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HP Ross

ROUGH DRAFT

FINAL REPORT

DETAILED GRAVITY SURVEYS IN VALLE DE LOS CHILLOS, ECUADOR

and

GRAVITY SURVEY MISSION FOR INE

Prepared for

INSTITUTO NACIONAL DE ENERGIA
QUITO, ECUADOR

by

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CONTENTS

ILLUSTRATIONS

INTRODUCTION

The Instituto Nacional de Energia de Ecuador (INE) has been engaged in the exploration for low-to-moderate enthalpy geothermal resources in the Valle de Los Chillos area near the volcano Ilalo'. Funding for this project has been provided in part by U.S. AID. The University of Utah Research Institute (UURI) has been contracted to provide expert technical assistance in a geothermal resource risk assessment, geophysical survey planning and execution, geochemical studies, and technology transfer and training of INE geologists. Previous geophysical work included electrical resistivity surveys at Sangolqui-El Tingo and Tumbaco-Cumbaya. Previous UURI assistance efforts have been documented by Dr. P. M. Wright, (1985, 1986) and Dr. J. N. Moore (1985).

Dr. Howard P. Ross, Senior Geophysicist of UURI completed a gravity mission for INE during July 2-July 13, 1986. The requirements of this work and funding for the project are provided in a contract agreement between INE and UURI dated 8 July 1986. A Statement of Work for the project as understood by UURI is provided in Appendix 1. Daily activities for the gravity mission are recorded in Appendix 2. A preliminary report describing the gravity mission was written in Quito and delivered to INE (Ross, 1986). This final report reviews the project in brief and describes the final data compilation and interpretation.

INE geologists have recognized the potential value of the gravity method for defining subsurface rock density contrasts.

Abrupt changes in the density distribution may indicate the presence of faults which serve as conduits for geothermal fluids in the Valle de Los Chillos. Thus the gravity survey may provide supporting data which, used in conjunction with geologic, geochemical, and electrical resistivity data, will indicate the preferred locations for drill testing. INE geologists have completed the gravity survey themselves using a leased gravity meter, and utilizing technology transfer provided by UURI during the July mission. The survey data were reduced in Quito and transmitted to UURI for review and interpretation. The data were received by UURI October 3.

THE GRAVITY SURVEY METHOD

The gravity survey method has been used for many years in a variety of geologic studies, including exploration for mineral deposits, petroleum exploration, and academic studies of the earth's crust. The method has been used in geothermal exploration for approximately 20 years, principally for the detection of faults and mapping of buried intrusives and volcanic features.

Much has been written about the gravity method and a detailed description of the method is not appropriate in this report. Several reports and studies were transmitted to INE geologists for reference and study and the interested reader is referred to these. Dobrin (1976) and Telford et al. (1976) provide excellent descriptions of the gravity method and basic interpretation techniques. A good introduction and summary of the method excerpted from Wright (1982) is provided as Appendix 3 of this report.

Feininger (1977) has compiled the data of several gravity surveys totaling 14,000 stations to produce a Simple Bougueer Gravity Anomaly Map of Ecuador, at a scale of 1:1,000,000. The gravity stations are irregularly spaced and mainly without terrain corrections. Nevertheless the map helps to provide a good regional understanding of the crustal geology of Ecuador. Feininger and Seguin (1983) describe the inferred crustal structure of Ecuador based on a numerical model interpretation of portions of these data, and provide useful density information on major rock units in Ecuador. A single profile of approximately 5 stations extends from Quito east to Cumbaya near the survey areas in the Valle de Los Chillos, and indicates a major north trending gravity low in the area of INE geothermal interest.

As indicated in Appendix 3 the precision and usefulness of the gravity survey depends on accurate elevation control and survey position. Gravity line positions and station elevations and locations for the Sangolqui-El Tingo and Tumbaco-Cumbaya surveys were established in advance of this gravity mission, by a private engineering firm located in Quito. It was impractical to make major changes in the survey as already laid out during the July mission. Some additions to the Sangolqui-El Tingo survey were made in response to recommendations by Ross (1986).

INSTRUMENTATION

The instrument used in this gravity survey was a Lacoste and Romberg, Inc. Model G Geodetic Gravity Meter, No. 325. The instrument was leased from Mining Geophysical Surveys, Tucson, Arizona, under funding from U.S. AID. This gravity meter is a high precision instrument with a world-wide reading range of 7,000 milligals, a reading accuracy of ± 0.01 milligal, and a normal drift rate of substantially less than 0.10 milligal per month. Review of the drift records for the completed surveys indicates several "tares" or instrument drift changes of 0.1 to 0.5 milligals, as discussed later. The operating principals and instructions for use are described in detail in the instruction manual provided with the instrument (Lacoste and Romberg, Inc., 19__?__).

The gravity meter is protected against minor vibration by a clamping mechanism which isolates the measuring spring and mass, and is sealed and internally pressure compensated. Nevertheless, the instrument is very sensitive to damage from being dropped, kicked, knocked over, or similarly disturbed. Instrument repairs can be very costly ($1,000-$10,000, U.S.) and could take a long time (10-100 days). Fortunately the surveys were completed without the need for repairs.

During the July gravity mission, three days were spent providing instruction in instrument reading, handling, and field techniques to INE geologists. Additional information was available in the instrument manual. Geologists Marco Acosta and Milton Balseca became quite proficient in the operation and handling of the instrument in this time. It appeared possible to achieve a reading precision of 0.01 milligals at most stations. Local noise and vibration conditions caused by unstable ground, strong winds, and truck traffic on rough roads would of course compromise this precision and accuracy at many stations.

INSTRUCTION FOR INE GEOLOGISTS

An important part of the July gravity mission was the training of INE geologists and discussions about the gravity survey method. This was most important since INE geologists would complete all the field observations, apply the numerous corrections to the data, and reduce the data themselves. An effort was made to transfer an understanding beyond that which can be obtained form the references since field conditions are variable and unexpected conditions could arise, and INE personnel would have to make many decisions leading to the successful completion of the survey. The major elements of the instruction and discussion are summarized below.

Instrument Operation

Training in accurate instrument reading and care of the instrument has been described in the previous section. INE geologists completed more than 12 instrument readings in the field in addition to daily instrument check readings at the INE office. Instruction, observation, and comments on instrument procedures were provided for these activities.

Field Instruction

Instruction in gravity meter measurement under field conditions was accomplished by identifying a survey base station for Sangolqui-El Tingo and a separate base station for Tumbaco-Cumbaya, and then completing a survey loop tying a secondary base on each profile to the survey area base station. A number of "typical" field problems were noted, including: missing survey stakes; unstable ground at the station due to thick grasses; high winds; traffic problems; unsuitable station location (adjacent to buildings, walls, or power poles; at the edge of severe topographic features; on pointed rocks, etc.); drifting meter values or instrument level bubbles. Best effort solutions to these problems were discussed and effected. This often required a movement of the station, estimating the elevation difference, and recording the changes in the survey notes.

Survey Methodology

Considerable time was devoted to discussions of survey methodology such as ties to known gravity values at the Quito Astronomical Observatory and the Quito Airport, establishing survey bases at Sangolqui-El Tingo and Tumbaco-Cumbaya, and the use of secondary bases on each profile during the conduct of the survey. The optimum methodology must account for characteristics of the established stations, useability of the road network, survey efficiency, characteristics of the data reduction scheme, and time and funds available. After considerable discussion and study of the data reduction program (Kwoon et al., 1977) and the survey maps, a general methodology was agreed upon and is described in the following pages.

Establishing Absolute Gravity

(Tie-in to known stations). The gravity meter records differences in the earth's gravitational attraction to a high precision but does not measure absolute gravitational attraction. The absolute value of the gravity field for survey stations can be achieved through a tie-in by completing an observation loop beginning and ending at one station for which the true gravitational field is known. Gravity values at all other stations can then be expressed in terms of the true observed gravity, true Bouguer gravity, or as the true Bouguer gravity anomaly by addition of the constant value determined for the known station.

Two principal stations in Quito for which the absolute observed gravity value is known are located at the Quito Airport and at the Quito Astronomical Observatory (QAOb). The gravity values for these stations are tied uniformly to the new basic value of gravity at Potsdam, through the Latin America Gravity Standardization Net (Feininger and Seguin, 1983). The exact location of the station at the Quito Airport was not known to INE geologists and is believed to be in a high traffic area unsuitable for multiple station reoccupation. The station in the QAOb was located in the basement floor of the old seismograph room, was identified by a brass marker, and was available for gravity observations. An initial observation at this site was taken on 9 July 1986, but was found to be noisy and drifting. The variable readings were attributed to construction in progress at the site and to heavy morning traffic. The results of ~~this~~ satisfactory later measurements and principal facts for the two known stations are shown below in Table 1.

TABLE 1

RELATIONSHIP TO ABSOLUTE GRAVITY VALUES

Gravity Station	Longitude W (Degrees-Min)	Latitude (Degrees-Min)	Elevation (m)	Observed Gravity (milli-gals)	Theoretical Gravity (milli-gals)	Differences
Apto M Sucre	78° 29.0′	0° 10.4′	2812.41	977270.32	978049.04	7.65 milligals observed
Q. Astron Obs.	78° 29.5′	0° 13.2′	2817.21	977262.67	978049.10	Grav.
Q. Astrom Obs.	78° 29.5′	0° 13.2′	2817.21	1011.26 ± .03		976251.41 ± .25

Table 1 shows that the absolute gravity for the QA Obs. is -7.65 milligals with respect to the Quito Airport value. Also, the 14 July meter readings by INE geologist with L & R G-325 of 1011.25 ± .03 milligals requires the addition of a constant, approximately 976,251.41 milligals to adjust the L & R G-325 value to absolute gravity readings. the constant correction value to express L & R G-325 gravity values in terms of absolute gravity can be expressed as:

$$K_{corr.} = G^{obs} (QS\ Obs) - G^{obs} (QA\ Obs) = +976251.41 \text{ mg}$$

<u>Base Station Looping</u>

To tie the survey data for Sangolqui-El Tingo (S - ET) and Tumbaco-Cumbaya (T-C) to QA Ob required a separate loop between QA Obs. and a selected base station for each area, since only poor roads exist between S-ET and T-C areas. A single loop should be sufficient for each tie-in unless a large drift and tidal variation is apparent upon repeat observations at QAO. If the difference after tidal correction is greater than 0.03 milligals, a repeat loop should be completed. The recommended procedure can be expressed as:

Loop 1: QAObs -- S-ET base -- QAObs

Loop 2: QAObs -- T-C base -- QAObs

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$$K_{.} = G_{(absolute)}(QS - Obs) - G_{(L \& R\ G\text{-}325)}(QA\ Obs) = +976251.41\ mg$$

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Loop 1: QAObs -- S-ET base -- QAObs

Loop 2: QAObs -- T-C base -- QAObs

The survey procedure for all profiles required additional loops to identify major instrument changes (tares) and to establish instrument drift and tidal changes. Tidal corrections were calculated by the reduction program (Kwoon et al., 1977). This procedure for a single days activity, for S-ET profile 5 (for example) could be:

```
     QAObs -- S-ET 3-28 -- QAObs     (previously established,
     Base 1    Base 2      Base 1     i.e., Day #1)

S-ET 3-28 -- S-ET 5-24 -- 5-1 -- 5-2 -- 5-3 ....-5-12 -- S-ET 5-24
 Base 2       Base 3                                      Base 3
 Morning      Morning                                     Mid-day
 Day #3

     -- 5-13 -- 5-14 -- 5-15 ..... -- 5-23 -- S-ET 5-24
                                               Base 3
                                               End of
                                               Day #3
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Similar procedures would apply to other profiles and to regional stations to be discussed later. This looping technique-appeared to be fully compatible with the input format required by the Kwoon et al. (1977) computer program which was used for data reduction. Thus, all data should be reduced with respect to the QA Obs and will be expressed as Bouguer Anomaly values rather than as absolute gravity values.

Data Reduction

Data reduction for gravity surveys must be carefully completed and requires considerable time, especially for terrain corrections. The correction process is described in Appendix 3 (note Figure 1) and other references. Because of the large number of gravity stations in the INE surveys, the need for exact manipulation of large numbers, and the looping of base stations the reduction process is most necessarily done by computer. INE geologists have implemented a computer program written by Kwoon, Rudman and Blakely (1977) on the INE computer to complete the data reduction.

Topographic corrections, both in field and in office map determinations, were reviewed in some detail. Topographic corrections were expected to be large for many stations in the survey area and could be the largest error in the corrected gravity values. It was recommended that topographic corrections be determined as well as possible and that a student be employed for some of this work. Short-cut procedures to reduce the required work were discussed with INE geologists. Templates, topographic correction charts and various forms were made available to INE.

A density of 2.45 g/cm^3 was used for topographic and Bouguer corrections. This is close to the 2.40 g/cm^3 used by Feninger and Seguin (1983) for volcanic fill of the Inter Andean valley.

Data Interpretation

Time permitted only a general discussion of data interpretation, density changes, regional gradients, etc. A general qualitative interpretation can be performed on survey gravity maps at scales of 1:10,000 or 1:25,000. Detailed quantitative interpretation could be completed with program GRAV2.D which models the density distribution of finite strike length two-dimensional bodies if the data warrant. The principal aim of the interpretation is to identify and define suspected faults which may be the conduits for geothermal fluids.

Dr. P. M. Wright recommended regional gravity stations between Quito and the survey areas to assist in defining the regional gradient. No engineering was completed to prepare gravity stations and these data were not obtained. Regional gravity stations on Ilalo' were considered more important.

Additional fill in gravity stations, at approximately 50 m intervals, were recommended to INE geologists when very steep gravity gradients were observed on profiles near the suspected faults. Time did not permit obtaining gravity data at intermediate stations before the gravity meter was returned to Mining Geophysical Surveys in the United States.

EVALUATION OF INE SURVEY DATA

A preliminary inspection of the INE Tumbaco-Cumbaya and Sangolqui-El Tingo gravity maps indicated generally smoothly varying gravity fields but also the presence of several single station anomalies, which often indicate observation or compilation errors. Some concerns also arose about optional ways to contour the data. A careful review of all steps of the data compilation was indicated prior to any interpretational efforts. This is a rather standard procedure even for gravity data compilations by very experienced groups.

The following work was completed in order to verify and improve the data compilation and resulting gravity maps.

1. <u>Station elevation verification</u>. The elevation of all gravity stations as tabulated by program GRAVSUR were compared with the survey engineer tabulation of elevations. Several errors were found in both areas (see Appendix 4), and gravity values were recomputed.

2. <u>Instrument drift</u> was determined for all base station reoccupations to determine instrument stability and drift correction magnitude. This was not printed out by GRAVSUR and had to be recalculated. Drift corrections varied from -0.375 to +0.569 but ~~was~~ were generally less than 0.20 mg. The largest single error occurs at station 34B, TCG-5 where an input meter value of 1099.980 should have been 1009.980. This resulted in huge drift corrections for 10 stations and a large, false anomaly.

3. <u>The elevation of the datum plane</u> was checked for all profiles. An input error on Profile TCG-5 caused the entire profile to be reduced to a datum plane of 5.00 m rather than sea level (0.00 m). Final Bouguer gravity values were corrected.

4. <u>Printed Bouguer gravity values</u> for each profile were compared with values plotted on the maps, station by station. Errors were corrected,and numerous values changed when rounded off to the nearest 0.1 milligal.

5. <u>Single station anomalies</u> and large or erratic gradient areas were compared with topographic corrections, drift corrections, elevation variation and observed gravity meter

readings to locate or identify possible errors. Good topographic maps were not available for further comparison.

6. Bouguer gravity maps were recontoured to emphasize questionable single station anomalies and to remove linear bias as deemed appropriate.

Program GRAVSUR was readily implemented by INE and has given rise to a satisfactory data compilation. Some aspects of the program and compilation could be improved in any future surveys. The topographic corrections are typically applied after the simple Bouguer anomaly has been calculated, (hence last) to permit tabulation of both the simple Bouguer anomaly and the terrain corrected Bouguer anomaly. Some reduction programs also print out topographic, tidal, and drift corrections for easy comparison with the fully corrected Bouguer gravity value. This would have been most useful in the present study.

The revised Bouguer gravity maps for Tumbaco-Cumbaya and Sangolqui-El Tingo are substantially different from INE preliminary maps, with generally smoother contours and fewer single station anomalies. Several questionable anomalies with gradients larger than 2.0 mg between stations, and several mg between lines, still occur. Most of these features can be attributed to unusually high or low observed instrument readings, as compared to nearby stations. The larger amplitude (3 mg or more) single station anomalies are almost certainly errors. No interpretation will be offered for these anomalies.

INTERPRETATION

The interpretation of gravity data often consists of three separate phases:

1. Qualitative evaluation: of noise level; identification of geologic caused anomalies and their magnitudes; character of regional gradients; concordance with known geology; and delineation of probable geologic features.

2. Quantitative interpretation: Numerical modeling, model matching, or curve matching to determine depths, density contrasts, size and shape with a reasonable degree of accuracy. Interpretation of this type is only warranted when anomalies are well defined and anomaly magnitudes are well above the uncertainty of regional gradients and survey and/or geological noise levels.

3. Geological interpretation: Identification of geologic causes or rock units giving rise to features interpreted from 1. and 2. above. Due to some limitations of the survey data this interpretation shall focus on phases 1 and 3.

TUMBACO-CUMBAYA SURVEY

The Bouguer gravity map for the Tumbaco-Cumbaya area is presented as Plate IA. Plate IB presents interpretational notes and interpreted features superimposed on the data base of Plate IA.

An inspection of stacked profile plots, tabulated Bouguer gravity values, and the final contour map suggest that much of the survey has been completed to an effective accuracy of $\pm$ 0.1 or $\pm$ 0.2 mg which is an excellent result. More than 10 single station anomalies of 1 mg or more do occur however, and since the gravity method is sensitive to the effects of elevation and instrument reading errors, and to topographic effects these "anomalies' must be considered as possible errors. A fairly large distance between lines, stations where readings could not be taken, and the lack of "fill in" or check values on isolated anomalies further complicates the interpretation.

Profile plots and Plate IA were searched for possible indications of geologic changes, generally represented by an increased slope of the Bouguer gravity data. These locations were plotted on profiles and Plate IB. The more likely continuity between these high gradient areas was inferred from the contour map itself using our basic understanding of the geologic environment, as presented by Acosta (1985).

The geology of the Interandean Valley, as described by Acosta (1985), includes a complex stratigraphy of Ilalo' volcanics, generally breccias and flows, overlain by several units of erosional debris. These include conglomerates, volcanic debris, lahars, colluvial and landslide deposits. In volcanic settings such as this the density contrasts between mappable units is generally small, 0-0.4 gm/cm^3. The identification of valid gravity anomalies is often difficult and depends to a large extent on the continuity of the geologic feature, especially faults.

Four basic types of geologic features which may be present in this area, and are important to geothermal exploration with the gravity method, are shown schematically in Figure 1. The gravity anomaly of a deeply buried fault (1a) should be indicated as a gradient across many (4-20) station intervals of 100 m. A shallow fault (1b) may be expressed as a weak anomaly gradient over a few station intervals, but may be superimposed on a much broader gradient if the fault extends to great depth. Local three-dimensional anomalies may occur along faults or at fault intersections. If brecciation and dissolution occur, as in Figure 1c, a weak gravity low may result. If silica or other mineral deposition occurs at a fault intersection, or if lava cooled in a fault intersection, a gravity high, possibly a single station gravity anomaly, may result (Fig. 1d).

Plate IB shows the interpreted structures for the Tumbaco-Cumbaya area. Low anomaly amplitudes and limited continuity across survey lines demands considerable uncertainty in the interpretation of many features. The more speculative faults are indicated by broken lines and question marks. Substantiation by independent data (geologic mapping, resistivity, etc.) is desirable before much credence can be given to these features.

Limited geologic control was available at a scale appropriate for comparison with the gravity data. Major linear features interpreted as structures by Acosta (1985) in his figure 3.2 have been added to Plate IB for comparison. Mapped pools (piscina) are also shown.

Linear 36B may be expressed in the gravity data along the northern portions of Profiles TCG-3, TCG-4, and TCG-5. Linear 9 may be expressed along the southern portion of TCG-5 and may cross TCG-6 near a well defined gravity low at station 13. The interpretation of structures crossing profiles at a small angle is often speculative however. Several more easterly trending features have been mapped, as shown. Easterly trending structures in the southern parts of all profiles may correspond somewhat with linears 16 and 17 of Acosta's Fig. 3.2.

SANGOLQUI-EL TINGO SURVEY

The Bouguer anomaly map of the Sangolqui-El Tingo area, Plate IIA, shows only a few questionable single station anomalies and is characterized by generally smoothly varying contour patterns. The dominant feature of the map is a systematic increase in Bouguer gravity from southwest to northeast as one approaches the volcano Ilalo'.

Another major trend is the decrease in gravity values from northwest to southeast. The gradients become quite steep between lines STG-7 and STG-8 near Barrio San Vincente. This gradient is imperfectly defined since it occurs mainly between profiles. A careful review of the data indicates the lower gravity values along Profile STG-8 arise directly from lower observed gravity meter readings, and the effect of elevation changes, drift and topographic corrections are not important in defining this feature. Hence it is considered to be a valid anomaly of geologic origin, although the rapid changes between stations 14-15, and 36-39 strongly suggest the possibility of errors in observed gravity values.

Probable and possible faults interpreted from the gravity data are shown on Plate IIB. No real correlation exists between major linears No. 25 and 30, mapped by Acosta (Figure 3.2), where these features cross the survey area. Linear feature No. 31 crosses STG-7 and STG-8 near interpreted faults in the eastern portion of the survey area. A fault indicated by Acosta in Fig. No. 3-4, Fault No. 4 closely parallels structures mapped on the northern portion of profiles STG-1, -2, -3, and -4. The gravity data have probably confirmed the location of a major structure in this area. Another mapped fault presented in Fig. No. 3-4, Fault No. 5 crosses profile STG-6 near two indicated possible structures, but these are inferred to have an easterly trending continuity.

A possible northeast trending fault is indicated approximately 100 m northwest of STG-8. If there is no error in the gravity data, a substantial fault may occur within 100 m of this location.

A few other possible faults are interpreted on Plate IIB, but their validity and importance in controlling geothermal fluid movement is unknown. Some pools, possibly thermal springs, occur near the mapped structure. Verification of these features will require additional field work by INE geologists.

SUMMARY AND CONCLUSIONS

In July 1986, Dr. Howard Ross of ESL/UURI completed a mission to Quito, Ecuador for the purpose of instructing INE geologists in the gravity survey method. Subsequent to this field mission, INE geologists successfully completed two detailed gravity surveys in the Tumbaco-Cumbaya and Sangolqui-El Tingo areas, Valle de Los Chillos. Data reduction and compilation was completed in Quito using a program GRAVSUR which had been implemented on INE's computer.

The gravity data compilation has been reviewed by ESL/UURI and some modifications have been made. Revised maps of Bouguer gravity for the Tumbaco-Cumbaya and Sangolqui-El Tingo areas are included in this final report.

An interpretation of these gravity data has been largely qualitative since the anomaly expressions are weak, some data were not recorded, and few anomalies are adequately sampled to justify a numerical interpretation. INE geologists are prepared to complete numerical modeling of selected anomalies using program GRAV2D if they desire to do so. A limited number of continuous fault structures have been mapped in each survey area. A larger number of possible, short or discontinuous structures have been interpreted.

Some correlation exists between mapped lineaments and faults and the structures inferred from the gravity data. The ~~special~~ spatial location of these interpreted structures can be no better than the basic station spacing of 100 m. The structures interpreted from the gravity data are considered too ambiguous to define drill test locations by themselves, but may contribute to target concepts and area selection in conjunction with thermal, geochemical, electrical resistivity and geological data. A field evaluation of inferred structure locations may aid in establishing the validity of the interpreted geologic structures.

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ACKNOWLEDGEMENTS

I wish to acknowledge the assistance and contributions of several people which made my short gravity mission both more pleasant and more productive. I thank Dr. Fausto Maldonado and his staff for meeting me at the airport and assisting the processing of the gravity meter through customs. Dr. Maldonado provided useful information on the status of U.S. AID funding for the INE geothermal program and the U.S. AID - INE cooperative effort. I especially thank Ing. Franklin Carrasco G., Director Ejecutive Encargado, INE, for the logistics and facilities provided by the INE staff. I also appreciate Ing. F. Cerrasco's efforts in promptly completing the INE - UURI contract which provides for this work.

I have very much enjoyed working with and training INE geologists Ing. Marco Acosta and Milton Balseca in the gravity survey method. A successful gravity survey has been completed through their effort. I thank all concerned for the opportunity to participate in this project and to visit the city of Quito and the Valle de Los Chillos study areas.

APPENDIX 1

STATEMENT OF WORK

INE GRAVITY MISSION

1. Travel SLC-TUC (R/T). Review operation of Lacoste a Romberg gravity meter with W. Gordon Wiederwilt. Complete field calibration loop to verify operating condition and calibration of instrument.

2. Travel SLC-Quito. Instrument as carry on luggage. Also transmit RIP2 and GRAV2 computer tapes and Wright's resistivity report to INE.

3. Instruct INE geologists in operation of gravity meter. Review gravity survey station locations and surveying results to date. Sign INE - UURI contract on behalf of P. M. Wright.

4. Begin gravity survey with INE trainees. Complete loops to establish base station for survey areas tied to central base station. Verify survey procedures, data taking, data reduction and terrain correction procedures.

5. Complete office discussions regarding status of project, communication problems, etc. Discuss resistivity survey interpretation and report. Discuss sampling techniques and procedures for radioactive age dating in USA (Duncan Foley's memo).

6. Review use of GRAV2D, basic interpretation. Write report of trip and work completed and leave with INE.

7. Travel Quito-SLC

8. Review and/or complete interpretation of gravity survey data after shipment to Salt Lake City. Prepare interpretative report (September-November, 1986?).

APPENDIX 2

RECORD OF DAILY ACTIVITIES

Dr. Howard P. Ross

2-13 July, 1986

Date	Activity
2 July 1986	Travel Salt Lake City to Tucson, Arizona. Review gravity meter operation with Mining Geophysical Survey geophysicists, verify meter condition. Return to Salt Lake City-hand carry meter.
6 July 1986	Depart Salt Lake City for Quito.
7 July 1986	Travel to Quito. Clear gravity meter through customs with assistance of U.S. AID personnel. Deliver gravity meter to INE geologists. Check in at Tambo Real Hotel.
8 July 1986	Visit Dr. Fausto Maldonado, U.S. AID, and discuss INE geothermal project. Met with INE geologists; begin warming of instrument and adjustment for local latitude and elevation. Verify instrument is working properly. Begin instruction in handling and operation of meter. Deliver computer tapes for RIP2 and GRAV2.D programs. Review INE-UURI contract. Leave meter on batter/eliminator.
9 July 1986	Take gravity reading at geodetic reference station, Quito Observatory. Travel to Sangolqui-El Tingo area, establish gravity base stations, all lines, return to base station. Training INE geologists.
10 July 1986	Travel to Tumbaco-Cumbaya area, establish base stations. Training INE geologists. Return to INE, review computer program for data reduction, noting input errors, program errors, etc.
11 July 1986	Instruction and discussions at INE: data reduction, terrain corr., interpretation, survey additions. Go to computer center.
12 July 1986	Work on report all day.
13 July 1986	Travel Quito - Miami - Salt Lake City.

APPENDIX 3

THE GRAVITY METHOD

This introduction to the gravity survey method as typically used in geologic exploration problems, is taken from:

Gravity and Magnetic Methods in Mineral Exploration, by P. M. Wright, Seventy-Fifth Anniversary Volume, Economic Geology, Society of Economic Geologists, 1981.

APPENDIX 4

CORRECTIONS TO GRAVITY DATA

Tumbaco-Cumbaya

Line	Station	Elevation	Bouguer Gravity	(Lectura) Gravity
TCG-2	42	2366.54	1560.323	---
TCG-4	27	2311.45	1556.770	---
TCG-5	34B	~~o.k.~~---	---	1009.980(?)
TCG-5	15	2292.42	---	---
TCG-5	(Datum Elevation should be 0.0 meters not 5.0; INE should recompute all stations on TCG-5 after correcting datum elev. and reading at 34B, 9h 58ø m, 7/17/86)			

spaces

Sangolqui-El Tingo

Line	Station	Elevation	Bouguer Gravity
STG-1	15	2475.19	1551.95
STG-2	49	2436.75	1559.018
STG-4	22	2460.32	1558.037
STG-4	29	2462.09	1548.473
STG-6	38	2468.01	1549.123

Data values on maps have been rounded off to the nearest 0.1 milligal.

INSTITUTO NACIONAL DE ENERGIA

MARIANA DE JESUS Nº 2307 Y M. DE UTRERAS
TELEX 2991 INE ED.
TELEFONOS: 541-500 - 541-588
CASILLA Nº 007 - C. QUITO - ECUADOR

Señor Doctor
Howard P. Ross
EARTH SCIENCE LABORATORY
UNIVERSITY OF UTAH RESEARCH INSTITU
391 CHIPETA WAY, SUITE C
SALT LAKE CITY, UTAH 84108
U S A

UNIVERSITY OF UTAH RESEARCH INSTITUTE

UURI

EARTH SCIENCE LABORATORY
391 CHIPETA WAY, SUITE C
SALT LAKE CITY, UTAH 84108—1295
TELEPHONE 801-524-3422

October 14, 1986

INSTITUTO NACIONAL DE ENERGIA
Attn: Ing. Franklin Carrasco G.
Director Ejecutivo Encargado
Ave Mariana de Jesus No. 2307 y
Martin de Uteras
Quito, Ecuador

Dear Sir:

We regret the delay in transmitting to you the listings for two subroutines for gravity modeling program GRAV2D. We had hoped to include the resistivity report in Spanish but this is not yet completed.

Our computer people are certain that subroutine GRAV2D.COM was included as the first file in the source code on the computer tape I presented to Marco Acosta while in Quito. The second enclosed subroutine, $__ MERG.COM was missing however. Computer listings for both subroutines and sample data files are included here.

Please inform Marco Acosta that we received the Sangolqui-El Tingo and Tumbaco-Cumbaya gravity data via DHL on October 3. We have begun our interpretation and a memorandum describing my preliminary evaluation is enclosed.

A detailed accounting of outstanding payments due to UURI through August, 1986, has been prepared and is transmitted herewith.

Dr. Phillip M. Wright has been away on travel much of the last two months. He will complete the resistivity report and respond to recent INE telex messages after his return to Salt Lake City.

Sincerely,

Howard P. Ross

Howard P. Ross
Section Head/Geophysics

Encl.

UNIVERSITY OF UTAH RESEARCH INSTITUTE

UURI

EARTH SCIENCE LABORATORY
391 CHIPETA WAY, SUITE C
SALT LAKE CITY, UTAH 84108—1295
TELEPHONE 801-524-3422

MEMORANDUM

TO: Marco Acosta
Instituto Nacional De Energia

FROM: Howard Ross

SUBJECT: Preliminary Evaluation
INE Gravity Survey Data

DATE: 10 October, 1986

Tumbaco-Cumbaya

1. Several single station gravity anomalies have been mapped which may be real geologic features or may be recording errors, uncertainty in topographic corrections, or data reduction errors. Questionable data values are:

   Line TCG2 Sta. 16; 23; 35; 43
   Line TCG3 Sta. 15; 17; 22; 26
   Line TCG4 Sta. 11; 18; 39
   Line TCG5 Sta. 40; 50
   Line TCG6 Sta. 40; 45

   A careful inspection of observed data, all corrections, and detailed topographic maps may determine which of these data values, if any, should be considered unreliable.

2. The expression of faulting is rather weak. Some indication of faulting may be present between:

   TCG2: Sta. 14 to TCG4: Sta. 17
   TCG1: Sta. 34 to TCG4: Sta. 33

3. A detailed review of the data, corrections, topography and other data may be warranted to determine if numerical modeling of the low amplitude anomalies is justified.

4. With the exceptions already noted, most of the data appear to be relatively free of noise and of good quality.

Sangolequi-El Tingo

1. The contoured bouguer gravity data are generally smoothly varying with very few single station anomalies which may be due to recording or correction errors, or to local topographic effects. The following stations are suspect, and the data will be carefully evaluated:

   Line STG1, Sta. 47
   Line STG3, Sta. 48
   Line STG4, Sta. 22; 29; 41
   Line STG5, Sta. 5; 18
   Line STG6, Sta. 38

2. A northeast trending geologic structure (fault?) may be present between Lines STG5 and STG6. There is also a suggestion of northwest trending structure near Sta. 41 on Lines STG 3 and STG 4.

3. Other structures may be present but the gravity anomaly amplitudes may be too small, or anomalies incompletely defined (i.e. at the northern end of the survey area) to interpret structure with much confidence.

Interpretation

This preliminary evaluation has identified several single station anomalies which may be unreliable data. The data reduction for these stations must be carefully checked before additional geologic interpretation can take place. After this effort the data will be recontoured if necessary, qualitatively interpreted,and then numerically modeled if the anomaly amplitudes are significantly above the level of local noise and regional gradients.

Howard

Howard P. Ross
Section Head/Geophysics

