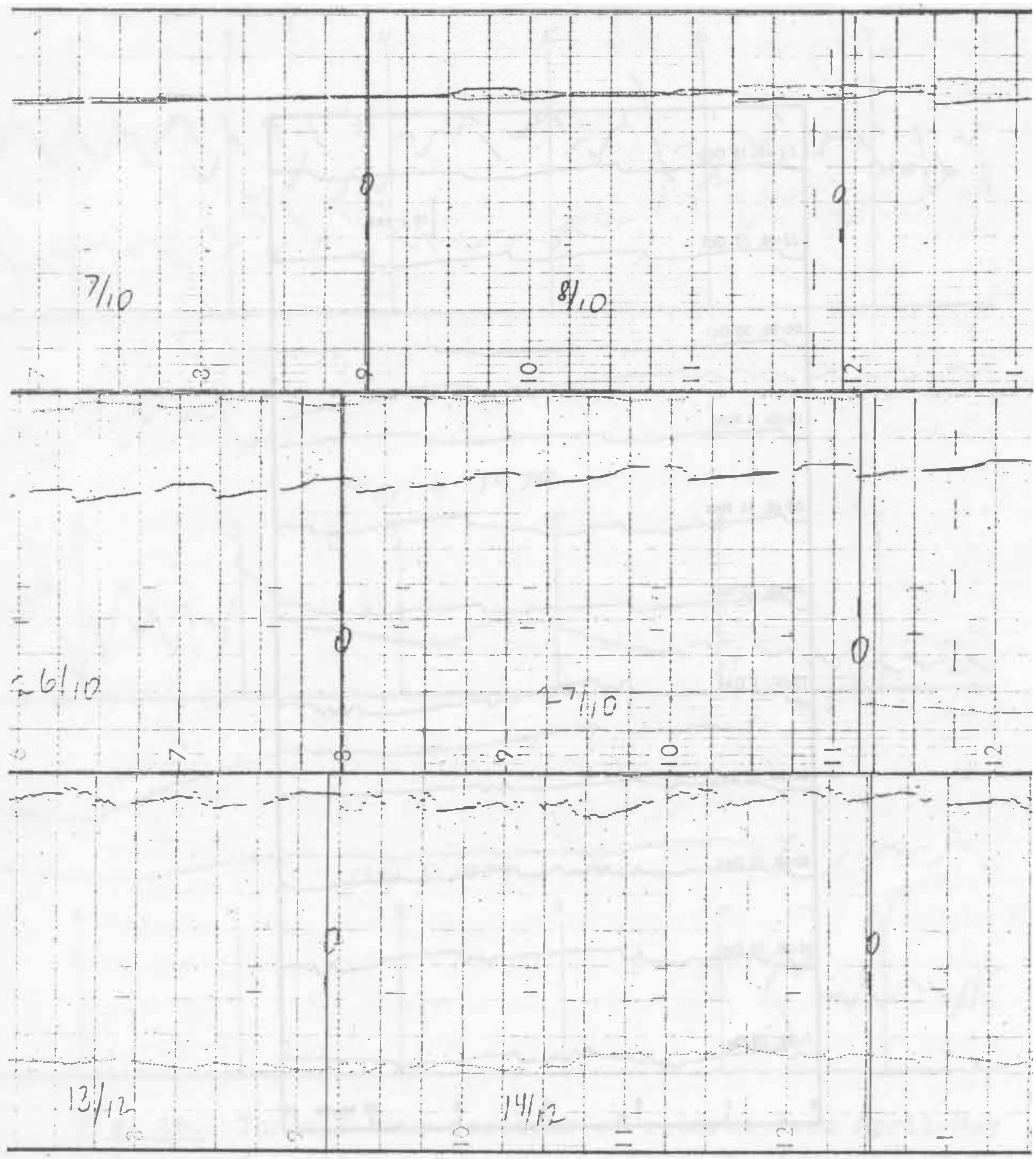


Fig. 14. Three 48 hours sections of tilt records from late 1980 in Litli Leirhnjúkur. The 7 hours periodic disturbance begins on October 8, but this type of disturbance had not been seen earlier. On October 26-27 this 7 hours disturbance is very clear and regular, but becomes more irregular by December 13-14.

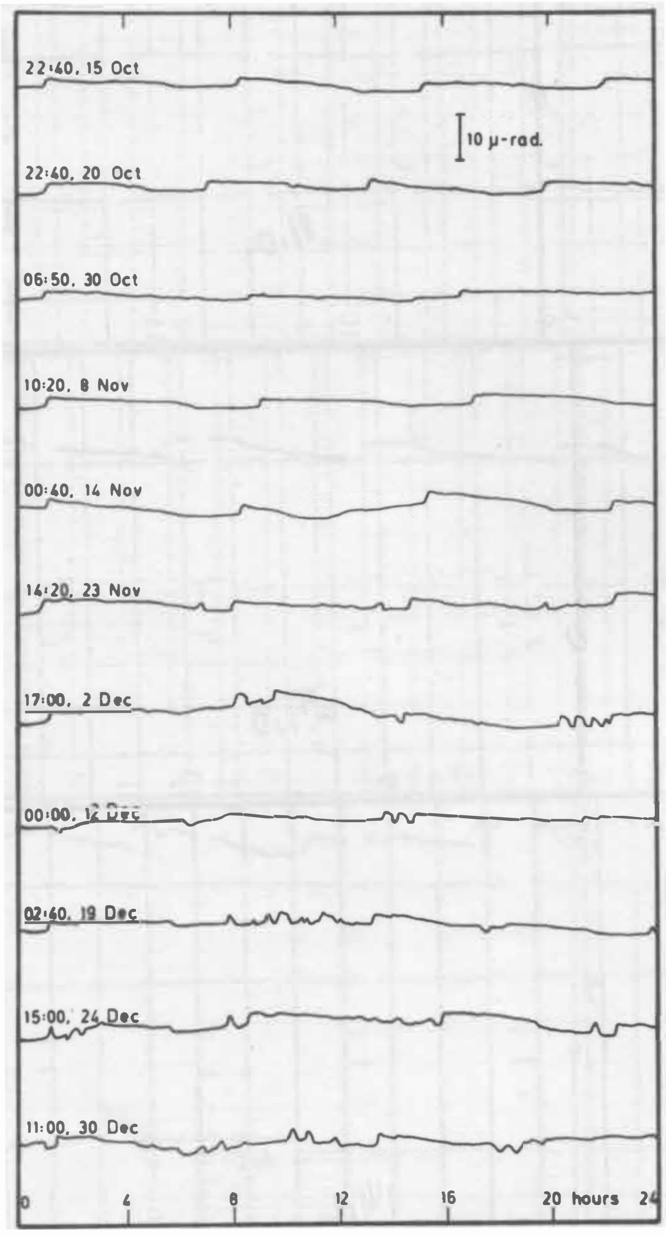


Fig. 15. Tracings of the N-component tiltmeter records at Litli Leirhnjúkur for 11 selected 24-hour intervals in 1980. The 7 hours periodic disturbance is especially clear on the 5 first records, but becomes less regular on later records.

