

# Measurement of tectonic rock deformation in Iceland with the DD 1 Strain Transducer

by Stefan Keil and Karlheinz Schäfer

Tectonic activity at the boundary between the American and European continental plates leads to deformations of the earth's crust. These deformations, which are of interest to geologists studying the mechanism that is responsible for the movement of the plates, can be only monitored in Iceland. After a short introduction to the geological aspects, this article describes how long-term measurements can be made on horizontal rock deformations using a modified strain transducer. Details are given on how the measuring sites were set up for measurement, including calibration techniques. The results bear a close relationship to the acute tectonic activity.

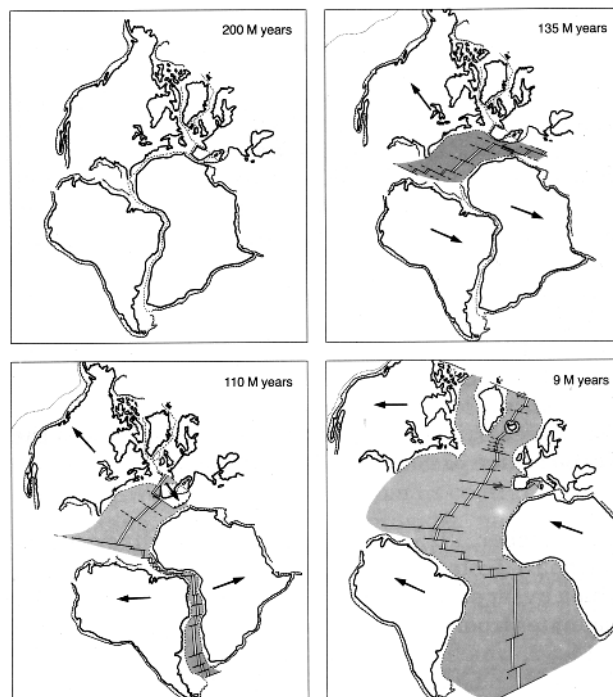
## Geological background

The continents of the earth are parts of wandering lithospheric plates which are moving with different drift velocities and directions. It is known from the research work of geologists, oceanographers and geodesists that there is no point on the earth's surface which is absolutely stable with respect to the earth's interior. It is also found that the lithospheric plates drift horizontally in different directions at an average rate of 1 cm to 10 cm (0.4 in to 4 in) per year and also produce vertical movements.

About 200 million years ago all the continents of the earth were joined together in a single land mass. It was only after the end of the Triassic period 190 million years ago that the continental masses separated and drifted gradually in the direction of their present positions. North and south America separated from Europe and Africa, producing the Atlantic Ocean. At the former point of continental contact is now the Mid-Atlantic Ridge, an imposing submarine mountain range which extends along the middle of the Atlantic Ocean. This submarine ridge breaks up in the central region, causing a continual expansion of the Atlantic and spreading out of the continents surrounding it. **Figure 1** shows a diagrammatic representation of the continental positions surrounding the newly formed Atlantic at various points in time.

There are principally three different types of plate movement which are apparent at the boundaries of the plates. With plates which are moving towards one another either one plate is pushed over the other which is subducted or both plates collide without subduction as can be seen in high mountain ranges with their prominent collision structures. Subductions, i.e. the penetration of heavy oceanic lithosphere into the deeper mantle of the earth, can be seen all around the Pacific Ocean. As topographical features, these subductions occur as deep-sea trenches having the greatest sea

depths. This type of plate boundary is termed constructive. Plates which slide past one another form "conservative" plate boundaries which occur relatively infrequently in the regions of the continents. This type of sliding joint appears, for example, with the San Andreas Fault in California and with the North Anatolian Fault in Turkey. At constructive plate boundaries the plates move away from one another. Fissures form which are then filled by magma from the earth's mantle. Constructive plate boundaries are found exclusively in the central submarine regions of the oceans.



**Fig. 1: The continents gradually drifted apart forming the Atlantic Ocean**

The Mid-Atlantic Ridge forms part of an approximately 70,000 km (43,500 miles) long rift system which marks a constructive plate boundary. This ridge system appears for only 350 km (217 miles) of its length above sea level where it is accessible for geoscientific examination. This 350 km length is situated in Iceland which is crossed by the rift system forming the junction between the European and American plates in the direction southwest to northeast. From geological investigations it can be inferred that during the last 16 million years Iceland has drifted apart by an average of 2 cm (0.8 in) per year. In Iceland active fissures, which are produced by the east and west parts of Iceland drifting away from one another, cut across the island from the south coast to the north coast. These fissures are being continually formed.

