CRUSTAL LOADING AND INDUCED SEISMICITY AT THE YACAMBU RESERVOIR, VENEZUELA

C.H. Scholz, Roger Bilham and David Simpson

Lamont-Doherty
Geological Observatory of Columbia University
Palisades, New York 10964

USGS CONTRACT NO. 14-08-0001-17644
Supported by the EARTHQUAKE HAZARDS REDUCTION PROGRAM

OPEN-FILE NO.81-387

U.S. Geological Survey
OPEN FILE REPORT

This report was prepared under contract to the U.S. Geological Survey and has not been reviewed for conformity with USGS editorial standards and stratigraphic nomenclature. Opinions and conclusions expressed herein do not necessarily represent those of the USGS. Any use of trade names is for descriptive purposes only and does not imply endorsement by the USGS.

Crustal Loading and Induced Seismicity at the Yacambu Reservoir, Venezuela

14-08-0001-17644

C. H. Scholz, D. W. Simpson
and R. Bilham
Lamont-Doherty Geological Observatory
of Columbia University
Palisades, New York 10964
(914) 359-2900

Annual Report

October 1, 1979 to September 30, 1980

Summary

The Yacambu engineering project is a scheme to create a reservoir on the southern side of the Venezuelan Andes and to divert its contents through a gravity fed underground aqueduct a distance of 24 km to a second reservoir in the arid Quibor Valley to the north. The tunnel will pass through the 4 km wide Bocono fault zone at a depth of about 1 km. The Yacambu Reservoir will be sufficiently deep (160 m) for it to be considered a likely candidate to induce seismicity at the time of impoundment.

The conditions under which reservoir-impounding can give rise to seismicity are related among other things to the existing tectonic stress level, the magnitude and rate of loading and the magnitude of internal pore pressure of the rocks in the failure zone. However, there is no simple method to predict whether a given reservoir will initiate seismicity when it is impounded. The experiment we have devised attempts to relate changes of surface strain and changes in piezometric pressure to the onset of seismicity.

We have chosen the Yacambu Reservoir to study because it is in a region of high seismicity and will be a more-or-less two-dimensional feature that is simple to model using finite element techniques. At the base of the reservoir an apparently inactive fault trends approximately parallel to the Bocono fault (15 km to N). In the finite element models we have developed for the reservoir, dam and surrounding areas, this fault is subjected to reduced normal stress upon impounding. The effect is partly due to the action of the water load and partly due to the hydrostatic containment by the dam structure and abutments to the south putting the floor of the reservoir into relative tension. A plausible hypothesis (outlined below) concerning the significance of the subreservoir fault and its relationship with induced seismicity has influenced the disposition of planned instrumentation in the area.

We have installed strainmeters in tunnels in the abutment and have partially installed an underwater strainmeter across the fault in the reservoir. Additional strainmeters and tiltmeters await the completion of suitable drainage tunnels in the abutment of the dam. Piezometers have been acquired for use in two deep boreholes that will be constructed by Venezuelan engineers specifically for the project. A series of geodetic measurements have been planned to extend the continuous observations near the dam to distances up to 5 km downstream. The region to the north is unsuitable for geodetic measurements.

Introduction: Experimental Plan

Although the fact that the filling of large reservoirs sometimes induces earthquakes has been known for some time, very little can be said for sure about the mechanism of reservoir induced seismicity. Such induced earthquakes presumably result from stress changes brought about by the reservoir load and changes in pore pressure beneath the reservoir (Gough and Gough, 1970; Snow, 1972; Simpson, 1976). These two effects, that of load and pore pressure, act in different ways, and in some tectonic settings cancel one another, whereas in others may enhance one another in producing induced seismicity (see Bell and Nur, 1978).

Furthermore, the mechanical and hydraulic properties of the large scale rock mass of the earth's crust are not well understood. For example, the short time duration between the onset of induced seismicity and reservoir filling in many known cases implies that the hydraulic diffusivity of the crust be surprisingly high, several orders of magnitude higher than that of rock measured in the laboratory if fluid pressure changes play a role in inducing the seismicity. If such high diffusivities do exist, most fluid transport must be through large scale fractures and not through the solid parts of the rock. Laboratory data (Gale, 1976; Kranz et al., 1977) indicate that fractures in rock may stay sufficiently open to remain efficient conduits for fluid transport under kilobars of effective normal stress. At present, there are very few measurements available to test whether the upper part of the earth's crust can have such a high diffusivity (Zoback, personal communication, 1980). We particularly want to test the possibility that the fault in the base of the reservoir is the fluid conduit, as in some of the models of Bell and Nur (1978).

In order to make progress towards understanding reservoir induced seismicity, then, we must do more than monitor the seismicity with a seismic network: we must attempt to measure the deformation produced by the reservoir load and the subsequent pore pressure migration. With these three processes known, we should be able to model the process and reconstruct the mechanism. The results of this study will have relevance far wider than simply to induced seismicity, of course, since it will bear directly on the broader questions of the earthquake mechanism and earthquake prediction. A measurement of the large scale hydraulic diffusivity of the crust, for example, is critical to the question of whether dilatancy can induce fluid flow in the various dilatancy theories of earthquake precursors.

This experiment naturally culminates a research direction that has been pursued for a number of years at LDGO. We have been studying reservoir induced seismicity for several years, at the Tarbela Reservoir in Pakistan and, under the direction of Dr. Simpson, at Nurek in the U.S.S.R. To date, however, these studies have been largely limited to seismicity so that this experiment will be our first attempt to do a more complete experiment. In the Rock Mechanics laboratory we have an ongoing experimental study of the fluid transport properties of fractured rock at high pressure and temperature and we expect the results of this work to be directly relevant to the proposed experiment.

The experiment is designed to provide valuable scientific results even if no seismicity is induced by the reservoir, since we regard it as a large scale, semi-controlled rock mechanics experiment. We thus expect to learn much about the large scale mechanical and hydraulic properties of the crust. We estimate the reservoir load alone will generate tilts and strains in the order of 10^{-5} and we will have levelling data to compare with signals recorded on short baseline tilt and strainmeters. Thus we can explore the effect that block motions may have on short baseline instruments, a problem of current concern in crustal deformation studies (Bilham and Beavan, 1978). We expect to obtain the first measurements of large scale hydraulic diffusivity in the crust - a property that is very important to any model of earthquake precursors that involve dilatancy.

Technical Discussion

The inducement of earthquakes due to reservoir impoundment is thought to be caused by an interaction of the load of the reservoir and the increased pore pressure at depth due to the increase of hydrostatic head produced by the reservoir. Whereas the load is transmitted immediately to the depths at which seismic activity occurs, the pore pressure there can only change after some period of time required for the water to diffuse through the permeable substratum of the reservoir. Although in some cases, such as at Koyna, this time delay was large, in other cases it is very short, such as at Kremasta and Nurek. This suggests that in some cases an efficient conduit for transport of water to depth, such as a permeable fault zone in the base of the reservoir, exists, whereas in other cases the water diffuses through the bulk rock.

However, the fault in the base of the Yacambu Reservoir is filled with clay fault gouge, and therefore must constitute a very impermeable, rather than permeable, zone. When the reservoir is filled, though, the force imposed on the reservoir walls may be sufficient to produce a tension on the floor of the reservoir. Since the fault has no tensile strength, it would then open, immediately producing a very large increase in permeability. We have developed a two-dimensional finite element model of the Yacambu Reservoir with which preliminary results indicate that in the absence of large tectonic normal stresses, impoundment will produce a tensile stress on the reservoir floor before the final water depth is reached. This result has led us to adopt this mechanism as a working hypothesis in this project and we have altered our priorities somewhat to reflect this.

The Yacambu Reservoir is being constructed in the northern Venezuelan Andes (Figures 1 and 2). It is a narrow, deep (150 m) reservoir in a seismically active region. A fault, with a gouge zone 30 to 100 m in width, lies along the base of the reservoir along its entire length. Although there is no observable Quaternary offset of this fault, it is parallel to, and is associated with, the Bocono fault, a seismically active strike-slip fault lying 15 km northwest of the reservoir. There is, therefore, a significant possibility that reservoir water may migrate down this fault and induce earthquakes along it.

The experiment we have planned is shown in a vertical cross-section of the reservoir (Figure 3, no vertical exaggeration). It is designed to measure the following phenomena induced by the filling of the reservoir:

A. Vertical deformation of the ground produced by the reservoir load. This will be measured by first-order levelling (Figure 3, #5) carried out downstream from the dam in the Yacambu River valley. This levelling is to be carried out several times prior to filling and at 3-month intervals for 15 months immediately after filling. The levelling line will begin just downstream of the dam and extend for 4 km downstream. It will have permanent benchmarks at every turning point, to ensure stability and to provide high precision.