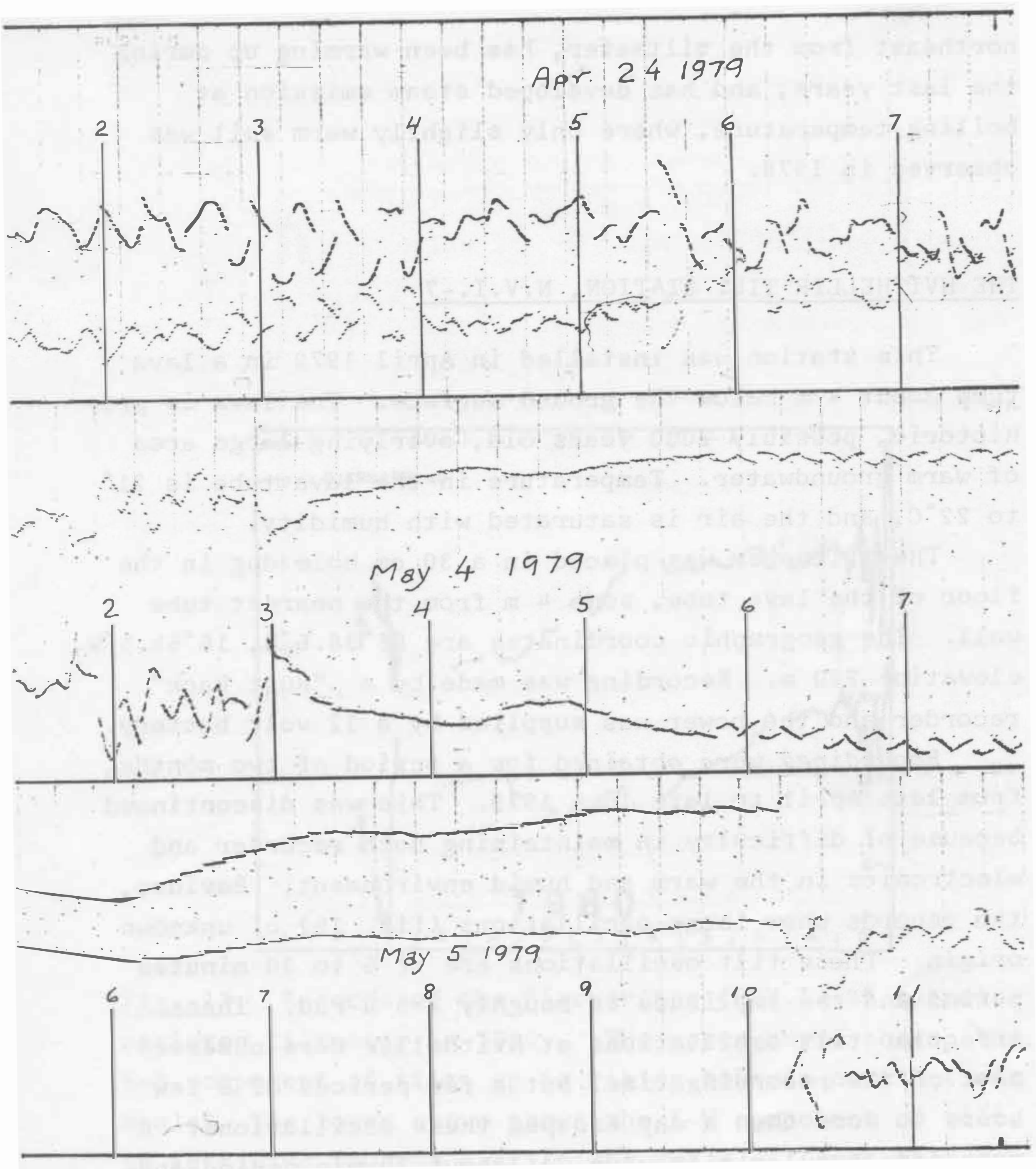


Fig. 16. Three 6-hour sections of records from April-May 1979 in Hvíthellir. Recorder runs 5.6 minutes, and is then turned off for another 5.6 minutes. Record of April 24 shows continuous irregular waves of roughly 15 minutes period. This pattern was broken at 3^h15^m on May 4 (central section) and a more regular wave of about 10 minutes period emerged at 5^h50^m. On May 5, at 10^h15^m (lowest section) the continuous irregular waves started again. The amplitude of these irregular waves is usually 2 to 5 μ-rad.

northeast from the tiltmeter, has been warming up during the last years, and has developed steam emission at boiling temperature, where only slightly warm soil was observed in 1978.

THE HVÍTHELLIR TILT STATION, N.V.I.-7

This station was installed in April 1979 in a lava tube about 4 m below the ground surface. The lava is prehistoric, possibly 2000 years old, overlying large area of warm groundwater. Temperature in the lava tube is 21° to 22°C, and the air is saturated with humidity.

The tiltmeter was placed in a 30 cm hole dug in the floor of the lava tube, some 4 m from the nearest tube wall. The geographic coordinates are 65°38.6'N, 16°54.5'W, elevation 290 m. Recording was made by a "Rust Rack" recorder and the power was supplied by a 12 volt battery.

Recordings were obtained for a period of two months, from late April to late June 1979. This was discontinued because of difficulty in maintaining both recorder and electronics in the warm and humid environment. Besides, the records show large oscillations (Fig. 16) of unknown origin. These tilt oscillations are of 5 to 30 minutes period and the amplitude is roughly 2-5 μ-rad. These irregular tilt oscillations at Hvíthellir were observed most of the recording time, but a few periods of a few hours to more than a day escaped these oscillations. A much more regular tilt wave of about 10 min period and amplitude of 0.5 μ-rad was observed during a quiet period on May 4, 1979 (Fig. 16).