The question of the type of driving mechanism that is responsible for the plate movement, causing the island to grow in the west-east direction, has still not been answered satisfactorily. It is not clear whether divergent pressures on the adjacent plates due to the thermal and mass currents rising from the earth's mantle at the constructive plate boundaries cause the lithospheric drift or whether they are caused by the tensile forces generated by the depressed destructive plate edges in the subduction regions. However, there are a number of factors pointing to a friction-coupled carrier effect which is caused by sublithospheric mass current flowing in the direction of the plate drift but flowing faster than the plate that it is pulling.

Each of these driving mechanisms induces deformations which affect the complete plate area, but which have a more pronounced effect in the direction of the plate drift. Locally unidirectional, horizontal principal normal stresses accompanied by the corresponding deformations can be expected in the elastically deformable earth crust regions.

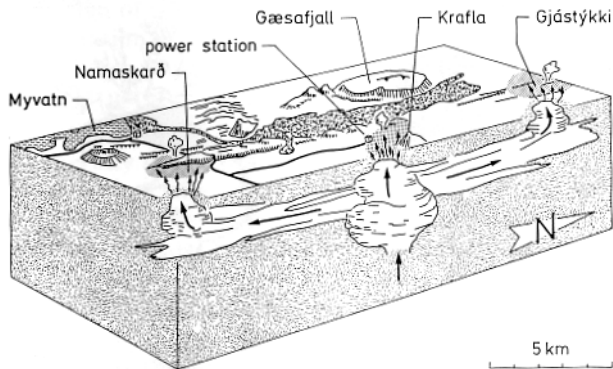


Fig. 2: Geological model of the volcanic system in the Krafla region of northeast Iceland from [2]

In December, 1975 sudden activity in the rift system of northeast Iceland began, causing divergent drifting which by far exceeded the yearly average. This activity emanates from a secondary magma chamber, as shown in Fig. 2, which lies about 3 km (1.9 miles) below the Krafla. A constant magma current of  $5 \text{ m}^3/\text{s}$  ( $6.6 \text{ yd}^3/\text{s}$ ) flows into this chamber from below. As a result the overlying layers rise by a few millimeters per day. The influx period lasts a few weeks or months until the

pressure in the chamber leads to the formation of fissures in the overlying layers and to the escape of lava, which results in the reduction of pressure in the chamber and the collapse of the layers. In the region of the Krafla this sudden subsidence may be as much as 2.5 m (8.2 ft). From December 1975 till September 1984 twenty-one of these pulses were counted, which led to a new swarm of fissures approximately 100 km (62 miles) long with an overall width of 7.5 m (25 ft). During this period new volcanic fissure eruptions took place. Figure 3 is an aerial photograph of these eruptions. Geodesic measurements showed that during rifting the ground level of the new fissure swarms subsided, whereas the regions to the east and west came under pressure and were raised [3, 4, 5].

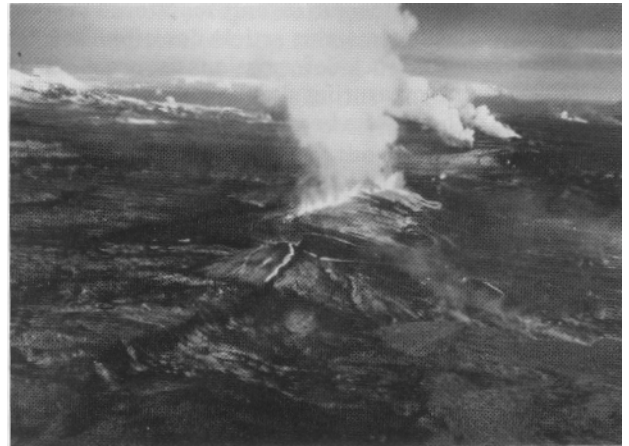


Fig. 3: Volcanic fissure eruption in the center of the Krafla-Caldera during a rifting period in September, 1977

In 1976, initiated by the sudden rifting phenomenon, cooperation was started between the specialist fields of geology and measurement engineering to measure the elastic rock deformations caused by the rifting. First of all strain gages were used in the overcoring method at twenty measuring points in the region of the rift activity to determine the current state of the mechanical stresses in the rock surface.

