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ELECTRO KINETIC MEASUREMENTS IN VARIOUS HYDROGEOLOGICAL ENVIRONMENTS OF ZIMBABWE, 1995

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Making an EK observation at Hatcliffe (Willowtree site) near Harare, Zimbabwe

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1. SUMMARY

The recently developed and still largely experimental electro kinetic sounding (EKS) technique was used in November 1995 in Zimbabwe. The purpose of the survey was to investigate and possibly calibrate the EK sounding methodology in a variety of diverse hydrogeological environments which included some existing groundwater sources. The overall project aim is to improve the efficiency of borehole and well siting in difficult overseas' terrains and hence alleviate water scarcity.

The hydrogeological settings comprise borehole sites in a variety of geological contexts, existing collector well sites and sand rivers. The data obtained, both geophysical (EK soundings) and hydrogeological, constitute our (BGS) first main overseas evaluation of the EK methodology that was introduced by Groundflow Ltd., the suppliers of the equipment. The emphasis of the work lay in obtaining good quality data and in carrying out tests to improve data quality in the context of the various hydrogeological environments. A significant portion of this report (Section 6) describes these early assessments of data quality.

More significantly, the methodology of the EK technique (as originally stated) has been examined in more detail since this work was performed. A number of extensive, multi-channel control experiments by ourselves and other groups (Butler et al., 1996; Mikhailov et al., 1997) have demonstrated a number of seismic waves that have to taken into account when interpreting EK voltage recordings. The recording of only two channels of information does not provide discrimination of the variety of EK modes that are routinely observed. The suggested modus operandi of the supplied equipment and methodology is to 'assume' that only vertically-propagating seismic waves produce EK coupling. On this basis 'time' may be converted to depth and an interpretation can proceed. This assumption is now considered flawed and an interpretation based on the two-channel methodology used in the 1995 survey is likely to be grossly in error.

This report summarises the geophysical and hydrogeological data that were obtained in the three main contexts of (i) boreholes, (ii) collector wells and (iii) sand rivers. The EK sounding data are only presented in cases where 'good quality' (meaning consistent and repeatable) data were obtained. No attempt is made to process/interpret the EK data through to hydrogeological information as suggested by the suppliers of the equipment. The data obtained and the data acquisition and interpretational procedures in-place are now considered 'insufficient' and 'flawed' for the stated hydrogeological purposes.

2. INTRODUCTION

This report describes an extensive fieldwork programme conducted in collaboration with the Department of Water Development (DWD) in Zimbabwe during November 1995 in support of the ODA TDR Project R6232 "Development of a new well siting technique". This project aims to assess to what extent a new, non-invasive surface geophysical technique known as Electro Kinetic Surveying (EKS) is able to map the saturated permeability/depth distribution of various lithologies and predict the presence and depth of groundwater. In addition we aim to develop and refine both the existing equipment and the field and interpretational techniques. The overall project aim is to improve the efficiency of borehole and well siting in difficult overseas' terrains and hence alleviate water scarcity.

We first give an outline of the EKS technique and the methods of collecting, processing and interpreting EK data; then follows a summary of the present field work. We then describe some typical results and problems encountered during this study before presenting specific results on a site by site basis, with each section preceded by a brief description of the geological- and hydrogeological setting.

3. AN OUTLINE OF THE EKS TECHNIQUE

The physical principle of EK geophysics is the conversion of acoustic (seismic) energy to an electromagnetic (EM) oscillation at a subsurface interface between saturated (permeable) and non-saturated formations. Dry or impermeable rocks do not generate an EK signal.

The fundamental feature that characterises the EK technique is that it directly stimulates fluid movement in relation to the rock matrix and then measures the response of the movement. Relative movement of pore fluids results in a net displacement of the charge potential that exists at pore walls (termed the electrical double layer). When relative motion is induced momentarily by a downgoing compressional seismic pulse an electric field is generated. The electric field produced is measured at the surface using pairs of grounded dipoles. When the two channel voltages are in-phase (the actual polarity of one of the channels having been reversed in the display) and repeatable, they are interpreted as an EK signal generated directly below the shot point. Noise (non-EK behaviour) will be observed above (or in the absence of) a subsurface, permeable and saturated horizon. Noise is identified as time-dependent behaviour which is 'independent' across the two channels. In practice, voltages are also generated by the seismic pulse traversing zones of partial saturation and such voltages must be taken into account in the EK interpretation.

The degree and character of the rock/fluid response is related to the ability of fluid to flow within a particular formation. The observed response is therefore related to the porosity/permeability of the formation. A highly simplified schematic of the principle of EK sounding is shown in Figure 3.1. Field tests confirm that in the limit of very low subsurface permeabilities (e.g. thick clay deposits and near-surface tight limestones) the field system consistently returns only very small voltages (typically < 0.1 mV/m) since no significant EK coupling takes place.

The basic EK field system comprises two dipole receivers positioned symmetrically about a shot point. The seismic source is a sledge-hammer blow on a metal plate. Typically a 7 kg hammer and a cylindrical steel plate (23 cm in diameter and 2.5 cm thick) are used. Two channels of electric fields are recorded symmetrically about the shot point. Grounded dipoles are formed from stainless steel stakes positioned at 0.5 m (inner) and 2.5 m (outer) from the shot point. This arrangement provides dipole lengths of 2 m.

The recording system (housed in a portable computer) is triggered by the hammer blow using an inertia switch attached to the hammer shaft. The recording system then samples the electric field oscillations that occur across the two electric field dipoles. A sampling interval of 20 kHz and a recording duration of 0.2 s (4000 data points) is used.

4. EK DATA PROCESSING

The three stages of EK data processing are illustrated in Figure 4.1. An EK sounding (time/voltage measurement) from a single hammer blow forms a shot record. In practice the shot is repeated between 5 and 10 times to investigate the repeatability of the sounding. Individual shot records are then stacked and averaged to yield a final stacked sounding. Examples of shot repeatability are shown later (e.g. Figures 6.2 and 6.3).

The stacking procedure results in a final sounding curve of voltage against time for the two receiver dipoles at each observation point. These data are examined with regard to the degree to which the two channels are in-phase. The second stage of processing (Figure 4.1), the conversion of time to depth, has been largely omitted in the present study since we have little understanding of the seismic velocity structure at the sites investigated.

The third processing stage, the translation of EK voltage/time behaviour to an estimate of the hydraulic conductivity as a function of time after shot instant (depth) is still at the research stage and is based on laboratory scale experiments on the rise-time of the electrokinetic effect in fluid saturated porous structures. The degree to which the laboratory scale results can be extended to the field scale remains uncertain. In practice, rise-times are estimated from the voltage/time data and are used to estimate permeability (hydraulic conductivity). The approach adopted requires estimates of the bulk moduli of the fluid and solid constituents, shear modulus of the solid frame and porosity. Although porosity may be iteratively adjusted during estimation of permeability, appropriate elastic moduli must be assigned for each new environment. It should be noted therefore that estimates of EK hydraulic conductivity in the present study should be regarded as relative rather than absolute determinations.

5. PRESENT FIELD WORK

We tested the EK technique in a wide range of Zimbabwe's diverse hydrogeological environments; our activities are summarised in Figure 5.1 and in Table 1 showing, respectively, the approximate location of the sites and, in chronological order of investigation, their name, number of stations occupied, the nature of the control data, lithology and grid reference.