THE BJARNARFLAG TILT STATION, N.V.I.-9

This tiltmeter was installed in September 1979, in a hole about 2.5 m deep, which had been dug for other purposes. The station lies between the palagonite ridge Náma-

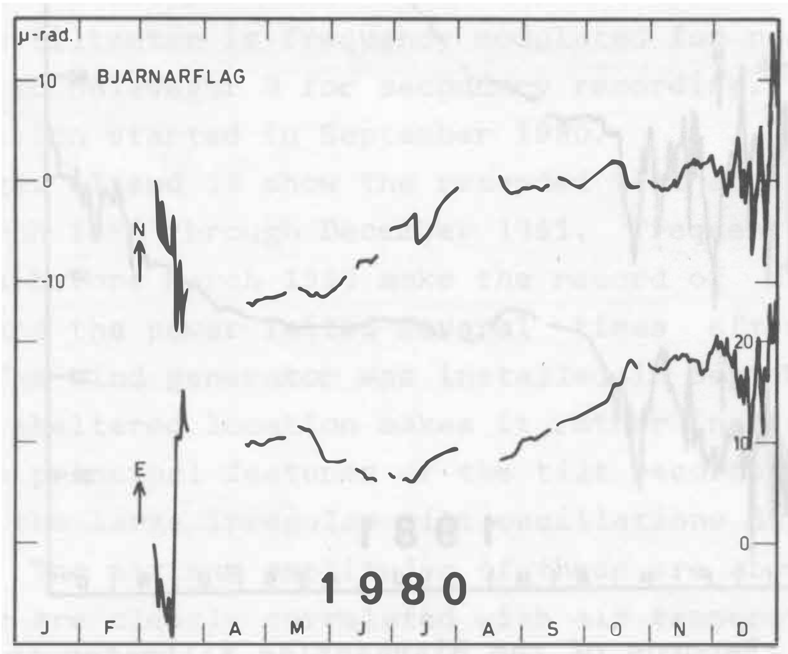


Fig. 17. Records of the Bjarnarflag (N.V.I.-9) magnetoresistor tiltmeter in 1980. The upper curve shows the N-S component of tilt, up is rising towards north (left scale). The lower curve shows the E-W component of tilt, up is rising towards east (right scale). Large tilt oscillations in winter are caused by thermal strain in the frozen ground.

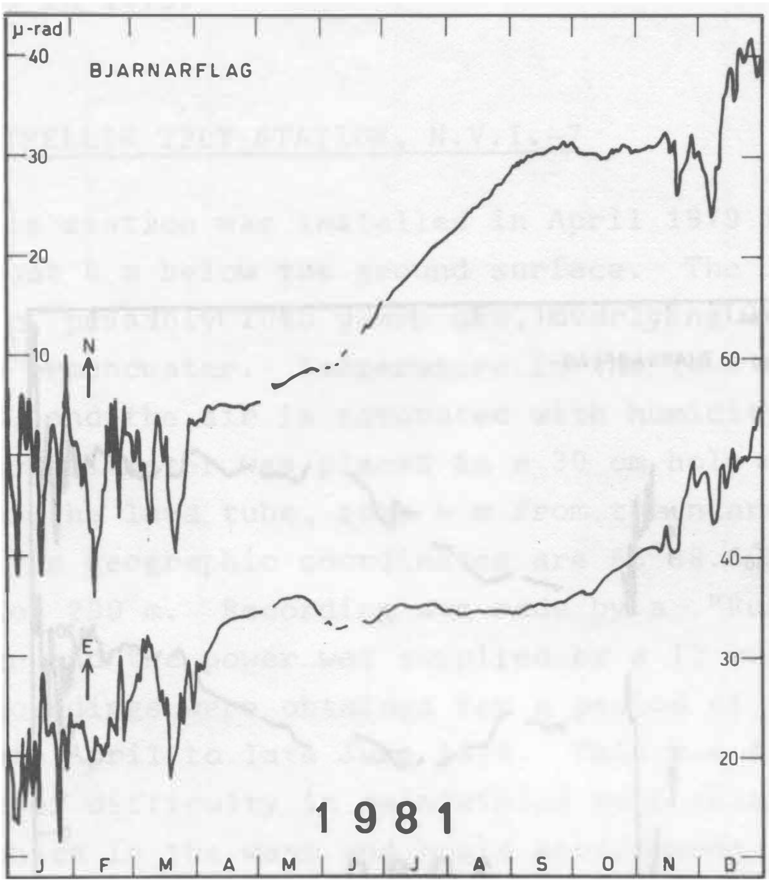


Fig. 18. Records of the Bjarnarflag tiltmeter in 1981. See Fig. 17 for explanation.

fjall and a postglacial crater row. The hole was dug in loose material, which had been washed from the Námafjall ridge, and filled what had been a trench between the ridge and the crater row. The geographic coordinates are 65°37.8´N, 16°50.5´W, elevation 353 m.

This tilt station is very similar to those at Víti and Litli Leirhnjúkur. The power is supplied by a 12 volt battery, which is charged by a wind generator. The recorder is a "Rust Rack". The sensitivity of the tiltmeter is about 9 μ-rad per full scale as recorded. The signal from the tiltmeter is frequency modulated for radio transmission to Múlavegur 9 for secondary recording. The radio transmission started in September 1980.

Figs. 17 and 18 show the recorded tilt at Bjarnarflag from March 1980 through December 1981. Frequent power failures before March 1980 make the record of dubious value, and the power failed several times after March 1980. The wind generator was installed in September 1980, but the sheltered location makes it rather ineffective.

The principal features of the tilt records (Fig. 17, 18) are the large irregular tilt oscillations during winter. The maximum amplitudes of these are about 20 μ-rad, and they are clearly correlated with air temperature during periods of freezing temperature. It is quite clear, that these irregular oscillations during winter are caused by thermal strain in the frozen ground. As the tiltmeter is not bound to the basement rock, this thermal strain need not be transmitted to the basement to be recorded.

The tilt records are rather smooth during summer, which shows that thermal strain in the unfrozen soil is not transmitted to the tiltmeter. The observed tilt during summer is considered as mainly of tectonic origin. Earth tide is clearly observed in summer time, although it has not been analysed. The tidal tilt oscillations can be seen on Fig. 19, central record.