```
C******************************************************* MERG.COM
C
C      COMMON BLOCK FOR MERG1-MERG13
C
C      DESCRIPTION OF COMMON VARIABLES
C
C              LR-      (INT.) RECORD LENGTH IN WORDS (4 BYTES EACH)
C              NSF-     (INT.) # OF SUBFILES THAT HAVE BEEN
C                       WRITTEN IN THE MERGE FILE.
C              TITLE-   (A-N) 60 CHARACTERS. TITLE CONTAINS THE
C                       DESCRIPTION OF THE MERGE FILE.
C              IPR-     (INT.) SEQUENTIAL RECORD READING POINTER
C              IPW-     (INT.) SEQUENTIAL RECORD WRITING POINTER
C              ISF-     (INT.) CURRENT SUBFILE STARTING RECORD POINTER
C              NUMR-    (INT.) # OF RECORDS IN THE CURRENT SUBFILE.
C                       NUMR IS ALWAYS FOUND IN THE FIRST WORD OF THE
C                       FIRST RECORD IN EACH SUBFILE.  THE RECORD COUNT
C                       INCLUDES THE RECORD WHICH CONTAINS NUMR.
C              IBUF-    (INT.) WORKING ARRAY USED BY VARIOUS MERG
C                       SUBROUTINES TO MOVE RECORDS FROM PLACE TO PLACE.
C                       IBUF MUST BE DIMENSIONED AT LEAST AS LARGE AS LR
C                       IN THE USERS MAIN PROGRAM.  THUS IT IS REQUIRED
C                       THAT THE MRG COMMON BLOCK IS DECLARED IN THE
C                       USERS PROGRAM.
C
C.............................................................................
C
      COMMON /MRG1/ IBUF(1)
      COMMON /MRG2/ LR,NSF,TITLE(15),IPR,IPW,ISF,NUMR
C
```

Missing SUBROUTINES for GRAV2D.

```
C************************************************* GRAV2D.COM
C
C         COMMON BLOCK FOR GRAV2D
C         ($INSERT FILE)
C
C..................................................................
C
C-----WHEN CHANGING IPWID,BE SURE THAT
C       1) POLYG * NVERTX MUST BE LESS THAN IPWID
C       2) IG2H,IG2HG,IG2HP ARE POSITIVE #'S,
C       3) DIMENSION OF DUM'S IS SUCH THAT THE COMMON BLOCK HAS
C          IPWID WORDS,
C       4) LIM IN SUBROUTINES WR,RR IS CHANGED,
C       5) NLEN=11 IS UPDATED IN SUBROUTINE INPUT IF
C          ADDITIONAL COMMON BLOCKS ADDED TO WORK/MERGE
C          FILE DATA
C
      PARAMETER IPWID =500
      PARAMETER NSRDIR=50
      PARAMETER NPOLYG=15
      PARAMETER NVERTX=33
      PARAMETER IPWID2=4*IPWID
      PARAMETER NSIRD2=NSRDIR+1
      PARAMETER NVTP  =NPOLYG*NVERTX
      PARAMETER NSTATS=IPWID
      PARAMETER IG2H  =IPWID-54
      PARAMETER IG2HP =IPWID-NVTP
      PARAMETER IG2HG =IPWID-5*NPOLYG-2*NSRDIR
      PARAMETER CSZ=0.1
      PARAMETER ISYM1=1
      PARAMETER ISYM2=4
C
      LOGICAL VALIDI
      REAL*8 CT,GTT,GTE,SS,XMI,XMA,XMAX,XMIN,DELM,
     $        AINV,SST,V,VT,TSVD
C
C--------------------------------------------------------------
C     COMMON BLOCKS FOR WORK AND MERGE FILE DATA
C
      COMMON /G2H1  / NLEN,HEAD(20),PROFID(20),DUMD(2),NUNITS,
     $                NBASE,IORD,ISS,HSCALE,VSCALE,VBOD,NSTAT,
     $                NPOLY,SSR,MAXIT,DUM1(IG2H)
      COMMON /G2H2  / TD(NSTATS)
      COMMON /G2H3  / TT(NSTATS)
      COMMON /G2H4  / DIFOC(NSTATS)
      COMMON /G2H5  / XSTAT(NSTATS)
      COMMON /G2H6  / ZSTAT(NSTATS)
      COMMON /G2H7  / NSIDES(NPOLYG),SUS(NPOLYG),STR1(NPOLYG),
     $                STR2(NPOLYG),ISUS(NPOLYG),XLIM(NSRDIR),
     $                DELX(NSRDIR),DUM6(IG2HG)
      COMMON /G2H8  / XSTART(NPOLYG,NVERTX),DUM2(IG2HP)
      COMMON /G2H9  / ZSTART(NPOLYG,NVERTX),DUM3(IG2HP)
      COMMON /G2H10 / IVO(NPOLYG,NVERTX),DUM4(IG2HP)
      COMMON /G2H11 / IVX(NPOLYG,NVERTX),DUM5(IG2HP)
C
C--------------------------------------------------------------
C     COMMON BLOCKS FOR TEMPORARY STORAGE
```

