BRITISH GEOLOGICAL SURVEY
Natural Environment Research Council

Cypriot Geological Survey Department (GSD)

Bureau de Recherche Géologiques et Minières (BRGM)

Technical Report WK/00/7

Geophysical exploration for groundwater resources over the volcanic rocks of the Troodos Ophiolite Complex, Cyprus

J P Busby & D Beamish

With contributions from GSD and BRGM

A contribution to the final report of INCO-DC Project 950176
'A new integrated geophysical approach for the rational management and exploration of groundwater resources'

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A view towards the disused sulphide mine at Mitsero on Lower Pillow Lavas.

A report prepared under INCO-DC Project 950176 for:
European Commission
DG-XII
Directorate B
Programme INCO-DC
75, Rue Montoyer
B-1040 Brussels

Keyworth, Nottingham

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Regional Geophysics Series

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Summary

The volcanic rocks of the Troodos Ophiolite Complex in Cyprus represent a poor groundwater source. However in regions where groundwater systems are developed along fracture zones, water boreholes are capable of providing water for the local community, particularly for agriculture. In order to increase the success rate of water boreholes several geophysical methods were trialed to investigate their ability to locate and charaterise fracture zones.

Azimuthal apparent resistivity (AZR), very low frequency electromagnetics (VLF) and audio-magnetotellurics (AMT) were applied at a number of test sites on the Upper and Lower Pillow Lava series and pillow lavas and dykes of the Basal Group. No distinct fracture zones were identified by the measurements. A conductive zone was identified over pillow lavas by AMT, but may have been due to a porous/more fractured layer or the conductive pillow lavas. The AZR results clearly demonstrate the heterogeneous nature of the Troodos volcanic rocks. Fracturing, where it has been identified, appears to be localised and to be of limited lateral extent. Azimuthal apparent resistivity is unlikely to be successful as a primary geophysical technique in the exploration for groundwater resources over the Troodos volcanic rocks. However it may be useful as a secondary technique, perhaps for tracing the strike of a known fracture zone which gives high water yields. Due to the conductive nature of the pillow lavas the resistivity contrast offered by any near-surface fracture zones will inevitably be small and likely to be below the detection limits of VLF.

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1. TROODOS OPHIOLITE FRACTURED AQUIFERS

The Troodos Massif is formed almost entirely of Cretaceous basic and ultrabasic igneous rocks. There is a complete ophiolite sequence (Gass, 1980) ranging downwards from pillow lavas, through a sheeted intrusive complex to a plutonic complex. Late Tertiary uplift (Robertson, 1977) centres on a serpentinite diapir beneath the summit of Mt. Olympus. A large positive gravity anomaly, exceeding 250 mGal, (Gass and Masson-Smith, 1963) indicates underlying dense ultramafic rocks, of the order of 30 km thick, which dip northwards below the island.

The pillow lavas extend in an incomplete ring around the periphery of the massif in a metamorphosed belt of pillow lavas and dykes. The series is divided into the Upper and Lower Pillow Lavas, the division being based upon a metamorphic discontinuity (Gass and Smewing, 1973). The Upper Pillow Lavas are dominantly olivine basalts with limburgite and picrite units and lie on the undulatory upper surface, sometimes unconformably, of the more siliceous Lower Pillow Lavas, which in turn are cogenetic with the Sheeted Intrusive Complex. In order to satisfy the hydrous conditions required by the geochemistry it is likely that the Lower Pillow Lavas are part of an axis sequence, erupted at a minor spreading axis in a marginal sea above a subduction zone. The Upper Pillow Lavas were erupted slightly off-axis and after the axis sequence had been metamorphosed. (Gass, 1980).

The pillow lavas are considered to be an aquiclude with the exception of weathered zones and highly fractured systems.

1.1. PHREATIC SHALLOW AQUIFER

In the upper part of the pillow lavas is a weathered layer of variable thickness which in places exceeds 30 m. Within this layer is a poor, shallow aquifer where the general direction of groundwater flow is towards the north. The water level ranges from a few metres down to 25 m below the ground surface. The aquifer is of only local importance and is exploited by farmers through shallow, large diameter wells. The yield of the wells is greatly dependent on the thickness of the weathered zone and the clay content.

1.2. CONFINED WATER SYSTEMS

Groundwater systems are developed along fracture zones in regions where the pillow lavas are highly fractured. The general direction of groundwater flow is towards the north, although it can vary locally. In most of the boreholes groundwater is found at a depth of 100 to 200 m, although fracturing can occur down to 300 m. Borehole yields vary from a few cubic metres per day up to 30 cubic metres per hour.

2. PROBLEM DEFINITION

In order to increase the success rate of water boreholes drilled into the pillow lavas, geophysical survey techniques are required which will locate and characterise fracture zones. Parameters that need to be defined are the length, width, orientation and depth of the fracture zone, the intensity of fracturing, fracture connectivity, fracture porosity and the depth of the water table. Only some of these parameters can be estimated from a surface geophysical measurement and they are dependent on physical property contrasts within the depth range of the measurements. The water level is generally found at depths in excess of 100 m and due to the low resistivity of the pillow lavas (typically 10 – 50 ohm.m) is likely to be a difficult interface to detect. Similarly there is probably only a small electrical conductivity contrast between the host rock and the fracture zones.

3. GEOPHYSICAL SURVEY

Three geophysical techniques were applied and these are briefly described below.