The subsidence events of the Krafla volcano are clearly seen during summer (July and October, 1980), but

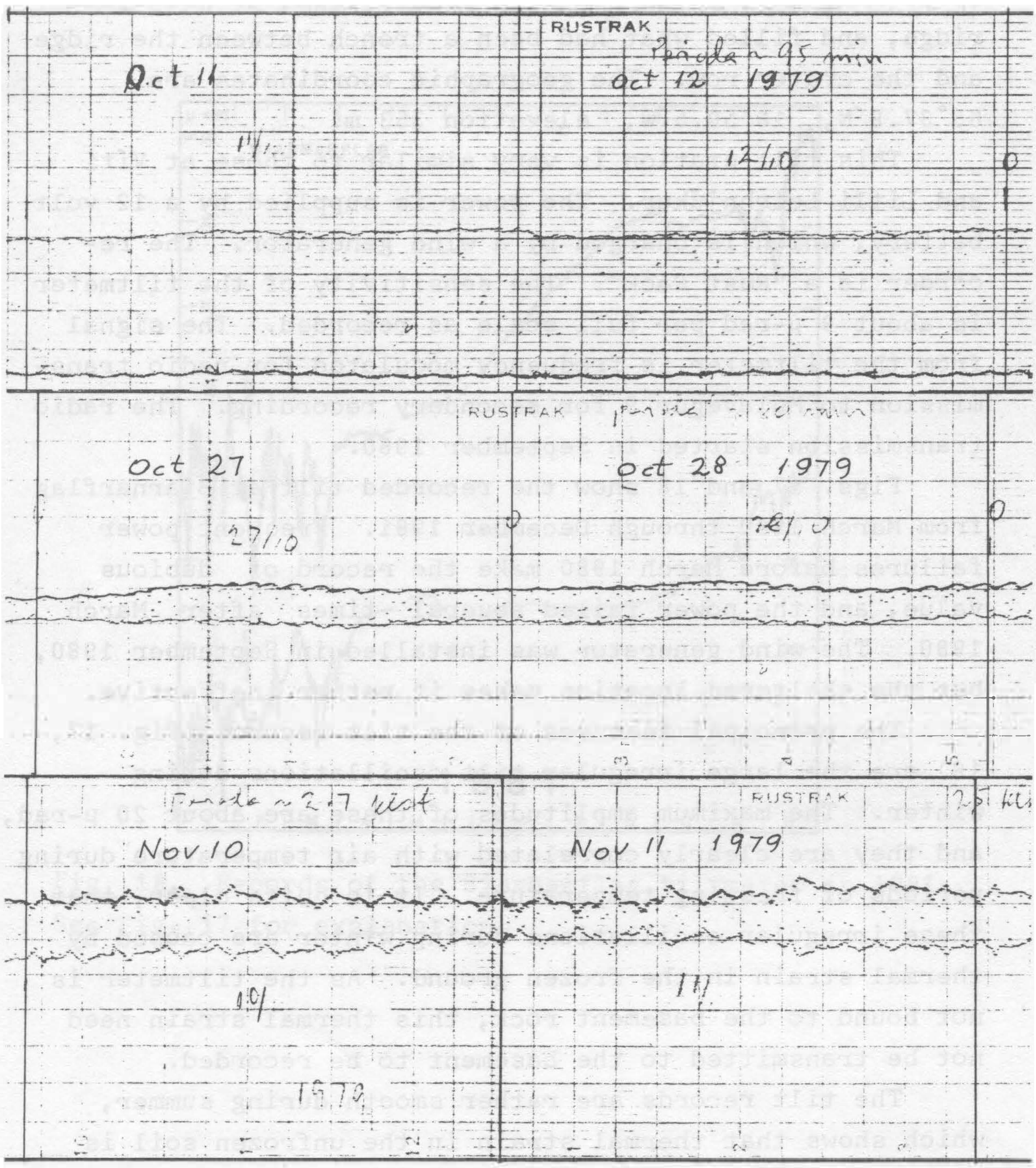


Fig. 19. Three 48 hours sections of tilt records from late 1979 in Bjarnarflag, showing regular 80-95 min period waves of 0.2 μ-rad amplitude (two upper sections), and irregular waves of about 160 min period (bottom section).

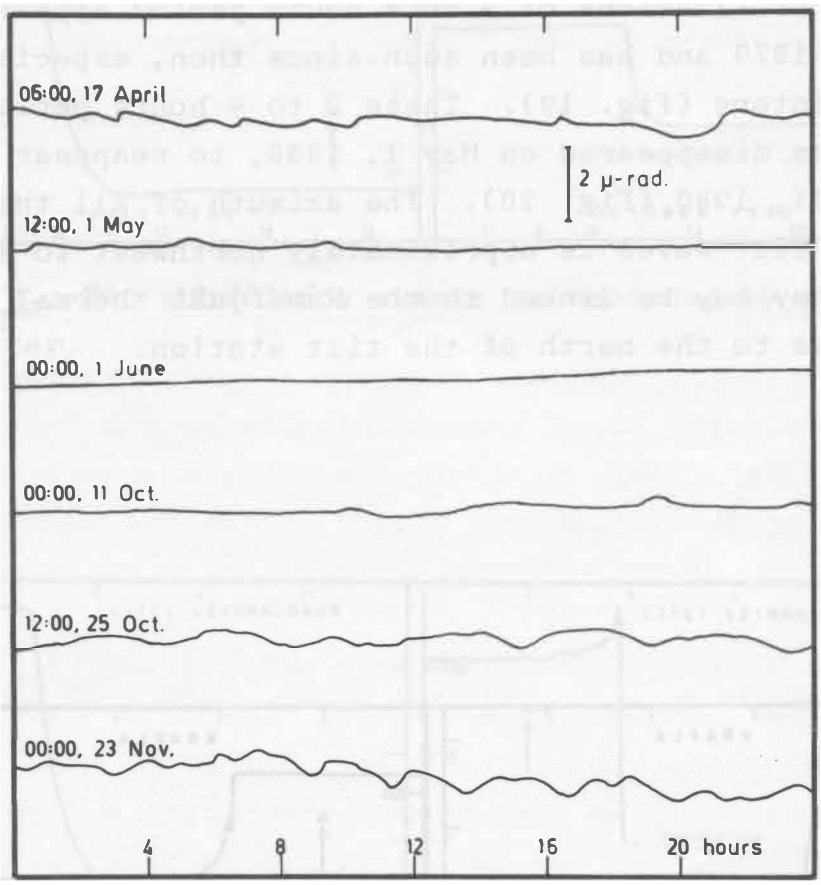


Fig. 20. Tracings of the N-component tiltmeter records at Bjarnarflag for 6 selected 24 hours intervals in 1980. Periodic disturbances are observed in winter and disappear in the evening of May 1 and reappear in the morning of October 11. Between these dates no such periodic disturbance was visible on the tilt records.

they are partly or wholly masked by the thermal tilt during winter.