```
C
      COMMON /G2HMAN/ SS(NSTATS),GTE(NPOLYG,NSTATS),GTT(NSTATS),CT,
     $                DELM(NPOLYG,NVERTX,NSTATS),XMA,XMI,XMAX,XMIN
C
      COMMON /G2HIV / TSVD(IPWID2),SST(NSRDIR,NSRDIR),
     $                V(NSRDIR,NSRDIR),VT(NSRDIR,NSRDIR),
     $                AINV(NSTATS,NSIRD2)
C
      COMMON /LU    / ITR,ITW,IUW,IUM,IUP,IUR
      COMMON /TERMS / ITRM
      COMMON /MRG1  / BUF(IPWID)
      COMMON /MRG2  / LR,NSF,TITLE(15),IPR,IPW,ISF,NUMR
      COMMON /OPRTXT/ NL,TEXT(12,6)
      COMMON /BLK5  / NIM,IM(200),SDUM(200),NSDUM
      COMMON /GPLOTS/ XCMAX,XCMIN,YCMAX,YCMIN,XMMIN,XMMAX,
     $                YMMAX,YMMIN,XCAL,YCAL,XMAL,YMAL,DALX,DALY,
     $                NOSYM,IPL1,IPL2
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 5) 118.500,0.010,0,0
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 7) 15.75,1.25,6,7
 8) 12.5,1.25,6,5
 9) 11.25,4.,3,5
10) 9.5,4.,3,4
11) 8.5,2.,3,4
12) 7.25,2.,3,0
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16) 2.,2.,1,2
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18) -100.,.01,0,0
19) -100.,0.,0,0
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( 13) -4.854,1.6,0.
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( 16) -14.024,2.2,0.
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( 18) -18.590,2.6,0.
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( 20) -21.173,3.0,0.
( 21) -22.015,3.2,0.
( 22) -22.627,3.4,0.
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( 25) -23.277,4.0,0.
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( 27) -22.632,4.4,0.
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( 29) -20.796,4.8,0.
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( 31) -18.411,5.2,0.
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( 36) -21.074,6.2,0.
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( 44) -42.009,7.8,0.
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( 46) -44.992,8.2,0.
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( 48) -47.387,8.6,0.
( 49) -48.395,8.8,0.
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( 51) -50.068,9.2,0.
( 52) -50.743,9.4,0.
( 53) -51.315,9.6,0.
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( 56) -52.428,10.2,0.
( 57) -52.603,10.4,0.
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59) -52.660,10.8,0.
60) -52.545,11.,0.
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63) -51.634,11.6,0.
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65) -50.572,12.,0.
66) -49.912,12.2,0.
67) -49.172,12.4,0.
68) -48.355,12.6,0.
69) -47.468,12.8,0.
70) -46.517,13.,0.
71) -45.509,13.2,0.
72) -44.448,13.4,0.
73) -43.341,13.6,0.
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76) -39.742,14.2,0.
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78) -37.047,14.6,0.
79) -35.564,14.8,0.
80) -33.955,15.,0.
81) -32.181,15.2,0.
82) -30.196,15.4,0.
83) -27.931,15.6,0.
84) -25.286,15.8,0.
85) -22.079,16.,0.
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87) -13.204,16.4,0.
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89) -9.042,16.8,0.
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92) -5.591,17.4,0.
93) -4.785,17.6,0.
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(         32) 39.336,.7,0,0
(         33) 20.064,13.,0,0
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(         35) -24.816,4.3,0,0
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 1) GRAVITY MODEL
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 3) 23
 4) 46
 5) -191.,-24.816,0.
 6) -205.,5.28,0.
 7) -206.,6.6,0.
 8) -207.,10.56,0.
 9) -207.9,15.312,0.
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13) -204.,25.06,0.
14) -203.,26.822,0.
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23) -194.,37.910,0.
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25) -192.,39.389,0.
26) -191.,40.445,0.
27) -191.,40.920,0.
28) -192.,42.240,0.
29) -192.8,43.824,0.
30) -193.,45.408,0.
31) -194.,46.306,0.
32) -195.,46.728,0.
33) -195.7,48.576,0.
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39) -201.,56.760,0.
40) -201.6,59.136,0.
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46) -207.,70.224,0.
47) -207.8,71.808,0.
48) -208.,73.656,0.
49) -210.,75.504,0.
50) -220.,90.816,0.
```

UNIVERSITY OF UTAH RESEARCH INSTITUTE
UURI
EARTH SCIENCE LABORATORY
391 CHIPETA WAY, SUITE C
SALT LAKE CITY, UTAH 84108—1295
TELEPHONE 801-524-3422

October 15, 1986

INSTITUTO NACIONAL DE ENERGIA
Attn: Ing. Franklin Carrasco G.
Director Ejecutivo Encargado
Ave Mariana de Jesus No. 2307
y Martin de Uteras
Quito, Ecuador

Dear Sir:

Transmitted herewith are a Statement of Account and Invoices 1, 2, 3, and 4 regarding UURI work on Instituto Nacional De Energia contracts. Please note that the Statement of Account is in agreement with the total fixed price amounts agreed upon in Contracts 1 and 2, that is $26,820 and $8,170 respectively.

A preliminary copy of the final resistivity report was transmitted to Marco Acosta during my gravity mission of July 6-13, 1986. A final version of this report is being completed in Spanish and will be transmitted to INE at no additional cost to INE.

A report describing the Gravity Mission of July 6-13, 1986 was presented to INE prior to my departure from Quito on July 12, 1986. A preliminary evaluation of the gravity survey data, and computer listings of subroutines missing from program GRAV2D (delivered earlier) accompany this letter. Additional interpretation and reporting of the gravity data will be completed by UURI and transmitted to INE at no additional cost to INE.

We regret any inconvenience to INE due to late reporting or transmittal of invoices which may have resulted from Mike Wright's extensive travel schedule. We have enjoyed working with INE geologists and wish INE success in the continuing exploration and development of geothermal resources in the Valle De Los Chillos.

Sincerely,

Howard P. Ross

Howard P. Ross
Section Head/Geophysics

Enclosures

cc: Dr. Fausto Maldonado
P. M. Wright
W. L. Forsberg

HPR:leo

STATEMENT OF ACCOUNT
INSTITUTO NACIONAL DE ENERGIA

Contract	Invoice No.	Amount	Date	Payments Received	Date
A. Geophysical Study At Valle De Los Chillos No. 1					
1. September 1983 Mission	1	$5,692.91	May 29, 1985	$5,692.91	Oct. 30, 1985
B. Geophysical Study at Valles De Los Chilles No. 2					
1. March 1984 Mission		$7,035.74			
2. July 1984 Mission		6,147.72			
Subtotal	1	$13,183.46	Dec. 31, 1985	$13,183.46	Oct. 30, 1985
3. April to November 1985	2	7,943.63	Dec. 31, 1985		
4. Feb. 1-28, 1986	3	00.00	Mar. 21, 1986		
Total B		$21,127.09		$13,183.46	
C. Total A & B		$26,820.00		$18,876.37	

D.	Technical Assistance to INE Geophysical study at Valles De Los Chillos. 4			
	1. Gravity Training Mission July '86	$ 8,020.00	Aug. 31,	
	2. Gravity Intern Program GRAV2D	150.00	1986	
E.	Total D	$ 8,170.00		
F.	Total C & D	$34,990.00		$18,876.37
G.	Balance Due			$16,113.63

UNIVERSITY OF UTAH RESEARCH INSTITUTE
UURI
EARTH SCIENCE LABORATORY
391 CHIPETA WAY, SUITE C
SALT LAKE CITY, UTAH 84108—1295
TELEPHONE 801-524-3422

INVOICE

Payor's Name & Address Instituto Nacional de Energia Mariana de Jesus No 2307 y M. De Utrevas Quito, Ecuador	**Payor's Reference** **Period of Agreement** **Total Amount** $18,876.38
Payee's Name & Address UNIVERSITY OF UTAH RESEARCH INSTITUTE Research Park 391 Chipeta Way Suite C Salt Lake City, UT 84108	**Payee's Reference** 5-84802 & 5-84803 **Invoice #** 1 — **Date Prepared** May 29, 1985 **Billing Period** Sept. 1983 - March 198

Description - Services Rendered		Amount	
Salary and Support Expenses for Phillip M. Wright, Mission to Ecuador in September 1983; 10 man-days total.	*	$ 5692.91	Pd. Oct. 30,1985
Salary and Support Expenses for Phillip M. Wright, Mission to Ecuador in July, 1984; 10 man-days total.	**	6147.72	Pd. Oct. 30, 1985 See attached invoice
Salary and Support Expenses for Phillip M. Wright and Joseph N. Moore, Mission to Ecuador in March, 1984; 13 man-days total.	**	7035.74	
TOTAL DUE		$18,876.37 U.S.	

* 5-84802

** 5-84803

INVOICE

Payor's Name & Address	Payor's Reference	
INSTITUTO NACIONAL DE ENERGIA MARIANA DE JESUS NO 2307 Y M. DE UTREVAS QUITO, ECUADOR	CARL DUISBERG, INE-AID	
	Period of Agreement OPEN	
	Total Amount $ 0.00	Total Fee $ 0.00

Payee's Name & Address	Payee's Reference	
UNIVERSITY OF UTAH RESEARCH INSTITUTE Research Park 391 Chipeta Way, Suite C Salt Lake City, Utah 84108	5-84802 & 5-84803	
	Invoice No. 1	Date Prepared TUE, DEC 31 19
	Billing Period SEPTEMBER 1983 TO MARCH 1984	

Description	Cost This Billing Period	Cumulative Cost
Direct Costs:		
Labor	$ 5,034.25	$ 5,034.25
Employee Benefits	2,009.79	2,009.79
Modified Total Direct Costs	7,044.04	7,044.04
G & A	913.24	913.24
Indirect Costs	3,028.94	3,028.94
Administrative Fee	2,197.24	2,197.24
Total Reimbursable Costs	$ 13,183.46	$ 13,183.46

AMOUNT PAYABLE PER THIS INVOICE: $ 13,183.46

UURI
Invoice

Payor's Name and Address	Payor's Reference
Instituto Nacional de Energia Mariana de Jesus No. 2307 Y M. de Utrevas Quito, Ecuador	Carl Duisberg, INE-AID
	Total Amount

Payee's Name and Address	Payee's Reference *	
UNIVERSITY OF UTAH RESEARCH INSTITUTE **Research Park** **391 Chipeta Way, Suite C** **Salt Lake City, Utah 84108-1295** **801-524-3422**	5-84802 & 5-84803	
	Invoice # 2	Invoice Date Tue, Dec. 31, 1985
	Billing Period April 1985 to November 1985	

* Please include Payee's reference number with payment

Description	Cost This Billing Period	CUMULATIVE *Amount*
Direct Costs:		
Labor	$ 3,245.37	$ 10,465.06
Employee Benefits	1,265.70	4,140.92
Travel	1,977.26	1,977.26
Purchased Services	199.00	199.00
Communications	37.25	37.25
Modified Total Direct Costs	6,724.58	16,819.49
G. & A	840.55	2,135.14
Indirect Costs	2,891.54	7,232.35
Administrative Fee	2,091.31	5,237.37
	$ 12,547.98	$ 31,424.35
Less Overrun on Fixed Price Contract No. 1	-4,604.35	-4,604.35
Total Reimbursable Costs	$ 7,943.63	$ 26,820.00
AMOUNT PAYABLE PER THIS INVOICE:	$ 7,943.63	

Total amount due and payable within 30 days of invoice date

UURI

Invoice

Payor's Name and Address	Payor's Reference
INSTITUTO NACIONAL DE ENERGIA MARIANA DE JESUS NO. 2307 Y M. DE UTREVAS QUITO, ECUADOR	CARL DUISBERG, INE-AID
	Total Amount

Payee's Name and Address	Payee's Reference *	
UNIVERSITY OF UTAH RESEARCH INSTITUTE **Research Park** **391 Chipeta Way, Suite C** **Salt Lake City, Utah 84108-1295** **801-524-3422**	5-84802 & 5-54803	
	Invoice # 3	Invoice Date FRI. MAR 21, 1986
	Billing Period 2/1/86 to 2/28/86	

* Please include Payee's reference number with payment

Description	COST THIS BILLING PERIOD	CUMULATIVE ***Amount***
Direct Costs:		
Labor	$ 210.83	$ 10,675.89
Employee Benefits	82.22	4,223.14
Travel	-	1,977.26
Purchased Services	-	199.00
Communications	-	37.25
Modified Total Direct Costs	293.05	17,112.54
G & A	36.63	2,171.77
Indirect Costs	126.01	7,358.36
Administrative Fee	91.13	5,328.50
	546.82	31,971.17
Less Overrun on Fixed Price Contract No. 1	- 546.82	- 5,151.17
Total Reimbursable Costs	00.00	$ 26,820.00

AMOUNT PAYABLE PER THIS INVOICE: $ 00.00

Total amount due and payable within 30 days of invoice date

UURI

Invoice

Payor's Name and Address	Payor's Reference
INSTITUTO NACIONAL DE ENERGIA MARIANA DE JESUS NO. 2307 Y M. DE UTREVAS QUITO, ECUADOR	CARL DUISBERG, INE-AID
	Total Amount

Payee's Name and Address	Payee's Reference *	
UNIVERSITY OF UTAH RESEARCH INSTITUTE **Research Park** **391 Chipeta Way, Suite C** **Salt Lake City, Utah 84108-1295** **801-524-3422**	Invoice # 4	Invoice Date WED, AUG 27, 1986
	Billing Period 7/1/86 to 7/31/86	

* Please include Payee's reference number with payment

Description	COST THIS BILLING PERIOD	CUMULATIVE ***Amount***
Direct Costs:		
Labor	$ 2,432.76	$ 13,108.65
Employee Benefits	1,041.23	5,264.37
Travel	1,635.33	3,612.59
Purchased Services	-	199.00
Communications	-	37.25
Modified Total Direct Costs	5,109.32	22,221.86
G & A	638.66	2,810.43
Indirect Costs	2,197.00	9,555.36
Administrative Fee	1,588.99	6,917.49
	9,533.97	
Less Overrun on Fixed Price Contract No. 2	- 1,363.97	41,505.14
Less Overrun on Fixed Price Contracts Nos. 1 & 2		- 6,515.14
		34,990.00
Total Reimbursable Costs	8,170.00	
AMOUNT PAYABLE PER THIS INVOICE:	8,170.00	

Total amount due and payable within 30 days of invoice date

INSTITUTO NACIONAL DE ENERGIA

MARIANA DE JESUS Nº 2307 Y M. DE UTRERAS
TELEX 2991 INE ED.
TELEFONOS: 541-500 - 541-588
CASILLA Nº 007 - C. QUITO - ECUADOR

SANGOLQUI - EL TINGO

GRAVIMETRIA

INSTITUTO NACIONAL DE ENERGIA

PROYECTO EXPERIMENTAL DEMOSTRATIVO DE GEOTERMIA DE BAJA ENTALPIA "VALLE DE LOS CHILLOS"

UBICACION PLANIMETRICA DE LOS PERFILES

STG1	STG2	STG3	STG4
STG5	STG6	STG7	STG8

ESCALA 1 : 10.000

FECHA DE REPLANTEO
ENERO 1986

REPLANTEADO POR:

ING. JOHNNY HIDALGO M.

APROBADO POR:

INSTITUTO NACIONAL DE ENERGIA

OFICIO # 861099 INE

Quito, a SEP. 29 1986

Señor Doctor
Howard P. Ross
EARTH SCIENCE LABORATORY
UNIVERSITY OF UTAH RESEARCH INSTITUTE
391 CHIPETA WAY, SUITE C
SALT LAKE CITY, UTAH 84108
U.S.A.

De mi consideración:

Una vez concluida la toma de datos en el campo de gravimetría y devuelto el gravímetro como estaba previsto por DHL, a la compañía arrendataria en Tucson, Arizona; se ha procedido a correr todos los datos en la computadora para efectuar las respectivas reducciones y llegar al cálculo de la anomalía de Bouguer.

Adjunto se servirá encontrar los listados de datos correspondientes a los 14 perfiles, 6 de Tumbaco-Cumbayá y 8 de Sangolquí-El Tingo; además, 2 copias de los mapas correspondientes a las áreas de estudio (1:10.000) con las curvas isoanómalas de Bouguer, construidas en el INE.

Para la implementación del programa de interpretación GRAV2D, esperamos el envío de las subrutinas que faltan, y el informe definitivo de resistividad eléctrica, para dar por concluido el convenio respectivo, suscrito el 12 de julio de 1984.

De acuerdo a la metodología de toma de datos, como se estableció durante su misión al Ecuador, se logro prolongar en 1900 metros los perfiles STG-5 y STG-8, con estaciones cada 200 metros, como se observa en el mapa.

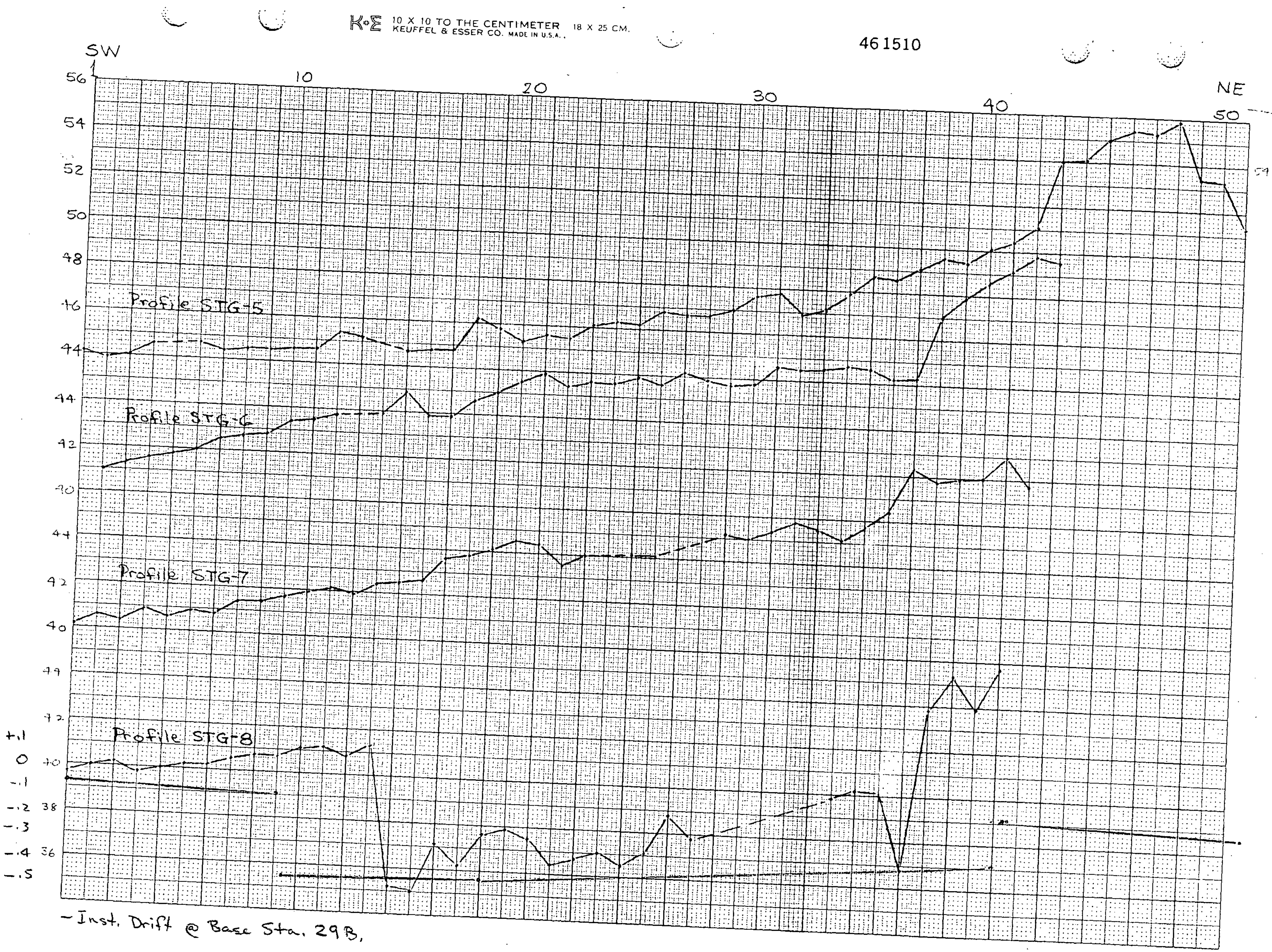
Una vez que Ud., ya ha revisado todos los datos enviados, le solicito nos envie sus comentarios preliminares a los mismos y recomendaciones.

Atentamente,

Ing. Franklin Carrasco
DIRECTOR EJECUTIVO, ENCARGADO
INSTITUTO NACIONAL DE ENERGIA

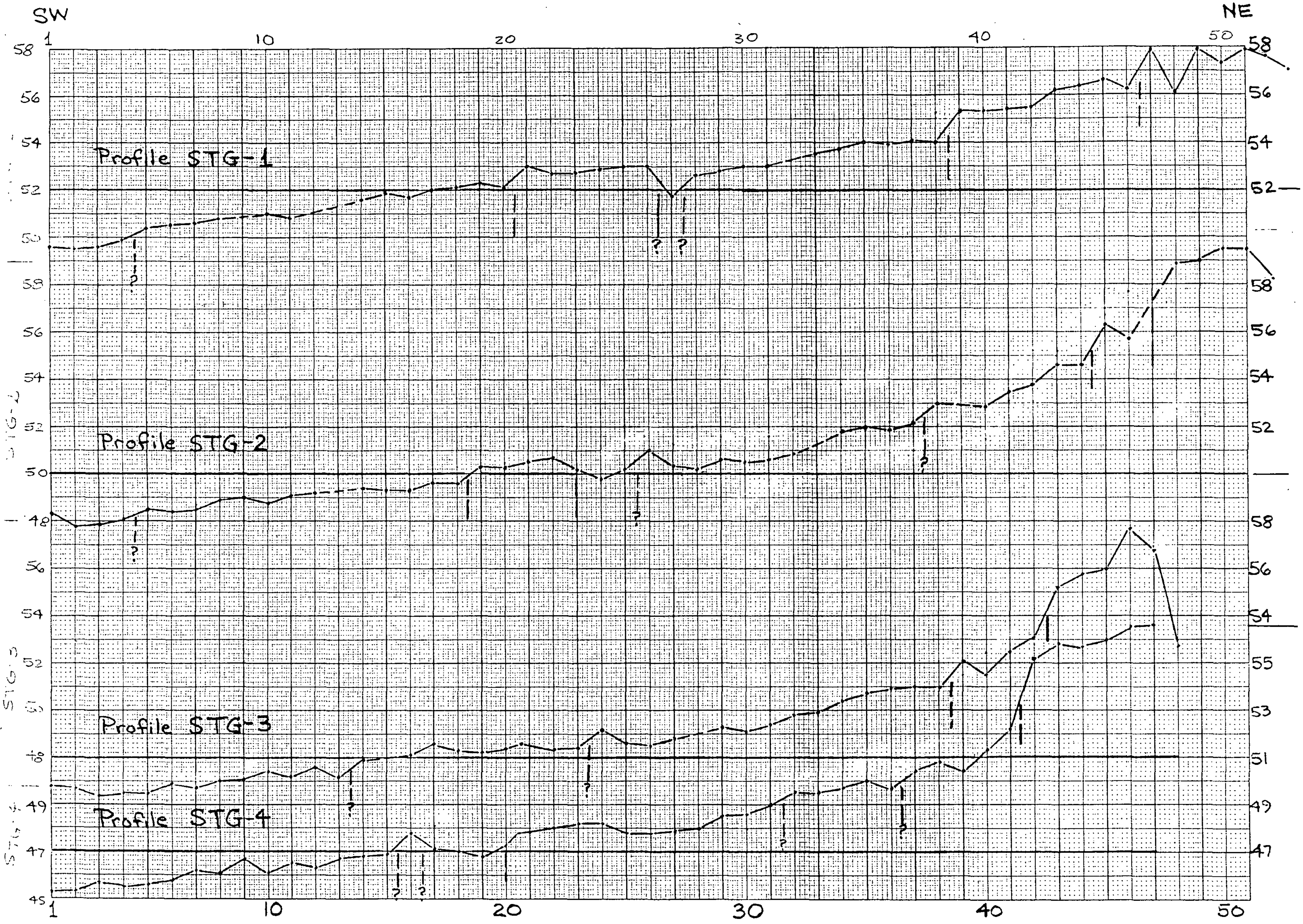
JZ/MB/msa.

Av. Mariana de Jesús N°. 2307 y Martín de Utreras TELEX 2991



K+E 10 X 10 TO THE CENTIMETER 18 X 25 CM. KEUFFEL & ESSER CO. MADE IN U.S.A.
461510
SW
NE
Profile STG-5
Profile STG-6
Profile STG-7
Profile STG-8
-Inst. Drift @ Base Sta. 29B.

K+E 10 X 10 TO THE CENTIMETER 18 X 25 CM.
KEUFFEL & ESSER CO. MADE IN U.S.A.
46 1510



SANGOLQUI - EL TINGO

GRAVIMETRIA

INSTITUTO NACIONAL DE ENERGIA
PROYECTO EXPERIMENTAL DEMOSTRATIVO DE GEOTERMIA DE BAJA ENTALPIA "VALLE DE LOS CHILLOS"
UBICACION PLANIMETRICA DE LOS PERFILES STG1 STG2 STG3 STG4 STG5 STG6 STG7 STG8

ESCALA 1 : 10.000	FECHA DE REPLANTEO ENERO 1986
REPLANTEADO POR: ING. JOHNNY HIDALGO M.	APROBADO POR:

H P Ross

PRELIMINARY REPORT

GRAVITY SURVEY MISSION FOR INSTITUTO NACIONAL DE ENERGIA QUITO, ECUADOR

by

Dr. Howard P. Ross
University of Utah Research Institute

July 12, 1986

CONTENTS

INTRODUCTION

The Instituto Nacional de Energia de Ecuador (INE) has been engaged in the exploration for low-to-moderate enthalpy geothermal resources in the Valle de Los Chillos area near the volcano Ilalo. Funding for this project has been provided in part by U.S. AID. The University of Utah Research Institute (UURI) has been contracted to provide expert technical assistance in a geothermal resource risk assessment, geophysical survey planning and execution, geochemical studies, and technology transfer and training of INE geologists. Previous geophysical work included electrical resistivity surveys at Sangolqui-El Tingo and Tumbaco-Cumbaya. All previous UURI assistance efforts have been documented by Dr. P.M. Wright, and are referenced in his final report of the resistivity surveys.

This preliminary report describes the activities, observations, and recommendations relating to a gravity mission for INE by Dr. Howard P. Ross, Senior Geophysicist of UURI, during July 2- July 13, 1986. The requirements of this work and funding for the project are provided in a contract agreement between INE and UURI dated 8 July 1986. A Statement of Work for the project as understood by UURI is provided in Appendix 1. A record of daily activities is provided as Appendix 2.

INE geologists recognize the potential value of the gravity method for defining subsurface rock density contrasts. Abrupt changes in the density distribution may indicate the presence of faults which serve as conduits for geothermal fluids in the Valle de Los Chillos. Thus the gravity survey may provide supporting data which, used in conjunction with geologic, geochemical, and electrical resistivity data, will indicate the preferred locations for drill testing. INE geologists desire to complete the gravity survey by themselves using a leased gravity meter, and utilizing technology transfer provided by UURI during this mission.

THE GRAVITY SURVEY METHOD

The gravity survey method has been used for many years in a variety of geologic studies, including exploration for mineral deposits, petroleum exploration, and academic studies of the earth's crust. The method has been used in geothermal exploration for approximately 20 years, principally for the detection of faults and mapping of buried intrusives and volcanic features.

Much has been written about the gravity method and a detailed description of the method is not appropriate in this preliminary report. Several reports and studies have been given to INE geologists for reference, and the interested reader is referred to these. Especially recommended are excerpts from Dobrin (1976) and Telford et al (1976). A good introduction and summary to the method excerpted from Wright (1982) is provided as Appendix 3 of this report.

Feininger (1977) has compiled the data of several gravity surveys totaling 14,000 stations to produce a Simple Bouguer Gravity Anomaly Map of Ecuador, at a scale of 1:1,000,000. The gravity stations are irregularly spaced and mainly without terrain corrections. Nevertheless the map helps to provide a good regional understanding of the crustal geology of Ecuador. Feininger and Seguin (1983) describe the inferred crustal structure of Ecuador based on a numerical model interpretation of portions of these data, and provide useful density information on major rock units in Ecuador. A single profile of approximately 5 stations extends from Quito east to Cumbaya near the survey areas in the Valle de Los Chillos, and indicates a major north trending gravity low in the area of INE geothermal interest.

As indicated in Appendix 3 the precision and usefulness of the gravity survey depends on accurate elevation control and survey position. Gravity line positions and station elevations and locations for the Sangolqui-El Tingo and Tumbaco-Cumbaya surveys have been established in advance of this gravity mission, by Cartotechla, S.A., a private engineering firm located in Quito. It is impractical to make major changes in the survey as presently laid out at this late date. Some additions to the present survey will be required to achieve a more accurate interpretation of the gravity survey.

INSTRUMENTATION

The instrument to be used in this gravity survey is a Lacoste and Romberg, Inc. Model G Geodetic Gravity Meter, No. 325. The instrument has been leased from Mining Geophysical Surveys, Tucson, Arizona under funding from U.S. AID. This gravity meter is a high precision instrument with a world-wide reading range of 7000 milligals, a reading accuracy of ±0.01 milligal, and a proven drift rate of substantially less than 0.10 milligal per month. The operating principals and instructions for use are described in detail in the instruction manual provided with the instrument (LaCoste and Romberg, Inc, 19_?).

The gravity meter is protected against minor vibration by a clamping mechanism which isolates the measuring spring and mass, and is sealed and internally pressure compensated. Nevertheless the instrument is very sensitive to damage from being dropped, kicked, knocked over, or similarily disturbed. Instrument repairs can be very costly ($1,000 - $10,000, U.S.) and may take a long time (10 - 100 days). The need for repairs to the instrument could prematurely terminate the survey.

I flew to Tucson, Arizona on 2 July 1986 to inspect the L&R Model G-325 meter and to review its operating procedures and verify its operating condition. Geophysicists W. Gordon Wieduwilt and Robert West, of Mining Geophysical Surveys, Inc. kindly reviewed the operating procedures with me and assisted me in the completion of several observations to verify that the instrument was in good working order. They then instructed me in handling and packaging the equipment for its return upon survey completion. I hand carried the instrument to Salt Lake City and then to Quito to avoid the possibility of mishandling and damage by airline baggage personnel.

Upon completion of the survey the instrument and battery charger/eliminator will be packed in the metal instrument box with additional foam and the metal box secured with additional tape and straps. The metal box will be placed upright in the foam-padded shipping container, and this carton sealed with glass fiber tape or other sealing tape. The aluminum level-ing tripod base and three Gel/Cell batteries will be individually wrapped in foam packing material and packed in a separate box. It may be practical to securely attach this smaller box on top of the upright instrument shipping container. The box (or boxes) should be identified with caution signs "Fragile - Handle with care" and the Mining Geophysical Surveys address. Mining Geophysical Surveys suggests that Air Frieght shipment and handling should be used rather than regular baggage shipment, Special Freight handling or courier service (DHL) would also be acceptable but at additional cost,

I have spent three days with INE geologists providing instruction in instrument reading, handling, and field techniques. Additional information is available in the instrument manual. Geologists Marco Acosta and Milton Balseca have become quite proficient in the operation and handling of the instrument in this time. It should be possible to achieve a reading precision of 0.01 milligals at most stations. Local noise and vibration conditions caused by unstable ground, strong winds, and truck traffic on rough roads may of course compromise this precision and accuracy at many stations.

Four most important points should be restated to insure a successful, accurate survey.

1) The gravity meter should <u>always</u> be clamped when an observation is not being made. Clamp the instrument <u>immediately</u> after determining that the meter reading is balanced and stable,
2) Check to determine that the instrument is still level when the meter reading is recorded.

3) Return the gravity meter to its metal carrying case <u>immediately</u> after the reading is completed and the mechanism is clamped.

4) Strap the meter, in its box, securely to the cushioned seat of the vehicle when the meter is in transit in the vehicle. <u>Never</u> transport the meter box sitting on the floor of the vehicle, or left loose on the seat.

INSTRUCTION FOR INE GEOLOGISTS

An important part of this gravity mission was the training of INE geologists and discussions about the gravity survey method. This was most important since INE geologists will complete all the field observations, apply the numerous corrections to the data, reduce the data and begin the interpretation of the data. It has been important to transfer an understanding beyond that which can be obtained from the references since field conditions are variable and unexpected conditions may arise, and INE personnel will have to make many decisions leading to the successful completion of the survey. The major elements of the instruction and discussion are summarized below.

<u>Instrument Operation.</u> Training in accurate instrument reading and care of the instrument has been described in the previous section. INE geologists completed more than 12 instrument readings in the field in addition to instrument check readings at the INE office. Instrument readings should be taken at the INE office every morning at the start of each work day, and a continuous record maintained of these daily readings. I have provided instruction, observation, and comments on instrument procedures for these activities.

Field Measurements. Instruction in gravity meter measurement under field conditions was accomplished by identifying a survey base station for Sangolqui- El Tingo and a separate base station for Tumbaco- Cumbaya, and then completing a survey loop tieing a secondary base station on each line (profile) to the survey area base station. A number of "typical" field problems were noted, including: missing survey stakes; unstable ground at the station due to thick grasses; high winds; traffic problems; unsuitable station location (adjacent to buildings, walls, or power poles; at the edge of severe topographic features; on pointed rocks, etc.); drifting meter values or instrument level bubbles. Best effort solutions to these problems were discussed and effected. This often required a movement of the station, estimating the elevation difference, and recording the changes in the survey notes.