B. Horizontal and vertical deformation of the reservoir wall (left abutment). The deformation and rotation of the left abutment due to reservoir loading will be measured with an array of strainmeters and tiltmeters installed in drainage tunnels within the left abutment (Figure 3, #2).

C. Opening (or closing) of the fault due to loading-pore pressure effects (Figure 3, #3). This will be measured with two strainmeters installed directly across the fault at two sites at the <u>bottom of the reservoir</u>. These will be continuously recording instruments, with data telemetered by cable from the reservoir bottom.

D. Pore pressure migration through the bulk rock (Figures 3, 4, and 5). Two boreholes, 1000 m deep, will be installed at 1/2 reservoir width distances in the base of the Yacambu River canyon downstream from the dam. Each will be instrumented with 2 piezometer arrays at intervals to measure pore pressure changes.

Crustal Deformation Measurements near the Yacambu Reservoir Scheme

In the years before impounding it is important to obtain a feeling for the noise level of crustal movements at Yacambu. Specifically we need to know the level of ambient microseismicity, the influence of rainfall on piezometric surfaces and on near-surface tilts and strains, the influence of seasonal thermal variations on strain and tilts and the effects of wind, atmospheric pressure variations and engineering noise on the observed parameters.

Crustal deformation measurements in the Venezuelan Andes near Yacambu are made difficult by an ubiquitous cover of tropical vegetation. Where this is absent due to ethnic habits of deforestation to provide grazing land, the precipitous terrain is rendered more unstable than in its natural state. The quest for bench mark locations that may be considered sufficiently stable to provide references for crustal movement studies is restricted to valley floors or mountain peaks. Fortunately, the engineering work for the Yacambu system has resulted in a number of tunnels suitable for the installation of strainmeters and tiltmeters. Two 1 km deep boreholes to provide piezometric measurements have been promised by the Venezuelan authorities.

History of Instrumentation of the Yacambu Region

In the first year of this project we installed a creepmeter on a surface branch of the Bocono Fault, three strainmeters in an inclined access tunnel near the Bocono Fault and we constructed analytical models of the reservoir region to determine the most effective locations for surface deformation measurements near Yacambu. We also designed a new tiltmeter system suitable for installation in the various access and drainage tunnels planned for the dam system. One of the strainmeters was destroyed shortly after installation. At the beginning of the second year of the project (November 1979) we planned to install three of the new tiltmeters and two carbon fiber strainmeters in Yacambu and to install two strainmeters of radically different design in the floor of the planned reservoir. The December 1979 visit was premature in the sense that the sites in which the strainmeters and tiltmeters were to have been installed were not fully completed by the Yacambu engineers. A single strainmeter was left operating in one of these unfinished tunnels and plans for the underwater strainmeters were discussed with the Yacambu engineers. It was decided that a return visit would be made when the in-situ construction of the underwater strainmeters was complete. The concluding event during the December 1979 visit was the loss of the tiltmeters and parts of the strainmeters by Pan Am during their shipment as accompanied baggage. We are still involved in attempts to be reimbursed for the loss ($16,000).

At some time in January the recording system for the Bocono fault instruments was stopped by the disconnection of all electrical power due to a shutdown of engineering activities. At this time we decided to install systems that would work on batteries to ensure data continuity. A visit to Yacambu in May 1980 was made to install these units and to install the electronics and recording systems for the now complete underwater strainmeters. The new recording systems were installed but the onset of the rainy season happened on the day we arrived and flooded the underwater strainmeters. The next opportunity to install the sensors for the underwater strainmeters will occur in late 1980.

A precision levelling line was outlined in December 1979 for monitoring vertical surface deformation resulting from reservoir impounding. The responsibility for monument construction and measurement of the line rests with the Venezuelan authorities. Two 1 km deep boreholes that are necessary for the success of the project have still not left the planning stage at FUNVISIS. The piezometers that will be installed in these holes were purchased in 1979.

Bocono Fault Creepmeter

A 20 m long creepmeter was operated for a year across one of the several dozen surface faults of the Bocono Fault system near Cubiro (Figure 4). The data indicate that this branch of the fault, at least, is locked since no movement was detected greater than 0.1 mm (5×10^{-6} strain). Two surfaced roads that cross the Bocono valley were inspected for evidence of fault movement. No cracks could be associated with known faults. It is unlikely that this section of the fault system deforms across the 4 km wide valley in a homogeneous fashion since under steady-state conditions the fault fabric would be more complex than it appears. We estimate that if aseismic slip is occurring on the Bocono Fault system between Cubiro and Sanare, the slip rate must be less than 10^{-6}/year across 4 km zone. A triangulation survey with microstrain precision was measured four years ago in connection with the 24 km tunnel project. The remeasurement of this line will provide more positive information on the activity of the fault.

Bocono Fault Strainmeters

Three 20 m long carbon fiber strainmeters were installed in a linear array in the inclined shaft (venta inclinata) which is presently under construction and which will provide access to the 24 km long aqueduct tunnel near where it crosses the Bocono Fault. The instrument locations are shown in Figures 2, 4, and 5. The units are modifications of a system developed at Ogdensburg Seismic Observatory. Engineering activity in the shaft introduces a large amount of noise at all periods. At high frequencies (periods less than 60 s) the noise is principally from strains induced by the passage of 20 ton trucks loaded with rock and cement, intermittent sump-pump operation ejecting ground water from the working face, and electrical noise from power surges in nearby conductors. At intermediate periods (60 s - 60 m) thermal noise is generated by the ventilation system. At longer periods forced ventilation introduces diurnal thermal variations. Even at times when forced ventilation is not in operation, natural convection occurs at night between outside air and the hot tunnel air.

Contamination of the data by high frequency noise is avoided by overdamping the strainmeters. At first the recording system incorporated 10 s analog filtering but now uses 200 s digital filtering prior to recording. The filtering is adequate to enable us to monitor strains of order 10^{-9} in the presence of extremely noisy industrial activity.

The deepest of the three strainmeters recorded exceptionally high strain rates (> 10^{-6}/day) from its installation in May 1979 until it was removed by engineers in September 1979 in order to repair an adjacent part of the tunnel. Movement on one or more rock joints near the strainmeters may have occurred towards the end of this period as indicated by the simultaneous recording of a transient strainfield on all three instruments (Figure 6).

The data from the strainmeters are converted to frequency. Initially the data were transmitted via opto-couplers to a surface location where they were multiplexed on a chart recorder with a range expansion facility of x16 (Figure 5). Although the strainmeter sensors were powered independently by dry cells, the recording system was powered by a local line voltage. This proved to be a problem. We found that there were approximately 45 power failures in the first month of data and the records were virtually useless. Quite by chance we discovered that the power failures were not line failures but were caused by the inspection-engineers pulling the plug on our recording system in order to boil water for coffee twice a day. We remedied this by introducing a trickle-charged uninterruptible supply with a capacity of 12 hours. The power was hard-wired into the line voltage and it was also found necessary to incorporate a heavy-duty fan to cool the inverter unit continuously. Continuous data were obtained until a further power problem occurred in January 1980. In this instance, power to the whole tunnel complex was disconnected due to tunnelling difficulties. When we learned of this decision two months later we realized that if we were to obtain data from the Yacambu region we must make the instrumentation independent of local power.

The recording units installed in May 1980 consist of self-powered recorders with independent clocks. The units gate the incoming strain (frequency) every 200 s to provide a digital number, seven bits of which are displayed after D-A conversion on an analog chart. Chart speed is less than 5 cm/day enabling year-long recording. A FUNVISIS engineer visits the two recording systems every month in the inclined-shaft in order to obtain the data and change the batteries.

Yacambu Strainmeters

Two types of strainmeter are being used around the Yacambu reservoir: carbon fiber strainmeters of high sensitivity in drainage tunnels in the abutment of the dam and underwater strainmeters in the floor of the reservoir.

The lining of the drainage tunnels is incomplete so that the full complement of planned strainmeters is not yet in position. In December, 1979, a strainmeter was installed in an unlined tunnel in the left abutment of the Yacambu dam (Figure 2). The left abutment is a natural ridge that at one time extended across the valley where the Yacambu dam is now being constructed. The ridge is bounded on both sides by faults which are considered inactive. The fault to the south cuts the apex of an anticline. The most significant of the faults to the north of the abutment is a strike slip fault that runs at the base of the reservoir and extends a distance of several tens of km in a direction that is subparallel to the Bocono fault. We have chosen to span this fault with two strainmeters because of its relationship with the Bocono fault system and because of its special relationship with the future reservoir.