3.1. AZIMUTHAL APPARENT RESISTIVITY (AZR)

Azimuthal apparent resistivity measurements are made by rotating an electrode array through 180° or 360° and taking measurements along a sufficient number of azimuths to define any variation of apparent resistivity with orientation. When plotted in polar form if the apparent resistivity variation conforms to an ellipse then it is taken to indicate anisotropic homogeneity. The orientation of the major axis of the ellipse is usually interpreted as indicating the strike direction of a sub-vertical fracture set or the direction of greatest fracture connectivity (Taylor and Fleming, 1988). Measures of the anisotropy can be used to estimate fracture intensity (Busby and Peart, 1997) or fracture porosity (Taylor and Fleming, 1988). The coefficient of anisotropy, l is defined as

$$l = \sqrt{\frac{r_y}{r_x}} = \frac{r_{x_{app}}}{r_{y_{app}}}$$

where r_y is the true resistivity normal to the fractures, r_x is the true resistivity parallel to the fractures, $r_{x_{app}}$ is the apparent resistivity parallel to the fractures and $r_{y_{app}}$ is the apparent resistivity normal to the fractures. For this study the co-linear Offset Wenner array (Barker, 1981) was found to be appropriate. In this arrangement there are five equally spaced electrodes. A standard Wenner measurement is made with the left four electrodes (r_{D1}) and then a second with the right four (r_{D2}). Their average is taken as the apparent resistivity for that spacing and is denoted by $r_{D1,D2}$. These two offset measurements should be equal over anisotropic homogeneous ground. Any difference between r_{D1} and r_{D2} indicates a dependence of apparent resistivity with the position of the electrode array. This may be due to near surface lateral effects or anisotropic inhomogeneity, such as a dipping interface. As indicated by Nunn et al. (1983) the variation due to lateral effects must be smaller than the variation due to anisotropic homogeneity before a fracture azimuth can be recognised.

3.2. VERY LOW FREQUENCY ELECTROMAGNETICS (VLF)

The VLF method uses government-operated radio wave transmitters operating at between 15 and 25 kHz. Although providing a distant (i.e. plane-wave) and powerful EM energy source, the limited bandwidth means that, although several measurements may be obtained using different frequencies (transmitters), a main attribute of the method is that of a single frequency sounding. As described by Beamish (1998), the main use of VLF in a hydrogeological context is to detect zones of lateral variability (faults etc.) in the near-surface.

On Cyprus, the strongest N-S transmissions were found at frequencies of 18.0, 18.1 and 23.5 kHz. In practice all these transmissions were found to be highly intermittent. The most reliable and strong VLF transmission was the 18.3 kHz transmission (HWE, Le Blanc, France). This transmission provides an E-W directed electric field for surveying and was used extensively during the VLF surveys.

Near-surface resistivities in the areas investigated ranged from 10 to 100 ohm.m (although predominantly closer to the lower value). The skin-depths (in uniform formations) at 18.3 kHz are 11.75, and 37.18 m, respectively. Aproximate depths of investigation are 17.6 and 55.8 m, respectively.

The VLF-Z method measures the amplitude/phase relationship between the vertical (secondary) magnetic field (Z) and the horizontal primary field (H). This is an entirely inductive measurement and relies on the VLF field interacting with 2D and 3D structure. The VLF-R measurement includes a measurement of the induced electric field (E) component and provides an impedance value usually expressed as apparent resistivity and phase. Both VLF-Z and VLF-R measurements were performed. Measurements were made along profiles at 5 m intervals using the Scintrex IGS-2 equipment.

3.3. AUDIO-MAGNETOTELLURICS (AMT)

Magnetotelluric methods use the measurement of natural magnetic and electrical fields at the ground surface created by remote sources such as solar magnetic activity or lightning. AMT operates in the frequency range 10^4 – 10 Hz with a depth of investigation ranging from tens of metres to a few kilometres. Raw data are presented as graphs of apparent resistivity against frequency. During the present survey the highest frequency used was 7500 Hz with the result that layers in the depth range above approximately 60 m will be only approximately defined. The data were therefore augmented with VLF data operating in the 16 – 22 kHz range. Interpretation is one-dimensional generating layered models of resistivity versus depth.

3.4. EXPECTATIONS FOR THE GEOPHYSICAL SURVEYS

The initial azimuthal apparent resistivity measurements were taken in a reconnaissance mode at widely spaced stations. Any identified aligned fracturing would be expected to indicate a fracture zone and its strike. Further detailed measurements would then allow estimates of relative fracture intensity to be made in the vicinity of the fracture zone. VLF measurements were made along profiles at the same localities as the azimuthal resistivity measurements in order to determine if any fractured areas corresponded to near surface zones of altered resistivities. AMT soundings were intended to determine the resistivity distribution with depth. Conductive layers may be more porous and/or more fractured.

3.5. DATA COLLECTION

Two main survey areas were established on Lower Pillow Lavas at Klirou and Mitsero. North-south faulting is mapped at both localities and a water borehole is located at Klirou. In addition sites were also established at Lythrodondra (northwest faulting within Lower Pillow Lavas), Mathiatis (north-northwest and northwest faulting in Upper Pillow Lavas) and Stavrovouni (Basal Group with some north - south oriented faulting). Locations of the measurements are tabulated in Table 1 and location maps for the Klirou and Mitsero areas are shown in Appendix 1. Some additional VLF data were collected in two areas at Klirou and Mitsero and these are shown on the location maps.