Where possible we have worked at sites with well documented and reliable control data. Some of the collector well sites established by BGS since 1982 were of particular interest because their siting had involved surface geophysical surveys to define the bedrock topography followed by intensive shallow drilling and detailed analysis of borehole and well samples and pump testing. This work was comprehensively reported in a series of readily available reports. We also made observations at boreholes completed as part of recent/on-going large scale development projects; however, in general the immediate goal of such drilling was water supply and detailed logging and hydrogeological testing were generally not undertaken.

Very occasionally we made EK traverses at locations for which little or no control exists, two examples being the profiles of the Unzingwane sand river near Bwemula School. Here we hoped to map systematic permeability variations within the thick alluvial river fill and to observe characteristic responses of the underlying Basement granite and Karoo sandstone.

We placed emphasis on the routine collection of a large volume of data applying the currently accepted field practices but in addition we undertook limited experimentation to investigate, for instance, the effect on EK signal of deeper electrode penetration, "digging in" of the seismic plate and variable electrode orientation.

Following the initial comments and discussion of the survey data in the following section, Sections 7, 8 and 9 present the main survey results. The results are discussed in the order: borehole sites (Section 7), collector well sites (Section 8) and then sand river traverses (Section 9). Within the first two of these divisions the sites are listed according to the age (oldest first) of the lithology tapped.

6. INITIAL COMMENTS AND DISCUSSION OF THE SURVEY DATA.

6.1. Use of the Groundflow system.

We used EKS equipment developed and supplied by Groundflow Ltd. for the present study. According to the operating manual (Version 2, March 1995) this equipment is designed to perform the following tasks and calculations:

Data acquisition
Converting signal acquisition time to depth
Depth to water table in unconfined aquifers
Average aquifer porosity
Depth and thickness of confined aquifers
Aquifer permeability versus depth
Depth to basement
Depth to water-filled 'fracture zones' in basement
Predict borehole flow versus depth

Table 1: Summarising the EK observations

DATE	SITE	STATIONS	CONTROL	LITHOLOGY	GRID REF
2/11	1a Hatcliffe (Willow tree site)	3	CW[1]	greenstones	TR 993 412
	1b Hatcliffe (wind pump site)	4	CW	greenstones	TR 982 403
	2a Murape school	4	CW	granite/gneiss	UR 081 039
3/11	2b Marikopo school	7	CW	granite/gneiss	UQ 118 984
	2b Marikopo football pitch	1		granite/gneiss	UQ 118 984
4/11	3a Stamford Farm borehole 14	3	BH[2]	dolerite/felsite	TR 812 353
	3b Stamford Farm borehole 15	3	BH	dolerite/felsite	TR 814 353
	3c Stamford Farm borehole 17	3	BH	dolerite/felsite	TR 815 351
7/11	4a Nhondamapango village borehole 40A	5	BH	granite/gneiss	UR 769 783
	4b Nhondamapango village borehole 40B	6	BH	granite/gneiss	UR 756 794
	4c Chivhinge village borehole 45A	4	BH	granite/gneiss	UR 726 908
	4d Chivhinge village borehole 45B	5	BH	dolerite	UR 729 906
9/11	5 Romwe village	9	CW	granite/gneiss	TN 673 037
10/11	6 Chiredzi Research Station	9	CW	granite/gneiss/dolerite	UM 515 757
	7a Machoka	4	CW	Karoo basalt	VM 083 760
	7b Masekesa	5	CW	Karoo basalt	VM 078 799
11/11	8 Guido's Pool (sand river)	5		sand fill on Karoo sst.	VN 183 017
	9a Mushikavanhu (Save) borehole 14	5	BH	alluvium	VN 264 401
	9b Mushikavanhu (Save) borehole 11	4	BH	alluvium	VN 266 416
	9c Mushikavanhu (Save) borehole 16	2	BH	alluvium	VN 264 345
	9d Mushikavanhu (Save) borehole 17	4	BH	alluvium	VN 264 340
14/11	10a Bwemula school (sand river)	5		sand fill on granite/gneiss	QG 614 025
	10b Bwemula school (sand river)	6		sand fill on Karoo sst	QG 606 035
15/11	11a Cawood Ranch (sand river)	13		sand fill on Karoo basalt	QF 879 685
	11b Cawood Ranch (sand river)	1	BH	sand fill on Karoo basalt	QF 873 689
16/11	12 Zhovu Dam (sand river)	7	seismic trav	sand fill on Karoo basalt	QF 799 823
18/11	13a Habani Township	7	BH	pegmatite (faulted?)	QH 038 531
	13b Esigodini College	4		greenstone	QH 029 511
19/11	14a Nyamandhlovu borehole S99 (rig u/s)	4	BH	Karoo bas. on sandstone	PJ 321 031
	14b Nyamandhlovu (Rochester) borehole 79	4	BH	Karoo bas. on sandstone	PJ 440 074
	14c Nyamandhlovu (Rochester) borehole 95	3	BH	Karoo bas. on sandstone	PJ 438 048
	14d Nyamandhlovu borehole 5 (in progress)	2	BH	Karoo bas. on sandstone	PH 407 997
21/11	15 Ndamuleni school	11	CW	Kalahari / granite/gneiss	PK 008 061
22/11	16a Mudingule village	2	BH		MK 647 764
	16b Lambo lay-bye	2	BH	granite/gneiss	MK 813 659
	16c Lambo 40km post	1	BH	Karoo sandstone	MK 815 640
23/11	17a Intundhle railway borehole	7	BH	Kalahari Deposits	NK 323 022
	17b Kennedy railway borehole	3	BH	Kalahari Deposits	NK 175 145
	17c Water Loop railway borehole	3	BH	Kalahari Deposits	NK 052 247
28/11	18 Mukumba School	5	CW	granite/gneiss	UQ 162 767
	19 St Lioba's School	8	CW	granite/gneiss	UQ 633 398

CW[1] collector well and shallow exploration boreholes

BH[2] borehole (dry, production or in progress)

As implied previously (Section 4), all but the first task (data acquisition) is speculative and the basis for many of the tasks of data processing and interpretation is not explained. In these circumstances we used the EKS equipment and software only for the first task, ie data acquisition. A suite of in-house BGS software routines and graphical displays was written to perform data processing and interpretation and to exercise full control of the sounding data.

The main difference between the Groundflow approach to a sounding and that adopted by BGS is in the demonstration of quantitative repeatability of the sounding characteristics. The Groundflow approach is to 'select' a single sounding (ie resulting from one shot) as being typical of three or four shots at any site. No data stacking is possible and their procedure requires the mental comparison of several sounding curves. BGS adopted the approach that the repeatability of any received signal must be demonstrated. This allows the identification (and rejection) of poor/inadequate data and the construction of a 'stack average' from a series of repeated soundings (i.e. between 5 and 10 hammer shots).

The Groundflow instrument was operated in accordance with the operating manual. Each of the two antennae is balanced using a potentiometer. The balancing procedure is necessary to compensate for differences in the contact resistance between each stainless steel electrode and the ground. The manual suggests that this resistance should be as high as possible and indicates that the operator should not wet the ground or make any other changes to the ground in the vicinity of the antenna. These instructions were adhered to during the survey.