The two strainmeters were constructed at considerable expense to our specifications by FUDECO engineers. The instruments are located in a narrow river channel to the east of the Yacambu dam and are arranged to cross the fault at 45°. The design of the two instruments had to take into account two different operating conditions: a period during which flood waters pouring down the Rio Negro will propel logs and rocks at the strainmeters and a period after impounding when sedimentation of the valley floor will bury the instruments beneath many thousands of tons of water-saturated mud. The lifetime of the strainmeters is planned to be at least five years and may have to be twice this if delays to the impoundment-date continue.

The chosen design takes into account these two factors and takes advantage of the relatively low sedimentation rate occurring at present. The length-standards for the strainmeters were chosen to be massive structural components which will be self-supporting and resistant to buckling short of a direct hit from a rockslide. In some parts of the valley this possibility is real but the chosen site is reasonably well-protected. An essential part of the design is a weir downstream from the two strainmeters. This weir is slightly higher than the instruments and consequently forms a pond which at all times floods the strainmeters. Natural sedimentation within this pond has encased the strainmeters in a tomb of protective mud.

The strainmeters consist of steel H-girders (40 cm x 16 cm I-beams) rigidly connected to the rock on one side of the fault and constrained with one degree of freedom on the other. The attachments to the rock are massive concrete piers, cast in position, reinforced with steel and bonded to the rock using standard rock bolts. The free end of each H-girder slides in a concrete channel. Relative movements of the free end relative to the mount are monitored by a hermetically-sealed, linear-variable differential-transformer (L.V.D.T.) powered by a current-drive electronic system supplied by Schaevitz. Power to each L.V.D.T. is supplied by an armoured submarine cable. The position signal from the L.V.D.T. is proportional to the current supplied to the device. This is sensed by an AD537 current-to-frequency converter which provides a position-sensitive frequency to a microprocessor controlled counter. The unit averages data for 200 s and for 3600 s to provide digital or analog outputs. Each submarine cable has four conductors; two service the L.V.D.T. and two are dedicated to a second AD537 wired to provide a temperature-to-frequency conversion. The units are shown schematically in Figure 7.

The sensitivity of the strainmeter system will be approximately 10 μm with a measurement range of 2540 μm. The equivalent strain sensitivity on the 9 m and 11 m instruments is approximately 10^{-6} and the range 2.5×10^{-3}. Since the thermal variation in the floor of the completed reservoir is not expected to vary by more than 5°C annually and 0.5°C daily we do not predict that the induced thermal signal will be troublesome. On the contrary, the measurement of temperature will provide us with a check on instrument calibration by applying the known thermal coefficient for steel (10.5×10^{-6} per°C) to the thermal data and determining the admittance of the coherent energy between the strain and temperature time series.

Tiltmeters

The tunnels of the left abutment are ideal sites for the location of water tube tiltmeters to study the impounding process. In December 1979 three of these instruments were prepared for installation but the tunnels were not yet ready to receive them. A decision was made to return the mechanical and electronic sensors to Lamont for minor modifications and testing. All this equipment was lost by Pan Am on the return flight to New York. A description of the tiltmeter sensors accompanies Figure 8. These will be rebuilt either by compensation funds from the Pan Am adjustment agents or by Venezuelan funds should these materialize.

Yacambu Engineering Schedules

When the project was originally conceived in 1978, the reservoir was scheduled to start filling in 1980 and to be completed by 1982. USGS funding started in late 1978 in order that instrumentation should be complete before impounding commenced. Since then, delays have occurred to two parts of the project. Firstly the aqueduct tunnel to convey water from Yacambu to Quibor must be finished before the impounding can be completed since the tunnel entrance lies well below the final reservoir level. Less than 1/5 of the tunnel has been drilled at this time and a filling date in 1984 or 1986 seems possible. Secondly, the vital boreholes needed for piezometric measurements and the background seismicity study which are the responsibility of our Venezuelan counterparts (FUNVISIS) have not materialized. The curtailment of USGS funds at the end of this year is sensible in view of these uncertainties. FUNVISIS has volunteered low-level funding to maintain the existing instrumentation and promise that routine seismic monitoring of the Yacambu region will commence shortly. Bids to contract the borehole drilling have been invited but we understand that Venezuelan government funds will be required in the form of a specific contract. Negotiations and planning for the request for drilling funds may take an additional year or more.

Data

Representative spans of data from the creepmeter, the 287 m-deep and 442 m-deep strainmeters near the Bocono fault are shown in Figure 9. A longer span of data from the two tunnel instruments prior to the termination of line power in January 1980 shows considerable contamination from thermal variations (Figure 10).

As mentioned previously, the creepmeter data demonstrate a totally passive surface behavior of this branch of the fault confirmed by the absence of visible evidence for recently displaced surface features.

Long-term data from the Yacambu strainmeter are somewhat fragmentary prior to May 1980 when self-contained recording systems were installed. Data acquired since then indicate drift rates are of the order of 10^{-7}/week and that noise levels are sufficiently low to monitor clear impounding-related strains (10^{-5}/week) when these occur. The measurement of body tide strain amplitudes is not feasible at present since all the tunnel data are subject to large diurnal thermal contamination (> 10^{-7}/day). Long spans of data (> 3 months) will enable the extraction of the M_2 tidal amplitude with an accuracy of approximately 10% but this is insufficiently accurate to be used for monitoring changes in local elastic constants. Since most of the thermal noise is caused by ventilation of the dam tunnels, it is clear that considerable suppression of the thermal noise will occur when these are closed.

Conclusions

The absence of surface fissures and displaced linear features in the Bocono valley at Cubiro and Sanare suggests that the Bocono fault is probably locked in this area. This has been confirmed by measurements across one prominent branch of the fault zone near Cubiro. The fault zone is approximately 1 km wide near Cubiro with relatively few associated faults extending 3 km to the NW. The zone is crossed by a first-order triangulation network established several years ago that will ultimately provide conclusive evidence concerning tectonic strain accumulation should this occur.

In view of the lack of evidence for significant tectonic strain concentrating near Cubiro rather than in the plate boundaries to the north and south, there is little immediate justification for continuing the operation of the inclined-shaft strainmeters. In their present location, the prevalence of excessive thermal noise renders the instruments of little use for monitoring the stability of elastic moduli near the fault or the testing of conjectural hypotheses concerning the nature of stresses at plate boundaries. The instruments have served a limited purpose in indicating existing noise sources and have provided us with important lessons concerning the operation of instruments amid a highly active engineering environment. The completion of the aqueduct tunnel and the subsequent evacuation of the 'venta-inclinata' will provide a superb environment for a few selected instruments and it is not difficult to imagine that this may become one of the world's future deep observatories within the decade (depth > 500 m). It is our recommendation that the 287 m and 450 m strainmeters should be moved from their present position to depths of 750 m and 1200 m and until that time, their operation should be discontinued on the grounds that their data are dominated by thermal noise and tunnel relaxation stresses.

By far the most important aspects of the reservoir impounding study are the planned seismic network for the Yacambu region and the deep boreholes. These items are the responsibility of FUNVISIS and for various reasons have been subject to delays. Unrelated to the FUNVISIS delay (but congruent with it) is what appears to be a minimum two-year delay in the impounding schedule. This delay is attributable to the difficulty of tunnelling in highly-stressed, incompetent rock. The severity of the tunnelling daunts would-be drilling contractors and the possibility of not obtaining 1000 m bores for piezometric measurements has been considered. A plan using a larger number of shallower bores was considered earlier but was rejected as too costly. The possibility of using the aqueduct-tunnel to access a linear array of piezometers has also been considered but will not provide the insight we require concerning vertical diffusivity. Since the success of the experiment depends on these boreholes, it is our recommendation that further instrumentation of the Yacambu region associated with the induced seismicity study be made contingent on a firm date for reservoir impounding and for the completion of the boreholes. Moreover, an essential prerequisite of any further work in Yacambu is the establishment of continuous seismic monitors in the region.

The instrumentation of the underwater strainmeters at Yacambu is of concern to the FUDECO engineers whether or not the cooperative venture to study induced-seismicity comes about. We believe that the submerged fault presents a possible source of instability and that it is essential that it be monitored. The strainmeters are physically in position and their recording systems are prepared for installation. We plan to complete the instruments at the next period of low water in the embryo reservoir. For this reason, we have requested a one-year no-cost extension to the present USGS contract.