Method	**Station No.**	**Area**	**Easting**	**Northing**	**AZR array spacing**	
					min	**max**
AZR	**KL-L1S0**	**Klirou**	**517082**	**3874193**	**2**	**64**
AZR	**KL-L1S1**	**Klirou**	**517055**	**3874285**	**2**	**64**
AZR	**KL-L1S2**	**Klirou**	**517010**	**3874394**	**2**	**64**
AZR	**KL-L1S3**	**Klirou**	**516955**	**3874480**	**2**	**64**
AZR	**KL-L1S4**	**Klirou**	**516927**	**3874559**	**2**	**64**
AZR	**KL-L2S5**	**Klirou**	**517110**	**3874380**	**2**	**64**

AZR	KL-L2S6	Klirou	517188	3874374	2	32
AZR	KL-L2S7	Klirou	516800	3874387	2	32
AZR	KL-L3S8	Klirou	517165	3874461	2	32
AZR	KL-L3S9	Klirou	517180	3874318	2	32
AZR	KLG1	Klirou	517224	3874393	4	8
AZR	KLG2	Klirou	517230	3874374	4	8
AZR	KLG3	Klirou	517249	3874380	4	8
AZR	KLG4	Klirou	517243	3874399	4	8
AZR	KLG5	Klirou	517211	3874368	4	8
AZR	KLG6	Klirou	517205	3874387	4	8
AZR	MI-L1S1	Mitsero	511210	3877175	2	32
AZR	MI-LIS2	Mitsero	511194	3877090	2	32
AZR	MI-L1S3	Mitsero	511130	3877005	2	32
AZR	MI-L1S4	Mitsero	511045	3876823	2	32
AZR	MI-L2S1	Mitsero	511105	3877328	2	32
AZR	MI-L2S2	Mitsero	511175	3877330	2	32
VLF	VLFK1	Klirou	517235	3874375	(start)	
			516735	3874375	(end)	
AMT	31	Klirou	517110	3874380		
AMT	32	Klirou	517010	3874394		
AMT	33	Klirou	516800	3874387		
AMT	34a,b	Mitsero	511045	3876823		
AMT	35	Klirou	511080	3877035		
AMT	36	Mitsero	511235	3877316		
AMT	37	Mitsero	517110	3874380		
AZR	L/1	Lythrodondra	529705	3868385	2	32
AZR	L/2	Lythrodondra	529260	3868200	2	32
AZR	M/1	Mathiatis	531480	3872305	2	32
AZR	M/2	Mathiatis	531100	3872124	2	32
AZR	S/1	Stavrovouni	540075	3862360	2	32
AZR	S/2	Stavrovouni	540190	3862410	2	32
VLF	VLFL1	Lythrodondra	529570	3868130	(start)	
			529600	3868660	(end)	
VLF	VLFL2	Lythrodondra	529360	3868120	(start)	
			529665	3868670	(end)	
VLF	VLFM1	Mathiatis	530970	3872140	(start)	
			531270	3872135	(end)	

VLF	**VLFM2**	**Mathiatis**	**530980**	**3872170 (start)**	
			531265	**3872165 (end)**	
VLF	**VLFS1**	**Stavrovouni**	**539860**	**3862280 (start)**	
			540365	**3862490 (end)**	

Table 1. Locations of geophysical observations over the Troodos igneous rocks. VLF data were collected along linear profiles, which are referenced by the co-ordinates of their start and end points and also in two areas, shown in Appendix 1.

4. RESULTS

The azimuthal apparent resistivity measurements were processed using methods described by Busby (1999a,b) to identify soundings where the azimuthal variations were due to homogeneous anisotropy (fracturing) as opposed to other causes of anisotropy (lateral variations). Out of a total of 128 soundings only 18 (14%) were considered to display anisotropic effects which might be attributable to fracturing. These were distributed between the measurement sites and not clustered as might be expected from a fracture zone. They demonstrate the heterogeneous nature of the Troodos volcanic rocks.

At Klirou (station KL-L2S6) for Wenner array spacings of 4 and 8 m the data indicated a clear fracture azimuth orientated north-south (see Figure 1). The coefficient of anisotropy, l, was equal to1.38. Further measurement sites, separated by 20 m, were established around this station (KLG1 – KLG6). The result was repeatable at KL-L2S6, but was not obtained at any of the new stations. This implies that the fracturing is shallow, localised and is not laterally continuous.

At Lythrodondra, on Lower Pillow Lavas, a clear fracture azimuth was indicated orientated at