Survey Methodology. Considerable time was devoted to discussions of survey methodology such as tie in to known gravity values at the Quito Astronomical Observatory and the Quito Airport, establishing survey bases at Sangolqui - El Tingo and Tumbaco- Cumbaya, and the use of secondary bases on each profile during the conduct of the survey. The optimum methodology must account for characteristics of the established stations, useability of the road network, survey effiency, characteristics of the data reduction scheme, and time and funds available. After considerable discussion and study of the data reduction program (Kwoon et al, 1977) and the survey maps a general methodology was agreed upon and is described in the following pages.

Establishing absolute gravity. (tie-in to known stations). The gravity meter records differences in the earth's gravitational attraction to a high precision but does not measure absolute gravitational attraction. The absolute value of the gravity field for survey stations can be achieved through a tie-in by completing an observation loop begining and ending at one station for which the true gravitational field is known. Gravity values at all other stations can then be expressed in terms of the true ~~gravitational~~ observed gravity, true Bouguer gravity, or as the true Bouguer gravity anomaly by addition of the constant value determined for the known station.

Two principal stations in Quito for which the absolute observed gravity value is known are located at the Quito Airport and at the Quito Astronomical Observatory (QAOb). The gravity values for these stations are tied uniformly to the new basic value of gravity at Potsdam, through the Latin America Gravity Standardization Net (Feininger and Seguin, 1983). The exact location of the station at the Quito Airport is not known to INE geologists and is believed to be in a high traffic area unsuitable for multiple station reoccupation. The station in the QAOb was located in the basement floor of the old seismograph room, was identified by a brass marker, and is available for gravity observations. An initial observation at this site was taken on 9 July 1986 but was found to be noisy and drifting. The variable readings are attributed to construction in progress at the site and to heavy morning traffic. Preliminary results of this measurement and principal facts for the two known stations are shown below in Table 1.

Table 1. Relationship to Absolute Gravity Values.

Gravity Station	Longitude W (Degrees-Min)	Latitude (Degrees-Min)	Elevation (m)	Observed Gravity (milligals)	Theoretical Gravity (milligals)	Differences
Apto M Sucre	78° 29.0'	0° 10.4'	2812.41	977270.32	978049.04	-7.65 milligals Observed Grav.
Q. Astron Obs,	78° 29.5'	0° 13.2'	2817.21	977262.67	978049.10	
Q. Astron Obs.	" "	" "	"	1011.43±.2 ~~(INE)~~		976251.24±.20 est.

Table 1 shows that the absolute gravity for the Q A Obs is −7.65 mgals with respect to the Quito Airport value. Also, the preliminary meter reading by INE geologists with L&R G-325 of 1011.43 ± .2 milligals requires the addition of a constant, approximately 976,251.24 milligals to adjust the L&R G-325 value to absolute gravity readings. Since the 9 July 1986 INE value was noisy, a new observation will be taken to determine this value more accurately, probably on a Sunday when human activities are much reduced. In general form the constant correction value to express L&R G-325 gravity values in terms of absolute gravity can be expressed as

$$K_{corr.} = G_{obs_{absolute}}(QA\,Obs) - G_{obs_{L\&R\ G\text{-}325}}(QA\,Obs)$$

Base station looping. To tie the survey data for Sangolqui-El Tingo (S-ET) and Tumbaco-Cumbaya (T-C) to QAOb will require a separate loop between Q A Obs and a selected base station for each area, since only poor roads exist between S-ET and T-C areas. A single loop should be sufficient for each tie in unless a large drift + tidal variation is apparent upon repeat observations at QAO. If the difference after tidal correction is greater than 0.03 milligals a repeat loop should be completed. The recommended procedure can be expressed as:

Loop 1: Q A Obs → S-ET base 3-28 → Q A Obs

Loop 2: Q A Obs → T-C base 2-13 → Q A Obs.

The survey procedure for all profiles will require additional loops to identify major instrument changes (tares) and to establish instrument drift and tidal changes.

This procedure for a single days activity, for S-ET profile 5 (for example) could be:

QAObs (Base 1) → S-ET 3-28 (Base 2) → QAObs (Base 1) (previously established, i.e. Day #1)

S-ET 3-28 (Base 2, Morning, Day #3) → S-ET 5-24 (Base 3, Morning) → 5-1 → 5-2 → 5-3 . . . → 5-12 → S-ET 5-24 (Base 3, Mid-day) → 5-13 → 5-14 → 5-15 . . . . . . → 5-23 → S-ET 5-24 (Base 3, End of Day #3)

Similiar procedures would apply to other profiles and to regional stations to be discussed later. This looping technique appears to be fully compatible with the input format required by the Kwon et al (1977) computer program which will be used for data reduction. Thus all data should be reduced with respect to the QAObs and will be expressed as Bouguer Anomaly values rather than as absolute gravity values.

Data Reduction. Data reduction for gravity surveys should be carefully completed and may require considerable time, especially for terrain corrections. The correction process is described in Appendix 3 (note figure 1) and other references. Because of the large number of gravity stations in the INE surveys, the need for exact manipulation of large numbers, and the looping of base stations the reduction process is most necessarily done by computer. INE geologists have implemented computer program written by Kwoon, Rudman and Blakely (1977) on the INE computer to complete the data reduction. Some errors have been identified in the latitude and longitude calculations and perhaps the tidal calculations and these must be corrected. In addition the program must be modified to accept the variable conversion from meter reading to observed gravity value appropriate for L&R G-325. Another recommend-ed addition is the incorporation of topographic corrections and subsequent listing. These should all be minor changes which can easily be accomplished.

Topographic corrections, both in field and in office map determinations, were reviewed in some detail. Topographic corrections will be large for many stations in the survey area and may be the largest error in the corrected gravity values. It is important that topographic corrections be determined as well as possible and that a student be employed for some of this work. Short-cut procedures to reduce the required work were discussed with INE geologists. Templates, topographic correction charts and various forms have been made available to INE.

Data Interpretation. Time permitted only a general discussion of data interpretation, density changes, regional gradients, etc. A general qualitative interpretation will be performed on survey gravity maps at scales of 1:10,000 and 1:25,000. Detailed quantitative interpretation will be completed with program GRAVZ.D which models the density distribution of finite strike length two-dimensional bodies. The principal aim of the interpretation is to identify and define suspected faults which may be the conduits for geothermal fluids.

One major problem in completing a successful interpretation is probable strong regional gradients associated with Vulcan Ilalo, and the limited profile lengths beyond the suspected fault locations. It is difficult to obtain adequate surveying to extend the Sangolqui-El Tingo lines before the project is completed (August 30 ?). Accordingly additional regiona gravity stations have been recommended for the Ilalo area, even if elevations can only be obtained with survey altimeters. The present survey design for the Tumbaco-Cumbaya area seems to be adequate

Dr. P. M. Wright also recommended regional gravity stations between Quito and the survey areas to assit in defining the regional gradient. No engineering has been completed to prepare gravity stations. Regional gravity stations on Ilalo are considered most important. If time permits the addition of 20-40 regional gravity stations between ~~the~~ Quito and the survey areas, using altimeter control and known elevation points, would be a very useful addition to the Ecuador gravity data program.

Additional fill in gravity stations, at approximately 50 m intervals, have been recommended to INE geologists when very steep gravity gradients ~~and~~ are noted on profiles near the suspected faults. The selection of a small number of additional stations (3-4 per li 100 m) will be left to the discretion of INE geologists after the data are reduced but before the gravity meter leaves the country. New stations should be marked and elevations determined after gravity values.

OTHER CONSIDERATIONS

I should mention several other aspects of this mission. A new computer tape has been delivered for RIP2 and this program is now working for INE. A computer tape for GRAV2.D was delivered but may be missing some subroutines. I will attempt to clarify the problem with UURI programers.

Instructions for collecting proper samples for age dating have been delivered to INE geologists, and are included here as Appendix 4.

I understand that funding for the Valle de Los Chillos geothermal project by U.S. AID will terminate on August 30. We certainly hope that adequate new funds will become available to drill holes to test the geothermal resource. The final resistivity report in Spanish should arrive at INE shortly. The final interpretation and gravity report will be completed after all the data are obtained and received in Salt Lake City. Most of the cost of the final gravity report will be borne by UURI since funds for this gravity mission will be used up by my return to Salt Lake City on 15 July 1986.

It should be noted that UURI has contributed much extra time on the resistivity survey and report, and that trip expenses for two missions have not yet been paid. We hope this will be corrected soon as we have given a substantial extra effort to this INE project, and our limited other work cannot subsidize the project any longer. We hope to see the INE-AID-UURI effort become a success with future geothermal fluid production and major energy savings.

SUMMARY AND CONCLUSIONS

Considerable work has been accomplished during this gravity mission, and INE geologists are now prepared to complete the gravity survey. Considerable work has to be done however, and only 45 days remain before August 30. survey completion deadline. I recommend that two student assistants be employed to aid in the gravity survey, the terrain (topo) corrections, and data reduction. It is also important that the data reduction program be debugged and improved as soon as possible. The data for each profile should be reduced immediately after a line is completed, and plotted up for preliminary evaluation.

Extreme care should be used in working with the gravity meter. Student assistants should not be used for the data acquisition and meter reading.

An interpretation of the data and a final report will be completed as soon as possible after all data are available for study. We hope that the gravity data will help identify fault locations and can assist in selecting drill sites. We note however that electrical resistivity data and geologic studies have already identified probable resource areas. ~~and~~ Since the resistivity data may be less ambiguous than the probable gravity results the resistivity results should be given high weight in finalizing the drill program. The gravity data may however provide important supporting information.

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ACKNOWLEDGEMENTS

I wish to acknowledge the assistance and contributions of several people which have made my short gravity mission both more pleasant and more productive. I thank Dr. Fausto Maldonado and his staff for meeting me at the airport and assisting the processing of the gravity meter through customs. Dr. Maldonado provided useful information on the status of US AID funding for the INE geothermal program and the US AID - INE cooperative effort. I especially thank Ing. Franklin Carrasco G., Director Ejecutivo Encargado, INE, for the logistics and facilities provides by the INE staff. I also appreciate Ing. F. Carrasco's efforts in promptly completing the INE - UURI contract which provides for this work.

I have very much enjoyed working with and training INE geologists Ing. Marco Acosta and Milton Balseca in gravity survey method. I am confident that a successful gravity survey will soon be completed through their effort. I thank all concerned for the opportunity to participate in this project and to visit this wonderful city of Quito.

APPENDIX 1.

STATEMENT OF WORK

INE GRAVITY MISSION

1. Travel SLC - TUC (R/T). Review operation of Lacoste α Romberg gravity meter with W. Gordon Wiederwilt. Complete field calibration loop to verify operating condition and calibration of instrument.

2. Travel SLC - Quito. Instrument as carry on luggage. Also transmit RIP2 and GRAV2 computer tapes and Wright's resistivity report to INE.

3. Instruct INE geologists in operation of gravity meter. Review gravity survey station locations and surveying results to date. Sign INE - UURI contract on behalf of P. M. Wright.

4. Begin gravity survey with INE trainees. Complete loops to establish base station for all lines, tied to central base station. Begin profiles. Verify survey procedures, data taking, data reduction and terrain correction procedures.

5. Complete office discussions regarding status of project, communication problems, etc. Discuss resistivity survey interpretation and report. Discuss sampling techniques and procedures for radioactive age dating in USA (Duncan's letter).

6. Review use of GRAV2D, basic interpretation. Write report of trip and work completed and leave with INE.

7. Travel Quito - SLC

8. Review and/or complete interpretation of gravity survey data after shipment to Salt Lake City. Prepare interpretative report (September-November, 1986?)

APPENDIX 2

RECORD OF DAILY ACTIVITIES
Dr. Howard P. Ross
2 - 13 July 1986

Date	Activity
2 July 1986 -	Travel Salt Lake City to Tucson Arizona. Review gravity meter operation with Mining Geophysical Survey geophysicists, verify meter condition. Return to Salt Lake City - hand carry meter.
6 July 1986 -	Depart Salt Lake City for Quito.
7 July 1986 -	Travel to Quito. Clear gravity meter through customs with assistance of U.S. AID personnel. Deliver gravity meter to INE geologists. Check In at Tambo Real Hotel.
8 July 1986 -	Visit Dr. Fausto Maldonado, US AID, and discuss INE geothermal project. Met with INE geologists; begin warming of instrument and adjustment for local latitude and elevation. Verify instrument is working properly. Begin instruction in handling and operation of meter. Deliver computer tapes for RIP2 and GRAV2.D programs. Review INE-UURI contract. Leave meter on battery/eliminator.
9 July 1986 -	Take gravity reading at geodetic reference station, Quito Observatory. Travel to Sangolqui - El Tingo area, establish gravity base stations all lines, return to base sta. Training INE geologists.
10 July 1986 -	Travel to Tumbaco - Cumbaya area, establish base stations. Training INE geologists. Return to INE, review computer program for data reduction, noting input errors, program errors, etc.
11 July 1986 -	Instruction and discussions at INE: data reduction, terrain corr., interpretation, survey additions. Go to computer center.
12 July 1986 -	Work on report all day.
13 July 1986 -	Travel Quito - Miami - Salt Lake City.

Gravity & Magnetic Methods
by Phillip M. Wright
Econ. Geology

APPENDIX 3.

Introduction

Although many differences exist between them, gravity and magnetic methods of prospecting are often discussed together because of similarities in data display and interpretation techniques. In this section we will consider the principles, instrumentation, data collection, and data reduction ~~and~~ for the gravity method. ~~application separately, and then review interpretation methods together. Good general references include Grant and West (1965), Dobrin (1976), Rao and Murthy (1978), and Parasnis (1979). Excellent current reviews are given by Tanner and Gibb (1979) and Hood et al. (1979).~~

The Gravity Method

Principles

In gravity prospecting we often speak about the acceleration of gravity, which is the acceleration that a freely falling body would experience in the earth's gravitational field. This acceleration is given by $G\,M_e/r_e^2$, where M_e and r_e are the mass and radius of the earth, respectively. It is found by measurement that the earth's gravitational acceleration is about 983 gals (cm/sec^2) at the poles and about 978 gals at the equator. The *gal* and the *milligal* are common units, named after Galileo, used in gravity prospecting. Gravity is less at the equator than at the poles because the equatorial radius is greater than the polar radius and because of the variation, with latitude, of centrifugal force due to the earth's rotation.

Modern gravity meters routinely measure spatial variations in the earth's gravity field to 0.01 milligals (1 part in 10^8) or better in field application, and the newest generation of instruments is capable of ± 0.002 milligals under ideal field conditions. These spatial variations in gravity are caused by lateral variations in rock density when measurements are restricted to the earth's surface. Near-surface density variations affect the gravimeter more than do deep variations, in accordance with the inverse square nature of Newton's law, and most gravity variations of interest in mining exploration result from changes in density within shallow crustal rocks. Because the gravimeter detects lateral variations in rock density, a *density contrast* must exist between the rock body under investigation and its cavity rock if an anomaly is to be found.

Rock density depends upon mineral composition, degree of induration, porosity, and compressibility. Shales display marked variations of density with depth because of their relatively high compressibility. As a general rule, older sedimentary rocks are higher in density than younger sedimentary rocks. Acid igneous rocks are less dense than basic igneous rocks. Most plutonic and metamorphic rocks display smaller ranges in density than do sedimentary and volcanic rocks. Volcanic rocks generally display rapid density variations due to porosity changes from place to place. Table 1 lists typical values of density for a variety of rock types. Note that density variations greater than 25 percent of the average crustal density, 2.67 gm/cm^3, are rare in near-surface rocks; in sharp contrast to electrical and magnetic properties of rocks, which can vary over several orders of magnitude.

Surveying and data reduction

Field surveys are performed by reading the gravimeter at selected station sites, either on a regular grid or in an irregular pattern as station access and optimum survey design dictate. Repeated readings are commonly made at one- to four-hour intervals at one or more previously established base stations in order to determine instrument drift and local gravity tidal variations.

TABLE 1

DENSITIES OF ROCKS AND MINERALS
(Modified from Dobrin, 1976, with additions)

NAME	DENSITY, gm/cm^3 Range	Average
Alluvium and Soil	1.6-2.2	1.90
Sandstone	1.6-2.6	2.32
Limestone	1.9-2.8	2.54
Dolomite	2.4-2.9	2.70
Shale	1.8-2.5	2.42
Granite	2.5-2.8	2.67
Diorite	2.6-3.0	2.84
Gabbro	2.8-3.1	2.98
Diabase	2.8-3.1	2.97
Dunite	3.2-3.3	3.28
Quartzite	2.6-2.7	2.65
Gneiss	2.6-3.1	2.75
Schist	2.6-3.0	2.82
Slate	2.6-2.8	2.81
Amphibolite	2.7-3.2	2.99
Eclogite	3.3-3.5	3.39
Salt	1.9-2.2	2.15
Pyrite	4.9-5.2	5.00
Pyrrhotite	4.5-4.7	4.60
Sphalerite	3.9-4.1	4.00
Magnetite	5.0-5.2	5.10
Water	---	1.00

Information in addition to the gravimeter reading must be known at each site in order to reduce the raw field data. The instrument must be carefully calibrated. Corrections must be made for differences in elevation and latitude among the stations. The latitude correction removes the effects of the northward increase in the earth's field. There are two elevation effects that are usually combined into one correction (Figure 1). A reference elevation is selected to which all elevation corrections are made. For simplicity, in the following discussion the reference elevation is assumed to be the elevation of the survey base station, although any elevation could be selected. The *free air* correction accounts for the decrease in the gravity field with increasing distance from the earth's center, but this correction ignores the mass of material that lies between the ground surface and the reference elevation. The *Bouguer* correction accounts for this mass by assuming it to be an infinite slab of uniform thickness and specified density. Variations from this slab assumption are accounted for by a *topographic correction* which is commonly applied only in areas of rugged topography. Both the Bouguer and the topographic correction require an assumption for the density of near-surface rocks. This density is often assumed to be 2.67 gm/cm^3.

The anomalous gravity value in milligals, G_{sta}, at the field station relative to the base value, G_{base}, is given by

$$G_{sta} = G_{base} + g_{obs} - 0.8121d \sin 2\phi \text{ mgal/km (north)} + 0.3086h \text{ mgal/m} - 0.04186\,\rho h \text{ mgal/m} + \text{terrain correction},$$

where

g_{obs} = observed gravity reading at the field station

d = distance in km the field station lies north of the base station

ϕ = geographic latitude of the base station

h = elevation difference between field station and reference elevation.

Any convenient value for G_{base} may be taken. If the gravity anomaly relative to the *International Ellipsoid* is known for the base, then that value is generally used because the field station then becomes tied to other similar stations elsewhere on earth.

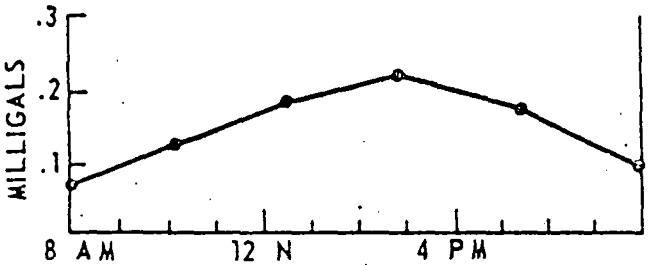
From the above formulas we see that north-south station location must be known to about 10 m and elevation must be known to about 0.05 m in order to make the latitude and elevation corrections of the same order as the 0.01 milligal specification of many surveys. Variations in measured gravity due to latitude and elevation effects will usually be much larger than the anomaly sought.

Applications

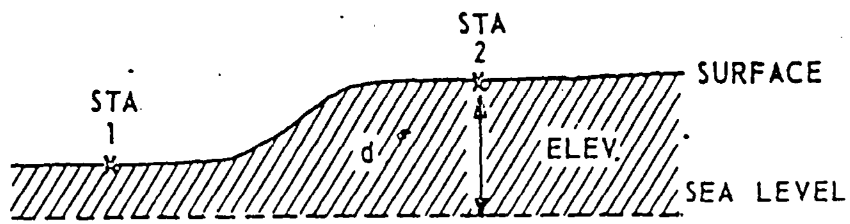
In some cases, orebodies have been directly detected by gravity surveys. Copper ore associated with massive pyrite bodies was discovered by underground gravity surveying at Bisbee, Arizona (Rogers, 1952; Sumner and Schnepfe, 1966). Gravity data were acquired along mining levels and were then contoured for interpretation both on levels and on vertical sections. Figure 2 shows such a vertical section at Bisbee (Sumner and Schnepfe, 1966; Fig. 4). The cross-hatched areas are the interpreted positions of dense sulfide bodies required to explain the observed gravity anomalies. Note the existence of gravity highs above the interpreted bodies and gravity lows below. The authors state that, of the recommended drill holes, 80 percent encountered sufficient sulfides to account for the gravity results.

GRAVITY CORRECTIONS

2 HR. REPEAT READINGS ON BASE A

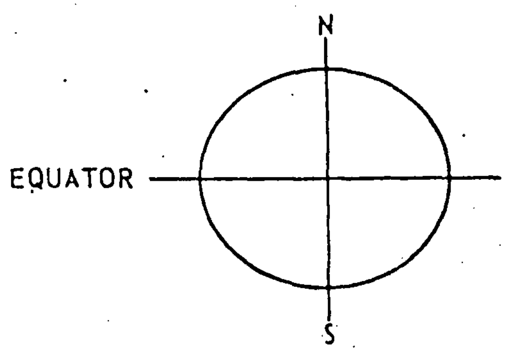


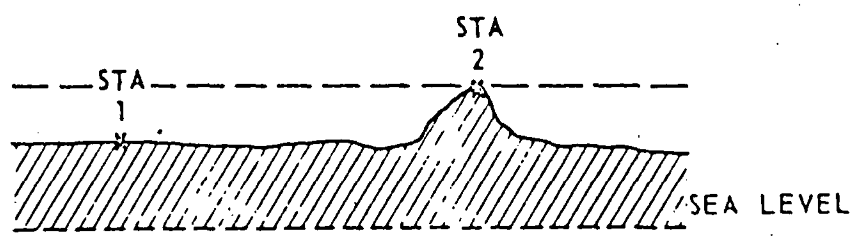
TIDAL & INST. DRIFT CORRECTIONS =
.3 mg/ 24 HRS



FREE AIR CORR. = + .094 mg/ FT. ELEV. = +0.3084 mg/m elev.

BOUGUER CORR. = - .013 d mg/ FT. ELEV. = -0.0419 d mg/m elev.
where d = density.





LATITUDE CORR: = - 1.3 mg/ MILE NORTH @ Lat = 45°
≈ 0.0 mg/km @ Lat = 0°

TERRAIN CORR: = + mg

⇒ Complete Bouguer Gravity

BOUGUER GRAVITY (mg) SEA LEVEL DATUM = OBS GRAVITY + TIDAL & DRIFT CORR. + LAT. CORR.
+ FREE AIR CORR. + BOUGUER CORR. + TERR. CORR.

Figure 1.

APPENDIX 4.

UNIVERSITY OF UTAH RESEARCH INSTITUTE
UURI
EARTH SCIENCE LABORATORY
391 CHIPETA WAY, SUITE C
SALT LAKE CITY, UTAH 84108—1295
TELEPHONE 801-524-3422

March 11, 1986

MEMORANDUM

TO: Howard Ross

FROM: Duncan Foley

SUBJECT: Collection of Samples for K-Ar Dating

Several preliminary questions need to be answered before geologic samples are collected for dating by K-Ar methods. The goal of the dating program must be identified, and the samples must be selected appropriately to meet that goal. A program to establish geologic ages of rock units will require different samples than a program to establish ages of alteration episodes or thermal events.

For young volcanic rocks, Paul Damon at the University of Arizona suggests the following procedures. Only fresh material should be collected. Remove all weathering and, if possible, collect massive rather than fractured portions of units. For basalt, this means that the middle of flows, rather than rubbly flow tops or bottoms, will give the best rseults. Damon separates plagioclase out of the groundmass for dating basalts. In rhyolitic units, he prefers to use potassium feldspar with good crystal face reflections, especially sanidine. These procedures are undertaken to minimize contamination by atmospheric argon, as such contamination could totally obscure the small amount of radiogenic argon generated in short geologic times. Other K-bearing minerals can be dated, but they may not give reliable results for young units. Damon has found, for instance, that biotite, which is often used in K-Ar dating programs, may contain significant amounts of excess argon.