Finally, the cessation of USGS funds to enable the study of induced seismicity at Yacambu occurs at a non-crucial time in the proposed study. The work could be recommenced with little effort in the year before impounding. The past two years have provided us with the necessary insight as to what instruments will be useful, how they must be powered and recorded and who they are likely to interest in Venezuela. It is important that our colleagues in FUDECO and FUNVISIS are not mislead into thinking that the cessation of funds is due to a lack of merit in the proposed work. The reason is principally due to the postponement of the expected completion date. A firm completion date and the availability of deep boreholes would provide a major incentive for continued interest from the U.S.

FIGURE CAPTIONS

Figure 1. Map of western Venezuela, showing the western portion of the planned Venezuelan telemetered seismic network, active faults, and the size of the Yacambu Reservoir.

Figure 2a. Cross-section of Yacambu dam and reservoir (no vertical exaggeration) indicating the crustal deformation measurement locations. See text for explanation.

Figure 2b. Cross-section of Yacambu system including transfer tunnel and two reservoirs (vertical exaggeration x 5), S = strainmeter, T = tiltmeter.

Figure 3. Plan of Yacambu reservoir. Preferred 1 km boreholes are at 4 and 5. S = strainmeters.

Figure 4. Plan and cross-section of Bocono fault zone showing prominent faults and strainmeter (S) and creepmeter (C) locations.

Figure 5. Schematic figures of carbon fiber strainmeters and recording electronics. The electronics have been altered subsequently to operate independently on dry batteries.

Figure 6. 12 hour record from the three inclined shaft strainmeters. Two of the three instruments show increased strain rates and a third

simultaneously records a transient strain over a period of 90 minutes. The total strain extension on the 450 m and 670 m instruments amounts to more than 10^{-7} in five hours. The strains presumably arise from adjustment of major rock joints to the presence of the newly formed tunnel. (The 287 m instrument is 287 m from the tunnel entrance.)

Figure 7. Underwater strainmeters. Two massive I-beams cross the subreservoir strike-slip fault shown in Figure 3. The beams are fastened to the rock on one side of the fault and slide freely in a channel on the other side. Horizontal movements of the fault will cause relative closure of one instrument and extension of the other. Opening of the fault will cause extension on both instruments. The relative movements will be detected by sealed displacement transducers (LVDT's).

Figure 8. Micrometer-capacitance fluid height transducer. The system is designed to monitor sub-micron water-height changes in a central reservoir that is connected hydraulically to a long baseline tiltmeter. The system uses a dense fluorocarbon dielectric (F) that floods two flat concentric capacitor plates (A+B) to a depth of 1 mm. Water (C) overlies the dielectric with which it is immiscible and acts as the third electrode in a capacitance quad-diode bridge. A cylinder (D) prevents water from flowing between the active central reservoir and the outer water reservoir but allows the flow of dielectric fluid. A change in water height compels the dielectric to compensate for the resulting pressure change by increasing its depth on one side of cylinder D and decreasing it an identical amount on the other side.

The capacitance change is linear for water level changes of about 2 mm. The range is extended by opening a valve (E) that briefly permits water to flow into the outer reference reservoir. A single carbon fiber cystal 8 m in diameter is fastened to the micrometer to detect the water surface. An audible alarm is triggered when electrical contact is made. We have found that micron setting precision is attainable even by unskilled operators. The micrometer enables calibration of the capacitance transducer and provides an independent measurement of long-term water-height changes.

Figure 9. Data from the Cubiro creepmeter (18 days) and the inclined shaft strainmeters (23 days/287, 4 days/450). As might be expected, thermal noise decreases with distance from the entrance. The 287 m instrument typically records a 10^{-7} diurnal signal and the 450 m instrument less than half this value. Drift rates on the three instruments initially showed a marginal increase with depth, reflecting increasing tunnel relaxation strains that have distorted the lining in places.

Figure 10. Simultaneous data from the inclined shaft strainmeters indicate that although thermal signals on the two co-linear instruments affect the instruments differently, data with periods longer than about 5 days are in reasonable agreement.

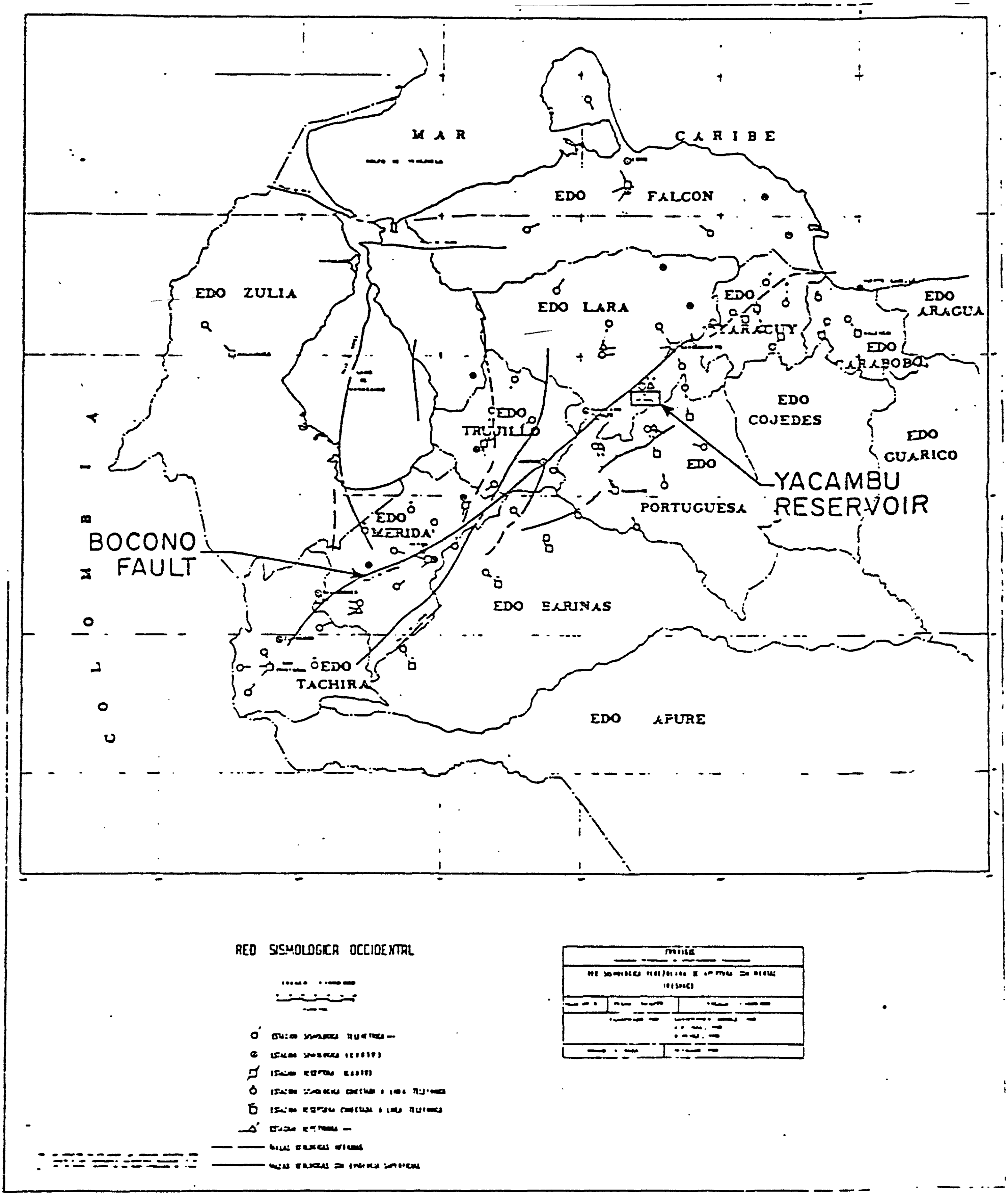

Fig. 1. Map of Western Venezuela, showing the western portion of the planned Venezuelan telemetered seismic network, active faults, and the site of the Yacambu Reservoir.