The acceptance of high contact resistance is counter-intuitive in the context of all other forms of electrical and electromagnetic soundings. High contact resistances are often associated with high noise pick-up and, conventionally, every effort is made (e.g. the use of porous pot electrodes) to minimise high contact resistances prevalent in arid terrains. Experimental tests in the UK (following this survey) revealed that high contact resistances of EK electrodes are also associated with high noise levels which can degrade an EK sounding. It seems probable that some of the present survey data, particularly those involving low signal amplitudes, were degraded by ground contact conditions.

6.2. Typical Responses.

Due to the scope of the survey a great variety of types of EK response were observed. The character of the voltage recordings was entirely site dependent. It is not possible to classify the character of the EK response according to geological/hydrogeological environment. The magnitudes of the voltages obtained ranged from very small (close to the noise level of the instrument i.e. about 0.1 mV/m) to values in excess of 5 mV/m observed as maximum peak excursions. Typically in our survey classification scheme the following comments broadly apply :

1) Borehole sites : generally low amplitude, spatially inconsistent and difficult to interpret.

2) Collector wells : a variety of types and magnitudes were observed ranging from small to large amplitudes.

3) Sand rivers : moderate to large amplitudes. The soundings display high levels of spatial consistency.

Examples of voltage response data, all to a common scale, are shown in Figure 6.1. The upper two frames are examples from Borehole sites (Sites 4d and 4a). The lower left frame shows a large amplitude response observed at a Collector Well site (Site 19) and the lower right frame shows a moderate amplitude response observed at a Sand River site (Site 12).

6.3. Data stacking and repeatability.

As noted previously, BGS adopted the approach that the repeatability of any received signal must be demonstrated. This allows the identification (and rejection) of poor/inadequate data and the construction of a 'stack average' from a series of repeated soundings (i.e. between 5 and 10 hammer shots).

An example of good data repeatability of a large amplitude signal with a high correlation between channels is shown in Figure 6.2. In this case the calculation of a stack-average sounding for each channel will provide a meaningful result. A further example of shot-repeatability at a different site is shown in Figure 6.3. In this example the first series of shots were obtained with electrodes along an azimuth of zero degrees. The shot repeatability of individual channels is reasonable and a meaningful average can be obtained for each channel. However, the cross-channel correlation (in-phase behaviour) is poor. The sounding was then repeated using the same centre but with the electrodes positioned along the perpendicular azimuth. The simple expectation is that the first sounding characteristics would be repeated. The second set of soundings (Figure 6.3) are again repeatable across individual channels and they now also show more consistent, in-phase behaviour. On the basis of these tests, the conclusion reached is that a single-orientation repeated sounding (made along an arbitrary azimuth) may produce repeatable individual channel voltages but these voltages may not be representative of the site.

A further example is shown in Figure 6.4. Here the first sounding, consisting of five repeat shots (left frame) yields repeatable individual channel voltages. The sounding array was then shifted by 1m (electrodes remaining parallel to the original expansion) and the results of five repeat shots at this location are shown in the right frame. Again, but to a lesser extent, individual channel voltages are repeatable. Once again, on the basis of these tests, the conclusion reached is that a repeated sounding (made along an arbitrary azimuth) at a single site may produce repeatable individual channel voltages but the voltages obtained may not be representative of the site.

6.4. Further experimental tests on data consistency.

During the survey a number of tests were performed to investigate parameters which may influence the consistency and validity of the recorded voltages. Although the 'true' EK coupling signal is not known at any one site, the expectation is that EK coupling will be identified when the two channels of data are identical in amplitude and phase. This characteristic together with repeatability from shot-to-shot are the basis for the tests.

Figure 6.5 summarises a series of five tests conducted at one location (Site 9a, BH14). It should be noted that typical maximum amplitude excursions are < 1 mV/m so the sounding should be considered one of low amplitude coupling (i.e. relatively low S/N). Apart from the fifth (lower) frame test (BH14_5, which shows the effect of electrode shake), only certain features of the sounding can be considered 'repeatable'. The early time data from 0 to about 4 ms is variable across the tests and the main 'signal' is the negative excursion centred at about 5 to 6 ms. Even this signal displays a variety of forms across the first four tests. Examination of the data behaviour reveals that one channel is 'more repeatable' across the first four tests while the second channel shows more variability. The clearest example occurs in test 4 (BH14_4) in which the large negative excursion is clearly unrepresentative. These, and other, tests indicate the following two conclusions :

1) Unless a high degree of experimental testing (as above) is carried out at a sounding site, the EK voltage recording has to be regarded as a mixture of signal and noise. Thus, even though an individual series of shots may provide consistent and repeatable data features (in one or both channels), the data obtained may not fully quantify the EK coupling characteristics at the site. This can be seen, broadly, to be a consequence of :

(i) the use of only two channels , and (ii) the assumption that the 'chosen' electrode azimuth for the sounding will provide representative characteristics.

2) The use of only two channels can result in a severe interpretation difficulty when the two channels display different characteristics (e.g. test 4, BH14_4, in Figure 6.5). The interpreter is required to assess the two channel sounding data for 'in-phase' behaviour. Portions of the record in which the channels move together will be regarded as due to EK coupling and the other portions will be regarded as 'noise'. In circumstances in which an 'isolated' recording (such as test4) is made and the channels display different behaviour, the interpretation is that 'simple' EK coupling is not observed. In fact, if additional observational information is obtained then the behaviour of one channel can often be defined as 'representative' of EK coupling at the site.

It might be argued that an 'experienced interpreter' can avoid the difficulties discussed above but one prime requirement for geophysical investigations is to (a) acknowledge that pitfalls exist and (b) devise methods (observational and interpretational) that acknowledge and avoid the pitfalls. This ultimately leads to a more robust and useful methodology.

A further example of the difficulties presented by differences in two channel behaviour comes from Site 5 (a collector well in granite/gneiss basement). A series of 5 soundings (distributed across a distance of about 14 m) were made in the vicinity of the well. The voltage data from the two individual channels are colour-contoured in Figure 6.6. The first 40 ms of the data is shown and the same contour scale has been applied to the upper (channel 1) and lower (channel 2) frames. The white contour zone (observed only in the upper frame) indicates values in excess of the maximum contour value (+1 mV/m). Voltage returns below about 25 ms approach the noise level (about 0.1 mV/m). Although the overall voltage returns are of low amplitude (maxima of order +/- 1 mV/m) it can be seen that the channel 1 and 2 voltages possess a reasonable degree of internal spatial consistency (along the profile) while the differences between the two channels are, however, significant.

The differences between the two channels are highlighted when the voltage rise-times are considered. Figure 6.7 shows the two channel contoured rise-times obtained from the data in Figure 6.6. A logarithmic contour interval is used with black denoting values less than 0.1 mV/m.ms. In this example the data presents the problem of which channel to interpret. The methodology used does not provide sufficient information to identify reliable characteristics of EK coupling at the site.

The difficulties discussed above are often exacerbated when the sounding voltages are of small amplitude. In order to provide some measure of reliability at many survey sites (where the data proved difficult to interpret visually on the field computer) a series of soundings was conducted to allow an assessment of 'spatial repeatability' at small sounding separations. In some cases orthogonal data were collected (using the same sounding centre) and in other cases the sounding centre was simply moved several metres.