The amount of sample collected will, of course, be dependent upon the amounts of K-bearing minerals in the various rocks. No general rule applies, but 10 to 30 lbs (5-15 kg) may be needed. It is always best to err on the side of too much sample.

An additional requirement is to estimate the age of the sample. This will allow Damon to estimate the amount of sample that will be loaded in the mass spectrometer.

INTRODUCTION

In response to a Solicitation by el Instituto National de Energía (INE), the Earth Science Laboratory of the University of Utah Research Institute (ESL/UURI) has proposed to provide assistance to INE in planning, supervision and interpretation of a geophysical resistivity survey in the vicinity of the volcano Ilaló in the Valle de los Chillos, about 15 km east of Quito. The purpose of the survey is to locate a site for an ~~test~~ observation and stratigraphic drill hole as a part of the first stage in development of low-enthalpy geothermal resources in the area. The resistivity field survey will be performed by an experienced geophysical crew from the Dirección General de Geologia y Minas (DGGM), under contract to INE. Topographic and resistivity line location surveying is to be provided by Cartotecnia S.A. an experienced private firm.

Thermal springs and wells are known at a number of locations around and near the base of Cerro Ilaló. Historic use of the thermal water has been principally for balneology. However, there are a number of potential industrial users ~~of the geothermal waters~~ who could displace burning of petroleum if geothermal waters of sufficient temperature and quantity could be found. Given the widespread occurrence of thermal springs and wells, it is reasonable to believe that one or more thermal aquifers exist and that the project has a good chance of success.

SUMMARY OF ACCOMPLISHMENTS OF THIS MISSION

During this mission I spent 10 days working on the Valle de los Chillos geophysical survey project. I spent considerable time reviewing existing geological and geochemical data for the project in order to help plan the geophysical work. I spent one day in the field in the survey area assessing the potential detrimental effects of the many power lines and other so-called cultural features in the area. A second field day was spent in a vain attempt to aquire some test resistivity data with the DGGM geophysical crew. Equipment failure forced abortion of this attempt. I spent time in studying air photos, recent topographic maps and maps showing power transmission lines to determine the best placement of dipole-dipole resistivity survey lines. The line lay-out map that resulted from this effort has been delivered to INE. Lastly, I spent about 1 1/2 days writing this memorandum.

The two important things I was not able to do were (1) to spend one or more days in actual field data collection, and (2) to achieve a signed contract between INE and UURI. Hopefully enough extra money can be found that I can return earlier than originally planned, for an extra trip during the first weeks of the survey, in November, to satisfy (1) above. Hopefully, too, a signed contract will be forthcoming, too.

I have left a record of my expenses with

INCE, who will approve them and pass them on to AID for reimbursement to me. This can not be done without the contract. In this record of expences is a day-by-day account of how my time was spent on this mission.

STATUS OF THE CONTRACT

At present there is no signed contract between INE and UURI. This is an uncomfortable situation for UURI because our expenditures to date on this project have been several thousand dollars which can not be reimbursed by US AID without such a contract. UURI and INE are agreed in principle and in detail on the terms of the contract, but INE is awaiting approval for the project before it can sign a contract. We hope that this matter can be cleared up quickly.

MATERIAL DELIVERED TO INE

In addition to this report, a number of other items have been delivered to INE to date. These include copies of about 12 reports on geothermal exploration work done by ESL/UURI in several areas of high-enthalpy and low-enthalpy resources in the United States. The studies documented in these reports have all been funded by the U.S. Department of Energy (USDOE), and are in the public domain. They may therefore be quoted and used by INE for any suitable purpose.

A computer tape containing two programs for interpretation of electrical resistivity data, along with a users guide, has also been delivered to INE. These two programs are computationally the same, i.e. they each produce computed surface resistivity based on an arbitrary two-dimensional model of the subsurface. The principal differences in the programs have to do with the amount of computer graphic interaction they contain. This causes one version of the program to be somewhat more complex than the other version and to require more computer memory. INE and/or DGGM will want to study both versions before deciding which to implement on their computers. Very likely modified versions will ultimately be implemented, with the computation aspects as given on the computer tape, but the input-output suited to the INE and DGGM computers

GEOLOGY OF THE GEOTHERMAL TARGET AREA

General Aspects

Cerro Ilaló is a relatively small volcano that lies in the inter-Andean graben about 10 km south east of Quito. Because of filling of the graben with erosional debris from the ranges on both sides and with flows, lahars and air-fall deposits during periods of nearby active volcanism, the base of Ilaló is covered with an unknown thickness of mostly poorly consolidated sedimentary material. Stratigraphic sections of this material can be studied in the canyon walls of both the río San Pedro, which crosses the western base of Ilaló, and the río de La Alcantarilla, which lies in the foothills and plains of Ilaló to the east (Vera, et al, 1982). Both rivers flow northward. Above basement rocks of Cretaceous age that consist of sediments composed of gabbros, diabases and basalts, are the Tertiary Pre-Chiche, Chiche and Pre-Cangahua, and the Quaternary Cangahua and Recent sediments. The depth to the basement beneath the exposed portion of the Pre-Chichi is not known. The Pre-Chiche consists mostly of andesitic volcanic sediment and breccias. The overlying Chiche is composed of volcanic conglomerates having boulders of mainly andesite composition. The overlying Pre-Cangahua is composed of fine volcanic lacustrine and fluvial sediments. The Cangahua consists of andesite tuffs that are in places vitreous and elsewhere devitrified. Also included is a flow containing lapilli. The Recent deposits consist of lacustrine sediments, lahars and flows.

Cerro Ilaló is partly drowned by these deposits. Ilaló itself consists mostly of basaltic lavas and breccias. The only dated sample gives a K/Ar age of 1.6 million years, but D. Paola (1983) documents the existence of a flow that appears to be new younger.

The structural setting of Ilaló is complex and not well known due to the ubiquitus cover of deposits of very young age, which effectively hide the faults and fractures. The predominant, and probably oldest faults, trend north-south, and are associated with the development of the inter-Andean graben. There is good evidence, both from geologic mapping and from study of lineaments on air photos, of younger fractures and faults that trend northeast and northwest. The río San Pedro and the río Chiche apparently follow such structures.

<u>Geothermal Manifestations</u>

Good evidence for a reasonably widespread geothermal resource is present in the areas surrounding Ilaló. Natural thermal springs used for balneology occur in the foothills about 2 km southwest of Tumbaco on the northwest side of Ilaló, at San Pedro del Tingo on the southwest side, at La Merced on the south side and at a location called Ilaló on the southeast side of Cerro Ilaló. In addition, there are several natural thermal springs in the canyon of the río San Pedro, and there are a number of wells that have reached thermal waters at depths up to 100 m, especially in the San Pedro del Tingo area.

The maximum measured water temperature is about 40°C at Tingo, but chemical data from 5 1 samples obtained by Michael Lopoukhine (quoted in Budney and Reed, 1983) indicate that higher temperatures could be expected at depth. Although the chemical data appear to be of good quality, great care must be used in their interpretation in terms of geothermal reservoir temperatures. The cation geothermometers (Na, K, Ca) can not be used because of the high magnesium content of the waters, and the silica geothermometers are notoriously unreliable for temperatures below about 100°C. Application of the silica geothermometer depends critically on which silica mineral the thermal waters are in equilibrium with at depth. If this mineral is assumed to be quartz, reservoir temperatures from 132°C to 161°C are indicated from the 5 samples. Perhaps the preferable mineral to assume equilibrium with, however, is beta-cristobalite (Budney and Reed, 1983), which yields reservoir temperatures of 35°C to 61°C.

It seems most reasonable to me to interpret all of the data I have seen in terms of the existence of a reasonably widespread occurrence of thermal waters whose temperatures at shallow to moderate depth do not exceed 100°C. I believe this is indicated by the chemical data, by the measured surface temperatures and by a lack of significant hydrothermal alteration of rocks in the thermal spring areas. However, this is not at all to say that a higher temperature reservoir does not occur in the vicinity of Ilaló. It simply means that the waters from any high-temperature reservoir are sufficiently changed by dilution with near-surface meteoric waters and by other mechanisms of change that they do not directly indicate the existence of a high temperature reservoir (+150°C). In any case, although chemical geothermometer data can indicate subsurface temperature, they can not be used to predict either the depth or the location at which such temperatures can be found. Other exploration techniques must be applied to do this.

In addition to the widespread occurrence of thermal springs and wells, there is an anomaly in NH_3 (Patricio Romero, personal communication) in the vicinity of San Pedro del Tingo, that lends encouragement to the existence of geothermal resources in that area.

<u>The Geothermal Target Concept</u>

Wells drilled to maximum depths of 100 m in the areas of interest around Cerro Ilaló generally encounter productive aquifers, some of which produce cold water (at mean annual air temperature) and some of which produce thermally anomalous water. In order for heated waters to be found at such shallow depths, they generally must flow up permeable faults or fractures, rising to the near-surface because of buoyancy due to their heat or because of hydraulic head in recharge areas. As these thermal waters rise they encounter aquifers filled with cold waters near surface, and are thereby diluted and lowered in temperature. In certain locations the thermal waters may come up along a permeable portion of a fault and then spread horizontally in one or more of the permeable volcanic-sedimentary horizons around the base of Ilaló. It is also conceivable that the flows and breccias of Ilaló itself form a hydraulic barrier and that subsurface water flowing toward Ilaló is channeled upward by this barrier.

In any case, we can not expect that faults, fractures or the volcanic-sedimentary graben fill material will be uniformly permeable. Certain channelways up faults or up along the subsurface slope of Ilaló will be more permeable, and will therefor carry the bulk of ascending geothermal waters. These waters will spread laterally into aquifers at depth in the graben-fill material and will be transported greater or lesser distances from the supply channels depending upon variations in permeability in the volcanic-sedimentary material. It is likely that there will be a system of aquifers, one above the other, ~~and~~ separated by impermeable beds, on one or both sides of any channelway for upward-moving fluids. In order to intersect thermal waters of the highest temperature and highest productivity, we must locate a well near or into one of these channels of ascending waters. To intersect an aquifer in the graben-fill material at some distance from a channel of ascending waters would also yield thermal waters, but probably of lower temperature and productivity, and would thus be a target of somewhat lower, but still significant priority.

In my mind there are, therefore, two types of geothermal targets:

1. A zone of upward-flowing thermal waters. Such a zone would probably be fault controlled, i.e. would probably be along permeable portions of a fault or fault zone. Because of the pervasive nature of the very young cover, there are probably many more faults in the subsurface than we see on the surface. The zone of upflow of thermal waters would be narrow but perhaps long -- a guess at dimensions may be 10-100 m by 50-500 m.
2. A horizontal aquifer or system of stacked aquifers that are fed by zones of the type discussed in (1) above. Occurrence of thermal waters in such aquifers would probably be aligned along the feeder zone. Estimated dimensions might be 50-500 m by 200-1000 m.

It is the job of exploration to locate these geothermal targets, if they exist, and to site one or more

PROPOSED ELECTRICAL RESISTIVITY SURVEY

Electrical resistivity has a significantly high chance of contributing to the exploration program in the Valle de los Chillos project. Resistivity has the advantage under the right conditions; of being able to detect thermal waters directly because they are lower in resistivity than non-thermal waters due to the increase activity of contained ions (the current carriers) at higher temperature. Other geophysical methods, such as gravity or magnetic surveys, may be able to locate faults, but would not be likely to distinguish permeable portions of those faults or thermal waters rising along the faults, nor could they detect flat-lying aquifers. In certain geothermal areas, soil mercury chemical surveys have succeeded in detecting portions of faults carrying thermal waters, as have radon gas surveys, but the sample density would have to be great. All things considered, resistivity seems to me to be the first exploration method to try, although some problems can be expected, as detailed below.

<u>Magnitude of Expected Resistivity Anomalies</u>

There is a relationship between the bulk resistivity of rock, ρ_B, the resistivity of the groundwater with which it is saturated, ρ_w, and the porosity of the rock, ϕ, known as Archie's Law:

$$\rho_B = a \rho_w \phi^{-m}.$$

In this equation, $\underline{a}$ and $\underline{m}$ are parameters such that

$$a = \begin{cases} 1-\epsilon \text{ for intergranular porosity} \\ 1+\epsilon \text{ for fracture porosity} \end{cases}$$

and

$$m = \begin{cases} 2-\epsilon \text{ for poorly sorted, poorly cemented material} \\ 2+\epsilon \text{ for well sorted, well cemented material} \end{cases}$$

In general, ϵ is small, and for our purposes here we will take Archie's Law to be

$$\rho_B = \rho_w \phi^{-2}.$$

Now, it must be emphasized that this relationship applies only to situations where ions bound to clay minerals do not contribute significantly to electrical conduction. This assumption seems reasonable to a first approximation in Valle de los Chillos in view of the general absence of hydrothermal alteration.

The resistivity of the groundwater, ρ_w, will depend upon the total content of dissolved ionic species and the temperature. A plot of total dissolved solids (TDS) versus temperature for Lopoukhine's chemical data for 5 samples quoted in Budney and Reed (1983) is shown in Figure 1. It can be seen that there is an apparent relationship such that higher temperature waters have a higher content of dissolved ionic species. This is to be expected. An equation for a straight line, eye-ball fit to the data is

$$TDS = 900 + 130(T-25) .$$

At the lower end, the curve must flatten as shown, as it probably does at the upper end, also. In particular, for purposes of this estimation, although the data would predict 10,000 ppm TDS at 95°C, I have used 6000 ppm.

Using these data along with the relationships shown on Figure 2, which gives water resistivity as a function of temperature and dissolved ionic species, we can estimate a resistivity for thermal and non-thermal waters. We get:

ρ_w = 12 Ω-m, non-thermal waters, 16°C, 500 ppm
= 1.3 Ω-m, thermal waters, 40°C, 3000 ppm
= 0.34 Ω-m, thermal waters, 95°C, 6000 ppm.

An upper limit of 95°C was used following Budney and Reed (1983, p. 7). If we assume 15% porosity for a reasonable aquifer, we can estimate the resistivity of the aquifer to be:

added zonarch 85: Assume ϕ = 30%, get values = blue

133 ρ_b = 530 Ω-m, non-thermal waters, 16°C, 500 ppm
14 = 58 Ω-m, thermal waters, 40°C, 3000 ppm
4 = 15 Ω-m, thermal waters, 95°C, 6000 ppm.

For higher porosities these resistivities would be lower, and vise versa.

I conclude that the expected resistivity contrast

PLOT OF TDS VS TEMPERATURE

VALLE DE LOS CHILLOS

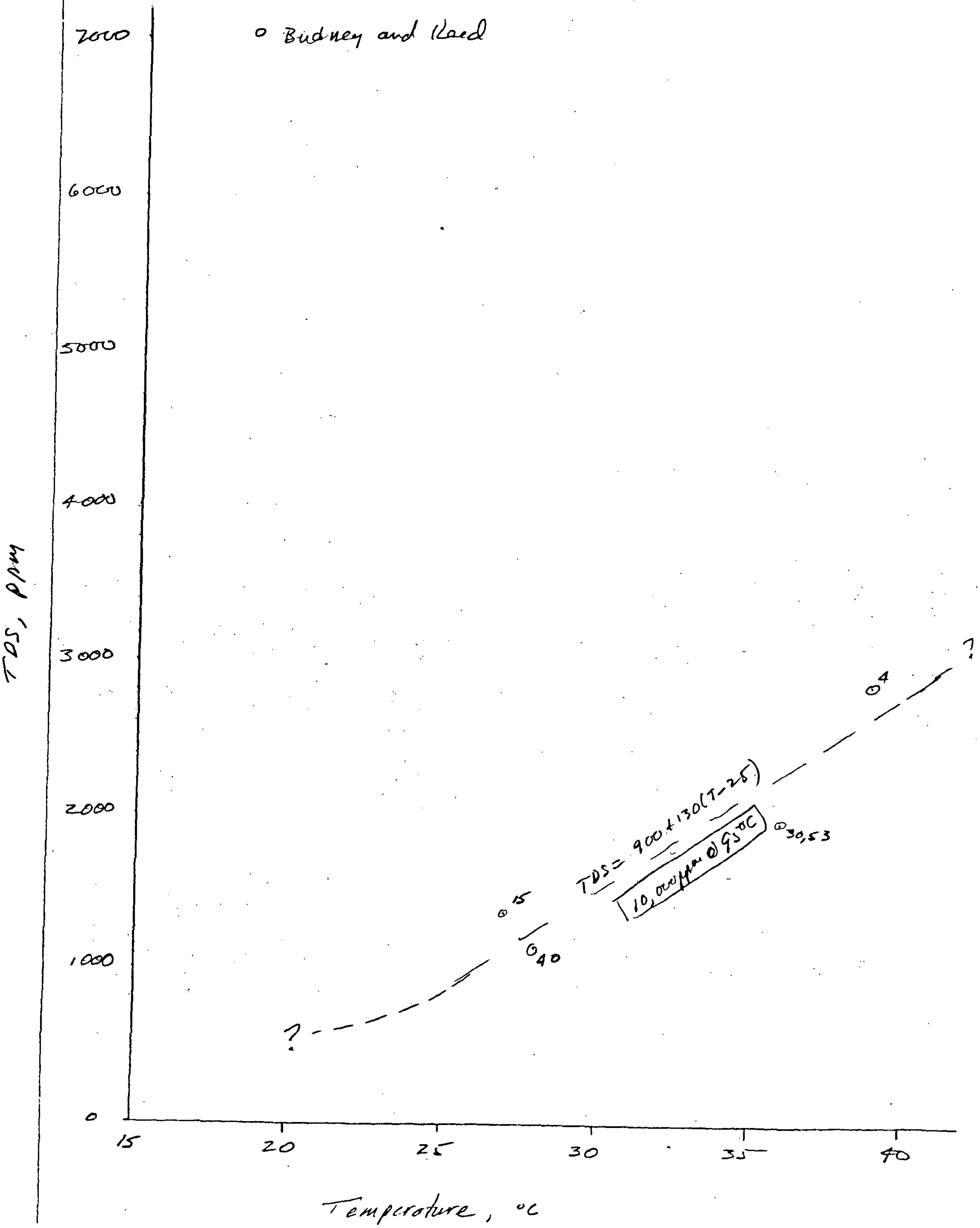
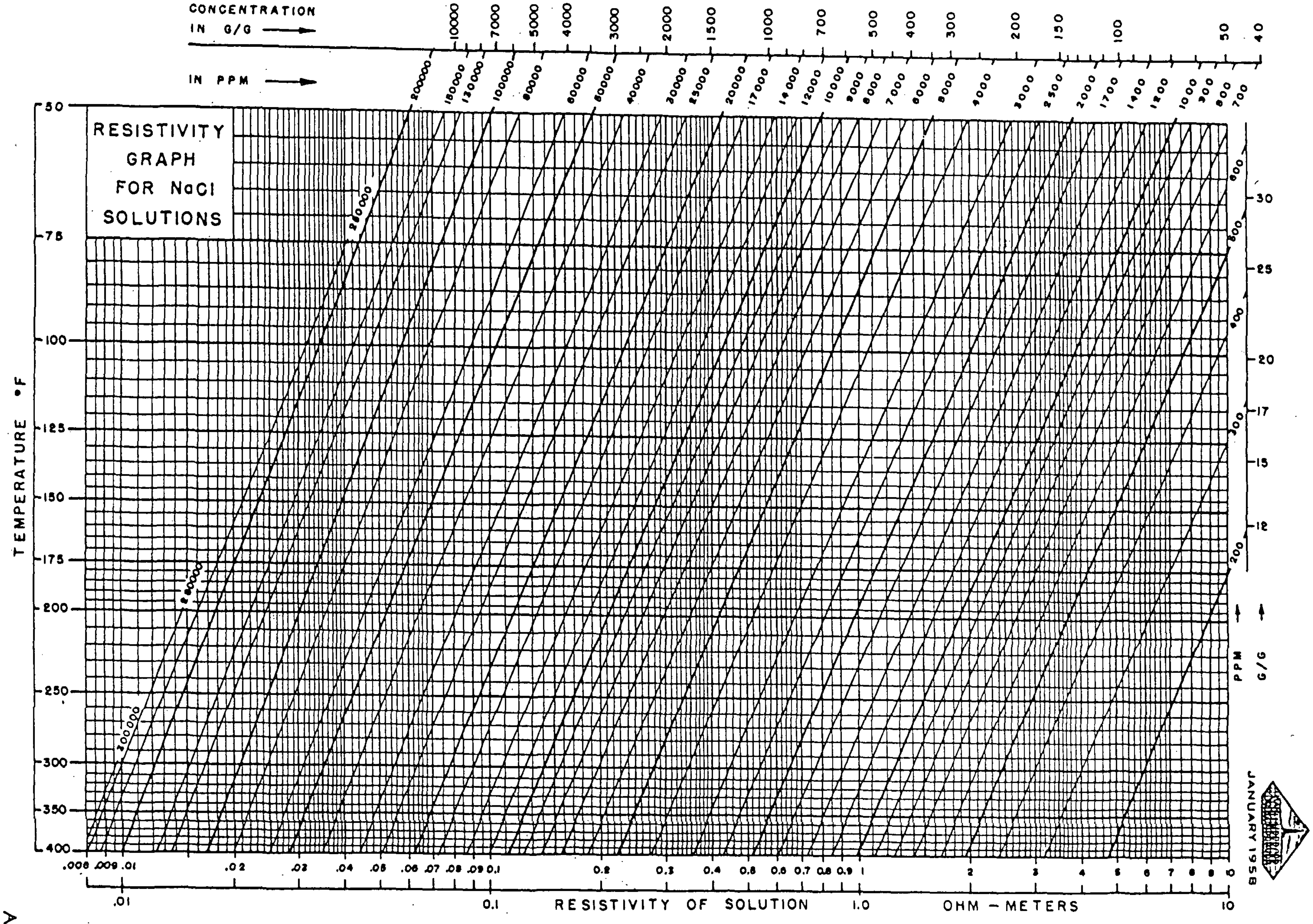


Figure 2



RESISTIVITY GRAPH FOR NaCl SOLUTIONS
CONCENTRATION IN G/G
IN PPM
TEMPERATURE °F
RESISTIVITY OF SOLUTION OHM – METERS
PPM
G/G
JANUARY 1958

between rocks saturated with non-thermal waters and those saturated with thermal waters will generally be in the range 5:1 to 40:1. These resistivity contrasts should be detectable at depths of 300 - 600 m using the survey techniques described below.

Summary Description of the Resistivity Method

The electrical resistivity prospecting method measures the apparent resistivity of the subsurface at selected station sites. This resistivity is termed "apparent" because it is a type of average of all nearby subsurface resistivity variations. An interpreted picture of actual subsurface resistivity variations is constructed by applying modeling techniques to the field data.

In order to make the resistivity measurement, a current is caused to flow in the ground between to electrodes, called the "current" or "transmitter" electrodes, and the voltage resulting from this flow of current is measured between two separate electrodes, the "potential" electrodes, located at some distance from the transmitter electrodes. By use of the measured voltage, the transmitted current and the geometry of the electrode array, i.e. the relative positions of the 4 electrodes on the surface, the value of apparent resistivity is calculated.

There are several methods of arranging the electrodes on the surface, and these are called electrode arrays (See Fig 3). For the present survey we will be using the dipole - dipole array, with a smaller amount of work using the Schlumberger array. This will be further discussed below.

Potential Problems due to Cultural Noise Sources

In the normal situation, current flows between the two transmitter electrodes in a fashion determined by the nature of the resistivity changes at depth. However, if there are surface conductors of electricity, such as power lines and pipe lines, and if these surface conductors are electrically connected with the earth (i.e. grounded), then the normal current flow can be disturbed in ways that can not be easily predicted. This causes values of apparent resistivity to be in error, and for all practical purposes this error can not be removed by any known correction method.

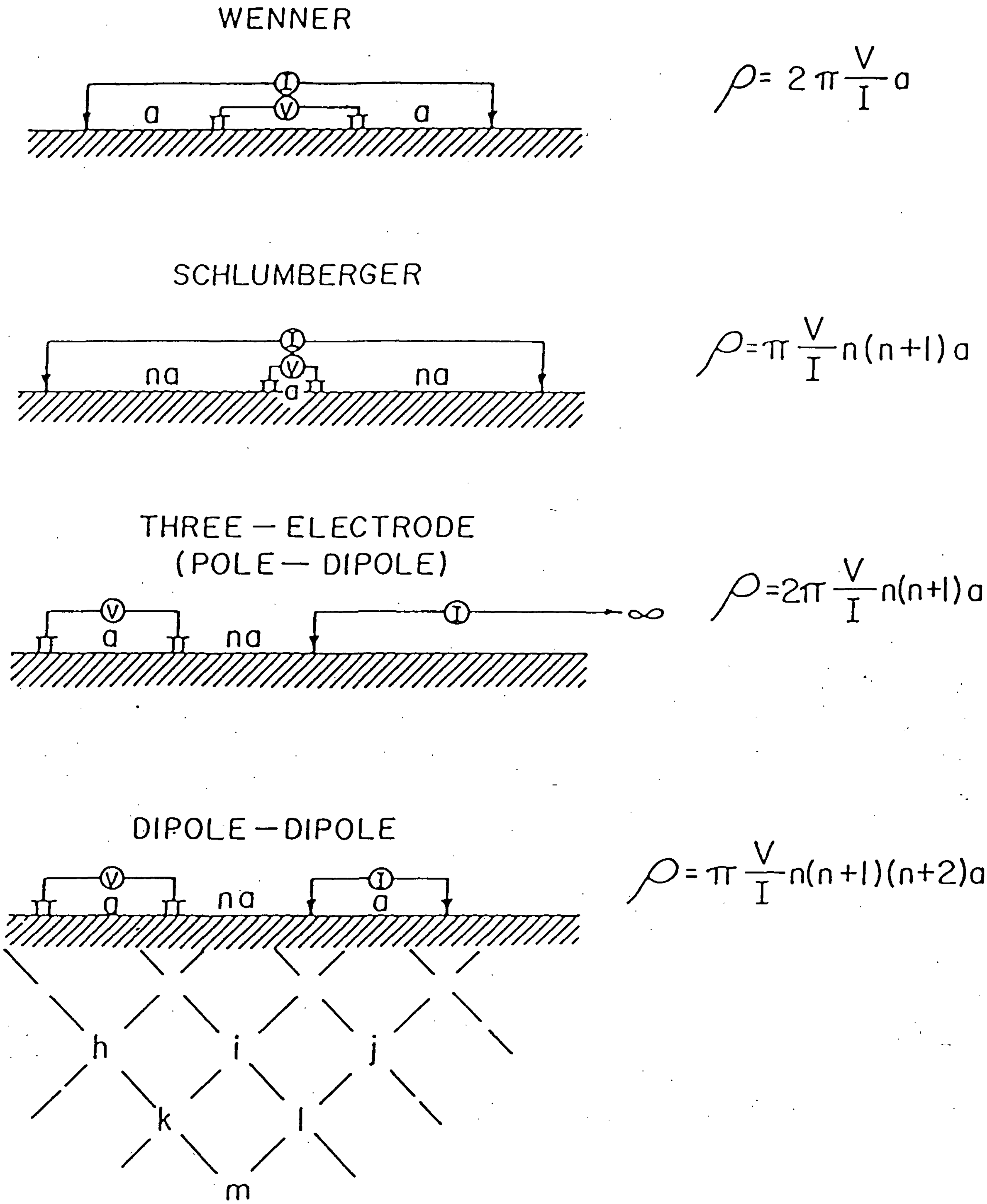


Figure 3. Common electrode arrays for electrical resistivity surveys.

In the Valle de los Chillos project area there are several towns, other smaller areas of urbanization, and numerous, more or less isolated farm houses. This is especially true in the San Pedro del Tingo area. As a result, there are numerous powerlines, which are usually grounded for reasons of safety, and a main petroleum pipeline. These so-called "cultural" features are potential sources of contamination of the resistivity data for two reasons:

1. As discussed above, grounded cultural features redistribute transmitted current flow, and
2. These features generally carry electrical signals of their own which cannot be completely removed by filters in the resistivity receiver and therefore can cause noisy data.

The main point of this section is not to indicate that the resistivity technique will be impossible to apply around Ilaló, but to indicate (1) that we don't know the level of difficulties without trying the survey, and (2) we will need to be very careful in selection of the resistivity lines to minimize cultural effects. In general, cultural effects can best be minimized by staying as far away from cultural features as possible.

A second way to minimize cultural effects is to survey in areas of heavy culture when the near surface soil is as dry as possible, since this minimizes the amount of electrical contact that cultural features have with the ground.

I do not expect that fences in the area will be a problem because none of them seem to be grounded -- they all have wooden or concrete fence posts.

Considerations on Dipole Length

In determining dipole length to use for the dipole-dipole survey, a number of considerations are important. First, the longer the dipole length, the deeper the depth of exploration of the technique. However, horizontal resolution (especially) of anomalous bodies in the subsurface becomes poorer with increasing dipole length. In addition, in the Valle de los Chillos area a longer dipole length would increase the odds that a given dipole will cross a power line that could (but may not necessarily) contaminate the data. Also longer dipoles increase survey time required due

At Valle de los Chillos, it would be desirable to prospect to a depth around 600 m. I have done some calculations on detectability of anomalies and also of expected signal strength, i.e. voltage expected between potential electrodes, for various options for the survey. For the following discussion, the reader is asked to please refer to Figures 3 and 4. In both of these figures the letter <u>a</u> is used for the dipole length, and <u>n</u> is called the "separation". <u>n</u> is usually an integer that varies from 1 to 6–10, depending on the objectives of the survey, although non-integral values can also be used. As <u>n</u>, the separation, becomes larger the signal strength at the receiver decreases, because the transmitter and receiver electrodes are further apart. This decrease in signal strength is compensated by the geometry factor for the array. In Figure 3 we see for the dipole-dipole array that the calculated apparent resistivity, ρ, is given by

$$\rho = \pi a \frac{V}{I} n(n+1)(n+2)$$

where V = voltage read at the receiver
I = current transmitted
a = electrode spacing
n = separation.

If we let $Q = n(n+1)(n+2)$
$F = aQ\pi/1000$ = geometry factor
(because the receiver will usually read in millivolts, the factor of 1000 is included)

Then $\rho = \frac{V\text{(millivolts)}}{I\text{(amps)}} F\text{(meters)}$ Values for Q and F are given in Figure 4 for separations $n = 1$ to 8.

Also shown in Figure 4 is expected signal strength in millivolts at the receiver for $a = 300$ m and $a = 400$ m, and for $n = 6$ and $n = 8$, as a function of various apparent resistivities. These calculations assume that 5 amperes can be transmitted into the ground. If currents actually achieved are less, then the signal strength at the receiver would be reduced in proportion.

A single measurement of the electrical noise spectrum was made in the field on Tuesday, 20 September, near San

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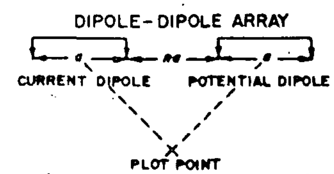
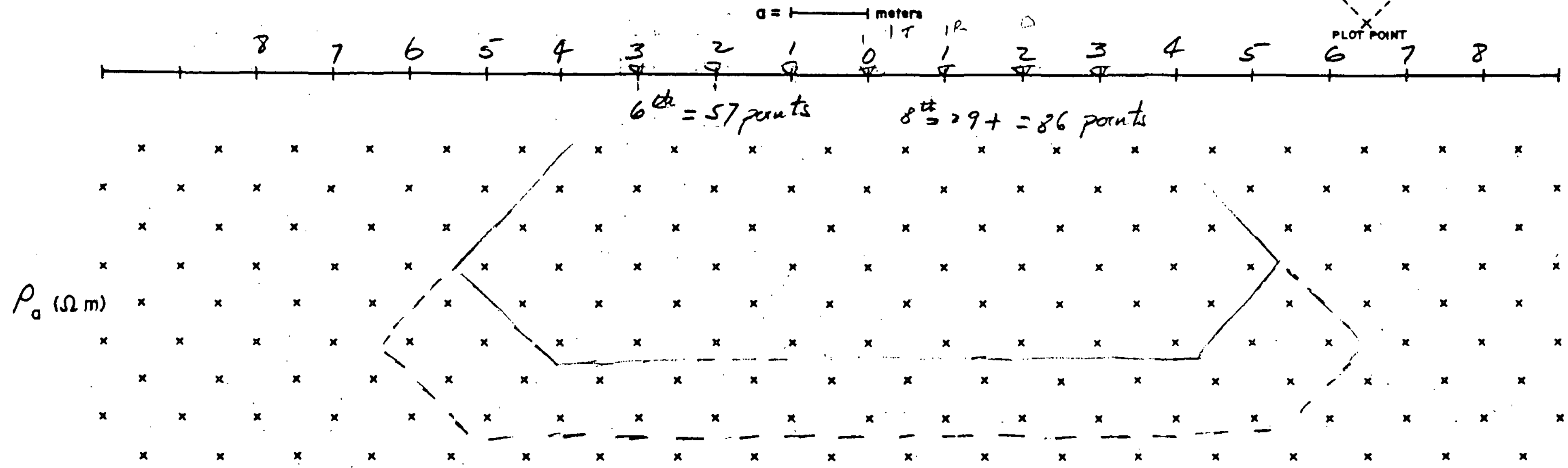
DIPOLE - DIPOLE ARRAY APPARENT RESISTIVITY





Geometry Factors

$F = aQ\pi/1000$

Separation	Q	F300	F400
1	6	5.655	7.540
2	24	22.62	30.16
3.	60	56.55	75.40
4	120	113.1	150.8
5	210	197.9	263.9
6	336	316.7	422.2
7	504	475.0	633.3
8	720	678.6	904.8

Calculated Signal Strength (mV), I = 5A

	a = 300m		a = 400m	
ρ (Ω-m)	6th	8th	6th	8th
ρ = 1	0.016	0.007	0.012	0.006
= 20	0.320	0.148	0.237	0.111
= 60	0.949	0.433	0.711	0.332
= 100	1.582	0.737	1.184	0.553
= 200	3.200	1.480	2.369	1.105

Figure 4

AREA ______ STATE ______ LINE ______ DATA BY ______ DATE ______ TRANSMITTER ______ RECEIVER ______

Pedro del Tingo, using a digital voltmeter of unknown frequency characteristics and a dipole length of 200 m. For short time periods there was about 200 microvolts of electrical noise, and over periods of several minutes the variations were as much as 1200 millivolts, all superimposed on an SP value of about 10 millivolts. Figure 4 shows that it should be possible to take reliable data for $a = 300$, $n = 6$ for resistivities of 60 Ω-m and above, and probably for resistivities of 20 Ω-m and above. The amount of electrical noise does indicate two important items, however:

1. The transmitter current must be as high as possible to overpower the electrical noise, and
2. A number of individual readings of the receiver should be made over a total period of time probably exceeding 5 minutes in order to average out electrical noise.

A brief study of anomaly detectability for $a = 300$ (300 meter dipoles) and $a = 400$ (400 meter dipoles) indicates that for an extensive anomaly 600 meters deep:

for $a = 300$, $n = 6$ we would read 1/2 of the anomalous value at the surface

$a = 300$, $n = 8$ we would read 2/3 of the anomalous value

$a = 400$, $n = 6$ we would read 2/3 of the anomalous value

$a = 400$, $n = 8$ we would read 3/4 of the anomalous value.

Eighth separation ($n = 8$) values are more time consuming to read than 6th separation values because the signal strength is low (the geometry factor is high) and more reading time is required to average out noise.

Considering all of the trade-offs and compromises among such factors as anomaly resolution, depth of search and signal strength (which affects receiver reading time required), I believe that the best overall compromise is to use $a = 300$ meters and to read to $n = 6$. This is what I recommend, at least for the beginning, and the proposed line lay-out given below is based on this recommendation.

DATA QUALITY

It will be very important to make sure that the field data are of the highest quality possible. Potential sources of contamination of the data include the cultural structures previously discussed as well as natural electrical noise currents (telluric currents) that flow in the earth in response to electromagnetic induction by magnetic fields generated mainly by movements in the earth's ionosphere, at altitudes of about 60 miles. Another source of electrical noise is lightning strikes within perhaps 50 km of the survey site. We thus have man-made electrical noise and natural electrical noise, neither of which we can diminish~~ed~~ in intensity during the survey. However, several steps can be taken to overcome this electrical noise. These include maximizing transmitted current and making a sufficient number of readings at each receiver site to enable us to effectively average out the noise. Other considerations might include use of the McPhar equipment in the frequency domain, even though the transmitter has lower power capabilities than the Scintrex equipment, to take advantage of filtering of noise available on frequency domain equipment.

The voltage signal at the receiver depends upon the resistivity of the earth, the electrode separation and the amount of current transmitted. Referring back to Figures 3 and 4, we can write

$$V = \frac{\rho I}{\pi a n (n+1)(n+2)} = \frac{\rho I}{F}$$

We can see that as the resistivity, ρ, decreases, the signal voltage at the receiver, V, decreases. If V drops too close to or below the level of electrical noise, maintaining good data quality becomes difficult or impossible. We can also see that as electrode separation, n, increases, the signal voltage decreases. We are unlikely to have problems with signal level for values of n = 1, 2, 3 or 4. But for n = 5 or 6, the drop in signal level becomes large (see the values for the geometry factors given in Figure 4). These are the wide electrode separations where good data are needed in order to have good depth of exploration.

We can also see that V increases as transmitted current, I, increases, and so to maintain high signal levels it is important to maximize transmitted current.

Maximizing Transmitted Current

In the transmitter circuit there are 3 principal resistances, the resistance of the wire (Rw), the resistance of the ground (Rg, not to be confused with the resistivity of the ground, ρ), and the resistance of the electrode-earth contact (Re). The transmitter is basically a constant-current device that has both maximum voltage and maximum current limits. The circuit parameters are related by Ohm's Law

$$V_t = I_t R = I_t (R_w + R_g + R_e)$$

where

V_t = voltage across the transmitter terminals
I_t = value of transmitted current.

From this relationship, it is obvious that if we want to maximize I_t (up to the limit of the transmitter), we must minimize R. Since $R = R_w + R_g + R_e$, two basic things can be done to minimize R:

1. We can minimize R_w = resistance of the wire by using larger diameter wire, or
2. we can minimize R_e = resistance of the electrode contact by using techniques decribed below.

The earth-electrode electrical contact is made by burying an electrical conductor, such as a metal stake, in the ground and wetting the soil with water and salt. The contact resistance can often be improved by one or more of the following tactics:

1. Digging a large hole and using plenty of water and salt: 1/2 lb salt, 2-5 gallons of water;
2. Using aluminum foil in a rectangular bed of salt and water, rather than a metal stake;
3. Using more than one electrode at a given transmitter site, and planting these electrodes 2-4 m apart
4. Digging the holes and applying salt and water 1 or 2 days in advance of the survey to allow plenty of

time for the water to soak in and make contact with natural ground water. The electrodes should be rewatered just before the survey if this technique is used.

I recommend that if a maximum or near maximum of transmitter current can not be more easily obtained and if the signal level is so low that receiver reading time is excessive, then one or more of the above tactics be tried.

Receiver Reading Time and Tactics

In spite of the maximum transmitter current, the receiver readings will still show some scatter or variation due to man-made or natural electrical noise, especially for more distant electrode separations (n=5,6) where signal level is lowest. The only useful strategy in these cases is to make a number of independent receiver readings at the site and then to average these readings selectively, to obtain an acceptable value. For example, consider the following three sets of data that I have made up for this illustration:

Receiver Readings, millivolts

A	B	C
298	298	298
296	292	426
301	356	12
299	303	159
300	295	351
297	297	262
298	300	151

There is little scatter in data set A, and the arithmetic average of these numbers would probably be a good reading.

In data set B there is also little scatter except for the single value of 356, which is far from the average. This single reading may be the result of a lightning strike or some other such transient. Such values are often seen on stormy days. The value of 356 can safely be eliminated from the data set, and the average can be taken of the remaining values.

Data set C is obviously badly contaminated by electrical noise. If the transmitter current can not be increased so that the transmitted signal is a larger percentage of the overall electrical signal reaching the receiver, then the resistivity value associated with this data set will be suspect or perhaps worthless.

In monitoring data quality it will be very important to:

1. Notice the scatter in individual readings, and
2. Make individual readings over a period of enough time to have confidence that the scatter shown is the maximum at that site.

In this context it is important to explain the term "individual reading." The normal receiver will ordinarily accumulate data internally from a number of transmitter cycles and display the average value of these cycles. It is not generally wise to let the receiver average more than 10 to 20 transmitter cycles, because if a single cycle is contaminated, the average will be contaminated (data set B above). Rather than let the receiver continue to accumulate and average data beyond 10 transmitter cycles, it is better to write this <u>individual</u> reading in the field notebook, and reset the receiver to take another set of, say, 10 readings. In this way contamination of individual readings can be more easily and reliably recognized.

In areas of heavy culture, where man-made electrical noise is present in quantities large enough to cause significant scatter in the data, individual readings, as defined above, should be taken over at least 5 minutes and in some cases more to ensure a final data set that can be selectively averaged with confidence.

EXPECTED RESULTS OF SURVEY

A recent report by OLADE and INECEL discusses results of test resistivity surveys in several areas in Ecuador and Colombia, including Ilaló (Anon, 1983). The primary purpose of this work was to test newly acquired resistivity/IP equipment made by McPhar, Ltd in Canada. At Ilaló, the Schlumberger array was used, and several important points were made. The first is that there was some interference from electrical noise generated by cultural sources. The second point was that relatively low apparent resistivities were detected, which the investigators felt certain were due to subsurface geothermal aquifers (an assumption which seems premature to me). Some rough field notes aquired from INECEL on an informal basis indicate apparent resistivities that vary between 18 and 180 ohm-meters, being lowest near surface (AB/2 = 15) and increasing with sounding depth. These values are of interest because they indicate what might be expected in the vicinity of Ilaló. The location was given as "Ilaló-Oriente", but no map of sounding location is available.

Torres (1975) also documents some resistivity values obtained by sounding using Schlumberger array in the vicinity of Cumbayá and Tumbaco, on the north side of Ilaló. These soundings generally found an upper-layer resistivity between 100 and 180 ohm-meters, a middle-layer resistivity averaging perhaps 25 - 70 ohm-meters, and a low-layer resistivity that was quite variable but was generally higher, averaging perhaps 75-180 ohm-meters. The thickness of the upper layer averaged 1-3 m, and that of the middle layer 25-60 m (see pages 125 and 126). Thus the magnitude of resistivity values agrees quite well between OLADE/INECEL and Torres, although insufficient detail was given by OLADE/INECEL to evaluate detailed agreement.

As a first approximation, we can expect resistivities that vary between perhaps 20 and 200 ohm-meters in non-thermal areas. In areas of thermal anomalies we may expect values below 20 ohm-meters -- perhaps values of 5-50 ohm-meters will characterize thermal areas.

The geometry of geothermally related anomalies may be expected to consist of linear or otherwise confined zones of lowest resistivity, corresponding to upwelling fluids, surrounded by more extensive zones of moderately low resistivity corresponding to aquifers containing thermal waters.

One copy of the layout of proposed resistivity lines was delivered to INE. This copy is on transparent vellum paper, and it overlays the 1:50,000 scale Sangolquí sheet. Only the proposed dipole-dipole lines are shown. I recommend that the sites for the six Schlumberger soundings be selected after at least part of the dipole-dipole data are obtained. Approximately 140 line-km of proposed surveying is shown on the plan map. A further ±40 line-km of dipole-dipole surveying will probably be recommended based on the results obtained on the first lines. It is likely that some fill-in surveying will be needed in areas of anomalous resistivities in order to provide more detail. Such detailed work may be done at shorter dipole spacings (a = 50-200 m) in order to provide increased resolution on the edges of anomalies.

It is recommended that the survey field work be started in the Tumbaco-Cumbayá area. Although this area is not the highest in priority for exploration work (the Sangolquí-Tingo area is highest), it has somewhat less culture and will be a good area in which to develop techniques for coping with culture before attempting the more difficult. The current plan is then to do Sangolquí-Tingo and La Merced in that order after Tumbaco-Cumbayá. Below I suggest an order for doing the lines, but this order is not critical and can be changed for any good reason.

Tumbaco-Cumbayá: TC-1 (since this line crosses the known thermal spring), TC-2, TC-4, TC-3.

Sangolquí-Tingo: ST-6, ST-7 (these two lines are in the heart of the area of known thermal springs and wells), ST-13, ST-8, ST-12, ST-5, ST-4, ST-3, ST-2, ST-1, ST-9 and ST-10.

La Merced: LM-5, LM-2, LM-1, LM-3, LM-7, LM-4, and LM-6

It should be stated that the recommended line locations were decided upon after studies of the air photos, the available topographic map (1983) and the grid of major transmission lines as furnished by INECEL.

RECOMMENDATIONS FOR FIELD WORK

On the line-layout overlay to the Sangolquí 1:50,000 sheet, the zero point and the end points are all numbered. The numbers refer to the number of 300-meter intervals to that point from the center (0) of the line. The tic marks along each line show the proposed positions of current electrodes. The ends of each line where there are no tic marks will be covered out to the end of the line with receiver stations only, in order to obtain readings to the sixth separation (n=6, Figure 4).

It is recommended that Cartofecnia be used to locate semi-permanent markers at the center and ends of each line, so that the true positions of the lines could be recovered in the field during the next several years, when drilling on the basis of the resistivity results may take place. Cartofecnia has also shown a willingness to furnish help to the geophysical crew in the form of digging and watering electrode holes, as described below. No detailed topographic surveying nor precise location of lines is needed. If the line locatio[n]

Two experienced geophysical survey technicians will be furnished by Dirección General de Geología y Minas to perform the field work. Their time can be better used, and survey efficiency increased if two workers are furnished to them, to be under their direction. These workers could be furnished by Cartofecnia, or INE could hire them directly. In any case, they can help pack equipment, tend one of the porous receiver electrodes, dig and water electrode holes, etc.

It is recommended that aluminum foil electrodes be used as a start. The DGGM crew is familiar with their use. The electrode holes should be dug, salted and watered thoroughly on the day before their use. This will help maximize transmitter current, as discussed before.

As each electrode position is established, it may have to be moved somewhat from the position indicated on the lay-out map in order to avoid obstacles or culture. In fact it is important to realize that <u>all of the line locations shown on the lay-out map are only approximate</u>. All or portions of some lines may need to be changed somewhat to avoid obstacles or culture. It may be apparent that a better location might be available once the actual field conditions along a line are observed. It is recommended that the DGGM crew be permitted to make such changes if, in their judgement, the field survey can be improved thereby.

The field data should be reduced and plotted each day as the survey progresses. This will allow identification of possibly bad data points in time to take corrective action. It is also recommended that copies of the field notes and of the reduced and plotted data be mailed weekly to UURI in Salt Lake City for checking and plotting. This way there will be a complete data set both in Quito and in Salt Lake City, which will greatly facilitate telephone discussions of survey progress and data interpretation.

The DGGM field crew should take great care to take plenty of individual receiver readings to help ensure good data quality, as previously discussed.

If cultural interference is indeed a problem, it may help to survey heavily cultured areas only when the soil is dry, when the cultural features are more poorly grounded. If this is found to help, non-cultured areas could be surveyed after periods of significant rainfall, reserving the cultured areas for dry periods.

It is recommended that the DGGM geophysical crew make a special effort to note the locations of all nearby powerlines and pipelines and to document these locations on a map in the field during the progress of the survey. Such mapping of the culture relative to the lines, especially for cultural features that cross the line or come within 200-300 m from the line, will be important in assessing potential cultural contamination of the data.

FUTURE PLANS

I have present plans, under the terms of the contract as it now exists, to come to Quito to check progress of the survey only once during the approximately 6 months that the survey will take. However, it would be highly desirable to make an additional trip early in the survey to watch the field crew in action, ~~and~~ to work out any problems and to personally assess the effects on the survey of power lines and other cultural features. Such a trip would require a modification to the draft contract to cover the costs of such a trip.

On the later trip, I will be accompanied by a senior geologist-~~geophysicist~~ geochemist, who will help in assessment of the data.

ACKNOWLEDGEMENTS

I must give special thanks to Patricio Romero and Marco Acasta, who spent many hours discussing this project with me, driving me around to meet many people who will be involved, and for taking me on a weekend field trip to Imbaburra and Quicoche. Any success I may have achieved on this mission is due in large part to their care and enthusiasm. Thanks also to Hugh Pierson, who met me at the airport and spent time with me in the field and in discussion. The crew at U.S. AID, especially Leo Gorza were a great help to me also.

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RECOMMENDATIONS FOR VALLE DE LOS CHILLOS
GEOTHERMAL PROJECT

by

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University of Utah Research Institute

Sent to [illegible]
3 July 1985

CONTENTS

LIST OF TABLES

INTRODUCTION

Geothermal development is an interdisciplinary endeavor. Figure 1 shows some of the components of the team that must work together successfully if a geothermal site is to be developed. Because geothermal resources are geological phenomena, earth science information is needed for essentially all phases of the development. This involvement of the earth sciences is similar to that required for development of petroleum and mineral reserves. However, the petroleum and minerals industries are well established whereas the geothermal industry is in its infancy.

The petroleum and minerals industries have developed earth science tools and techniques to solve their particular problems in an optimum way, and this has required the expenditure of tens of billions of dollars for research and technology development. By contrast, relatively little has been spent in developing earth science tools and techniques especially for application in the geothermal environment. Because the geothermal industry is so young and is not yet generally profitable except at a few sites, it is unable to generate the money needed for this research and technology development. Geothermal developers have had to resort to application of existing exploration and development techniques and equipment, which are not generally optimum for geothermal application. In some cases, no tools or techniques have existed to solve a particular geothermal problem.

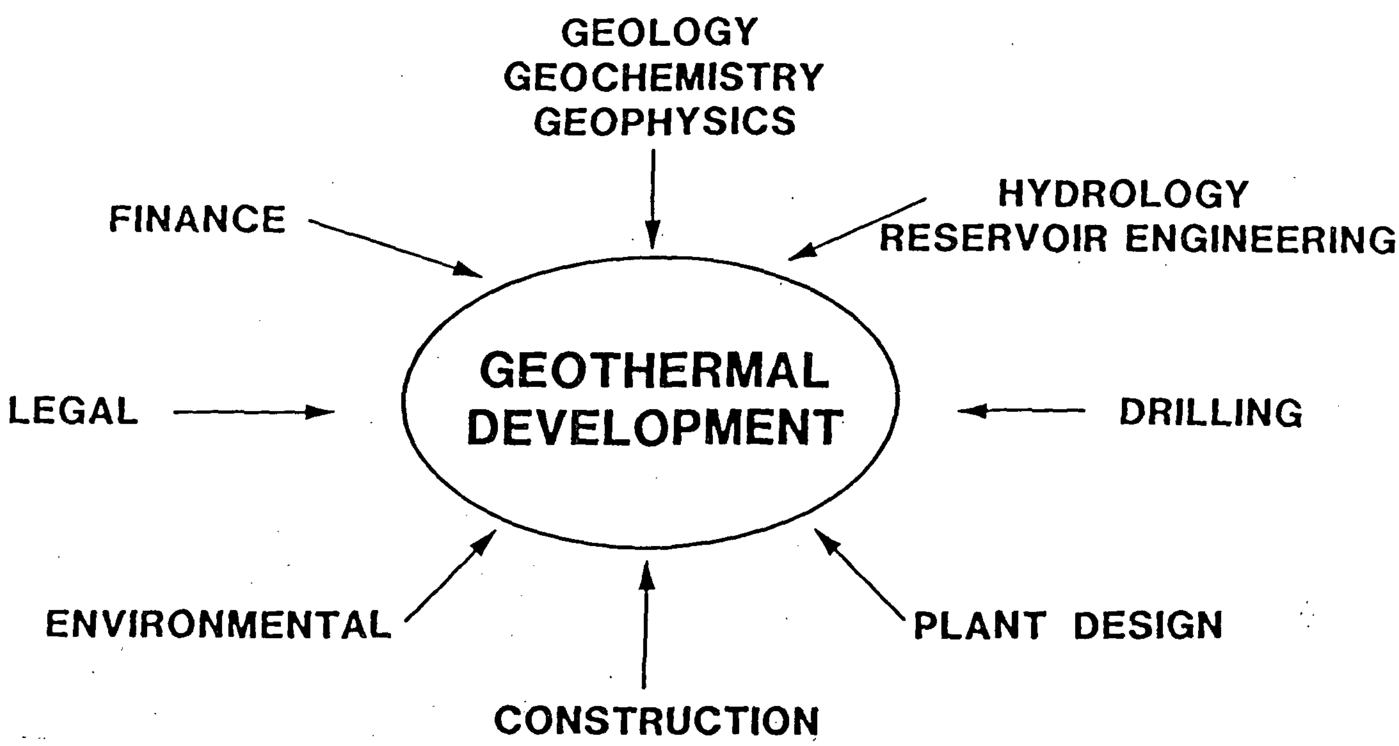
The geosciences have two primary applications in geothermal development:

1. Exploration for geothermal systems, and
2. Exploration within geothermal systems.

Figure 2 indicates one suggested series of steps for this exploration for high-temperature geothermal systems. The reconnaissance stage is designed to filter available prospect areas and to prioritize them for detailed explora-

GEOTHERMAL DEVELOPMENT

AN INTERDISCIPLINARY ENDEAVOR



BECAUSE GEOTHERMAL OCCURRENCES ARE GEOLOGICAL PHENOMENA, EARTH SCIENCE INFORMATION IS NEEDED FOR ALL PHASES OF DEVELOPMENT

THE DEVELOPMENT TEAM MUST WORK CLOSELY TOGETHER FOR THE PROJECT TO SUCCEED

Figure 1.

SUGGESTED HIGH TEMPERATURE HYDROTHERMAL EXPLORATION STRATEGY

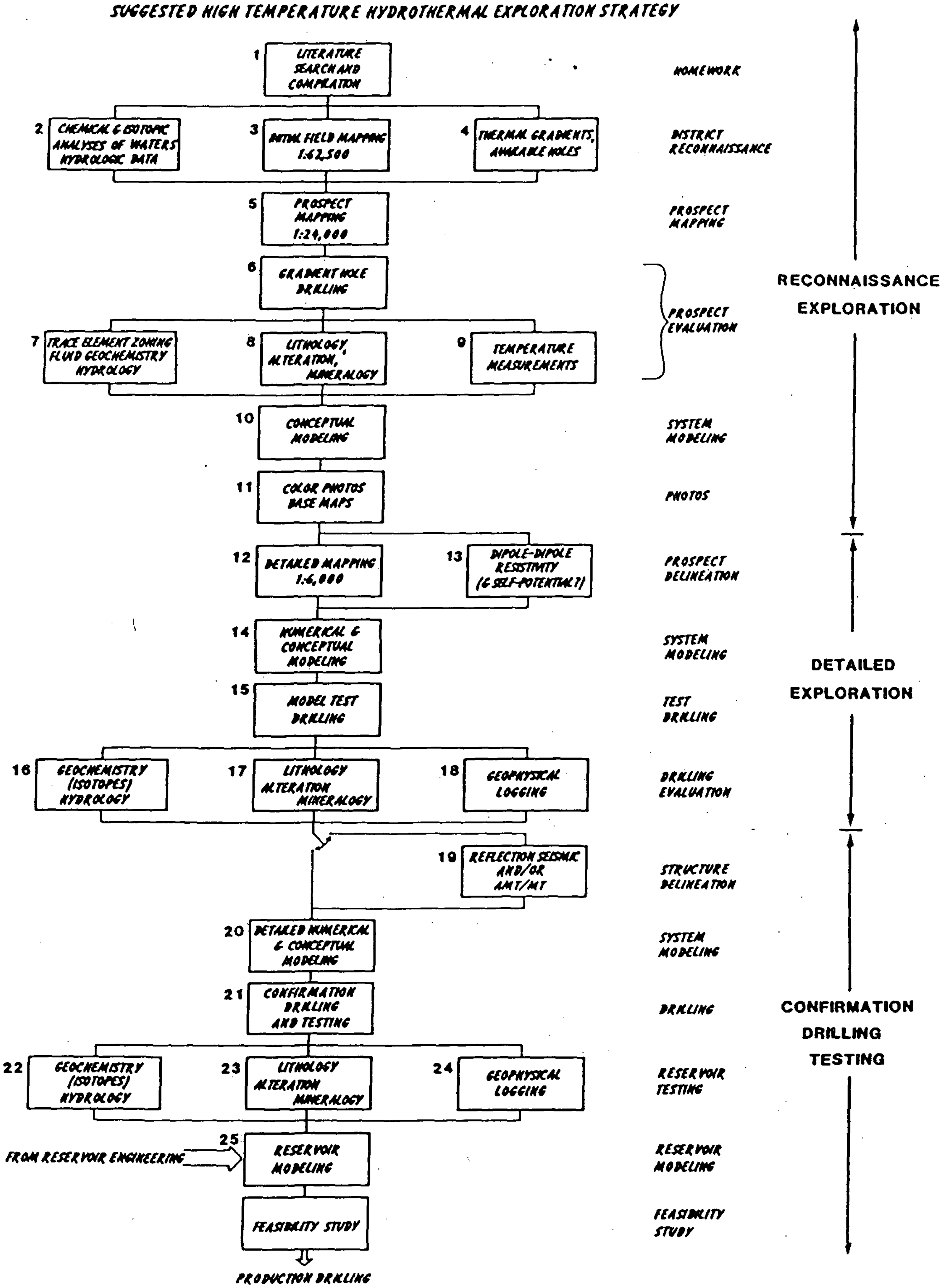


Figure 2.

tion. This stage refers to (1) above, i.e. exploration for geothermal systems. Once a geothermal system has been located, exploration becomes more detailed within the system. The primary objective of both phases of this exploration is to select drill sites--drill sites to locate a resource area, to confirm the presence of a resource, and then to obtain production of fluids for the utilization plant and to dispose of spent fluids through injection. Because the drilling of geothermal wells is so costly, proper application of exploration techniques has great potential for lowering development costs by avoiding wasted drill holes.

Exploration programs for low-enthalpy geothermal systems usually are more modest than those depicted in Figure 2 for high-enthalpy systems because low-enthalpy applications often cannot generate enough money to amortize a large exploration effort. The exploration is usually confined to geologic mapping, geochemical surveys of existing springs, and some form of electrical geophysical survey.

Once a geothermal system has been explored to a certain extent, the scientists and engineers working on the project can begin to form a conceptual resource model. Figure 3 indicates this process. Data for the model come from the fields of geology, geochemistry, geophysics and hydrology. These data are preferably detailed enough to be a function of three 3 space coordinates and of time (x,y,z,t). The model consists of a depiction of subsurface conditions, i.e. a sketch of the subsurface that accounts for known geology, geochemistry, geophysics and hydrology and shows the estimated boundaries and geologic features that control the location of the geothermal system. The conceptual resource model is, in turn, used to form hypotheses and make predictions for use in further exploration and in reservoir engineering and management. The conceptual model is continually refined by comparison of

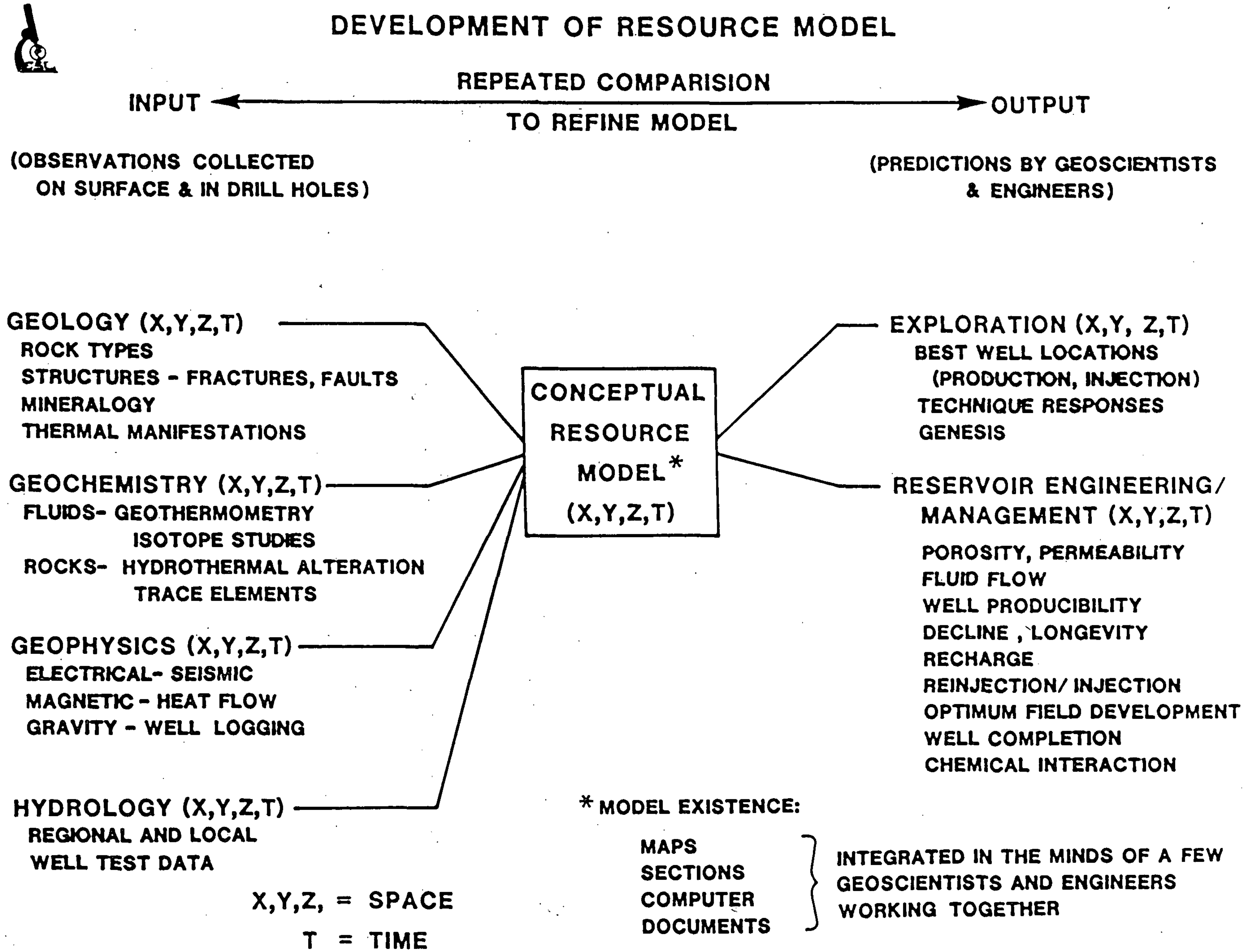

DEVELOPMENT OF RESOURCE MODEL
REPEATED COMPARISION
TO REFINE MODEL
INPUT
OUTPUT
(OBSERVATIONS COLLECTED ON SURFACE & IN DRILL HOLES)
(PREDICTIONS BY GEOSCIENTISTS & ENGINEERS)
GEOLOGY (X,Y,Z,T)
ROCK TYPES
STRUCTURES - FRACTURES, FAULTS
MINERALOGY
THERMAL MANIFESTATIONS
GEOCHEMISTRY (X,Y,Z,T)
FLUIDS- GEOTHERMOMETRY
ISOTOPE STUDIES
ROCKS- HYDROTHERMAL ALTERATION
TRACE ELEMENTS
GEOPHYSICS (X,Y,Z,T)
ELECTRICAL- SEISMIC
MAGNETIC - HEAT FLOW
GRAVITY - WELL LOGGING
HYDROLOGY (X,Y,Z,T)
REGIONAL AND LOCAL
WELL TEST DATA
CONCEPTUAL RESOURCE MODEL* (X,Y,Z,T)
EXPLORATION (X,Y, Z,T)
BEST WELL LOCATIONS
(PRODUCTION, INJECTION)
TECHNIQUE RESPONSES
GENESIS
RESERVOIR ENGINEERING/ MANAGEMENT (X,Y,Z,T)
POROSITY, PERMEABILITY
FLUID FLOW
WELL PRODUCIBILITY
DECLINE , LONGEVITY
RECHARGE
REINJECTION/ INJECTION
OPTIMUM FIELD DEVELOPMENT
WELL COMPLETION
CHEMICAL INTERACTION
* MODEL EXISTENCE:
MAPS
SECTIONS
COMPUTER
DOCUMENTS
INTEGRATED IN THE MINDS OF A FEW GEOSCIENTISTS AND ENGINEERS WORKING TOGETHER
X,Y,Z, = SPACE
T = TIME

Figure 3.

predictions to the expanding data base. As new data become available, these data are used to update and perhaps change the model so that it always agrees with known facts in an optimum way. The conceptual model thus forms the context in which all work on the project is considered. It should be mentioned also that each scientist working on the project may have a different conceptual model in mind--rarely do all scientists agree on the same model.

Even though the development and refinement of such a resource model has gone on far more than 20 years at some well-known geothermal areas such as The Geysers in California, developers there still are unable to predict with certainty the boundaries of the resource, the best places to drill a well, and such important reservoir engineering results as optimum field development strategies or reservoir longevity. A great deal more research and development will be required to provide techniques to increase the reliability of models and of predictions made from these models.

STRUCTURE OF GEOTHERMAL PROJECTS

Geothermal projects are carried out in phases. At the end of each phase is a so-called "decision-point" at which a decision can be made either to continue the project or to stop. At each such decision point, all information generated to that time is reviewed and project plans are updated with the primary objectives of (1) determining what remains to be done on the project, (2) revising the estimates of the total project cost, if necessary, and (3) reassessing the chances that the project will succeed.

The following phases are suggested as being logical units into which a typical geothermal project can be divided:

1. Exploration Surveys
2. Exploration Drilling
3. Aquifer Identification
4. Production Drilling
5. Reservoir Testing
6. Application Engineering
7. Economic Feasibility Analyses
8. Construction
9. Operation and Maintenance

I will briefly discuss each of these in turn.

Exploration Surveys

Objectives: 1. To estimate the chances for occurrence of a geothermal resource in the subsurface;

2. To locate sites for drill testing.

Appropriate techniques from the disciplines of geology, geochemistry, geophysics and hydrology are applied. The exploration should be optimized and integrated. By optimizing, I mean that it should be apparent that each exploration method selected can make a necessary contribution to achieving the project objectives. No technique should be applied just because equipment and personnel are available for it. If there is not a good scientific reason for applying a technique, it will probably be a waste of money and time. Obviously, understanding of and experience with each potentially useful technique is needed in order to choose an appropriate mix of exploration techniques.