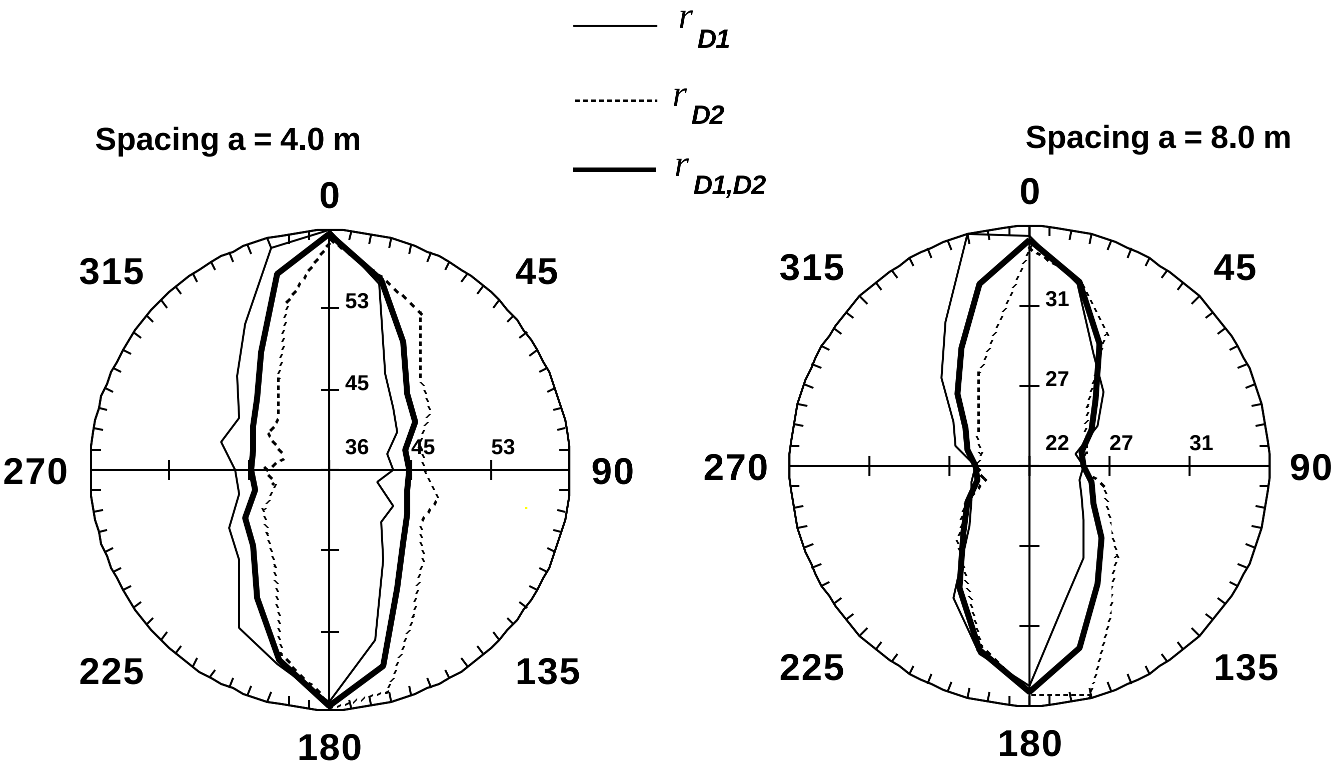

Figure 1. Azimuthal apparent resistivity ellipses measured at KL-L2S6 at Klirou, exhibiting north-south orientation.

160° and generated a coefficient of anisotropy l, of 1.22 (see Figure 2). This azimuth is consistent with the orientation of mapped faulting. A water borehole is located on the site. It is not possible to determine if the borehole has been fortuitously sunk in a highly fractured zone, as indicated by the azimuthal resistivity, or whether the effect of water abstraction is to heighten physical property contrasts within the rockmass.

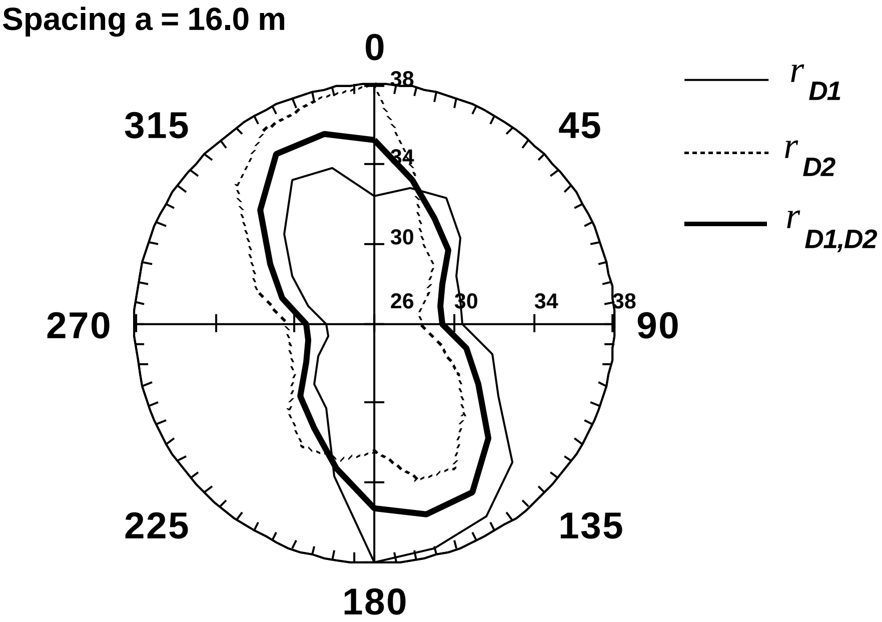

Figure 2. Azimuthal apparent resistivity ellipses from Lythrodondra L/2. The estimated orientation of fracturing, utilising an array spacing of 16 m, is 165°. The average value obtained from all soundings considered to be significant at Lythrodondra is 160°.

The VLF apparent resistivity data in all the Troodos survey areas (Table 1) indicated a highly conductive near-surface zone. The resistivities encountered were typically 10 ohm.m or less across substantial areas. The effect is attributable to extensive weathering of the pillow lavas. The depth of investigation in the conductive environments encountered is less than 20 m. The apparent resistivity data obtained at Klirou (Lower Pillow Lavas) are shown in Figure 3. Apart from a zone of interference associated with a pipe/cable run along a track, the resistivity values average about 7 ohm.m. and the detection of lateral effects is minimal. Data collected in the VLF areas at Klirou and Mitsero detected no anomalies attributable to fracture zones (Eleftheriou, 1999). A similar picture emerged at the other survey locations, as shown by the data from Mathiatis in Figure 4.