Such data sets are examined for consistency using a 3BOX plot developed for the survey. It allows selected soundings to be plotted as overlays and the data repeatability to be examined. The 3BOX scheme shows :

BOX 1 : the voltage/time data on a common scale (800 data points = 40 ms). Channel 1 is a thick line and channel 2 is a thin line.

BOX 2 : The voltage difference (between the two channels)/time data. This is plotted using a logarithmic scale.

BOX 3 : The rise time (time derivative) of the BOX 1 voltage data. Channel 1 is a thick line and channel 2 is a thin line. The time derivative is a very sensitive measure of data consistency both between channels and across several soundings.

Figure 6.8 shows a series of 3 soundings obtained at Site 3a (Stamford Farm) near BH14. The poor level of consistency indicates data that we regard as unsafe for subsurface interpretation. Figure 6.9 shows a similar series of 3 soundings obtained at Site 3b (Stamford Farm) near BH15. Again poor consistency indicates unsafe data. Figure 6.10 repeats the exercise at Site 3c near BH17.

We have frequently observed poor data consistency, both intra- and inter-channel and intra-site, during the present study. Such data are clearly unsuitable for either calibration or interpretation and are not presented here. Relevant hydrogeological information at these sites is however summarised in Appendix 1, for possible subsequent re-examination.

7. RESULTS FROM BOREHOLE SITES.

Our work at existing borehole sites is discussed in the order: acid Basement, intermediate Basement, Karoo sandstone and basalt, Kalahari Deposits and Recent fluviatile sediments.

BOREHOLE SITES - Acid Basement

SITES 4a, 4b, 4c, 4d (Murewa boreholes 40A, 40B, 45A and 45B)

The data are unsuitable for quantitative interpretation. Hydrogeological information is summarised in Appendix 1.

Site 13a (Habani Township borehole B/7038)

Six equispaced soundings comprising a 100 m profile were made in the vicinity of this borehole, located at 30 m along the profile. The borehole proved 3 m of clayey soil underlain by 57 m (to total depth) of pegmatitic granite, highly weathered (faulted?) to 21 m. The main water strike was at 22 m depth and the yield is reported as $6.2m^3h^{-1}$.

The 2 channel voltages are colour-contoured in Figure 7.1. Only low voltages (-1.0 to 0.5 mV/m) were observed. The main voltage excursions occur at different times/locations across the two channels indicating a lack of in-phase behaviour. This independent channel behaviour is confirmed when the data gradients are examined as in Figure 7.2. The rise-times contoured in Figure 7.2 are a detail between 10 and 30 ms and confirm the lack of in-phase behaviour. The data are considered unsuitable for quantitative interpretation.

BOREHOLE SITES - Intermediate Basement

SITES 3a, 3b, 3c (Stamford Farm boreholes 14, 15 and 17)

These data have been discussed in Section 6.4 above; they are considered unsuitable for quantitative interpretation. Hydrogeological information is summarised in Appendix 1.

SITE 13b (Borehole siting at Esigodini College)

A borehole was sited in the grounds of Esigodini College following four EK soundings near the supposed faulted contact between acid and intermediate Basement lithologies. The borehole site was chosen on the basis of a qualitative comparison of the EK sounding curves; the data are considered unsuitable for quantitative interpretation.

BOREHOLE SITES - Karoo formations

SITES 14a-d (Nyamandhlovu boreholes S99, 79, 95 and 5)

The EKS data are considered unsuitable for quantitative interpretation. Hydrogeological information is summarised in Appendix 1.

SITE 16a (Mudingule Village)

The EKS data are considered unsuitable for quantitative interpretation. Hydrogeological information is summarised in Appendix 1.

BOREHOLE SITES - Kalahari Deposits

SITES 17a-c (Railway boreholes at sidings: Intundhle, Kennedy and Water Loop)

Numerous EKS were made in the generally loose, windblown sands near these railway sidings; they are considered unsuitable for quantitative interpretation. Hydrogeological information is summarised in Appendix 1.

BOREHOLE SITES - Recent fluviatile deposits

SITES 9a-d (Mushikavanhu (Save) Agritex boreholes 14, 11, 16 and 17)

Numerous boreholes drilled in this section of the Save Valley on behalf of Agritex have proved thick (to 110m) Recent fluviatile sediments deposited in a down-faulted trench and comprising primarily clays/silts and various sand grades through to occasional cobbles and boulders. The major aquifer is a basal confined boulder layer, separated from the upper, unconfined sandy aquifer by the Save clay unit. The upper unconfined sandy aquifer is in hydraulic continuity with the Save River. Aquifer transmissivities of up to 1500m^2/day and yields of between 40l/s and 100l/s are obtained. Additional hydrogeological information is summarised in Appendix 1.

SITE 9a (Borehole 14)

The series of five experimental test soundings undertaken in the vicinity of BH14 were discussed in Section 6.4 (Figure 6.3). The data are considered unsuitable for quantitative interpretation.

SITE 9b (Borehole 11)

A series of four experimental test soundings were conducted near BH11. The results of these tests are summarised in Figure 7.3. Two orthogonal soundings (1 and 2) were conducted in the shade of large trees and different sounding characteristics were obtained in the two directions. Two further orthogonal soundings (3 and 4) were conducted in open ground; again different (but less pronounced) sounding characteristics were obtained from the orthogonal array. Again, the lack of data consistency at this site indicates that the data are unsuitable for quantitative interpretation.

Site 9c (Borehole 16)

Two soundings, both yielding low amplitude signal, were made within 40m of the borehole. The data are considered unsuitable for quantitative interpretation.

Site 9d (Borehole 17)

Two sets of orthogonal soundings were made in the vicinity of the Borehole (each within 40 m). The data are considered unsuitable for quantitative interpretation

8. RESULTS FROM COLLECTOR WELL SITES.

Our observations at collector well sites are discussed in the following order: acid Basement, intermediate Basement, Karoo basalt and Kalahari Deposits.

COLLECTOR WELL SITES - acid Basement

SITE 2A (Murape School).

Four soundings (1, 2, 3 and 4) were made in the vicinity of the collector well (within 10 m). A variety of sounding characteristics were observed. The data are considered unsuitable for quantitative interpretation. Hydrogeological information is presented in Appendix 1.

SITE 2b (Marikopo School).

Seven EK soundings were made in the vicinity of the collector well. The variety of sounding characteristics observed indicate that these data are unsafe for interpretation. Hydrogeological information is included in Appendix 1.

SITE 5 (Romwe Village)

A short profile (14m) of five soundings at this site was discussed in Section 6.4. The data are shown in Figures 6.6 and 6.7. As stated previously, the methodology used did not provide sufficient information to identify reliable characteristics of EK coupling at the site.

Hydrogeological information is summarised in Appendix 1.

SITE 6 (Chiredzi Research Station)

The series of nine EK soundings made in the vicinity of the collector well display a variety of characteristics and quantitative interpretation would appear to be unsafe. Hydrogeological information is summarised in Appendix 1.