Periodic tilt oscillations of about 90 min period were observed in the fall of 1979, and another type of periodic oscillations of 2 to 4 hours period appeared in November 1979 and has been seen since then, especially during winters (Fig. 19). These 2 to 4 hours periodic tilt waves disappeared on May 1, 1980, to reappear on October 11, 1980 (Fig. 20). The azimuth of all these periodic tilt waves is approximately northwest to south-east. They may be linked to the Námafjall thermal area, which lies to the north of the tilt station.

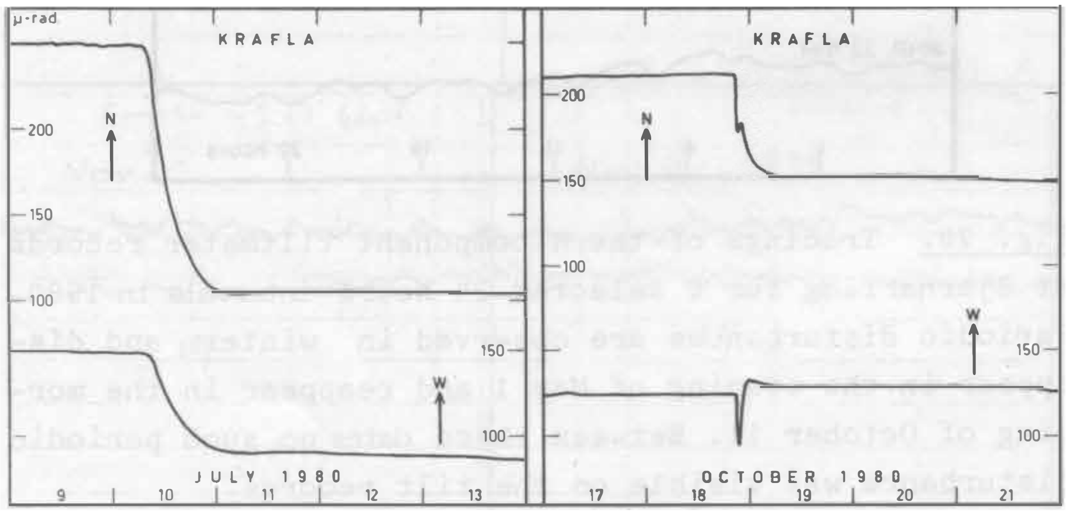


Fig. 21. Two subsidence events as recorded by the Krafla magnetoresistor tiltmeter. The reversal in tilt during the subsidence of October 18, is related to opening of ground fissures near the tiltmeter.

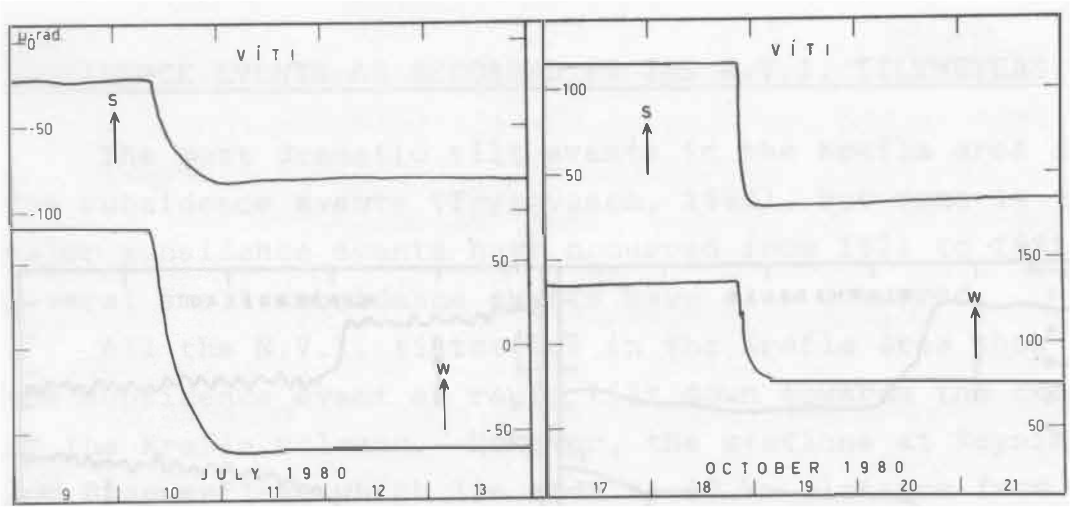


Fig. 22. Two subsidence events as recorded by the Víti tiltmeter.