It is very important that an integrated interpretation be made of all data generated from the exploration surveys. Geologists, geochemists, geophysicists and hydrologists must each have access to all available data and must work together in its interpretation. The objective of the interpretation should be to construct or update the conceptual resource model, as discussed before.

At each stage in the exploration, we must ask ourselves several questions to determine whether or not it is appropriate to drill yet. Among these questions are:

1. Do the facts support the existence of a geothermal resource at depth?
2. Do the data tell us where on the surface to locate a drill hole to test for the presence of a geothermal resource?
3. Should additional exploration surveys be run before drilling, and if so what surveys and why?

Exploration Drilling

Objective:
1. To obtain equilibrium measurements of subsurface temperature at all depths in the hole;
2. To obtain geologic data from the subsurface.

One obviously drills an exploration hole in order to determine the geothermal properties of the subsurface. Samples of drill core (from core drilled holes) or drill cuttings or chips (from rotary drilled holes) are useful for geologic input to the conceptual resource model. However, the most important item of information is the measured subsurface temperature.

Because the drilling process, including circulation of drill muds or water during drilling, disturbs the thermal equilibrium of the hole, one must be careful that one is obtaining true formation temperatures. The best method to assure that equilibrium formation temperatures are being measured is to wait for a suitable length of time after drilling before a temperature log is made. Estimates can be made of the time required for equilibrium from the drilling rate and total time required for drilling. Although temperature logs made during or shortly after drilling will not measure true formation temperature, such logs are useful because they can indicate zones of uptake of drill fluid, i.e. zones of permeability that may be aquifers. These zones will show a more disturbed temperature than will adjacent zones where permeability is low.

A method to obtain approximate equilibrium temperatures during drilling is to lower a maximum reading mercury thermometer or a conventional logging tool to total depth when drill bits are changed or at the end of a wire-line core run. The temperature right on the bottom of the hole will not be disturbed from equilibrium by a great amount, and a good idea of formation temperature can thus be obtained. Such bottom-hole temperature measurements should be routinely made during drilling whether with rotary or with core.

Because drilling is expensive, it must be carefully planned and executed. There is always a risk of being unable to drill to the depth objective or of having the hole cave in. This risk is greatest in difficult drilling environments (such as volcanic areas tend to be) or in unknown environments, where there is little drilling experience. Thus, one must be prepared to risk the cost of drilling and even though one may fail to achieve the drilling objectives. It is very important that management understand this risk before drilling is begun.

There are basically two drilling techniques that are usually used for exploration drilling, core drilling and rotary drilling.

Core Drilling. In core drilling, a hollow drill bit with diamond inserts is used to grind the rock away around the periphery of a solid core of rock. The core moves up into the drill rods as drilling progresses and into a core barrel. It is brought to the surface periodically by lowering a wire through the drill rods to retrieve the core barrel. Once emptied on the surface, the core barrel is lowered in the rods again and drilling is resumed.

In core drilling, the diameter of the drill bit is only slightly greater than the diameter of the rods, and the drill rods themselves help keep the hole from caving in. Water is circulated down through the drill rods and it exits through the bit at the bottom of the hole, where it raises along the outside of the rods and brings up the drill cuttings, which are very small rock particles, like dust. At times the drill water will exit the hole in some permeable zone (lost circulation). This is generally not a problem in core drilling, and drilling can continue. The circulation water also helps to cool and lubricate the drill bit and rods.

Most core drills produce a hole from 3 to 4 inches in diameter, which is generally too small to be used as a production hole and which is too small for a pump. Larger core holes can be drilled, but the cost increases rapidly with diameter.

Rotary Drilling. In rotary drilling, the drill bit cuts away the entire bottom of the hole by breaking the rock, rather than the grinding action of core drilling. The rock chips or cuttings produced are much larger than core chips, and they constitute the sample used for geologic purposes.

The rotary bit is significantly larger than the drill rods in order to allow room between the rods and the wall of the hole for the cuttings to flow upward. The cuttings are carried upward in a drill mud which has the three purposes of (1) keeping the cuttings in suspension until their removal at the surface so that they do not block the drill bit or rods, (2) preventing the hole from caving in by forming a mud cake on the walls of the hole and by virtue of their greater density and therefore pressure at a given depth compared to the pressure of the adjacent hydrostatic water column, and (3) cooling and lubricating the drill bit and rods.

At times the drill mud may flow out into the formation before reaching the surface (lost circulation). This is much more serious than is the case of lost circulation in core drilling, because since the rotary drill chips are rather large, they tend to fall out of suspension at the point of lost circulation and to accumulate around the drill bit and/or the rods. If the chips become too tightly packed, they cause the drill bit to become stuck, and it can be very difficult to free the bit. Thus, when circulation is lost in rotary drilling, the drilling operation is stopped and an attempt is made to plug off the permeable zone. Circulation must be regained before drilling can be resumed.

Most rotary drill rigs produce a hole that is 4 to 10 inches in diameter. At the larger diameters, such holes may be useful for production.

Comparison of Core and Rotary Drilling. Each type of drilling has advantages and disadvantages, as discussed below, for projects like that in Valle de los Chillos:

	Advantages
Core Drilling	1. Water or very light muds used, so that potential aquifers are not plugged and are easier to identify 2. Produces a core, a complete geologic sample 3. Can continue to drill in permeable zones of lost circulation

Disadvantages

1. Hole diameter is too small for geothermal production

Advantages

Rotary Drilling

1. Produces a larger diameter hole which may (or may not) be useful for production

Disadvantages

1. Uses heavier drill muds which may tend to plug and hide aquifers or permeable zones
2. Must plug zones of lost circulation in order to continue drilling. Such zones may be aquifers.

For the Valle de los Chillos project, I tend to favor core drilling, especially for the first few holes. I believe that either method may be capable of reaching the 400 m depths of the planned hole. However, there are other factors that must also be considered. Among these are:

1. What types and capacities of drilling rigs will actually be available in Ecuador?
2. What are the comparative costs of core and rotary drilling? In the Cascades volcanic province of the U.S., core drilling and rotary drilling are about the same cost for holes up to 4000 feet deep, and core seems to be preferred by the geothermal industry;
3. What would be involved in converting each type of hole to a production well? (This is discussed further below).

The best way to answer these and similar questions and to plan the drilling program is to work with one or more drilling contractors in detailed design and cost estimates for the project.

Aquifer Testing

Objective: 1. To determine whether or not there is an aquifer in the subsurface that is capable of producing water.

Before production drilling can be recommended it is absolutely necessary to know that (1) the subsurface equilibrium temperature is high enough for the intended application, and (2) there is an aquifer potentially capable of producing the volumes of fluids needed. Most exploration drill holes are too small for the type of flow testing needed to definitively test the aquifer (discussed under Flow Testing, below). Large-diameter exploration holes are more costly, however, than small-diameter holes, and the desire to keep exploration drilling costs to a minimum until viable temperatures are confirmed accounts for the fact that exploration holes are not usually large diameter.

In small diameter (3-6 inches) exploration wells there are several methods of testing the potential aquifer(s). They all include bringing water to the surface, i.e. producing the hole. Therefore, provision must be made at the surface for handling and disposing of the water produced. These methods are discussed below.

Swabbing. If the hole is core drilled or rotary drilled with flush-inside joint drill pipe, there is a device called a "swab" that can be lowered down the hole inside the drill pipe. It has a one-way water valve on the bottom so that water can flow up into the swab but not back down the hole. There is a device to seal the sides of the swab against the inside of the drill pipe. When the swab reaches the bottom of the well, it is lifted out again, and it pulls up the entire column of water out of the hole. At the surface, provision must be made to handle this water. By repeated lowering and raising of the swab, an evaluation can be made of how much water flows into the hole between swabs, giving some idea of aquifer producibility. Also, the hole can be swabbed until a clean water sample is obtained, and then an uncontaminated water sample can be taken for geochemical analysis. Verification of the uncontaminated nature if the water sample is done by monitoring a parameter, such as electrical conductivity (which is a function of total dissolved solids), of the water at the surface until this parameter becomes constant at the aquifer valve.

Bailing. If the hole is rotary drilled without use of flush-inside joint casing, a device called a bailer can be used to obtain water from the hole. Its operation is similar to that of a swab, but it is used with the drill pipe out of the hole and it cannot be sealed against the sides of the hole because of the roughness of the hole wall. Thus, the water brought up is only that which the bailer itself contains and not the entire water column. Nevertheless, bailing is a frequently used method of aquifer testing.

Air Lifting. If there is sufficient air compressor equipment on the drill site (such as rotary rigs usually have), it can be used to induce flow in the well. A small diameter tube, called a "bubbler" tube or "induction" tube is lowered into the hole. Then compressed air is injected into the hole through the tube. As the air exits the tube at its bottom, it rises and the air bubbles expand. With high enough air volume, water may be brought to the surface.

This type of test is desirable because it produces a continuous water flow at a volume that can be easily measured. The air lift can be continued long enough to obtain an uncontaminated sample for geochemical purposes.

Drill-Stem Tests. With either core or rotary drilling, a drill-stem test is possible. Equipment to perform these tests in small-diameter wells is recently available. In the DST, packers are lowered into the hole to seal off the aquifer. Then an air tube is used to introduce air into the sealed off portion. This causes fluid to rise inside the drill pipes, which are left in the hole for this purpose. A continuous or periodic flow to the surface can be achieved.

For the Valle de los Chillos project, the drilling contractor should be asked whether or not he can provide one or more of these tests. At least one type of test will be necessary to assure ourselves that water production can be obtained from the well, i.e. that there is an aquifer at depth. This will give us the confidence to proceed with production drilling.

Costs will vary among the aquifer testing methods. If the hole is rotary drilled, so that large air compressors are available on the rig, the airlift may be cheapest. If the hole is cored, swabbing will probably be cheapest. The DST is likely to be the most expensive.

Production Drilling

Objective: 1. To obtain geothermal water of high enough temperature and in large enough quantity to support the intended application.

Production geothermal wells are large diameter, typically 8 inch to 14 inch, because of the large amount of water they must produce to support an application. They are different from exploration wells in being larger in diameter and also in being completed as production wells. Whereas the typical exploration hole will not be completed so as to produce fluid, the production well will be carefully cleaned after drilling, and will have a production liner or screen installed, sometimes with a gravel pack between the liner and the wall of the well. This allows water to enter the well freely. Such completion techniques, while necessary, are costly. Design of a production well must include the completion method selected. Completion is done with the drill rig on the hole because the rig provides the equipment necessary for setting the production casing.

At times, exploration holes can be converted to production wells by appropriate completion techniques. This would probably be less expensive and more satisfactory with a rotary exploration hole than a core hole because rotary holes are usually somewhat larger in diameter. The process of conversion consists of installing a production casing (slotted liner or screen), perhaps with a gravel pack. For smaller diameter holes it may be necessary to ream the hole out to a larger diameter before completing it. Reaming is similar to drilling, requires a drill rig and is expensive.

The diameter required for sufficient production of water for the intended use is a function of how much water can be moved through well casing of a certain diameter. This, in turn, depends upon aquifer pressure (whether the well flows by itself, for example) and on depth in the well to standing water. If the well must be pumped, then the diameter of the portion of the well in which the pump is to be installed must be, say, 8 inches or larger. The installation depth of a pump depends on standing water level, and, more importantly, on the water level when the well is under production. These parameters are not determined at this point, but are determined during flow testing (reservoir engineering testing) to be discussed next.

Flow Testing (Reservoir Engineering Testing)

Objective: 1. To determine the response of the well to various rates of water production and, ultimately to determine the best rate of continuous production to preserve well life and achieve project objectives.

Reservoir engineering testing consists of flowing the well at several different rates of production while at the same time measuring wellhead and downhole pressure. If the well does not flow spontaneously, then pumping will be required for the flow test. Each rate of production is maintained at a constant level for a specified length of time, and the pressure response is measured. By considering changes in the pressure response curves, the reservoir engineer can determine aquifer permeability, maximum rates of production, and can make predictions about useful well life. This type of testing can be quite expensive, especially if a pump is required.

Application Engineering

Objective: 1. To design the surface equipment for the method geothermal use.

In order for the engineer to design the surface system for utilization of the geothermal resource, he must know the production temperature and rate for the well. He then uses this information along with the requirements for the end use to specify sizes and materials for pipelines to transport the geothermal waters, and of the heat exchangers and other equipment used to extract and use the heat.

Generally a preliminary design is specified by the engineer, and then an economic feasibility analysis is performed to make certain that the project will be economically successful. If the project appears to be economically viable at this point, then a final design would be made, with detailed cost numbers generated.

Economic Feasibility

Objective: 1. To determine whether or not the project is feasible from an economic viewpoint.

The economist works closely with the engineers to determine a cost for installation of the surface utilization system. To this is added costs for the project to that time to arrive at a total estimated project cost. This is compared with the potential savings from the use of the geothermal water, and a decision can then be made about whether or not to continue.

Construction

Objective: 1. To install the utilization system.

Provided the project is determined to be economically viable, a final system design is made by the engineer, and the project construction is undertaken following that design.

Operation and Maintenance

Objective: 1. To optimize and perform operation and maintenance of the geothermal system.

Once installed, the system will require trained personnel to operate and maintain it.

RISKS ASSOCIATED WITH GEOTHERMAL DEVELOPMENT AT VALLE DE LOS CHILLOS

It must be clearly understood that there is a certain level of risk that the project will not succeed. In Table 1 below I have briefly described and evaluated the risks that come to my mind. Other risks exist, including running out of money before the project is finished, but I cannot evaluate these.

As Table 1 suggests, I currently believe that the greatest risk is in finding temperatures at depth that are too low to support a viable application. Only of slightly less risk is drilling but being unable to intersect a production aquifer.

We must make sure that management is willing to accept the fact that the project may fail through no fault of those working on it.

TABLE 1

RISKS IN THE VALLE DE LOS CHILLOS GEOTHERMAL PROJECT

	Area of Risk	Nature of Risk	Present Level of Risk for Valle de los Chillos	Comments or Steps to Decrease Risk
1.	Exploration Surveys	- The resistivity low may not correspond to geothermal waters in the subsurface	Low to moderate	- None apparent
2.	Exploration Drilling	- The well may be drilled in the wrong location	Low	- Adequate exploration surveys
		- Drilling may be so difficult that the depth objective would not be reached before available money is spent	Moderate	- Include a contingency fund of money to be used only in this case
		- The hole may cave or otherwise be lost before an equilibrium temperature profile can be obtained	Moderate	- Install inexpensive casing
		- The maximum measured down-hole temperature may be too low to be of interest for application	Moderate to high	- This is one item the drilling is designed to test
3.	Aquifer Identification	- The drilling may not intersect a producible aquifer at the depths desired	Moderate	- This is the second item the drilling is designed to teste
4.	Production Drilling	- The production well may not be successfully drilled	Low to moderate	- Experience with exploration drillling will help assess this risk
		- The production well may fail to find adequate temperatures	Low	- Successful exploration drilling decreases this risk
5.	Reservoir Testing	- The flow rate from the production well may be inadequate to support an application	Moderate to high	- Successful aquifer testing decreases this risk
6.	Project Completion	- Even though geothermal parameters may be known the application may not be economic	Low	

RECOMMENDED TECHNICAL ASSISTANCE FOR VALLE DE LOS CHILLOS PROJECT

As requested by INE, I have had conversations with a number of geothermal groups in the U.S. over the past weeks in order to assemble a team of university personnel that could provide technical assistance for the entire project. The groups that are interested in doing this work are:

University of Utah Research Institute
Stanford University
Oregon Institute of Technology

Each of these groups has specific expertise and experience that would be useful on the project, and I see the division of labor among participants as shown on Table 2. UURI, of course, specializes in all aspects of earth science through drilling. OIT specializes in flow testing design of utilization systems and economic analyses. Stanford (Dr. Roland Horne) would consult during the flow testing (reservoir engineering) studies, which is their particular expertise. UURI would be willing to coordinate this work and to subcontract with both Stanford and OIT, as requested by INE. Costs for this technical assistance are given in a separate letter to Dr. Carlos Quevedo T. Attached in Appendices A, B and C to this report are resumes for each of the potential participants.

TABLE 2

PARTICIPATION BY TECHNICAL ADVISORS IN VALLE DE LOS CHILLOS GEOTHERMAL PROJECT

	Exploration Surveys	Exploration Drilling	Aquifer Testing	Production Drilling	Flow Testing	Application Engineering	Economic Feasibility	Construction	Operation Maintenanc
UURI	X	X	X	X	X				
STANFORD					X				
OIT			X		X	X	X	X	X

TECHNICAL REPORT

RECOMMENDATIONS FOR RESISTIVITY SURVEY
VALLE DE LOS CHILLOS

BY

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CONTENTS

INTRODUCTION

From Thursday, June 28, 1984 to Saturday, July 19, 1984, I was on a mission to Quito, Ecuador to assist INE and DGGM in getting the resistivity surVey in Valle de los Chillos underway. The work I accomplished during this second mission is documented in this report. It is based on and amplifies work described in my first report, written in September 1983 after a 10-day mission to Ecuador.

My September, 1983 report deals with design of the resistivity survey, the nature and magnitude of expected resistivity anomalies due to anticipated subsurface geothermal waters, potential problems with culture (the many electric power lines, pipelines, fences and other electrically grounded structure in the survey areas), and recommendations for survey and interpretation procedure. This report makes further recommendations for field and interpretation procedures, discusses cultural problems, presents an anticipated (and perhaps optimistic) project schedule and documents other miscellaneous work and ideas.

I would like to call attention to my first report because it contains information on survey planning, expected resistivity anomalies. The problem that I anticipate because of culture due to the many towns and urbanizations in the area of Ilaló and other information which the reader of this report will need to know.

OBSERVATIONS AND RECOMMENDATIONS PERTAINING TO THE FIELD SURVEY

Based on my observations of field work to date, I would like to make a few comments in this section.

1. The DGGM Field geohysicists, Carlos Rodríguez and Manuel Altamirano understand the field surveying techniques quite well. They can be counted on to do a good job in data acquisition. I am very happy with their competency.

2. During the course of the field work, several items may require changing from line to line, area to area or day to day. I recommend that if such changes are needed in the judgment of Carlos and Manuel to improve the survey, that they be allowed to make the changes, with the agreement of INE, of course. Examples of items that may need changes are:

   A. The locations of certain survey lines or portions of survey lines to avoid culture or obstacles, or the locations of individual current or potential electrodes along the lines;

   B. The method of making electrical connection with the earth, especially for current electrodes. Along some lines, steel stakes may be best whereas along other steel grate (parrilla) or aluminum foil may be better. I recommend that if electrode resistance can not be reduced with stakes, for example, that other electrodes be tried, that more electrodes be added or that electrodes be established and watered the day before their actual use (see my September 1983 report for further details on electrodes).

C. It may be worthwhile to consider changing to the McPhar equipment if electrical noise is too great. The Scintrex equipment and the McPhar equipment each have certain advantages over the other:

Scintrex.- Has a higher power transmitter and can thus transmit more current, giving a bigger signal at the receiver to help overcome electrical noise. But because this equipment operates in the time domain, filtering of electrical noise is not very good.

McPhar.- Has a lower power transmitter, but operates in the frequency domain, where filtering of electrical noise in the input signal can be accomplished.

If the field geophysicists believe it to be worthwhile, a test of the McPhar gear against the Scintrex gear to see which gives the best results fastest would be a possibility. If a change in equipment is made, then the McPhar gear must be cross-calibrated with the Scintrex gear (see below).