As a result of these measurements tensile stresses running in a  $124^\circ$  direction were found within a 2.5 km (1.6 miles) wide zone of active crack formation running from NNE to SSW. Outside of this zone compressive stresses occurred which were aligned in a NW-SE direction. Compressive stresses running in the direction of the cracks were only found in the main branch of the southern rift region [7].

Long-term measurements were carried out with strain gages at fourteen of the measuring points from 1976 to 1980. It was found that by 1977 the region of tensile stresses aligned in the NW-SE direction had extended over the complete northern axial rift zone. In the summer of 1978 a systematic rearrangement of the measured strains was observed with the directions of the compressive stresses pointing in the direction of the active rift zone in north Iceland. Also in 1979 the principal directions of the largest horizontal compressive stresses still lay in the direction of the Krafla.

The results of the strain measurements with strain gages and their relation to the rifting phenomena led to the continuation of the measurements using a method specially modified for this application. The method is based on the DD1 Strain Transducer which operates on the strain gage principle in a modified form as a strain gage caliper. This method is described below.

## Measurement principle

The aim of the measurements is the determination of the horizontal surface deformations on exposed rock surfaces over an extended period of time. At selected measurement sites bolts were cemented into the rock surface and the changes in the distances between these measurement bolts were measured using the DD1 Strain Transducer. The measuring arrangement was designed such that the transducer did not have to be installed permanently at the site, but instead could be positioned on the measuring point to carry out the measurement. The advantages of this method were that only one transducer was needed for all of the measuring points and it was not subject to the effects of the weather for long periods.

In order to be able to determine the principal strains at the measurement site and their directions, changes in length in three directions had to be measured. For this reason each of the measuring sites which were set up in 1980 consists of four measuring bolts aligned for measurement in the directions north-south, east-west and southwest-northeast. The nominal distance between the measuring bolts was 100 mm (3.9 in). For sites that were installed later and using experience gathered on the optimum method of boring the holes for the bench marks, nine bench marks were installed per measuring site. In addition the southeast-northwest direction was added and there were three bench marks for each direction. Therefore two measurements were available for each direction using these bench marks. An overview of the locations of the measuring sites in Iceland is given by Fig. 4.

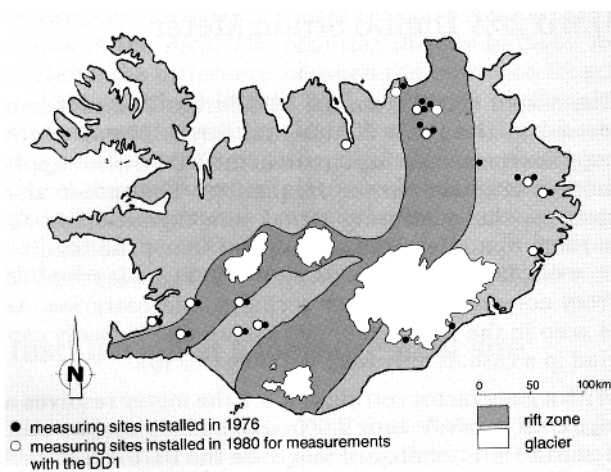


Fig. 4: Locations of the measuring sites in Iceland for measuring rock deformation