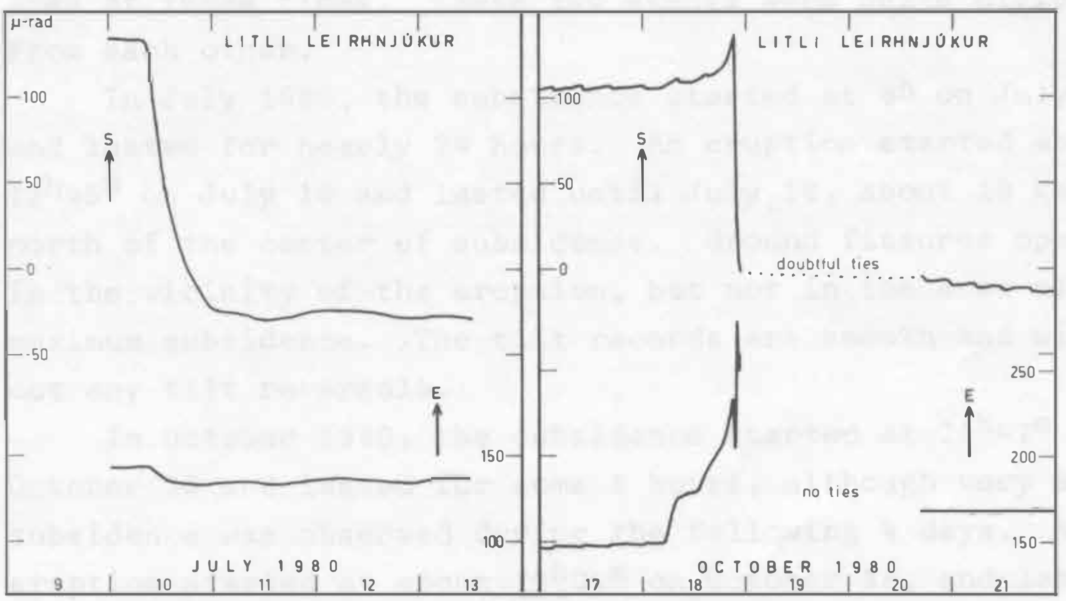


Fig. 23. Two subsidence events as recorded by the Litli Leirhnjúkur tiltmeter. The event of October 18, 1980, started about 16 hours before any of the other instruments showed that subsidence event had begun. Very rapid tilt variations during the October 18 subsidence event made the records illegible. The 6-8 hours periodic disturbance is seen before and after the October 18 event.

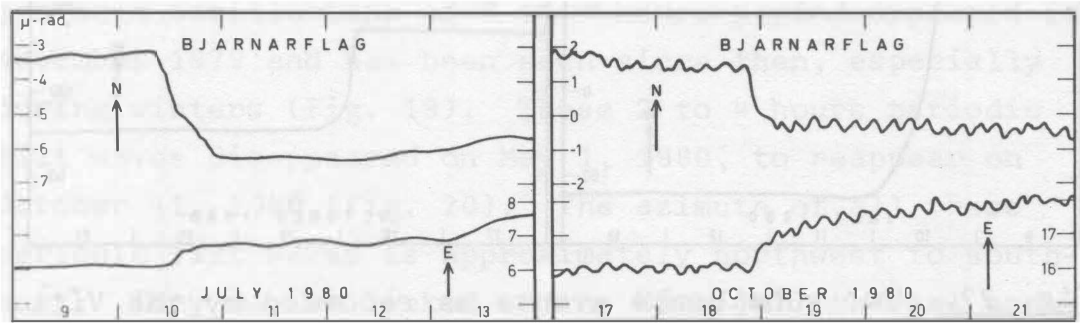


Fig. 24. Two subsidence events as recorded by the Bjarnarflag tiltmeter. Earth tide is visible on the July 9-13 records, but 3-5 hours periodic disturbance is very clear on the October 17-21 records.

SUBSIDENCE EVENTS AS RECORDED BY THE N.V.I. TILTMETERS

The most dramatic tilt events in the Krafla area are the subsidence events (Tryggvason, 1980), but some 14 major subsidence events have occurred from 1975 to 1981. Several small subsidence events have also occurred.

All the N.V.I. tiltmeters in the Krafla area show the subsidence event as rapid tilt down towards the center of the Krafla volcano. However, the stations at Reynihlíd and Bjarnarflag, which lie at 9 to 10 km distance from the center of subsidence, record so small tilt during these events, that it is masked by thermal strain tilt during the winter.

Figures 21 through 24 show tilt as recorded during the subsidence events of July and October 1980 by the four N.V.I. magnetoresistor tiltmeters operated in the Krafla area at those times. These two events were quite different from each other.

In July 1980, the subsidence started at 8^h on July 10 and lasted for nearly 24 hours. An eruption started about 12^h45^m on July 10 and lasted until July 18, about 10 km north of the center of subsidence. Ground fissures opened in the vicinity of the eruption, but not in the area of maximum subsidence. The tilt records are smooth and without any tilt reversals.

In October 1980, the subsidence started at 20^h42^m on October 18 and lasted for some 8 hours, although very slow subsidence was observed during the following 4 days. An eruption started at about 22^h04^m on October 18, and lasted until the evening of October 23. This eruption started on a fissure extending from Leirhnjúkur, near the center of subsidence, towards north about 7 km. Fissures opened to the south of Leirhnjúkur. The tilt records at Krafla, Víti, and Litli Leirhnjúkur all show very rapid tilt with brief reversal of tilt on one or both components. These reversals of tilt during subsidence events have been seen during events if fissures have opened through the center of subsidence. They apparently occur when the ground is rifted in the vicinity of the tilt station.

The Litli Leirhnjúkur tiltmeter shows extremely rapid tilt during the October 1980 subsidence event. Oscillating tilt on the east component was so rapid, that the record could not be read and the total tilt is unknown. Readings of the tiltmeter stage in June 1981 indicate that the tilt may have been some 600 μ-rad up towards east during this event.

A precursor to the subsidence event was recorded at Litli Leirhnjúkur. A rapid tilt up towards east or slightly south of east, started at 5^h on October 18, about 16 hours before any other instrument showed indication of the subsidence event. The direction of this precursory tilt at Litli Leirhnjúkur was approximately towards the location where the eruption started, as if the eruption site had been uplifted prior to the subsidence of a much larger area.

THE VESTMANNAEYJAR I TILT STATION, N.V.I.-3

This tiltmeter was installed in May 1978 in the town of Vestmannaeyjar. The geographic coordinates are 63°26.5´N, 20°16.1´W, elevation about 10 m. The instrument is placed in a 2 m deep well dug in prehistoric lava. Recording is by a "Rust Rack" recorder, and the recording sensitivity is about 18 μ-rad per full scale on the recorder. The recorder and electronics box is housed in the town office building and town officials operate the tiltmeter.

Records of tilt have been obtained from June 6 to October 20, 1978, from February 13 to September 6, 1979, from October 10, 1979 to February 4, 1980, and from February 14 to end of December 1981. The last period of operation has not been analyzed and is not discussed here.

Figs. 25 and 26 show the tilt records obtained in 1978 through 1980. The principal feature of the tilt records is a pronounced annual tilt cycle with about 50 μ-rad amplitude on the north component and about 10 μ-rad on the east component. Maximum tilt, up towards north, is observed in September and a broad minima occurs in February to April. A rapid tilt down towards north occurred in mid November 1979. This coincides with very heavy rainfall.

It is obvious that the annual tilt cycle at Vestmannaeyjar I, has to do with the annual temperature cycle. The maxima in September coincides roughly with maximum ground temperature and the minima coincides with minimum ground temperature. The large tilt variation, which is caused by temperature variation in the ground, makes it impossible to detect small tectonic tilt, and no sign of tectonic tilt is seen on the records obtained to date.