SITE 18 (Mukumba School (Chiota))

Numerous earlier exploration boreholes proved depth to fresh bedrock (granitic gneiss) within the extensive school grounds in the range >16m to about 2.5m. An EK traverse was made across the steepest depth-to-bedrock gradient, from Borehole 6 (>16m) on a bearing of 58^0 for some 60m to where bedrock shallows to a depth of 10m. The water level in the collector well at the time of the EK survey was 6.15m bgl. The geological log of the well showed a top 1m thick grey clay underlain by granite saprolite of variable hardness to about 13m where granite saprock was encountered. Radials drilled at the base of the collector well proved a large degree of lateral inhomogeneity and degree of weathering in the granitic saprock. Estimated regional transmissivity and yield are respectively $3m^2$/day and 1.4l/s (Wright et al, 1988).

The results of the EK traverse are shown colour-contoured in Figure 8.1; location 0 is the site of the collector well while locations 20 to 80 represent the straight line traverse across the proved depth to fresh bedrock gradient. The first 40 ms of the data is shown and the same contour scale has been applied to the upper (channel 1) and lower (channel 2) frame. Voltage returns below about 40 ms approach the noise level. Although the overall voltage excursions are of low amplitude it can be seen that the channel 1 and 2 voltages possess similar characteristics and are thus predominantly in-phase.

Interpretation proceeds using the contoured two channel rise-times as shown in Figure 8.2. Deeper (i.e. at later times) enhanced permeability is observed at increasing profile distances (i.e. towards 80 m along profile). This result is at variance with 'known' geology which suggests that depth to basement is decreasing with increasing profile distance

SITE 20 (St Lioba's School (Wedza))

The local geology comprises younger granites (exposed as "whalebacks"), locally heavily faulted. Extensive surface geophysics and exploration drilling preceded the construction of the collector well which was not sunk where the weathering was deepest since these zones contained excessive clays and occasional shallow bands of hard granite. The exploration boreholes demonstrate that fresh bedrock deepens to the south, from about 16m bgl near the well to a nadir of about 27m bgl at 70m south of the well. Thereafter the fresh bedrock surface rises gently to 21m bgl at about 140m south of the well. While this apparent distribution of fresh bedrock is supported by 11 shallow boreholes, Wright *et al* (1988) admit that the presence of large core stones (impenetrable by the light rig used) may result in an erroneous interpretation. The collector well was sunk to 11.3m, proving pale clayey quartzo-feldspathic material to 8m, then white feldspathic rock to 10m with the remaining 1.5m of clayey quartzo-feldspathic sands. The water level in 1986 was about 3m bgl.; the regional transmissivity and yield were estimated as 2.8m^2/day and 0.9l/s respectively (Wright *et al*, 1988).

In the present study a traverse of 8 equispaced EK soundings (covering a length of 210 m) was made, starting at the collector well (location 0) and bearing due south across the depth to bedrock gradients described immediately above. The voltage data from the two individual channels are colour-contoured in Figure 8.3. The first 40 ms of the data is shown and the same contour scale has been applied to the upper (channel 1) and lower (channel 2) frame. Voltage returns below about 40 ms approach the noise level. The voltage excursions (-5 to + 5 mV/m) are some of the largest observed during the survey. Although channel 1 data contains some positive excursions (yellow-red-white contours) not reproduced in channel 2, the overall level of two channel consistency over the 210 m profile is good.

Interpretation proceeds using the contoured two channel rise-times as shown in Figure 8.4. In these data the high values obtained at a profile distance of 150 m (in channel 1) are not precisely reproduced in channel 2. Across the first 60 m of the profile, a consistent set of vertical undulations is observed.. A lateral modification to this structure occurs at about 90 m along profile and again beyond 180 m along profile.

COLLECTOR WELL SITES - Intermediate Basement

SITE 1a (Willowtree collector well at Hatcliffe)

The EK data collected here are not sufficiently consistent to justify a quantitative interpretation. Hydrogeological information is summarised in Appendix 1.

SITE 1b (Windpump collector well at Hatcliffe)

Four EK soundings were made within 10m of the collector well. A disturbing lack of data consistency was demonstrated at two sites here after hammering the electrodes much further into the ground than usual and repeating the shots. This lack of consistency suggests that the electrode/ground contact impedance may influence the data characteristics observed. The EK data collected here are not sufficiently consistent to justify a quantitative interpretation. Hydrogeological information is summarised in Appendix 1.

COLLECTOR WELL SITES - Karoo basalt

SITE 7a (Machoka Village)

Four soundings made within 10m of the collector well show quite varied responses and are considered unsuitable for quantitative interpretation. A thick cover of dark gray fine silt (a product of weathered basalt) occurred at this site and in the attempt to penetrate to a more conductive underlying layer we experimented with long (1.5m) electrodes. The resulting relatively large amplitudes (> 2 mV/m) measured may result partly from long period electrode shake. Hydrogeological information is summarised in Appendix 1.

SITE 7b (Masekesa Village)

Five soundings were made within 35 m of the collector well. These provide an example of very low voltage returns i.e. EK-coupling. Hydrogeological information is summarised in Appendix 1.

COLLECTOR WELL SITES - Kalahari Deposits

SITE 15 (Ndamuleni School)

The Lupani River is incised into Kalahari Deposits (largely unconsolidated sands and occasional calcrete) and at Ndamuleni its flood plain is some 300m wide. Here the Kalahari Deposits attain their maximum thickness (about 9m) adjacent to the regular river course (which is not central to the flood plain but displaced to south-west) and they pinch out near the stony tree line at the edges of the flood plain.

The collector well was constructed about 100m north of the river course (to minimise the risk of flooding); it was dug to 7m, terminating in an horizon of hard consolidated sand. The only significant inflow of water occurred at the base of well and from a radial drilled towards the north east. Seive analysis of a sample from a radial hole comprised mainly medium/fine sand with an 18.5% mud fraction that suggests the permeability of these alluvium deposits will not exceed 1m/day. Subsequent drawdown tests indicate that the aquifer is unconfined and has a low transmissivity of between $2.2m^2$/day and $6.5m^2$/day (Herbert and Rastall, 1991). The water level at the time of the present survey was 3.09mbgl.

A NE-SW traverse of 11 EK soundings covering a distance of about 360 m was run; the collector well is at location 0 while the normal river course (thickest sediments) is at about location -120 (ie 120m south of the well). The voltage data from the two individual channels are colour-contoured in Figure 8.5. The first 40 ms of the data is shown and the same contour scale has been applied to the upper (channel 1) and lower (channel 2) frame. Voltage returns below about 40 ms approach the noise level. Although the overall voltage excursions are of low amplitude it can be seen that the channel 1 and 2 voltages possess similar characteristics with the exception of the sounding obtained at the end of the profile (120 m).

Interpretation proceeds using the contoured two channel rise-times as shown in Figure 8.6. The rise-time results, used as an analogue of permeability, appear to contradict the geology; the thinnest sediments are characterised by the most persistent rise times.

9. RESULTS FROM SAND RIVER SITES

Four EKS traverses of the Umzingwane Sand River were made; the locations ranged from Bwemula School in the north to Cawood Ranch some 80 km to the south east. The bedrock into which the Umzingwane was incised (during former pluvial periods) includes granite/gneiss Basement and Karoo sandstones and basalt. Subsequently highly varied fluviatile deposits (ranging from fine silts to boulders) have been deposited according to the Umzingwane's flow regimes.

The EK sounding characteristics across each traverse display a high degree of 'uniformity' and thus sand rivers appear to provide a highly repeatable environment in terms of EK soundings. The sand river data sets have been examined in some detail. The data from all four profiles are presented in the form of individual (two-channel) soundings followed by colour-contoured cross sections.