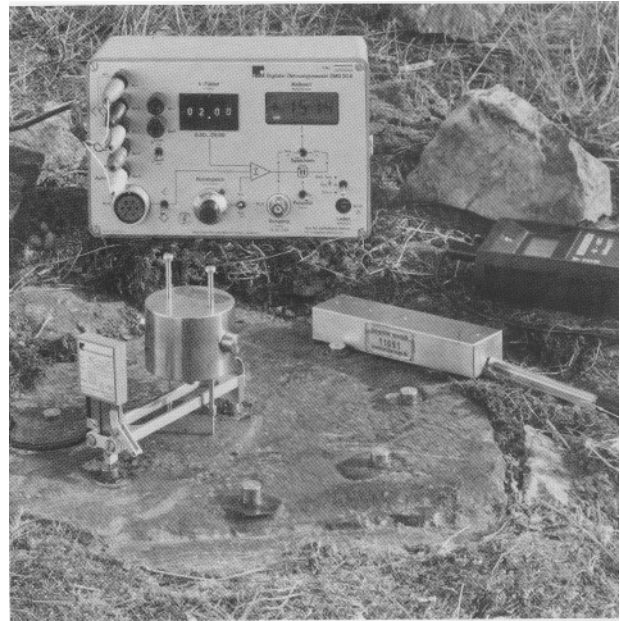


Fig. 5: View of a measuring site during a measurement

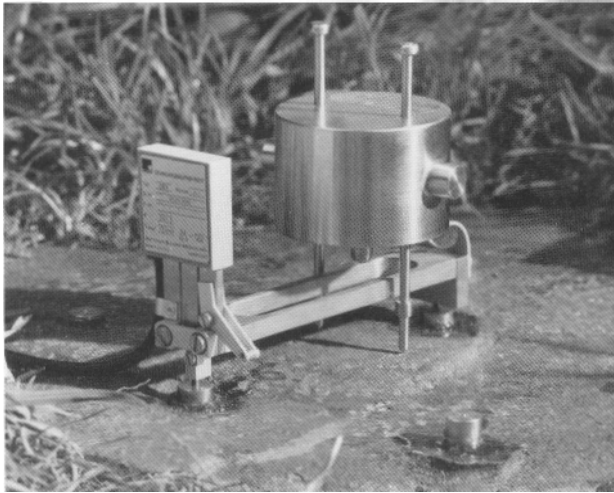
The measurement equipment that was used consists of the strain transducer which was placed on the measuring bolts and the battery-powered DMD 20A Digital Strain Meter which amplified the measuring signal from the transducer and displayed it on a digital meter. It also supplied the required supply voltage for the operation of the transducer. Figure 5 shows the complete measurement equipment during an on-site measurement.

At the measurement equipment's most sensitive setting one division on the display is equivalent to a signal resolution representing a change in length of 0.000125 mm (0.005 mils) between the measuring bolts.

## DD1 Strain Transducer

The strain transducer used for the measurements can measure the distance between two permanently installed bench marks very accurately. The bench marks consist of 1.5 mm (60 mils) diameter steel balls which are set into the heads of steel bolts. To fix the bench marks in position, the bolts are cemented into the surface of the rock as can be seen in Fig. 5. The strain transducer is placed with its two feet onto the balls of two bench marks. One of the two feet of the device is fixed to a measurement tongue which can be moved in the direction of measurement. The tongue can be displaced up to  $\pm 2.5$  mm (0.1 in) from its central position by bending. The transducer provides an electrical signal from internally mounted strain gages which is proportional to the displacement of the measurement tongue. The strain gage is located on the end of the tongue opposite the measuring foot.

For the first measurements the instrument was placed on two bench marks and held with the hand. The measurements made in this way produced an unwanted spread in the results due to the unavoidable tremor of