The purpose of the VLF surveys was to investigate lateral effects (fractured zones) which would appear, typically, as a conductive anomaly within the background. Such surveys proved effective in the far more resistive (reef limestone) environment of Xylophagou (Beamish, 1998). No such conductive/fracture zones were detected by the Troodos VLF surveys. The negative outcome may be attributable to the fact that the resistivity contrast offered by any near-surface zones, if present, is below the detection limits of VLF.

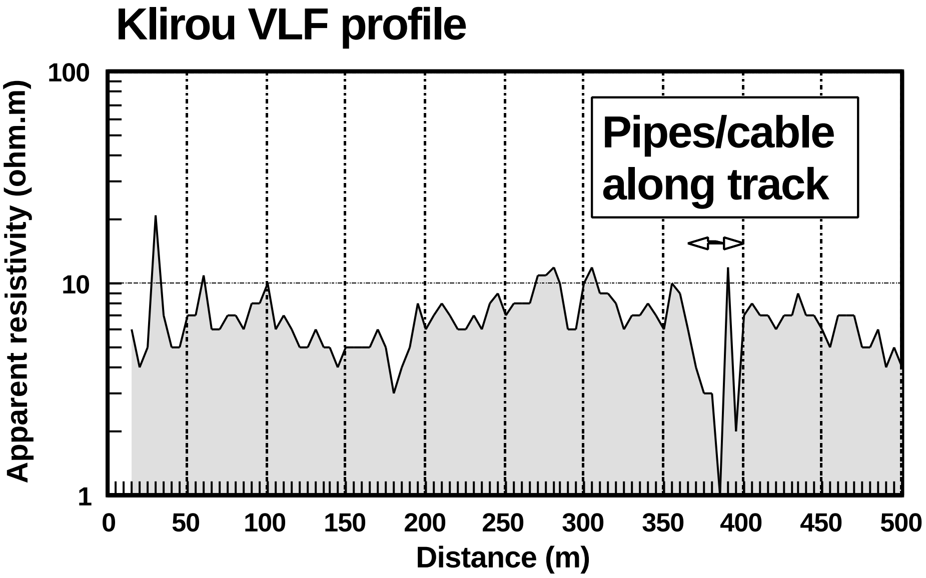

Figure 3. VLF-R apparent resistivity data obtained along the traverse at Klirou (VLFK1), Lower pillow lavas. Frequency is 18.3 kHz, sampling is 5 m.

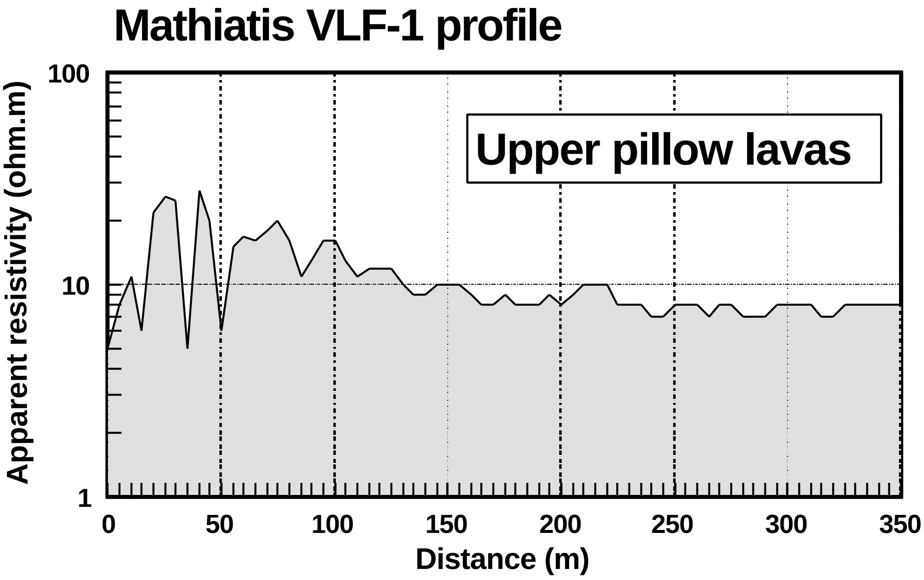

Figure 4. VLF-R apparent resistivity data obtained along the traverse at Mathiatis (VLFM1). Upper pillow lavas. Frequency is 18.3 kHz, sampling is 5 m.

The processing and interpretation applied to the AMT data are described in Legchenko et al. (1997). Interpreted results from Mitsero and Klirou are shown in Figure 5. At both areas a conductive layer was interpreted between more resistive surface and deeper layers. One possible explanation is that the conductive layer is more porous and/or more fractured and is saturated with salty water. Alternatively the conductive layer may be due to weathered pillow lavas, which are known to be conductive, overlying the more resistive sheeted dyke complex.

The pillow lavas have been altered by hydrothermal metamorphism, which occurred soon after their formation.