SAND RIVER SITES - Acid Basement

SITE 10a (Bwemula School - North)

A traverse of 5 soundings at 30m interval (mainly) was run. These 5 soundings are overlaid in Figure 9.1 where channel 1 is shown as a solid line and channel 2 as a dotted line.

The voltage data from the two individual channels are colour-contoured in Figure 9.2. The first 40 ms of the data is shown and the same contour scale has been applied to the upper (channel 1) and lower (channel 2) frame. Voltage returns below about 40 ms approach the noise level. Although the overall voltage excursions are of low amplitude it can be seen that the channel 1 and 2 voltages possess similar characteristics.

The voltage rise-time data from the two individual channels are colour-contoured in Figure 9.3. The first 40 ms of the data is shown and the same contour scale has been applied to the upper (channel 1) and lower (channel 2) frame. Rise time data below about 20 ms are not coherent across the channels.

SAND RIVER SITES - Karoo sandstone and basalt

SITE 10b (Bwemula School - South)

A further EK traverse of the Umzingwane River was made at Bwemula, about 1.5km south of that described above. This comprised 6 soundings made at 30m interval. Here the bedrock is Karoo Forest Sandstone (a generally fine grained and finely bedded rock of aeolian deposition). The fluviatile deposits are reportedly thicker at this site than to the north of the faulted contact between Pre-Cambrian gneiss and Karoo Sandstone (Owen, personal communication).

The 6 soundings are overlaid in Figure 9.4. Channel 1 is a solid line and channel 2 is shown as a dotted line for each sounding.

The voltage data from the two individual channels are colour-contoured in Figure 9.5. The first 40 ms of the data is shown and the same contour scale has been applied to the upper (channel 1) and lower (channel 2) frame. Voltage returns below about 40 ms approach the noise level. Although the overall voltage excursions are of low (< 3mv/m) amplitude it can be seen that the channel 1 and 2 voltages possess similar characteristics through the first 30ms of the recording.

The voltage rise-time data from the two individual channels are colour-contoured in Figure 9.6. The first 40 ms of the data is shown and the same contour scale has been applied to the upper (channel 1) and lower (channel 2) frame. Rise time data below about 10-20 ms are not coherent across the channels.

SITE 11a (Cawood Ranch)

Numerous boreholes tap the sand river at Cawood Ranch where the fluviatile sediments are reportedly up to 23m thick, comprising a complex clay to coarse sand assemblage overlying Karoo Basalt (Bristow, personal communication). Presently the water table is about 9m bgl; yields up to 140l/s are abstracted. Unfortunately water quality is deteriorating, presumably due to leaching of agrochemicals deposited in the orange orchards occupying the adjacent overbank sediments.

Our EK traverse of the Umzingwane here reoccupied the profile of a multielectrode resistivity traverse conducted earlier in the year by a joint University of Zimbabwe and Lund University (Sweden) collaborative team. Hopefully we will get the opportunity to attempt a correlation of the two data sets.

Our profile comprised 13 soundings about 20m separate; the total profile length is 280m. For the sake of clarity these soundings are shown in two figures; the first 7 soundings, NE to SW, are overlaid in Figure 9.7. The second 6 soundings (including an "overlap" sounding from the first 7 (at 160m)), NE to SW, are overlaid in Figure 9.8. Channel 1 is a solid line and channel 2 is shown as a dotted line for each sounding.

The entire voltage data from the two individual channels are colour-contoured in Figure 9.9. The first 40 ms of the data is shown and the same contour scale has been applied to the upper (channel 1) and lower (channel 2) frame. Voltage returns below about 40 ms approach the noise level. Th voltage excursions reach a large negative amplitude between 5 and 10 ms. It can be seen that the channel 1 and 2 voltages possess similar characteristics at certain positions across the section.

The voltage rise-time data from the two individual channels are colour-contoured in Figure 9.10. Again the first 40 ms of the data is shown and the same contour scale has been applied to the upper (channel 1) and lower (channel 2) frame. Rise time data below about 10-15 ms are not coherent across the channels.

SITE 12 (Zhovu Dam)

Our EK traverse here was made immediately upstream of the recently constructed Zhovu Dam. Bedrock comprises Karoo Basalt and the overlying fluviatile sediments achieve a thickness of up to 22m, as indicated by the results of a commercial seismic refraction survey completed prior to the dam construction and subsequently proved in a trench dug to solid basalt for the dam foundation.

Seven EK soundings were completed at (mainly) 30m separation, giving a total profile length of 155m. These 7 soundings are overlaid in Figure 9.11. Channel 1 is a solid line and channel 2 is shown as a dotted line for each sounding.

The voltage data from the two individual channels are colour-contoured in Figure 9.12. The first 40 ms of the data is shown and the same contour scale has been applied to the upper (channel 1) and lower (channel 2) frame. Voltage returns below about 40 ms approach the noise level. The voltage excursions reach a large negative amplitude between 5 and 10 ms. It can be seen that the channel 1 and 2 voltages possess similar characteristics at certain positions across the section.

The voltage rise-time data from the two individual channels are colour-contoured in Figure 9.13. Again the first 40 ms of the data is shown and the same contour scale has been applied to the upper (channel 1) and lower (channel 2) frame. Rise time data below about 20 ms (in the centre) are not coherent across the channels.

In the case of this data set, the velocity structure across the section is known from the seismic refraction experiment. Overburden, saturated sand and fresh basalt velocities increase in the sequence 400, 1500 and 4000 m/s. Depths to basalt range from 10 to 22 m across the section. The velocities and interface depths at the sounding locations were used to convert time to depth. The rise-time data for channel 2, converted to depth, are shown in Figure 9.14. The depth to seismic basement is shown by the white broken line. While the high values of rise-time appear within the sand sequence there are other high values (in green) that occur within a large area of the underlying basalt. These high values are considered an artefact of the assumptions involved in two-channel EK sounding.

10. CONCLUSIONS

This overseas project element had, as its aim, an assessment of the new method of Electrokinetic sounding. Conceptually, the work involved accepting the instrumentation and procedures of the first-ever commercial EK instrument and the application of these procedures in a number of hydrogeological contexts. This framework should have given rise to a fair degree of assessment and calibration.

It proved necessary to develop and refine the existing practices within the stated operational context of the equipment and procedures. A suite of in-house BGS software routines and graphical displays was written to perform data processing and interpretation and to exercise full control of the sounding data. Three main conclusions concerning EK data quality are :

- Data stacking (of repeated shots) to identify/reject poor quality data and to confirm the validity of a response should be used routinely.

- The presence of high electrode contact resistances (indicated as acceptable in the manual) degrades EK data. To improve data quality in arid environments, metal electrodes should be watered or porous pot electrodes should be used.

- Single 'spot' EK soundings should be avoided. In general there appears to be sufficient 'near-surface' complexity to warrant detailed traverses and/or azimuthal assessments of EK sounding behaviour.