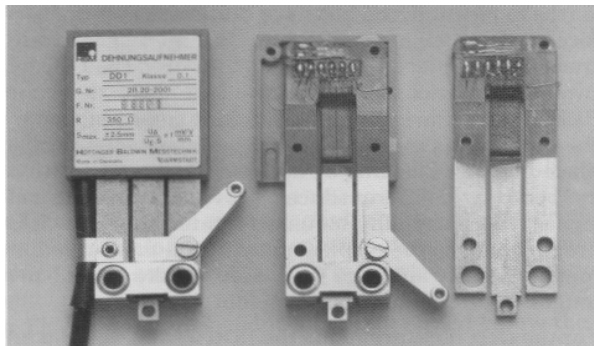


**Fig. 6: DD1 Strain Transducer and balancing weight positioned on two bench marks**

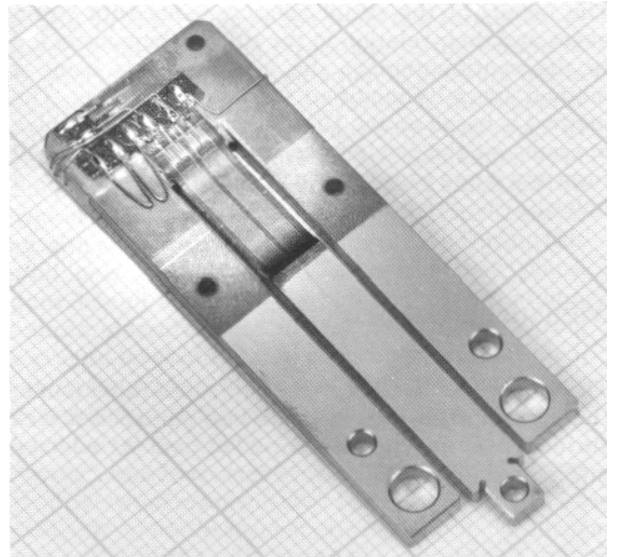
the human hand. A significant increase in the reproducibility of the results was achieved with a holding device which held the instrument on the bench marks with the aid of a cylindrical weight. As can be seen from **Fig. 6** the weight acts on the transducer through a spring arm and balances the mechanical system using two supports which can be adjusted in length using spring clips. To ensure that the instrument, including the holding device, was not held tilted sideways on the bench marks, a spirit level was set into the upper face of the holding device, which enabled horizontal alignment of the instrument transverse to the measurement direction.

From **Fig. 6** the measuring tongue can also be clearly seen. It has a measuring foot at the lower end and the other end, which carries a mounted strain gage, is protected by a flat housing. A view inside this housing is provided by **Fig. 7** which also illustrates the construction of the measurement tongue and holder.

The tongue and its fork-shaped holder are produced from one piece of titanium. In the photograph the strain gages can be seen with one half of the protective housing, as well as a small lever with which the measuring tongue can be locked against unintended bending. The strain gages which are bonded to both



**Fig. 7: Internal construction of the DD1 Strain Transducer, showing the lock for the measuring tongue**



**Fig. 8: The mounted strain gages, also showing resistances for compensation for the effects of temperature on the DD1 measuring element**

sides of the measuring spring are of a shape that was specially developed for this application. The full bridge circuit is temperature compensated both with respect to the zero-point signal and the sensitivity in the range -10°C to 60°C. One half of the full Wheatstone bridge circuit with resistors for temperature compensation can be clearly seen in **Fig. 8**. The other half of the bridge circuit is located on the underside of the measuring spring which is hidden from view in the photograph. The balance resistors for the adjustment of the nominal resistances and for symmetrization are located in a capsule fitted to the end of the connection cable. The DD1 Strain Transducer is calibrated during manufacture and has a sensitivity of 1 mV/V per 1 mm (40 mils) of tongue movement at the point of the measuring foot. This relationship applies to the complete measurement range of  $\pm 2.5$  mm (0.1 in). The greatest deviation in linearity, including hysteresis, is smaller than  $\pm 0.05$  %.

## DMD 20A Digital Strain Meter

The output signal from the DD1 Strain Transducer is passed to the DMD 20A Digital Strain Meter which supplies the measuring circuit in the DD1 with a supply voltage (225 Hz carrier frequency). The meter also resolves the measuring signal into digital steps according to a selectable setting and shows the reading on a display. The DMD 20A shown in **Fig. 5** is supplied from non-rechargeable or rechargeable batteries. As is seen in the photograph, it is small and is easily carried in a case. It only weighs 1.5 kg (3.3 lb).

With a gage factor setting of  $k = 2$  the meter resolves a signal of 1 mV/V into 2,000 steps which means that 1 mm (40 mils) change of length on the DD1 is resolved into 2,000 steps and therefore one digit on the meter's display corresponds to a movement on the measuring tongue of 0.0005 mm (0.02 mils). In its most sensitive

setting the meter is able to resolve 1 mV/V into 8,000 steps. In this case one digit corresponds to a tongue movement of  $125 \cdot 10^{-6}$  mm ( $5 \cdot 10^{-6}$  in) which is equivalent to a strain of  $\epsilon = 1.25 \cdot 10^{-6}$  for a measurement length of 100 mm (3.9 in), i.e. the distance between the cemented bench marks. This measurement arrangement has approximately the same sensitivity as a directly mounted strain gage, but due to the compensated and balanced full bridge circuit, it is significantly less prone to disturbances. The method is very well suited to in situ long-term measurements, because only the relatively invulnerable bench marks are left at the measuring site which can easily be covered for protection against the weather.