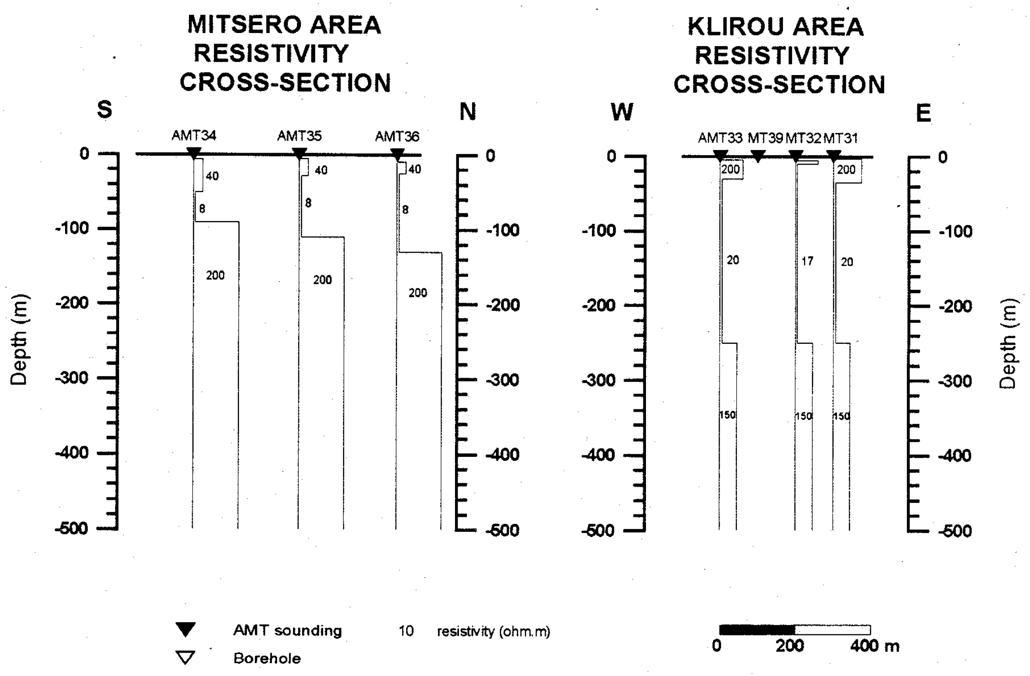

Figure 5. One dimensional resistivity interpretations of the AMT data.

5. INTEGRATION

All three data sets illustrate the conductive nature of the pillow lavas and Basal Group assemblage of pillow lavas and dykes. No correlations were found between the AZR and VLF measurements, both of which investigated to shallow depth. The deeper penetrating AMT indicated regional scale conductivity layering.

6. CONCLUSIONS

No distinct fracture zones were identified by the measurements. The only technique providing information to a sufficient depth to identify the water level was AMT, but it was not able to do so. A conductive layer was identified, but it may have been due to a porous/more fractured layer or the conductive pillow lavas.

The AZR results clearly demonstrate the heterogeneous nature of the Troodos volcanic rocks. Fracturing, where it has been identified, appears to be localised and to be of limited lateral extent. Azimuthal apparent resistivity is unlikely to be used as a primary geophysical technique in the exploration for groundwater resources over the Troodos volcanic rocks. However it may be useful as a secondary technique, perhaps for tracing the strike of a fracture zone which is known to give high water yields.

Due to the conductive nature of the pillow lavas the resistivity contrast offered by any near-surface fracture zones will inevitably be small and likely to be below the detection limits of VLF.

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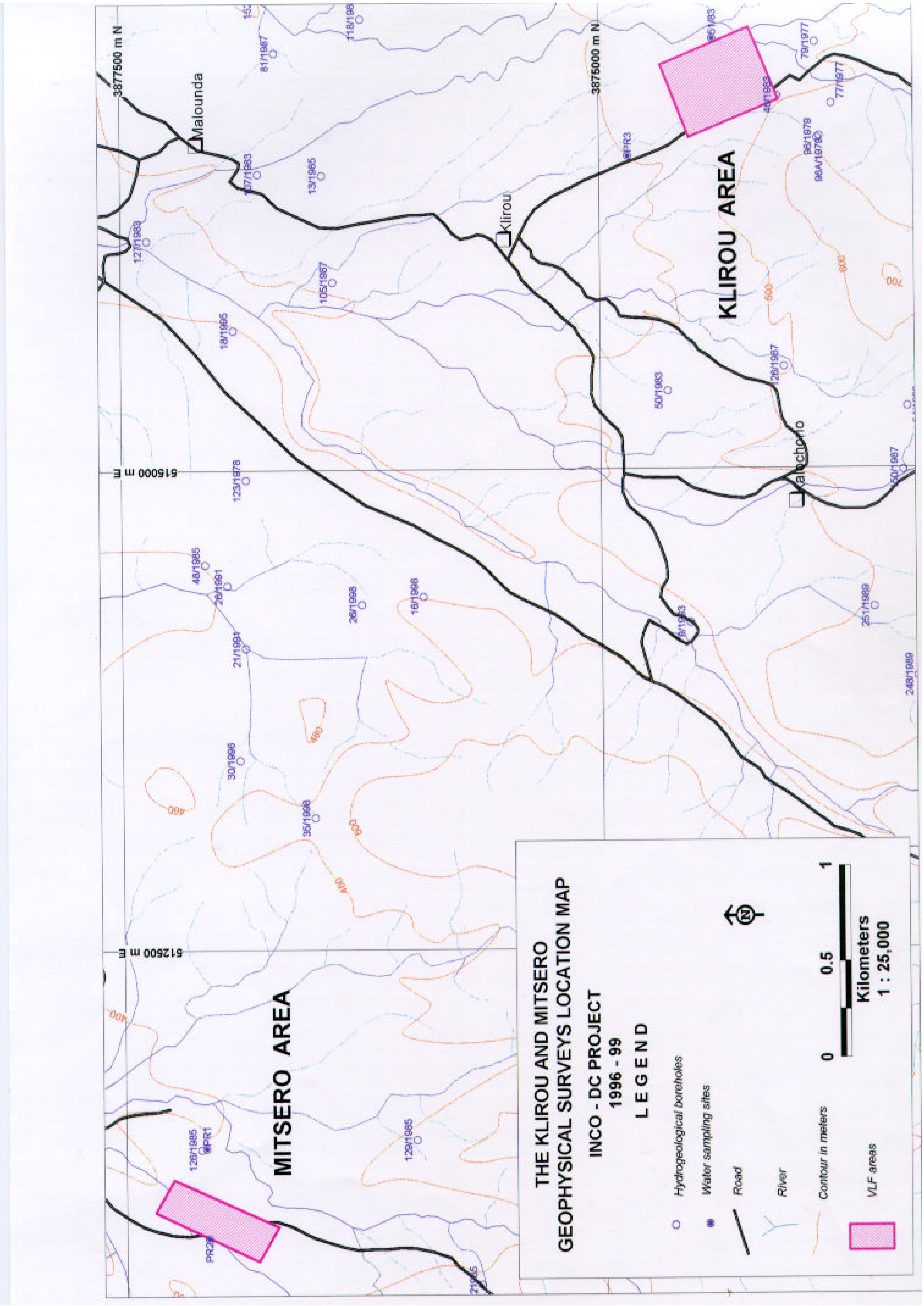
APPENDIX 1