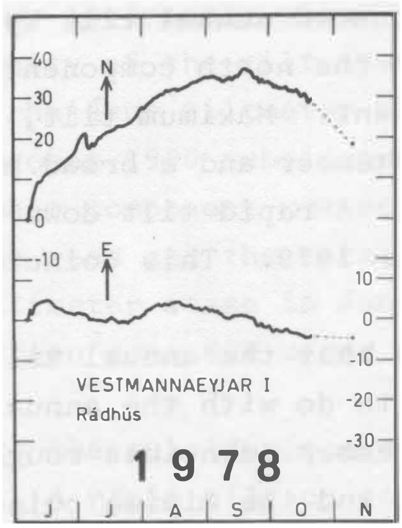
Tidal oscillations are clearly recorded, but they have not been analyzed. A few readings indicate that the recorded tide is in phase with ocean tide, and high ocean tide coincide with uplift towards north to northeast.

A clear difference between the tilt record at Vestmannaeyjar and that at stations in the Krafla area, is that the large irregular tilt oscillations, which are observed during winter in the Krafla area, North Iceland, are not seen in Vestmannaeyjar, South Iceland.

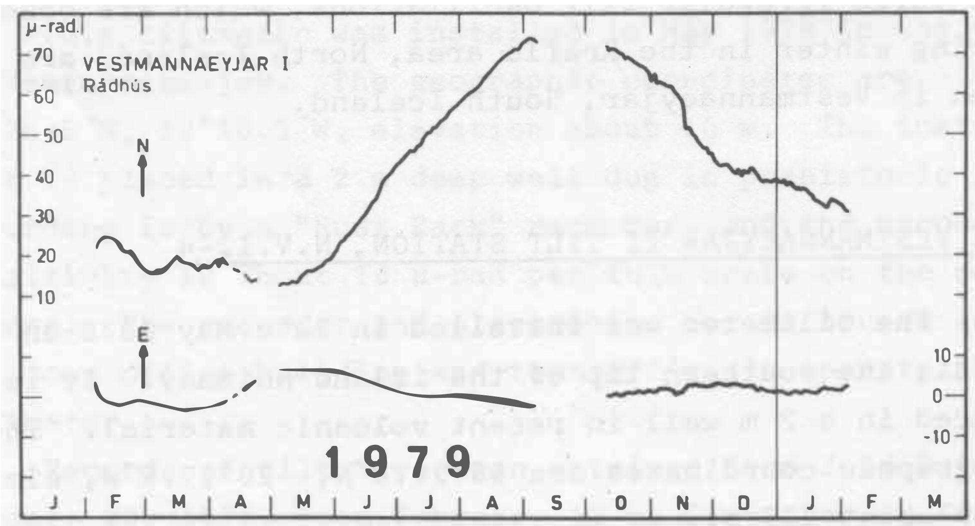
THE VESTMANNAEYJAR II TILT STATION, N.V.I.-4

The tiltmeter was installed in late May 1978 on Stórhöfdi, the southern tip of the island Heimaey. It is placed in a 2 m well in recent volcanic material. The geographic coordinates are 63°23.9´N, 20°17.5´W, elevation about 120 m.

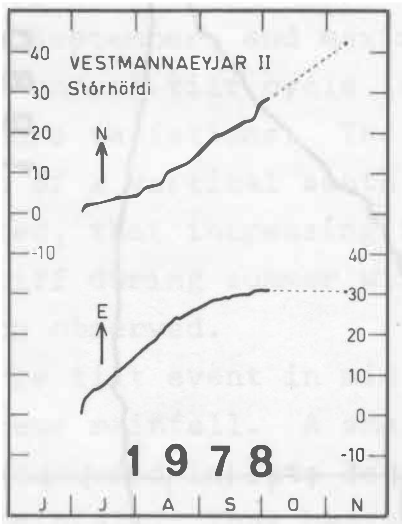
The tilt signal is recorded on a "Rust Rack" recorder and the sensitivity is about 11 μ-rad per full scale on the recorder. The recorder and the electronics is housed in the Stórhöfdi lighthouse, and the lighthouse operator also operates the tiltmeter.



<u>Fig. 25.</u> Records of the Vestmannaeyjar I (N.V.I.-3) magnetoresistor tiltmeter, July to November 1978. Upper curve shows N-S component of tilt, up is rising towards north (left scale). Lower curve shows E-W component of tilt, up is rising towards east.



<u>Fig. 26.</u> Records of the Vestmannaeyjar I tiltmeter February 1979 to February 1980. No records were obtained from early February 1980 to early 1981. See Fig. 25 for explanation.



<u>Fig. 27.</u> Records of the Vestmannaeyjar II (N.V.I.-4) magnetoresistor tiltmeter, July to November 1978. See Fig. 25 for explanation.