## Carrying out a measurement

The measured quantity is the distance between two bench marks which is measured as an absolute change in length. This is obtained quite simply with the measurement equipment described above, provided a reference length is available with which the equipment can be calibrated before each measurement. The reference length consists of a steel block of rectangular cross-section into the surface of which two small steel balls have been set at a nominal distance of 100 mm (3.9 in). The distance between the center points of these two balls was measured in the laboratory at a temperature of 20°C using special test equipment ( $l_{R20^{\circ}\text{C}} = 99.984$  mm). The linear thermal expansion coefficient of the steel block was  $\alpha = 16 \cdot 10^{-6}/\text{K}$ . Therefore the actual reference length for each measurement could be found if the temperature of the steel block was measured. The temperature was taken with a thermometer by pushing its sensor into a hole in the block. The block used for calibration can be seen in Fig. 5, together with the sensor of the thermometer instrument inserted in the block. The strain transducer and balance weight are first placed on the reference length before a measurement is taken and then the DMD 20A Digital Strain Meter is balanced to zero.

At the same time the temperature is measured and the corresponding reference length at the measured temperature is read off a preprepared table. Then the transducer and balance weight are placed on the bench marks in the rock. The resulting display in digits represents the difference between the reference length and the required length. With a positive display the measurement is greater than the reference length and it is smaller with a negative display. Since the objective of the measurements is to obtain changes in length and all measurements are made with the same reference length, the value for the reference length itself at the reference temperature is of minor importance.

## Installation at a measurement site

The majority of the measuring sites were set up on the flat rocky floors of wide glacial valleys at a sufficient distance from the slopes of the valley. For the remaining measuring sites care was taken to ensure that the distance of the measuring site to the nearest moun-

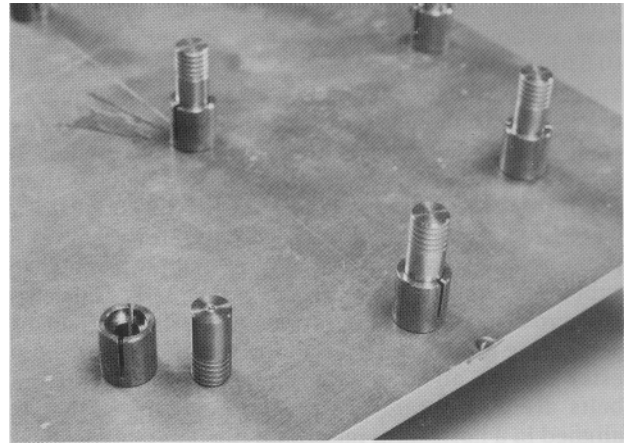


Fig. 9: The bench marks are inserted into slotted bushings on the template

tain or valley was at least twice as large as the difference in height between the nearest peak or valley floor and the measuring site. On each site the weathered crust of the rock was ground away to expose the clean, bare rock.

As can be seen from Fig. 9, the bench marks consist of steel bolts of 10 mm (0.39 in) diameter which are available in various lengths. A small steel ball of 1.5 mm (60 mils) diameter was pressed into the center of the bolt's head and this steel ball supported one foot of the strain transducer. At the other end of the bolt is a thread to provide a key when anchoring the bolt into the rock. The measuring site is set up using a steel plate as a template. This has nine holes and is placed over the measuring surface supported by four feet which are adjustable in height. After aligning the template with a compass, nine holes of 6 mm (0.24 in) diameter and 26 mm (1 in) depth are drilled in the rock surface.