Location maps of the geophysical surveys at Klirou and Mitsero


THE KLIROU AND MITSERO
GEOPHYSICAL SURVEYS LOCATION MAP
INCO - DC PROJECT
1996 - 99
LEGEND
Hydrogeological boreholes
Water sampling sites
Road
River
Contour in meters
VLF areas
0
0.5
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Kilometers
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KLIROU AREA
MITSERO AREA
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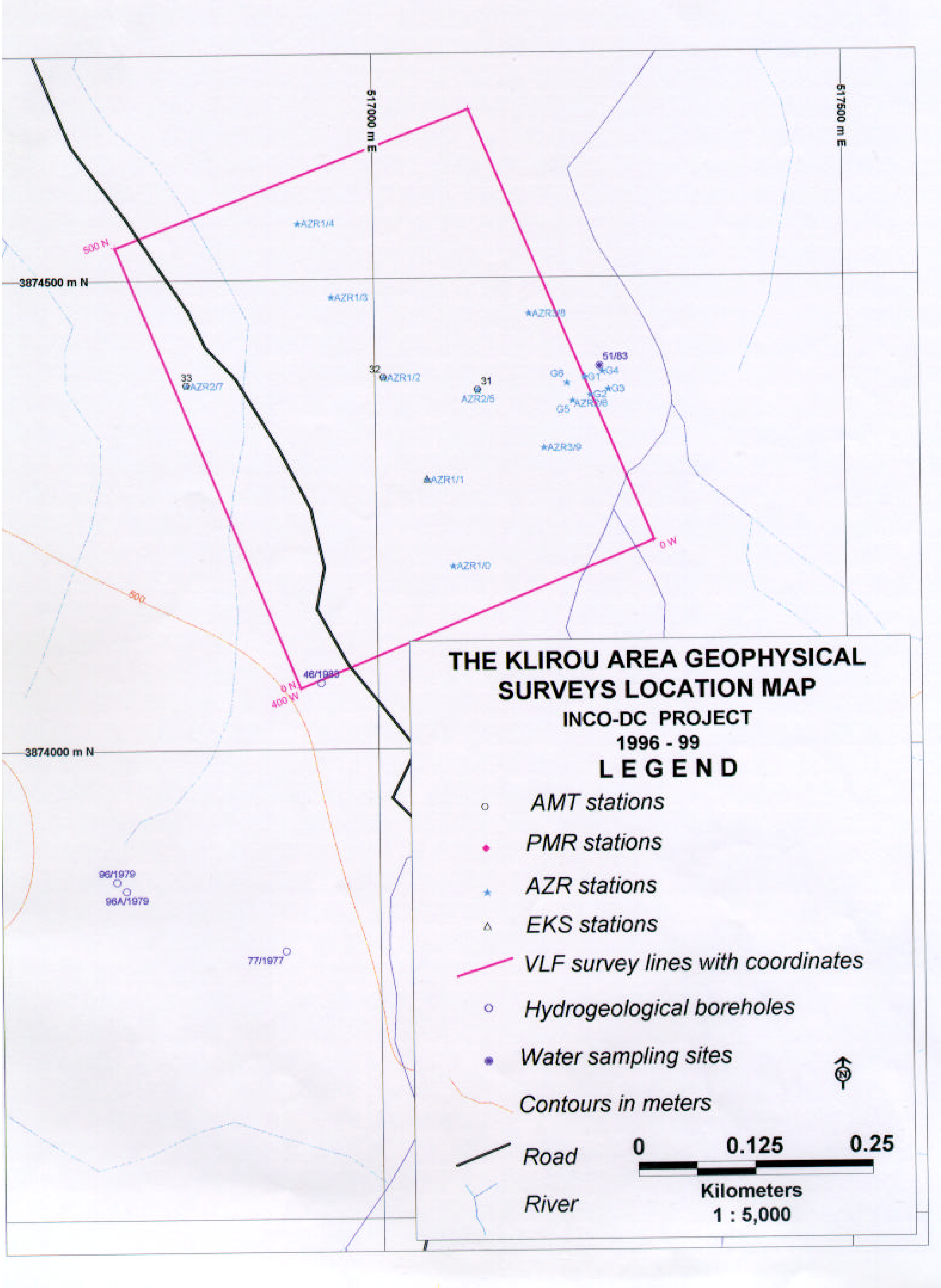
THE KLIROU AREA GEOPHYSICAL SURVEYS LOCATION MAP
INCO-DC PROJECT
1996 - 99
LEGEND
AMT stations
PMR stations
AZR stations
EKS stations
VLF survey lines with coordinates
Hydrogeological boreholes
Water sampling sites
Contours in meters
Road
River
0
0.125
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Kilometers
1 : 5,000
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517000 m E
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0 W
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AZR1/4