Some good quality, spatially repeatable data were acquired during the survey. The traverse data obtained across sand rivers were particularly noteworthy in this regard. Such data could have been assessed according to the stated methodologies for obtaining hydrogeological information. The assumption underlying these methodologies is that coupling takes place as a result of vertical acoustic wave propagation only. The testing of this assumption required the introduction of more sophisticated multi-channel data acquisition systems and procedures. These control experiments have now been conducted in the UK by ourselves and, independently, by other groups (Butler et al., 1996; Mikhailov et al., 1997). It is evident that the instrumentation and procedures put in place by the suppliers are insufficient to identify the variety and extent of both vertical and horizontal acoustic wave coupling that is generally observed.

In summary, electrokinetic coupling is a physical phenomenon that occurs extensively in many diverse hydrogeological environments. It is now known from recent theoretical predictions (Pride and Haartsen, 1996) and control experiments (Mikhailov et al., 1997) that a variety of surface and body waves (including compressional and shear) can generate streaming potentials and contribute to the voltage returns observed at the surface. Electrokinetic coupling has the potential to become a geophysical tool capable of returning hydrogeological information such as zones of high permeability. The complexity and superposition of large and small amplitude wave effects within the subsurface is likely to require a far higher degree of methodological sophistication than is currently in place.

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APPENDIX 1: HYDROGEOLOGICAL INFORMATION

BOREHOLE SITES - Acid Basement

SITES 4a, 4b, 4c, 4d (Murewa boreholes 40A, 40B, 45A and 45B)
Geology: Younger Granites with adamellites and granodiorites intruded as specific stocks. Generally very tight and low yielding.

Site 4a. Borehole 45B: water rest level 12m, first strike 47m, yield 0.15l/s, total depth 55m. Some dolerite chips seen in remaining drill samples.

Site 4b. Borehole 45A: dry, total depth 61m, looks ideal site (valley setting with rich red soil etc).

Log:	0m to 2m	ferricrete
	2m to 4m	sandy clay
	4m to 13m	weathered micaceous granite
	13m to 61m	fresh granite, much black mica

Site 4c. Borehole 40A: dry, total depth 55m

Log:	0m to 3m	soil with ferricrete
	3m to 15m	gneiss (soft) with large crystalline chips
	15m to 55m	hard gneiss (fine dust)

Site 4d. Borehole 40B: yield 0.42l/s, total depth 43m.

Log:	0m to 1m	dark, reddish/brown soil
	1m to 43m	weathered granite

BOREHOLE SITES - Intermediate Basement

SITES 3a, 3b, 3c.
Stamford Farm boreholes (14,15 and 17)

Geology: phyllites, felsites and metadacites (metamorphosed rhyolite), weathered to thick clays (15m + seen in nearby brick pits).

Boreholes c 200m separate, yield c 1l/s reportedly from weathered/faulted rock. VES at bh sites (Jeremy Prince) indicate: very conductive near surface (5ohm.m black cotton soil), from 6m to 35m conductive (15ohm.m (clay)) underlain by resistive (> 200ohm.m) bedrock.

BOREHOLE SITES - Karoo formations

SITES 14a-d.
Nyamandhlovu boreholes (79, 95, S99 and 5 (in progress): a series of high yielding boreholes are being developed to supply Bulawayo. The geology comprises block faulted Karoo sandstone (Forest Sandstone) with variable cover of Karoo Basalt; the main aquifer appears to comprise the indurated contact zone with supplementary flow from fractures and joints within the Forest Sandstone. EKS were made at sites displaying strongly contrasting yields and variable thickness of basalt cover.

Site 14d. Borehole 5 (near 10km peg on Nyamandhlovu to Bulawayo road): first water strike at 36m, supplementary strike at 53m, total yield 1.8l/s.

Borehole log:	0m to 6m	sandy soil
	6m to 53m	fine weathered sandstone
	53m to 64m	grits and shale
	64m to 84m	granite (slightly weathered)
	84m to 106m	granite (fresh)

Site 14b. Borehole 79 (Rochester well field): reported water level 22.5m bgl, yield 7.2l/s (50m3/h), first strike 28m, screen at 42m to 48m.

Borehole log:	0m to 1m	black cotton soil with some basalt rubble
	1m to 18m	basalt, mainly weathered but some hard bands
	18m to 102m	fine sandstones, some basalt pebbles near top

Site 14c. Borehole 95 (Rochester well field): reported water level 32.7m bgl, yield 10.08m3/hr.

Borehole log:	0m to 8m	hard basalt
	8m to 15m	weathered basalt, occasional sandstone
	15m to 16m	coarse sandstone
	16m to 90m	fine sandstone, occasional hard bands

Site 14a. Borehole S99 (1km west of Nyamandhlovu clinic, in progress):

Borehole log:	0m to 2m	soil
	2m to 30m	variably weathered basalt with occasional calcite
	30m to 35m	hard basalt
	35m to 141m	siltstones and fine sandstones with occasional silcrete
	141m to 229m	siltstones (primarily)

SITE 16a (Mudingule Village)

Mudingule village (borehole 8157 funded by Danida): first strike 27m, main supply 40m, yield 0.4m3/hr. Apparently fresh rock is shallow; groundwater probably stored in fractures/joints. Damp, clayey surface conditions.

borehole log:	0m to 70m	tight Karoo shales, silts with occasional limestone and sandstone bands (Ripple Flags of the Escarpment Series).

BOREHOLE SITES - Kalahari Deposits

SITES 17a-c (Railway boreholes at sidings: Intundhle, Kennedy and Water Loop)
Railway boreholes (at sidings: Intundhle, Kennedy and Water Loop) (Reference MacDonald, 1970).

Site 17a. Intundhle borehole (G 3/406): reported water level 12.19m bgl, yield 6.7l/s, quality fresh. The main aquifer is the pipe sandstone of Kalahari Deposits age; a small confined supply found below the underlying basalts was plugged off as it was of poorer quality.

Borehole log:	0m to 97m	Kalahari Deposits (sand, sandstone, pipe sandstone and silcrete)
	97m to 217m	Karoo basalt
	217m to 293m	Karoo fine grained sandstones, mudstones and shales

Site 17b. Kennedy borehole (G 3/56): reported water level 8.2m, yield 3.8l/s, quality fresh.

Borehole log:	0m to 64m	Kalahari Deposits (sand, sandstone, pipe sandstone and silcrete).

Site 17c. Water Loop borehole (G 3/139): reported water level 18.7m bgl, yield 11.25l/s, quality fresh. The main aquifer is the pipe sandstone underlying loose, unconsolidated and running sand. Basement Complex was proved at 95m.

Borehole log:	0m to 56m	running sands (Kalahari Deposits)
	56m to 87m	pipe sandstone (Kalahari Deposits)
	87m to 95m	Basement (quartz schist)

BOREHOLE SITES - Recent fluviatile deposits

SITES 9a-d (Mushikavanhu (Save) Agritex boreholes 14, 11, 16 and 17)
Save Valley boreholes drilled on behalf of Agritex

Site 9a. Borehole 14: present water level 9.55m bgl, total depth 80m, first strike 27m, main supply 31m, yield 70l/s to 80l/s, quality fresh.

BH log:	0m to 5m	soil
	5m to 24m	clay
	24m to 57m	sand
	57m to 63m	clay
	63m to 76m	sand
	76m to 80m	clay

The series of five experimental test soundings undertaken in the vicinity of BH14 were discussed in Section 6.4.

SITE 9b. Borehole 11: present water level 11.65m bgl, total depth 84m, first strike 7m to 10m, main supply 26m to 30m, yield 70l/s, quality fresh.