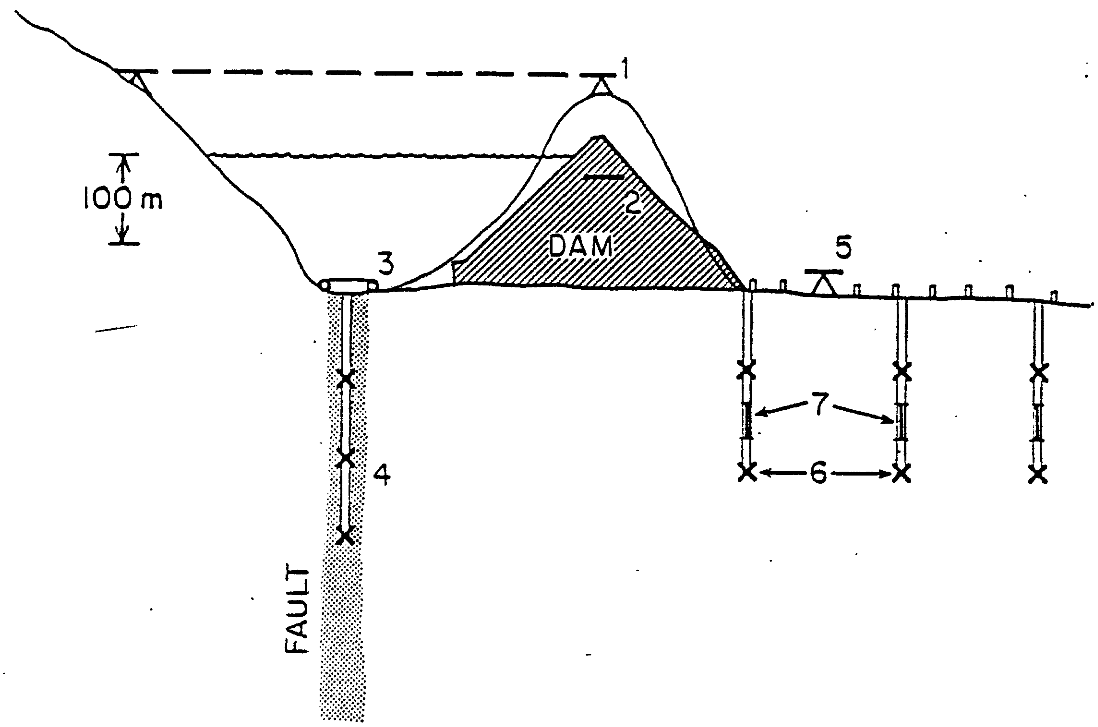

Figure 2a

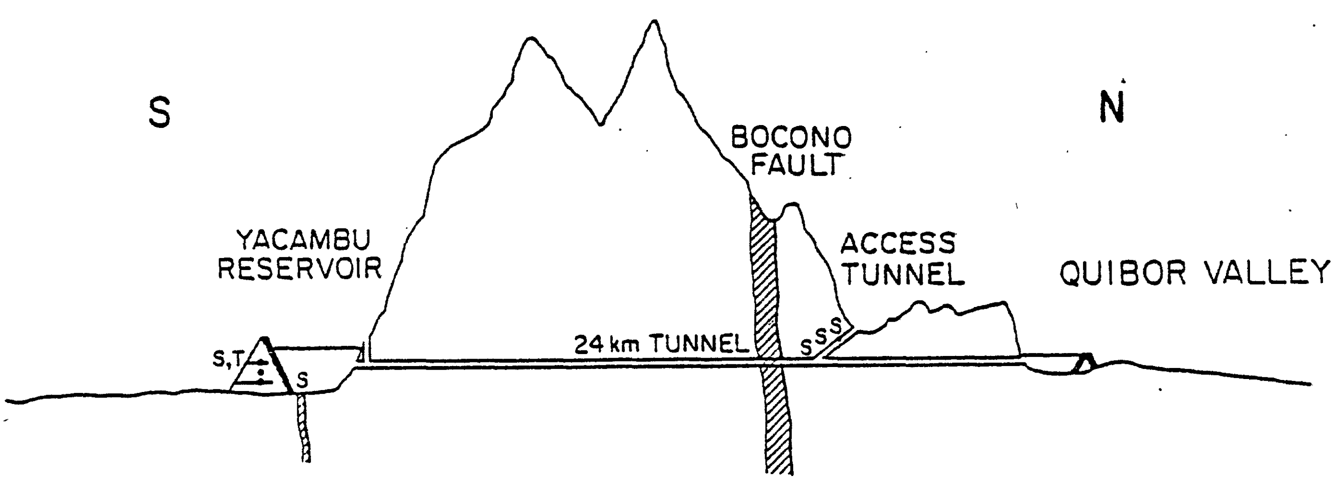

Figure 2b

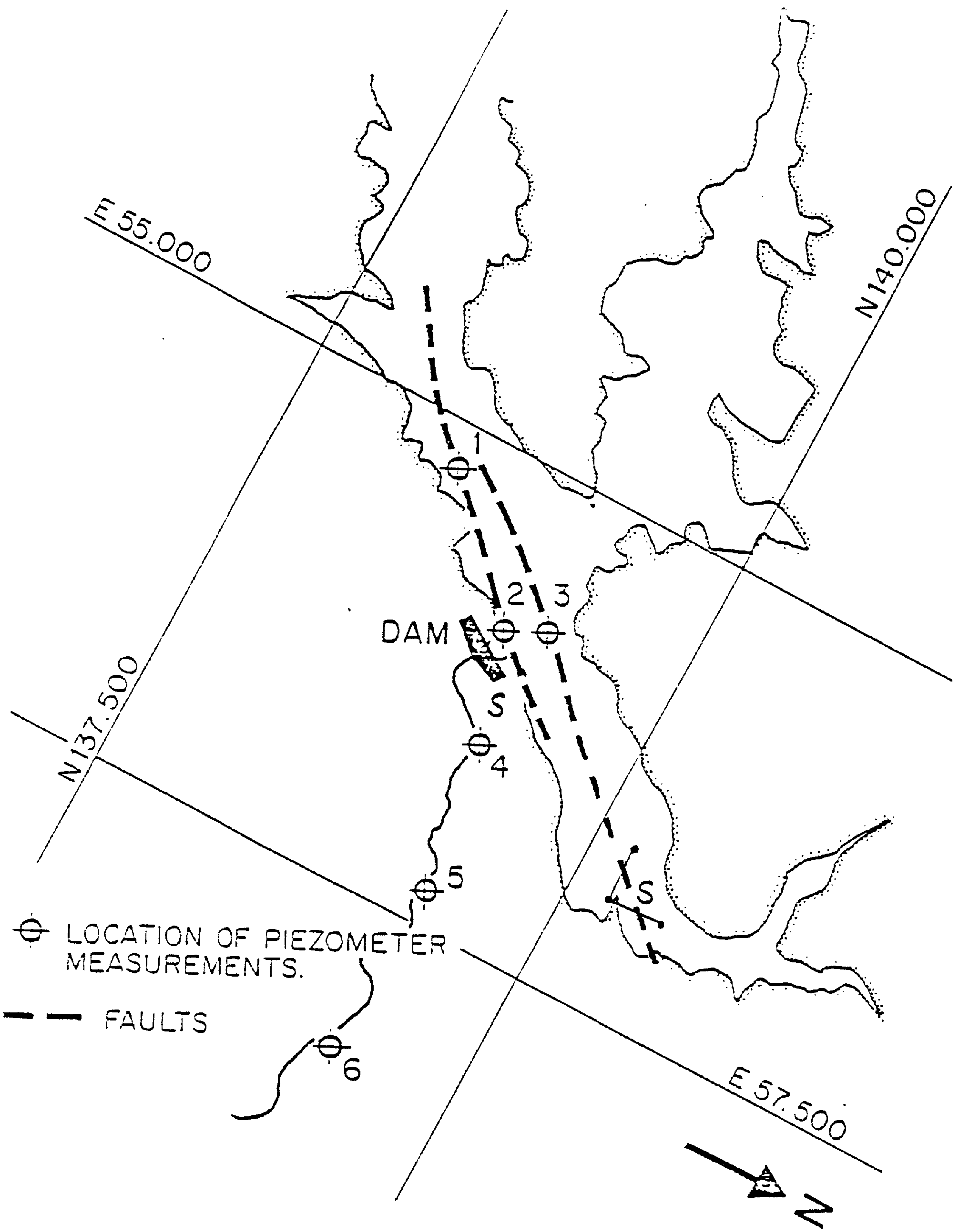
E 55.000
N140.000
N137.500
E 57.500
1
2
3
4
5
6
DAM
S
S
LOCATION OF PIEZOMETER MEASUREMENTS.
FAULTS
N