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AZR1/1
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AZR3/8
AZR3/9
AZR3/6
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G1
G2
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G4
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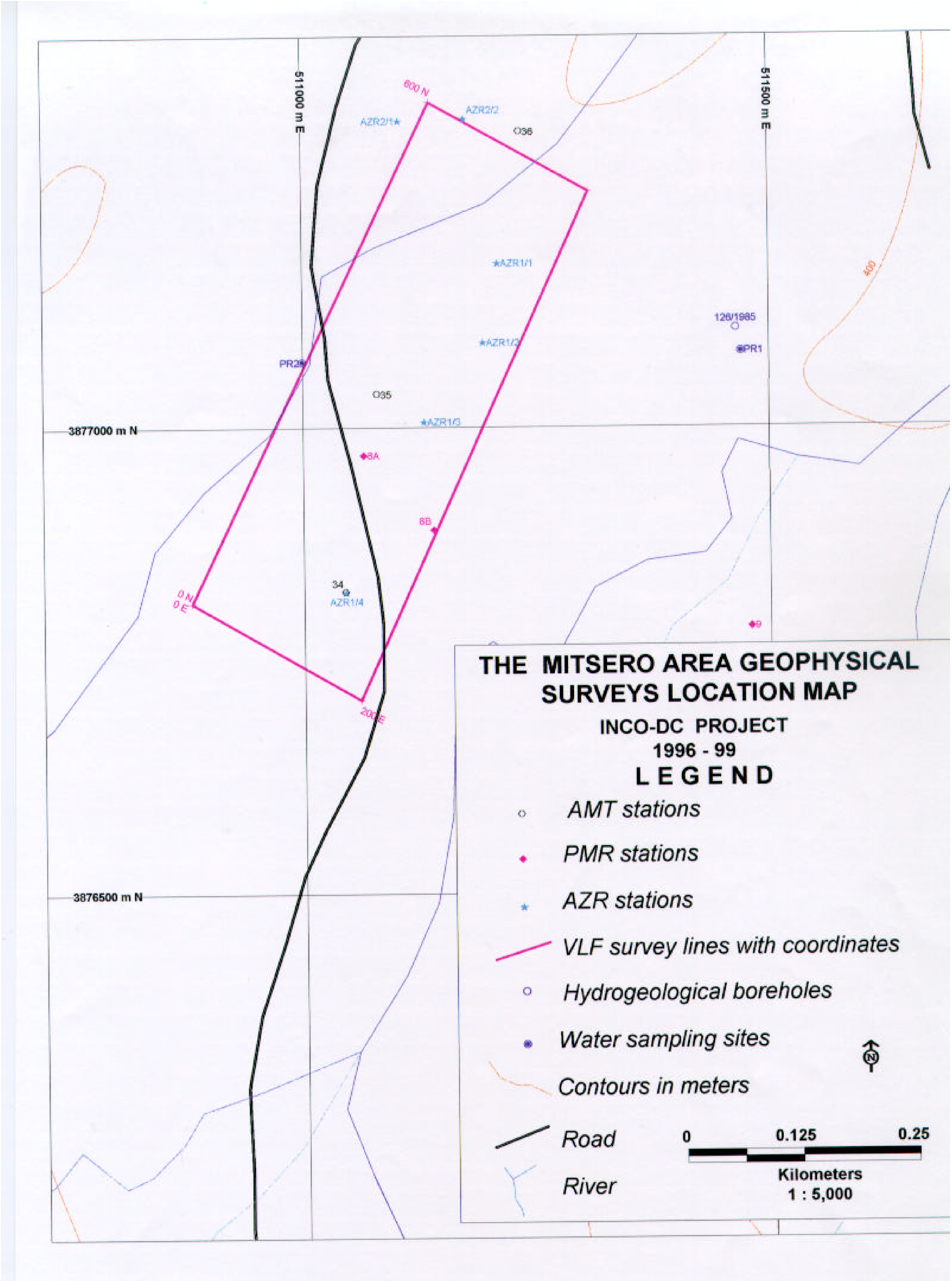
96/1979
96A/1979
77/1977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AZR1/1
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126/1985
PR1
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PR2
O35
3877000 m N
AZR1/3
8A
8B
34
AZR1/4
0 N
0 E
200 E
9
3876500 m N
THE MITSERO AREA GEOPHYSICAL SURVEYS LOCATION MAP
INCO-DC PROJECT
1996 - 99
LEGEND
AMT stations
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VLF survey lines with coordinates
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Contours in meters
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River
N
0
0.125
0.25
Kilometers
1 : 5,000