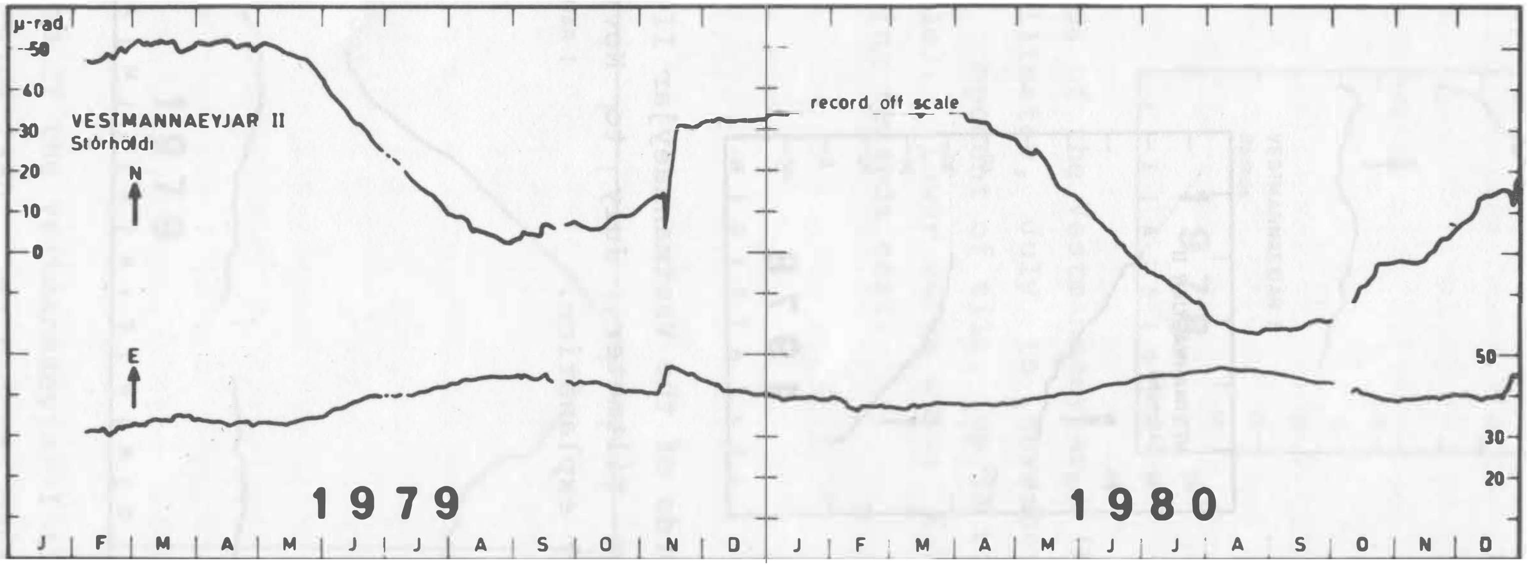


Fig. 28. Records of the Vestmannaeyjar II tiltmeter 1979-1980. The rapid tilt in mid November 1979 occurred during very veavy rainfall. See Fig. 25 for explanation.

Records have been obtained since early June 1978, with a break from October 1978 to early February 1979. The recorded tilt is shown on Figs. 27 and 28. Records from 1981 have not been analyzed and are not shown here.

The most pronounced feature of the tilt record is a large annual tilt cycle, similar as at Vestmannaeyjar I. The annual tilt amplitude is about 40 μ-rad in N-S direction and much smaller, or about 10 μ-rad in E-W direction. Minimum tilt (up towards north) is observed in late August or early September, and maximum tilt in February to April. This annual tilt cycle is obviously caused by annual temperature variations. The location of the tiltmeter is on top of a vertical south facing cliff and it may be postulated, that increasing temperature of this south facing cliff during summer will tilt the cliff edge in the direction observed.

A very large tilt event in mid November 1979 coincides with extreme rainfall. A smaller, but otherwise similar event, occurred in late December 1980, also at time of heavy rainfall. Thus heavy rainfall may affect this tiltmeter.

Tidal oscillations are observed as at Vestmannaeyjar I, but slightly larger amplitudes. Timing of maxima and minima seems to indicate that ocean loading to the south of the station is causing the observed tidal tilt oscillations.

THE WALFERDANGE TILT STATION, N.V.I.-8

This tiltmeter was installed in a mine shaft near Walferdange, Luxembourg, in August 1979. The geographic coordinates are 49°39´53"N, 6°09´10"E. The purpose of this tiltmeter installation was to compare it with well established and sensitive tiltmeters of other designs. Also to observe the behaviour of the N.V.I. tiltmeter, when it is run at very high sensitivity.

The installation was in a shallow hole in the floor of the mine, about 100 m below the ground surface. The instrument drifted considerably during the first several weeks of operation, and there were also some problems with the transmission of the signal from the sensor to the recorder.

The records have not been analyzed, and will not be discussed further at this time.

THE LITLA HEKLA TILT STATION, N.V.I.-10

This tiltmeter was installed on top of Litla Hekla, 1.7 km NNW of the central crater of Hekla, South Iceland, in May 1981. The geographic coordinates are 64°00.3´N, 19°41.0´W, elevation 940 m.

The installation was in about 2.5 m well, dug in permanently frozen ground consisting of unconsolidated tephra. Power to the tilt station is supplied by a wind generator charging 12 volt battery. Recording is by a "Rust Rack" recorder. Besides, the signal is frequency modulated and sent via radio to Reykjavik through a relay station in Bláfjöll.

The recording was discontinued temporarily in late November 1981, because of power failure. Repair was made in January 1982.

The short operating period does not allow any conclusions to be drawn from the obtained tilt data.

CONCLUDING REMARKS

The N.V.I. tiltmeters have proven satisfactory in observing tilt of active volcanoes. Their sensitivity has remained nearly constant through a period of 4 years.

The installation as practiced in Iceland, at about 2 m depth below the ground surface, makes the instruments sensitive to thermal strains in the surface layer, especially when the ground is frozen. Installation at greater depth would certainly reduce the thermal strain effect, but the optimal depth has not been determined. It will depend on the magnitude of the tilt to be observed and on the character of the ground, such as thickness of loose soil, and also on the climate.

The long time stability is poorly determined, and appears to depend on installation rather than on the instrument itself.

Linearity of tilt response appears to be quite good, as no significant deviations have been found over a wide range of tilt. Tests indicate that a linearity to within one per cent exist over a tilt range exceeding 500 µ-rad.

There are several tests that are desireable to evaluate the reliability of the N.V.I. tiltmeter. One involves optical leveling in the immediate vicinity of the tiltmeter in order to determine if the tilt obtained by repeated levelings correlates well with the tilt recorded by the tiltmeter. Another includes the installation of a second tiltmeter very close to an existing tiltmeter. This would be of special interest where the tiltmeters show unexplained tilt oscillations, as at Litli Leirhnjúkur and Bjarnarflag. A third desireable test would include the installation of two or more tiltmeters in the same well, but at different depth, to determine how the observed tilt, especially that caused by surface thermal strain, changes with depth below the ground surface. All these tests would give information on how the installation of the tiltmeter could be changed to improve the reliability of the tilt observations.

ACKNOWLEDGEMENTS

The construction of the N.V.I. tiltmeter is largely based on principles suggested by Ævar Jóhannesson and the details were worked out by Sigurjón Sindrason and Halldór Ólafsson. Installation of the tiltmeters has also been supervised by Halldór Ólafsson and Sigurjón Sindrason, and most of the later maintenance has Sigurjón Sindrason taken care of.

I wish to express my gratitude to Hjörtur Tryggvason, who has kept a constant watch on the tiltmeters in the Krafla area, North Iceland, changed batteries and paper on the recorders and reported any instrument failures. Also to Már Karlsson and Óskar J. Sigurdsson, who have cared for the tiltmeters in Vestmannaeyjar.

The water tube tiltmeter in the Krafla power station has been maintained by the National Energy Authority and Hjörtur Tryggvason has made most of the daily observations.

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