Figure 3

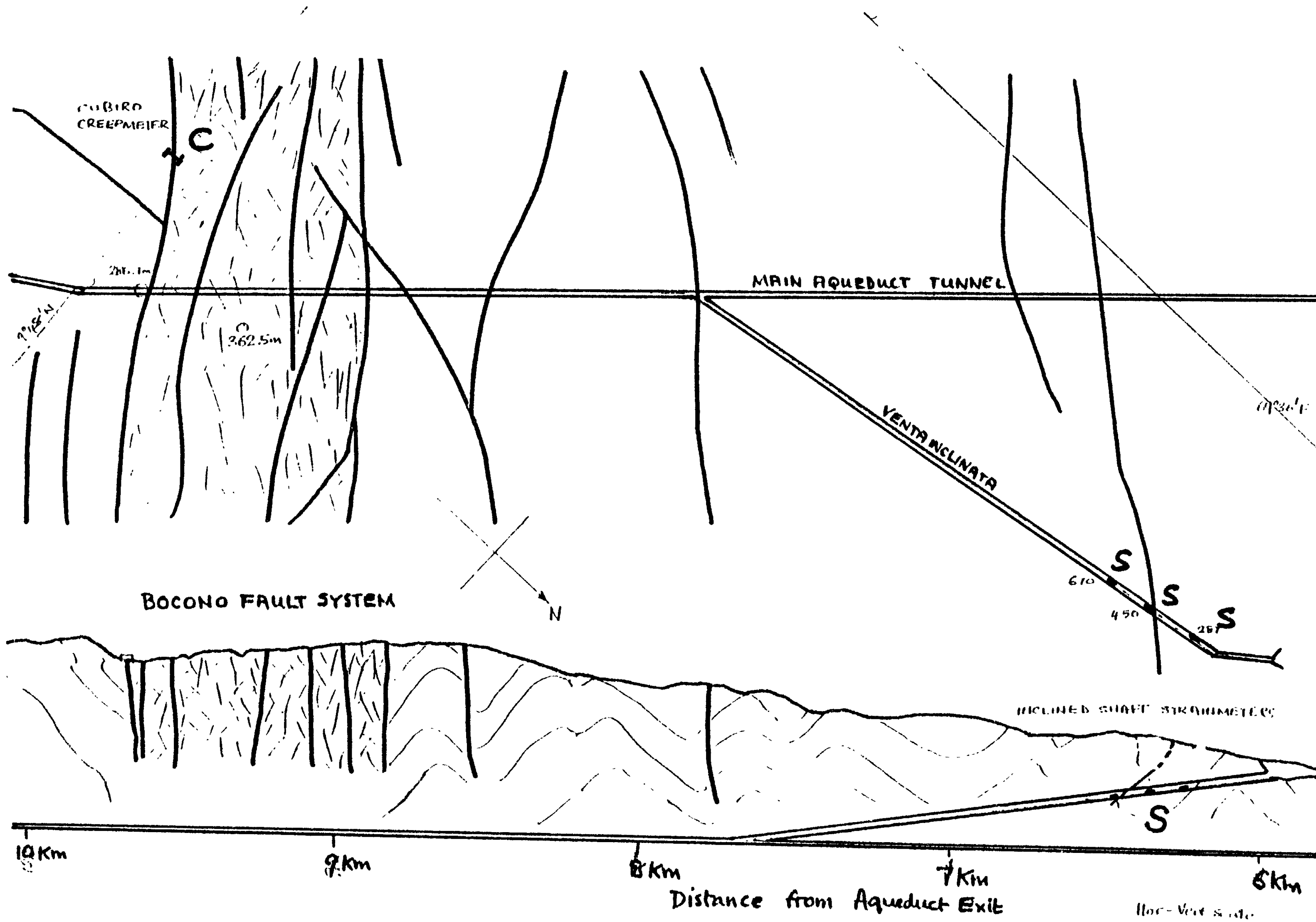
CUBIRO CREEPMEIER
C
MAIN AQUEDUCT TUNNEL
362.5m
VENTA INCLINATA
S
610
S
450
S
BOCONO FAULT SYSTEM
N
S
10Km
9Km
8Km
7Km
6Km
Distance from Aqueduct Exit

Figure 4

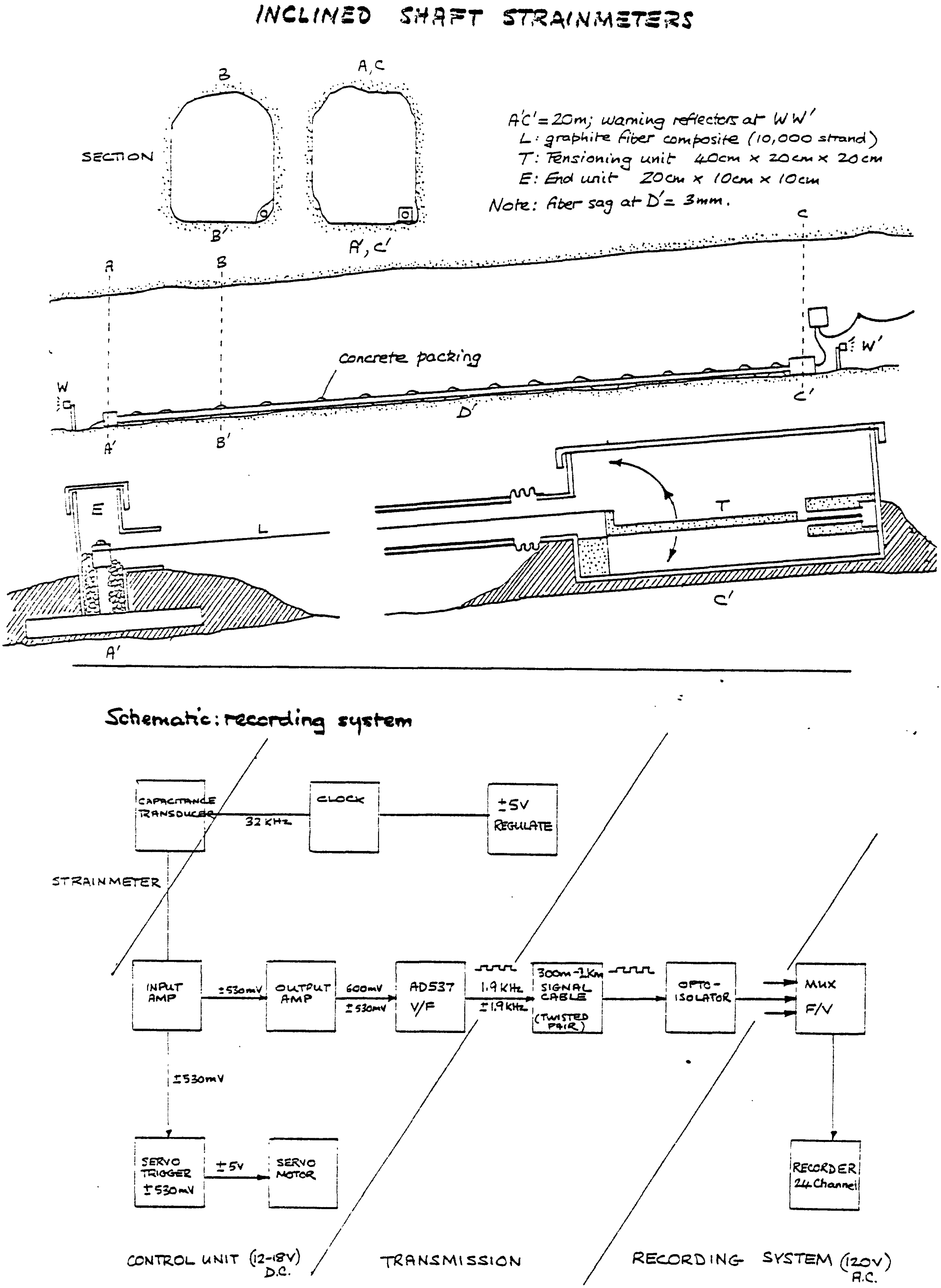
INCLINED SHAFT STRAINMETERS
SECTION
B
B'
A,C
A',C'
A'C' = 20m; warning reflectors at W W'
L: graphite fiber composite (10,000 strand)
T: Tensioning unit 40cm x 20cm x 20cm
E: End unit 20cm x 10cm x 10cm
Note: fiber sag at D' = 3mm.
concrete packing
W
W'
D'
E
L
T
C'
Schematic: recording system
CAPACITANCE TRANSDUCER
32 KHz
CLOCK
±5V REGULATE
STRAINMETER
INPUT AMP
±530mV
OUTPUT AMP
600mV
±530mV
AD537 V/F
1.9 KHz
±1.9 KHz
300m-1Km SIGNAL CABLE (TWISTED PAIR)
OPTO-ISOLATOR
MUX F/V
±530mV
SERVO TRIGGER ±530mV
±5V
SERVO MOTOR
RECORDER 24 Channel
CONTROL UNIT (12-18V) D.C.
TRANSMISSION
RECORDING SYSTEM (120V) A.C.