D. I have designed one possible way to divide each line into parts that can usually be accomplished in one working day (see Figure 1). If for any reason experiences in the survey areas shows that some other method of field operation would improve the survey results or make surveying more efficient, changes should be made.

3. In the event that the Scintrex equipment breaks down, there are at least two other options.

A. The McPhar equipment be made ready for field operation, if it is not ready now, in the event that it must be used.

B. The Fluke multimeter belonging to DGGM can be used as a receiver. It can be used in the same way as a conventional resistivity receiver by connecting it to the potential electrodes. It will measure the following voltages:

- A constant voltage due to the self-potential SP effect (Bucked-out in Mcphar & Scintrex gear)
- A noise voltage due to telluric currents and electrical noise from culture
- The transmitted signal, which looks like this: +V, O, -V, O, +V etc. Thus, a typical set of Fluke data will have transmitted voltage and SP components as follows:

V1 = V + SP

V2 = SP   Transmitter off

V3 = -V +SP   Transmitter reversed

We can see that:

$$V = \frac{V1 - V3}{2}$$

For example, supppose the signal due to the transmitted current is 40mv, there is a constant 10mv SP signal and = 5mv of electrical noise, including telluric currents and the noise carried to the receiver by nearby powerlines. A typical set of Fluke data may look like this:

FLUKE READING (MV)

	XMTR (+)	XMTR OFF	XMTR (-)
	50	12	- 27
	54	13	- 33
	55	15	- 25
	48	10	- 34
	46	9	- 35
	49	6	- 32
	51	9	- 28
V1=	50.4		V3= -30.6

Averages of the high and low groups would be formed, and we would find:

$$V = \frac{V1 - V3}{2} = \frac{50.4 - (-30.6)}{2} = 40.5$$

which is close to the real voltage desired.

It is <u>important</u> to rate that if equipment is changed for any reason, the new equipment <u>must be cross-calibrated</u> with the Scintrex equiment. This can be easily done by <u>measuring 5 to 10 resistivity values with the new equipment that have already been measured with the Scintrex equipment</u>. The reason for doing this is that receivers made primarily for IP (induced polarization) work, as the Scintrex and McPhar receivers are, may not measure precisely the <u>true</u> value of resistivity, although the <u>relative</u> values of resistivity will be correct. (It is the relative values that are most important in resistivity surveying.) Thus, different sets of equipment will usually yield slightly different values for resistivity. If this is found to be the case with the McPhar or Fluke equipment, then cross-calibrated would allow us to determine a <u>constant correction factor</u> by which all of the McPhar or Fluke data would have to be multiplied in order for the values to match with data previously taken with the Scintrex equipment. For example, we may derive a correction factor as follows:

Scintrex Resistivity R1	McPhar Resistivity R2	R1/R2
29.5	32.4	0.91
36.8	40.7	0.90
103.2	112.6	0.92
47.6	51.4	0.93
66.9	73.3	0.91
	Average Correction Factor =	0.91

4. At times the received signal may be very low -- lower than the 0.3 mv full scale of the receiver at its most sensitive setting. This may be due to either of two causes:

   A. Low resistivity at depth. For a transmitted current of 5 amps, a signal of 0.3 mv n = 6 corresponds to a calculated resistivity of 19 ohm-m. If resistivity is lower than this value, the VP meter will not read to full scale.

   B. Cultural interference. At times, cultural interference will cause very low signal levels to be measured. This is due to redistribution of transmitted current by the cultural features, powerlines, pipelines, etc.

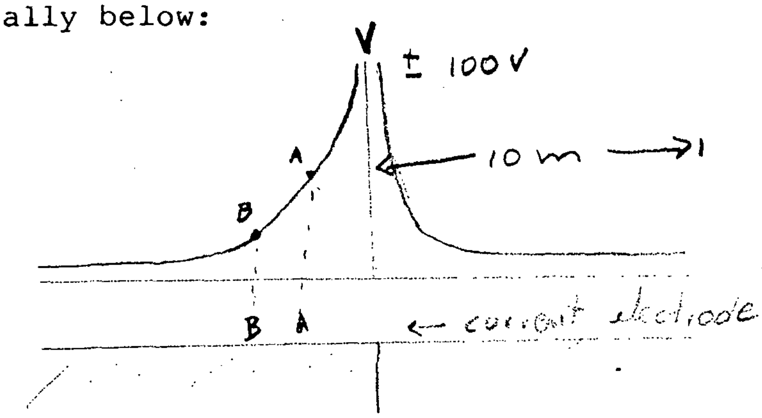
If low signal levels are a problem, it will be the decision of the field geophysicist whether or not to continue surveying or to move on to another part of the line. In general, I recommend that an attempt be made to continue because if the low signal is caused by cultural problems, the next dipole may not be affected by such problems. In any case, it is important to measure the signal level, even if it is below the full-scale deflection of the meter. This will allow a calculation of the maximum value the resistivity could possibly be, which is important to know.

5. The most reliable measurements can be made when the transmitted current is the maximum possible. This is especially true when n = 4, 5, or 6. For n = 1, 2, or 3 it will sometimes (but not always) be ok to transmit less than maximum current, but for n = 4, 5 or 6 the transmitter should always be operated so that maximum possible current is transmitted.

6. I recommend that the time of day be added to the field receiver notes for each receiver site. This will allow us to make judgements about possible changes in survey design on the basis of a more firm knowledge of the time consequences of such changes. It will also help document survey progress as a function of actual surveying time.

In the case that radio contact cannot be maintained between the receiver operator and the transmitter operator, it may be necessary to survey "on time", i.e. for the transmitter operator to transmit continously, changing depoles each 10 minutes. In this case, both the transmitter operator and the receiver operator must keep accurate records of the time at which they transmitted to or read a specific dipole.
It would be good practice, but not essential, for the transmitter operator to keep a set of notes showing dipole, current, time and comments.

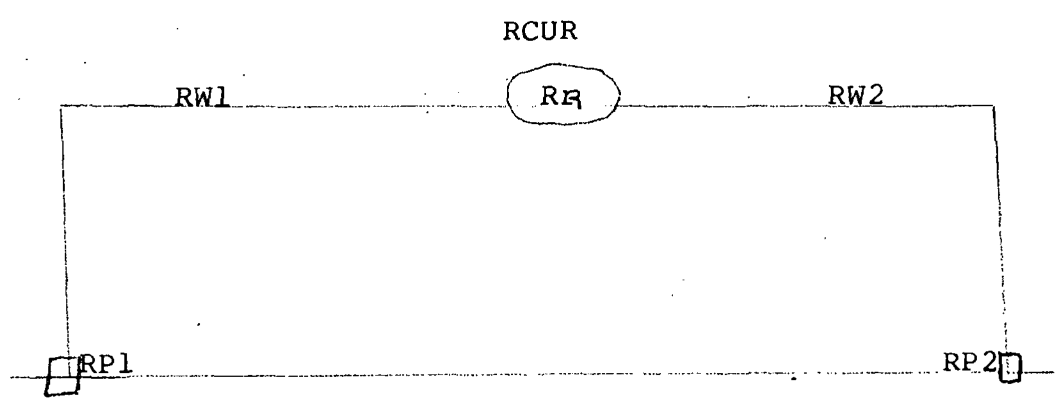
7. I recommend that an easily visible sign be made to be placed at each current electrode site to warn people, especially children, of the danger of touching or standing or laying near one of the electrodes. Voltages as high as 1500 volts above ground potential may be present in the transmitter wire. This is more than enough to kill someone. The voltage gradient away from an electrode is very high near the electrode, as shown schematically below:

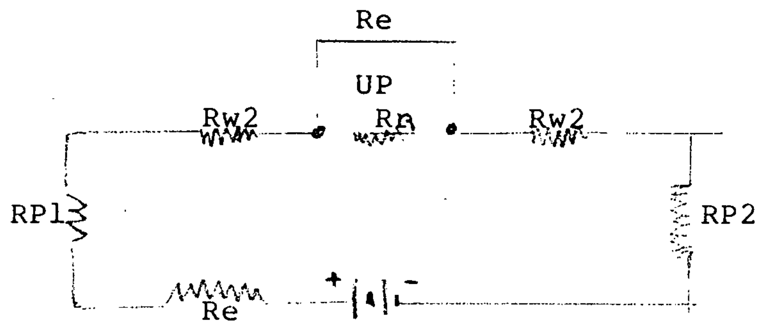


We can see from this diagram that a person stands with one foot at point A and the other foot at point B, he could be across a voltage of several hundred volts, and could be injured if his shoes are wet and conductive. This effect could be even worse for someone laying down near an electrode that is carrying current. One does not need to touch an electrode to be hurt. It would be wise never to stand closer than 2 - 3 m from an electrode, and never to touch an electrode.

If enough field helpers are available, I recommend that one be stationed at each electrode site to warn people away.

8. I recommend that the resistance of the potential electrodes be measured periodically. The input impedance of the Scintrex equipment is 3 megaohms ($3 \times 10^6 \Omega$). If the resistance of this value, than the resistivity value measured will be in error by 5%. A current diagram for the receiver when it is connected to the electrodes is shown below.





Rr = Resistance of receiver = 3 megaohms
Rpl, Rp2 = resistance of potential electrodes
Rwl, Rw2 = wire resistance
Re = resistance of the earth

Due to the transmitted signal, a voltage, V, is induced across the potential electrodes, as shown by the symbol for the battery. This voltage causes a small current, I, to flow in the circuit. There is a voltage drop across each of the resistances due to I. The voltage drop across Rr, the receiver, is what is measured as UP on the instrument. We want UP to Equal V, i.e. we want the receiver to measure the whole signal. But we can see that

$$V = I\ (Re + Rpl + Rp2 + Rwl + Rw2 + Rr)$$
$$= I\ (Re + Rpl + Rp2 + Rwl + Rw2) + IRr.$$

Now if $Rc = Re + Rpl + Rwl + Rw2 = 0.05\ Rr$.

Then 5% of the total signal voltage, V, well be dissipated in the potential electrode circuit, and IRr = 0.95V, so the receiver will measure only 95% of the true signal.

In order to prevent problems, which are unlikely in the Valle de los Chillos survey, we should measure Re + Rp1 + Rp2 + Rw1 +Rw2 = Rc with the Flube meter periodically, say once a day for one receiver depole. We will usually find that Rc will be less than, say, 10,000 ohms. IF Rc is as high as 1% of RR, i.e. if Rc _ 30,000 ohms, then measures should be taken to reduce Rc. This can usually be done by applying water to the holes dug for the potential electrodes. Only 1/4 to 1/2 liter should be enough. The muchacho who dig the electrode hole could carry a canteen or bottle of water to do this.

ANTICIPATED SURVEY PROGRESS AND SCHEDULE

During my mission in September, 1983, I studied air photos, maps that showed towns, urbanizations, power lines, railroads and other cultural features, and spent several days in the field, all for the purpose of deciding on a survey design. The results of this work were plotted on maps and documented in my report, delivered to INE, when I returned home, near the end of September. Since that time, topographic work has been done by Cartotecnia, S.A., who established, by survey, permanent points along each of these lines as well as plotting topographic and cultural features at a scale of 1:10,000. In some instances, lines had to be shifted somewhat from the positions that I originally recommended in order to avoid cultural objects. No adverse effects in the survey are expected from these shifts.

The September, 1983 report recommends the surveying of lines of varying length and varying numbers of current electrodes, roughly as follows:

Area	Number of lines	Number of current electrodes
Sangolquí - Tingo	12	69
Tumbaco - Cumbaya	4	17
La Merced - Ilalo	7	27
Totals	23	113

As the survey progresses, certain additional lines may be recommended, especially to obtain detailed data over resistivity anomalies of interests. Thus, the lines planned so far should be considered to be the minimun number.

In determining an approximate schedule for the survey, I have made a number of assumptions, as given below. If the actual survey is not conducted in accordance with these assumptions, then the schedule will not be accurate. The assumptions are:

1. In a normal day's work, 4 current electrodes can be established and 7 receiver sites associated wih these 4 current electrodes can be occupied for a total of 18 resistivity readings per day;
2. Twenty per cent of the total time will be lost because of bad weather, equipment breakdown, lack of adequate vehicles, training new field laborers and other unspecified occurrences that plague geophysical surveys the world over;
3. Additional lines will be planned to obtain detail over approximatly 10% of the area, increasing survey time by 10%.

During my second mission, progress has been much slower than this, and I assume that once the survey gets underway in earnest that a minimum of 4 full 6-9 hour days per week can actually be spent acquiring data.

Using these assumptions and the lines as presently planned, the aproximate surveying time will be as follows:

Area	Survey time (months)
Sangolquí - Tingo	4
Tumbaco - Cumbaya	1
La Merced - Ilaló	2
TOTAL	7

We can, therefore, anticipate the schedule given in figure 2.

Of course many factors could upset this schedule. Equipment breakdown is one event that is likely to cause problems. If the security equipment breaks down, the Mcphar gear could be used to continue surveying. It is recommended that the Mcphar equipment of UGGM be made operational, if it is not operational now, so that it would be ready if needed.

A second probable cause of loss of time would be lack of adequate field vehicles. The surveying crew and the resistivity crew will each need to have one truck all day for each day in the field.

ANTICIPATED SCHEDULE

SURVEYING AND INTERPRETATION

July	August	September	October	November	December	January	February	March
	surveying	Sangolquí	Tingo					
				Surveying La Merced - Ilaló				
						Surveying Tumbaco Cumbaya		
10 days Mission Wright				1	5 - day Wright Moore			2

1. Preliminary report, Sangloquí-Tingo
2. Final report, all areas

FIGURE 2

TESTING OF VARIOUS CURRENT ELECTRODES

One Wednesday, 4 July 1984 the field crew went to the Sangolquí - Tingo area in Valle de los Chillos to test various current electrodes and to assure ourselves that the Scintrex resistivity gear would operate correctly. We established current electrode positions at 1200s and 1500s along line ST-1. A variety of electrodes was tested:

a. aluminum foil
b. steel grate (parrilla)
c. copper stakes
d. stainless steel stakes.

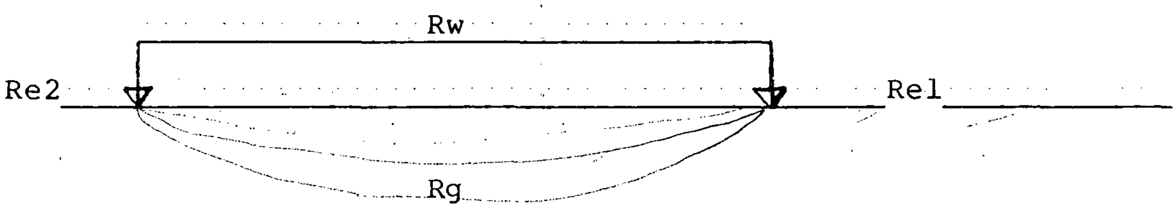
The aluminum foil was placed in the bottom of one pit about 12" wide x 24" long x 8" deep which had been watered and salted at each site. Steel grate was placed in a pit of about the same size and about 4" deep at each electrode site. The stake electrodes were all driven in about 18" deep and salted watered. Four copper and four steel stakes were used at each electrode site.

The soil conditions at each electrode site were similar. Soil was soft and clayey. The cipper 2 - 3[a] were dry, but the soil was quite damp below that depth. All electrodes were thus placed in damp soil, and the contact was further enhance by adding salt and water.

Once the electrodes were in place, wire was led from each of the four types to the transmitter station along a road, and then the four types were connected in turn to the transmitter. Voltage was increased on the transmitter until the maximun current obtainable was transmitted.

Typical electrode circuit resistances as measured by the transmitter and by a Fluke multimeter ranged from about 80 to more than 500 ohms. We found it difficult to obtain a reliable measure of electrode circuit resistance because the electrodes would normally become polarized, i.e. they acted like batteries, driving a very small current of their own through the meters and disrupting the resistance readings. This is a normal occurrence as the metal electrodes and does not often create a problem in making actual field resistivity measurements because the transmitter current is much larger than the polarizing current. In extreme situations, electrode polarization can cause problems in current regulation for the transmitter, but we saw no evidence that this was a problem in this case.

Although different sizes of wire were used to connect the four electrode types to the transmitter. The differences in wire resistance introduced into the circuit are not believed to be very significant because the main component of circuit resistance is due to the electrode contact with the soil. In the figure below, Rw is the resistance of the wire, Rg is the resistance of the earth and Re is the contact resistance of the electrode with the earth. The total circuit resistance, against which the transmitter works is Rti.



$$Rt = Rw + Re1 + Re2 + Rg$$

Because for short wire lengths, Rw _ Re, our tests are believed to be valid tests among the various electrodes.

As a result of these tests, we were able to classify the electrodes from best to worst as follows: steel stakes, steel grate, aluminum foil and copper stakes. Four steel stakes and the steel grate were about equal. Using fewer stakes would increase Rt, above, and decrease maximum current that could be transmitted.

I recommend that either steel stakes or steel grate (parrilla) be used, at least to begin the survey. If fewer than 4 stakes per electrode site are available, then a decision must be made about whether to buy more stakes (these are presently 11 steel stakes in DEEM at a cost of 2000 - 3000 sucres or to use steel grate. Steel grate may prove to be cheaper and faster to use than steel stakes.

DATA INTERPRETATION

Intrerpretation of geophysical data is a two-step process:

1. Interpretation of reduced and corrected field data in terms of the subsurface variations of the physical property being measured, in this case electrical resistivity; and

2. Interpretation of the subsurface variations of resistivity in terms of variations in subsurface geology and hydrology.

Step 1 is the speciality of the geophysicist. He is familiar with methods and techniques for interpretation. Of course, he must be careful not to make a geophysical model of the subsurface that is not gelogically realistic. Step 2 must be a cooperative effort between the geophysicist and the geologist and/or hydrologist. This is a critical stage in obtaining the best possible results from the survey, and people who understand the geophysical work must work closely with people who are in the best position to select among various geological options that would explain the geophysical data. Because step 2 is a cooperative effort, it will not be discussed here. In this section we will treat only step 1.

Geophysical interpretation (step 1) of dipole - dipole resistivity data is itself a very broad topic. Interpretation techniques range from the very simple to the very complex. Interpretation is always made in terms of models of the subsurface vanations in resistivity can be computed for an assumed model and compared with the observed variations. The model is then changed until an adequate agreement is reached between expected and observed variations.

Models fall into one of three general categories: 1 - dimensional, 2 - dimensional, and 3 - dimensional:

1 - D 1 - Dimensional (resistivity chages only vertically)	Layers are specified by depth to top and resistivity (P) only. Layers extend to infinity in horizontal directions.

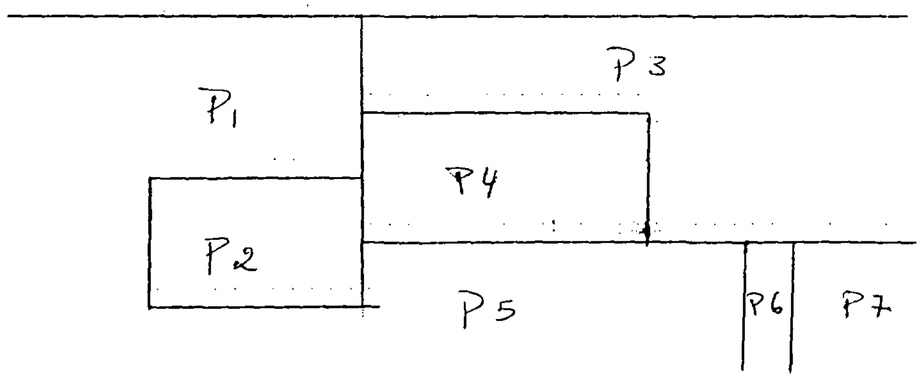
more than two layers may, of course, be presented.

2 - D - Dimensional (resistivity changes in the vertical and on horizontal dimension)	Bodies are bounded in 2 two dimensions, but extend to infinity in the third dimension
3 - D 3 - Dimensional (resistivity changes in all three dimensions).	Bodies are bounded in all three dimensions.

Mathematical formulations of the resistivity response over 1 - D bodies (layered - earth models) are quite simple; those over 2 - D bodies are reasonably complex; and mathematical formulations for the resistivity response of a 3 - D body is highly complex.

Of course, in building a reasonably realistic model of the subsurface, we must use generally use 2 - D or 3 - D models because the earth seldom displays resistivity chages only in the vertical direction. 1 - D models are therefore of limited use.

To build, say, a 2 - D model that as representative of subsurface resistivity changes usually requires us to put together the resistivity effects at the surface of several (5 - 20 or more) individual 2 - D bodies, as shown below:



Calculation of the resistivity effect at the surface of such a model quickly becomes more complex as more bodies are added, and a large computer running a complex program is required. The 3 - D case is even more complex. In general, 3 - D modeling is not used except to check 2 - D model results because 3 - D models require too much computer time. 2 - D models are adequate if resistivity chages are minimal for distances 3 - 6 times the electrode spacing (a) on each side of the time. This assumption is valid in a large number of cases.

In order to form a "first-guess" 2 - D model, various, simple interpretation techniques are applied. In fact, using these simpler interpretation technique can yield a great deal of information from the data in the field without resort to a computer. So, simple interpretation techniques can be used to:

1. Get a first overview of resistivity results, including variations in resistivity with depth, location of vertical or dipping contacts, etc.
2. Form a first model to begin computer interpretation.

Some simple interpretation techniques

Figures 3, 4, 7 and 8 show some very elementary models that are of use in thinking about interpretation. Figures 3 and 4 show the expected resistivity pseudosection for cases in which the earth is composed of only two layers - an upper layer of resistivity 100 dm - m and a lower layer of 10 dm - m. The differences among the models is that the depth to the top of the horizontal resistivity interface increases -- in Figure 3 (a). This depth is a/2, where a = electrode spacing = 300 m for our Valle de los Chillos survey. So inteface is 150 m. In Figure 3 (b) the depth is a = 300 m, in Figure 4 (a) the depth is 1.33 a = 400 m, and in Figure 4 (b) the depth is 2a = 600 m.

We notice several things from these models :

1. Contoures of values of resistivity are horizontal;
2. Resistivity decreases as electrode separation, n, increases, due to a deeper depth of exploration for larger n and the fact that the lower layer has lower resistivity;
3. For depth = 6/2 (Figure 3 a), the shallowest resistivity values (n=1) are less than half of the true upper - layer

resistivity, whereas for depth = 2 a (Figure 4 b), the shallowest resistivity values do reflect the upper layer resistivity. However, as depth increases, the deepest resistivity values (n = 6-8) are higher than the true lower layer resistivity.

4. The above items illustrate the very important point that the values of resistivity measured in the field are apparent resistivity only -- they are a kind of average of subsurface resistivities. Proper interpretation techniques must be applied to convert the values of apparent resistivity on the pseudosection to a model of true resistivity changes with depth.

5. In the case of these pseudosections, the horizontal apparent resistivity contours tell us immediately that the appropriate model is a layered earth. I have left a complete set of layered earth modeling curves with INE and OGGM, and have explained their use. Theoretical models for 3 or more layers quickly become difficult to use because the number of models needed to describe all possible combustions of resistivity and thickness becomes large. This layer earth curves are usually adequate for first overview interpretations.

6. Figures 5 and 6 illustrate how values of aparent resistivity are plotted versus electrode separation, nlignore the curves marked 0.01 - 0.5 on these Figures. After plotting the field data on this particular log - log

paper, the points are connected by a somooth curve, and then the observed curves are compared with various ones of the theoretical curves that I have given to INE and OGGM. Note that the curves that I have given to INE and OGGM. Note that the curves may be moved along the vertical (resistivity) axis to achieve a match, but the values of electrode separation (n) must overlie each other on both the theoretical and observed plots.

7. Figure 7 shows the models for a vertical resistivity contact. For 7 (a) the contact is locted between electrode positions, whereas for 7 (b) the contact is located at one of the electrode positions. Notice that the resistivity contrast across the interface is 10:1, as in the layered earth models. Important points to note are: (a) when both current and potential electrodes are wholly on one side of the interface, the true value of resistivity is measured; (b) when current and potential electrodes are on opposite sides of the interface, an intermediate value of resistivity is measured -- this intermediate value does not actually occur in the subsurface; (c) the intermediate value of resistivity is approximately constant in a pie - shaped are whose apex pocats toward the location on the surface that corresponds to the position of the contact. Thus the contact can be located by the anomaly shape, and the values of resistivity on each side can be determined (d) if the

contact is not vertical, but dips at same angle, this in general the dip must be shallower than about 45° before dip effects are seen on the pseudosections.

8. Figure 8 shows someshat more complex models. A vertical resistivity contrast is buried beneath a layer of varying thickness. On these models we can see effects of both the vertical contact and the horizontal upper layer. As we would expect, the picture is much clearer on Figure 8 (a), where the contact is shallower than on Figure 8 (b).

These models show only a modest beginning to those that should be considered for purposes of simple interpretation. I plan to send along more models and explanation when I return to the USA.

ACKNOWLEDGEMENTS

I want to acknowledge the help I have received from a number of people. Michel Lupoukhine provided a great deal of enthusiastic assistance in organizing the field work and getting it started. Milton Balseca was a key person in taking care of the many logistical problems associated with successful field work. The OGGM field geophysicists, Manuel Altamirano and Carlos Rodríguez provided competent and efficient inpetus to the field work. Marco Acosta helped me in discussions wiht others associated with the survey. The two USAID people whom I worked, Carl Duisberg and Hugh Pierson provided assistance in getting the INE-UURI contract in order as well as other help and encouragement. And last, but most importantly, Ing. Raúl Maldonado R., Executive Director of INE made it possible to achieve a signed contract. I thank each of these people very much.

TRANSMISSION OF DATA TO UTSA

We have agreed among INE, OGGM and UURI to transmit data to Utah on a weekly basis (or more frequently if needed) by using the USAID office. Carl Duisberg will mail the data to Utah.

Items that will be sent are:

(1) copies o the receiver notes

(2) copies of any transmitter notes

(3) copies of plotted apparent resistivity pseudosections and the plotting paper furnished by UURI

(4) a copy of the appropriate portron (s) of the map to show line and electrode locations.