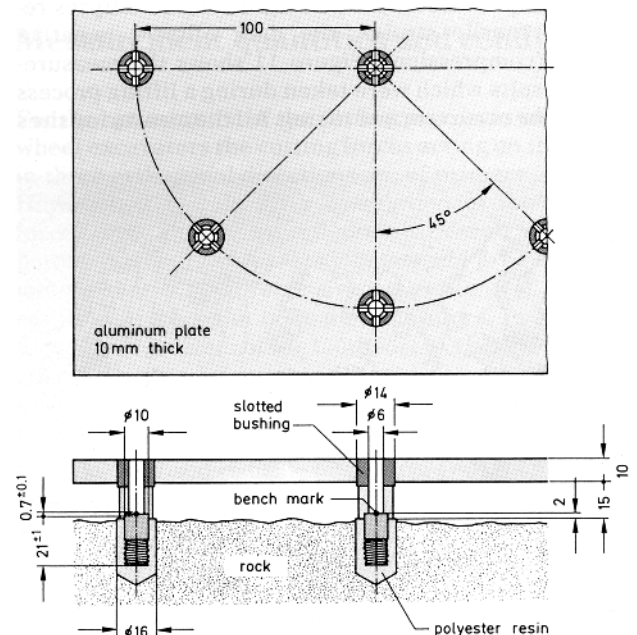
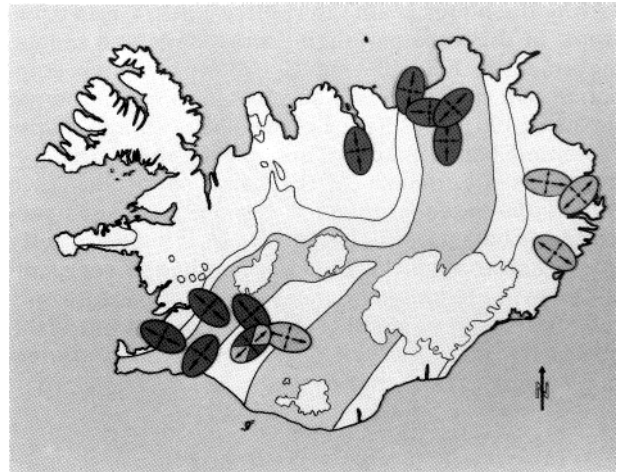


Fig. 10: Diagram showing the insertion of the benchmark bolts into the holes in the rock using the steel template

These holes are then widened in a second drilling process without a template to a diameter of 16 mm (0.63 in). The template plate has a slotted bushing in each of the nine holes and the bolts for the bench marks are inserted from underneath as shown in **Fig. 9**. They can be inserted up to an end stop and are held in position by friction. The plate, fitted with the bolts, is then used to set the bolts into the holes in the rock which have been previously filled with polyester resin. The plate is leveled with a spirit level and with the four supporting screws at the corners of the plate. **Figure 10** is a cross-sectional diagram showing the method of cementing the bolts. After about 15 minutes the polyester hardens and the plate can be taken off. The nine bolts are now located in the rock with their heads aligned in a horizontal plane and the nominal distance between the bolts is 100 mm (3.9 in). The exact distance can be determined with an initial measurement using the reference length.

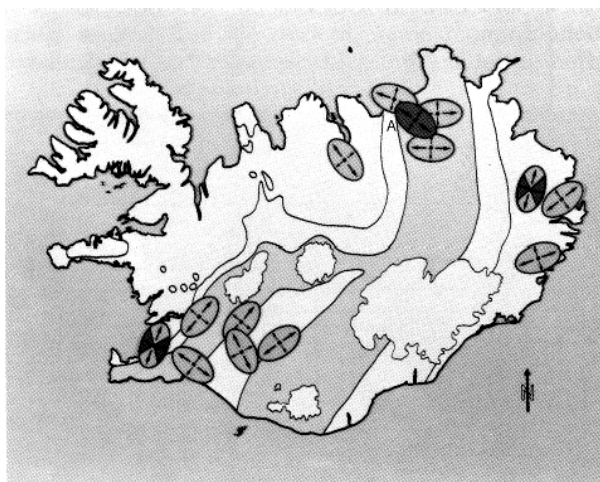


**Fig. 12: Examples of results of measurements taken shortly after rifting**

## Results of the measurements

Changes in length occurring over a period in time were measured at each measuring site. From these readings the changes in strain were determined for the separate measurement directions. By applying the normal evaluation formulae for rosette strain-gage measurements, the changes in strain were then used in turn to compute the principal strains and principal directions of the strain condition which had become superimposed on the previous measurement.

The changes in the strain condition occurring at each measuring site over a period in time can be clearly represented in the form of strain ellipses drawn on a map of Iceland. **Figures 11 and 12** are examples of such maps. The ellipses are aligned with their major axes in the principal directions. The light-colored ellipses represent tensile strains, the dark ellipses negative strains (compression). **Figure 11** shows the measurement results which were taken during a lifting process before the occurrence of rifting. All the measuring sites



**Fig. 11: Examples of results of measurements taken shortly before rifting**

with the exception of site A exhibited tensile strains as would be expected in the wall of a vessel under internal pressure. In contrast **Fig. 12** shows compressive strains in the rift zone which were recorded after the collapse following rifting. The recorded results bear a close relationship to the pulses emanating from the Krafla volcanic center.

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