Figure 5

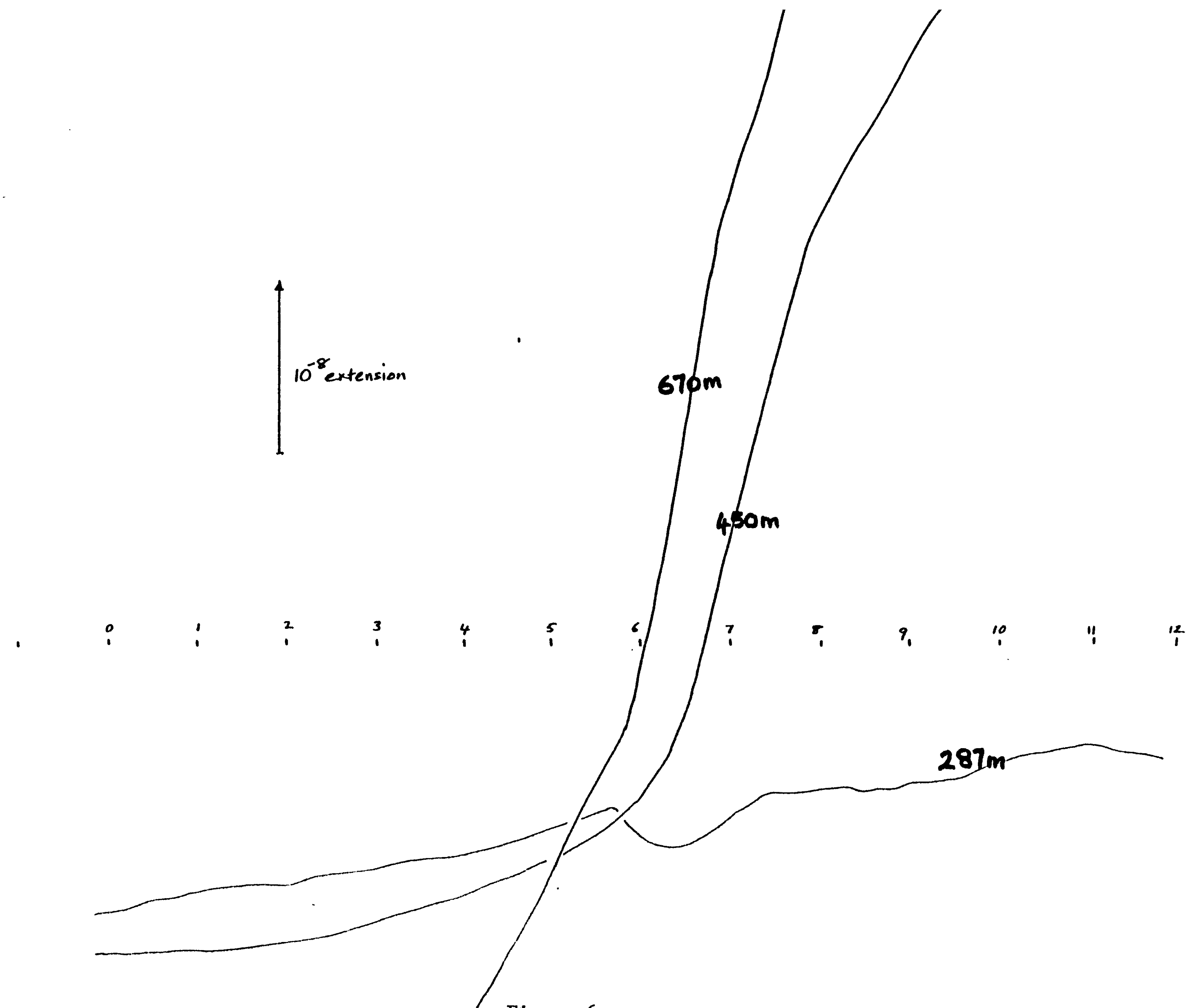

Figure 6

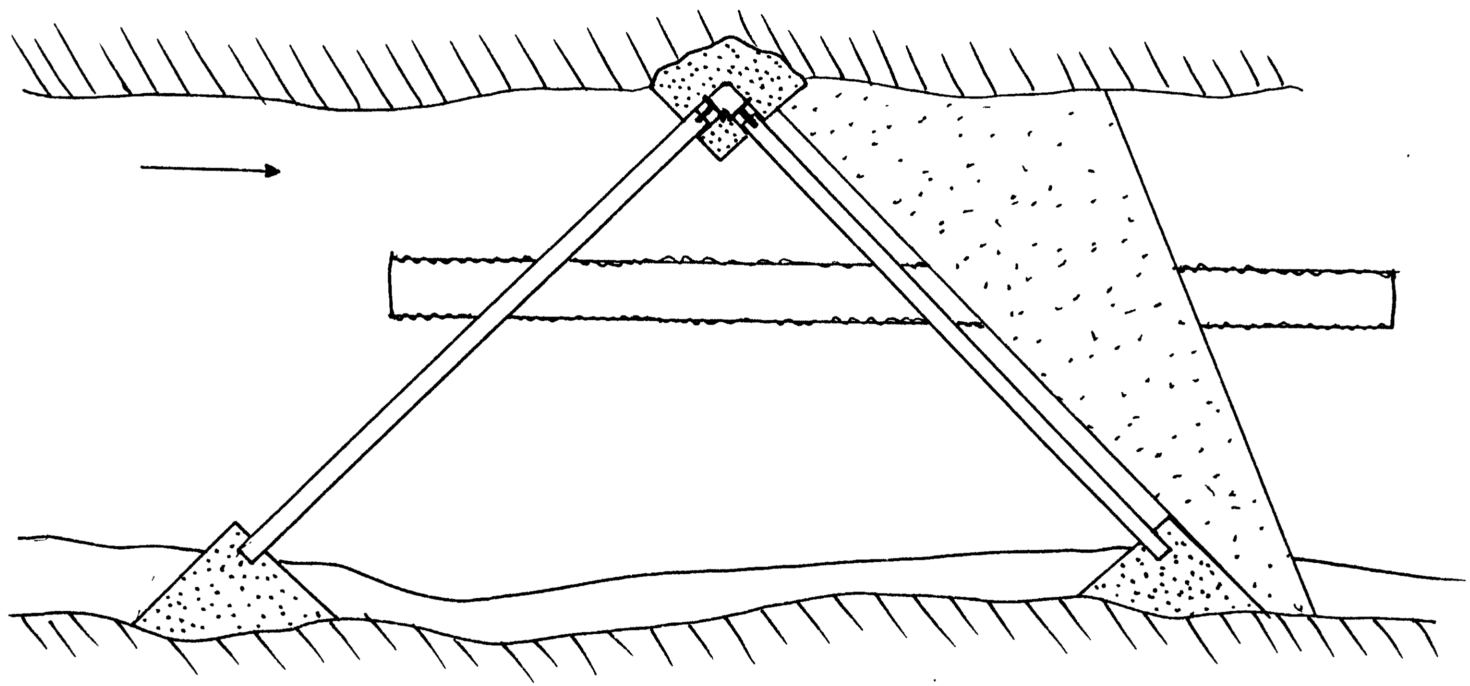

Figure 7

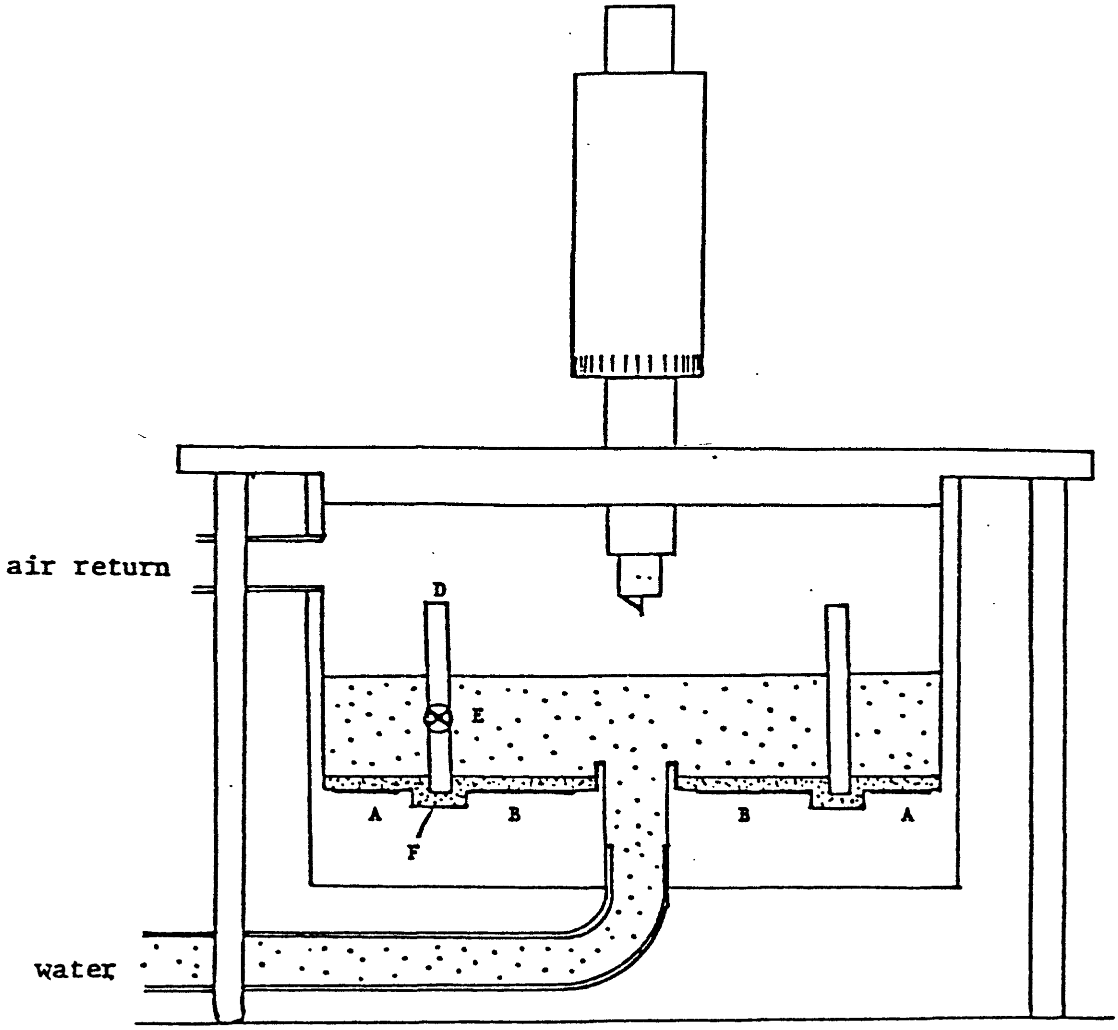

Figure 8

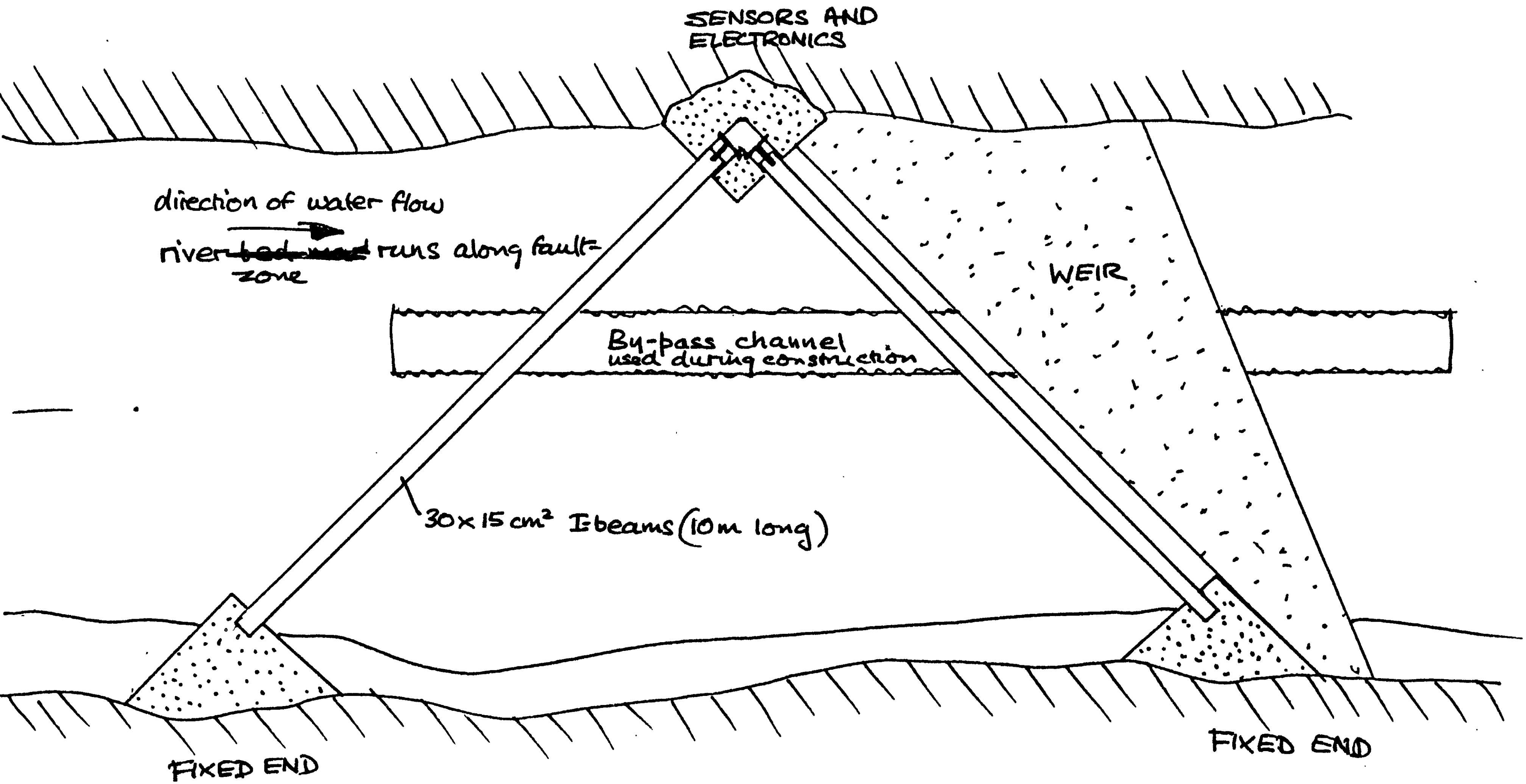
SENSORS AND ELECTRONICS
direction of water flow
river ~~bed~~ runs along fault zone
WEIR
By-pass channel used during construction
30x15 cm² I-beams (10m long)
FIXED END
FIXED END

Figure 9

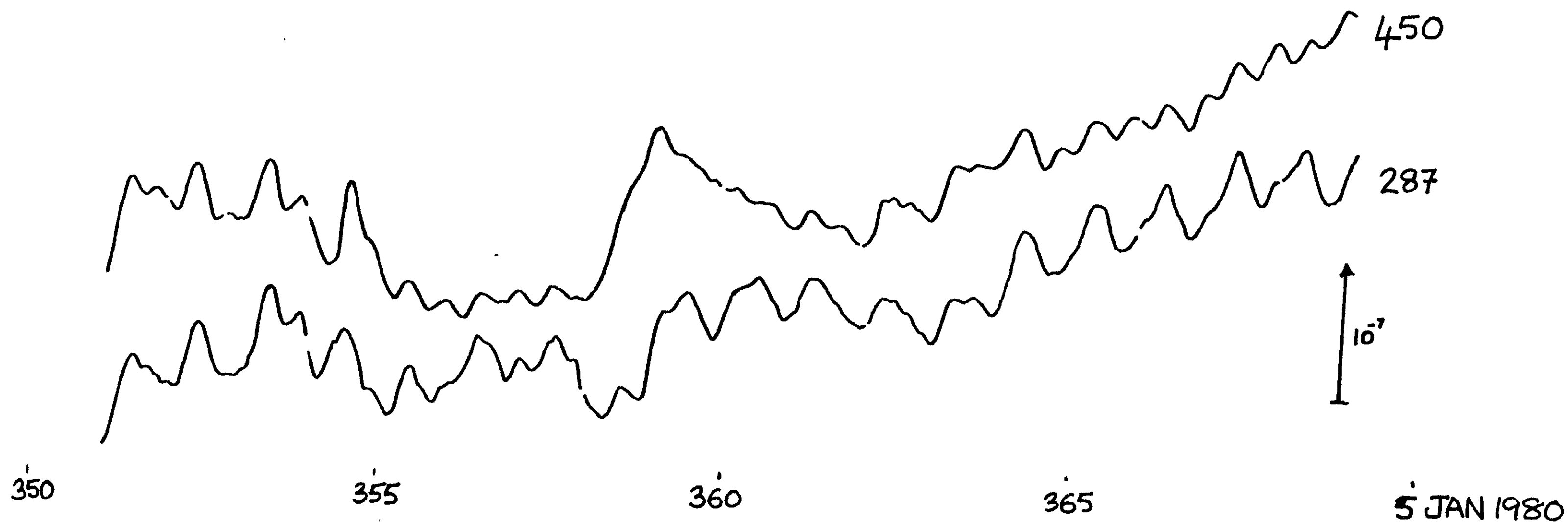

Figure 10