BH log:	0m to 6m	clay (little sand)
	6m to 12m	river sand
	12m to 13m	fine/med sand
	13m to 28m	river sand
	28m to 30m	fine sand
	30m to 44m	river sand
	44m to 50m	clay (some sand)
	50m to 55m	fine to coarse sand
	55m to 65m	clay in fine/medium sand
	65m to 70m	fine sand
	70m to 75m	equal sand/clay
	75m to 81m	fine/medium sand
	81m to 84m	sandy clay

A series of four experimental test soundings were conducted near BH11. The results of the tests are summarised in Figure 7.3. Two orthogonal soundings (1 and 2) were conducted in the vicinity of trees and different sounding characteristics were obtained in the two directions. This makes the data unsafe for interpretation. Two further orthogonal soundings (3 and 4) were conducted in open ground and different sounding characteristics were again obtained. The differences are less pronounced at the open ground site.

Site 9c. Borehole 16: present water level 6.11m bgl, total depth 90m, PVC screen 30m to 48m, yield 80l/s, quality fresh.

Borehole log:	0m to 5m	clayey soil
	5m to 7m	boulders
	7m to 12m	very coarse, clean sand
	12m to 42m	sand, coarse fining downwards to fine/med, increasing clay with depth to 42m.
	42m to 88m	intimate mixture very fine and coarse sand
	88m to 90m	boulders with some coarse sand and silt

Site 9d. Borehole 17: water level (11/9/95) 6.81m bgl. Total depth 79m, first strike 10m, screen 23m to 26m and 28m to 48m, yield 60l/s to 70l/s, quality fresh.

Borehole log:	0m to 5m	soil
	5m to 17m	coarse sand
	17m to 34m	sand, some clay
	34m to 43m	clay and sand
	43m to 49m	fine sand and clay
	49m to 60m	fine to coarse sand
	60m to 79m	hard sandstone

COLLECTOR WELL SITES - acid Basement

SITE 2A (Murape School).

Geology: granitic gneiss; fractures striking north-north-east and west-north-west observed in collector well. Series of 22 exploration boreholes indicate regolith thickness of 18m at collector well, thinning uniformly towards the south (12m thick 25m south of well). Log of collector well shows upper 8m generally unconsolidated (sandy/gravelly above to more clayey below), succeeded downwards by very weathered but largely consolidated material (friable and fractured augen granitic gneiss). Water inflow commenced at 4.5m depth but main inflows below 12.5m, associated with visible fractures. Radial drilling demonstrated lithological irregularity with little apparent correlation with sequences observed in nearby boreholes; hard granite indicated within 10m radius to north, north-east and south-west. Transmissivity 7m^2/day, yield 1.5l/s (Wright et al, 1985). Present water level 5.70m bgl.

SITE 2b (MARIKOPO SCHOOL AND FOOTBALL PITCH)
Geology: granitic gneiss with the edge of an extensive (south-dipping) dolerite sill some 200m to the south. Site originally reported as inappropriate for collector well due shallow massive bedrock and low permeability of overburden. 53 exploration boreholes sunk; slug tests in 3 boreholes in granitic gneiss indicated transmissivity less than $1m^2$/day. Well dug where bedrock relatively deep (12m): upper 6m unconsolidated (clay/silt content peaking at 35% between 1m and 3m depth), below 6m essentially consolidated (weathered granite with some clay infillings, sand and gravel dominant, clay/silt less than10%) with massive granitic bedrock at 12m. 8 radials drilled at 45^0 intervals, mostly to 30m length; proved hard granite to north-west,west,south west, south east and north east, alternating hard/soft granite (boulders or variable weathering) to north and east, weathered granite and clay to south; no significant improvement in yield of well.

Resistivity surveying indicated a conductive intermediate layer (between surface and massive bedrock) to south and west of well site; values to the north and east where shallow bedrock anticipated the specific resistivities are relatively low. Suspected either that "bedrock" here underlain by more conductive rock or, while rock remains hard (to drill) it has suffered weathering to some 10m to 20m. (Wright et al, 1985). Present water level 11.17m bgl.

SITE 5 (Romwe Village)
Romwe: yield 0.96l/s, transmissivity $0.98m^2$/day. Two exploration boreholes proved more than 15m of weathered bedrock prior to well construction; the first EKS observations were made here almost at the site of borehole 3 (some 8m west of collector well), logged as:

0m to 1m	clay soil, some weathered gneiss fragments
1m to 15m	fragments weathered gneiss, especially clayey below 5m.

Log of collector well:	at 1m	gravel and fragments weathered rock, little clay
	at 2m	soft weathered rock and balls of soft clay
	at 3m	soft clay lumps, pieces weathered rock
	at 4m	hard fragments weathered rock in clay matrix
	at 5m	soft weathered rock with clay and silt
	at 6m	hard/soft weathered rock, less clay
	at 7m	missing
	at 8m	soft weathered rock, some clay
	at 9m	soft weathered rock, some clay
	at 10m	hard fragments feldspar-rich rock in clay matrix
	at 11m	hard fragments dark rock, less clay
	at 12m	hard fragments of dark, slightly weathered gneiss

Laterals drilled to NW,NE,SE,SW: major inflow from NE (numerous fractures); unweathered rock (at 11m) immediately to NW and NE of CW, soft weathered rock to some 5m to SW and SE; unweathered rock beyond to SW. (Note: extreme inhomogeneity). (reference: Chilton and Talbot, 1992)

Geology: granitic gneiss with interbedded bands of mafic rock (Limpopo Mobile Belt)

SITE 6 (Chiredzi Research Station)
Present water level 5.77m bgl. Yield 2.97l/s, transmissivity 7m^2/day (reference:Chilton and Talbot, 1990). Collector well sited following drilling of 9 exploratory boreholes: locally depth of weathering ranges between 10m and 30m, well sited at "intermediate" site midway between boreholes 12 and 13.

Geology: Basement complex comprising acid granulites with some schists and orthogneisses, intruded by dolerite; strong linear north-north-east structural trends and hence possibility of local recharge from irrigated fields or irrigation canal.

CW log:	at 1m	weathered rock (little clay or sand)
	at 2m	large (10cm) fragments weathered dolerite
	at 3m	hard angular fragments weathered dolerite
	at 4m	ditto
	at 5m	ditto
	at 6m	ditto
	at 7m	smaller fragments (1cm) weathered dolerite, some sand
	at 8m	both small/large fragments, less weathered
	at 9m	mostly small fragments as above
	at 10m	both small/large fragments weathered rock
	at 11m	ditto
	at 12m	less weathered, small hard fragments dolerite

water struck at 5.2m, total depth 12m.

Radials: to ne (hard gneiss with bands quartz and dolerite, 1l/s from joints etc), nw (hard, unfractured rock, dry) sw (initially hard gneiss then broken dolerite with clay, little water) and se (fault 1.5m from well, (significant inflow) then alternating hard/soft dolerite.

Borehole 12 log:	0m to 1m	brown soil
	1m to 26m (TD)	soft, weathered pegmatitic gneiss

water struck 8.5m and 10m, tested yield 0.4l/s, rest level 4.3m bgl

Borehole 13 log:	0m to 1m	red/brown soil
	1m to 12m	weathered dolerite
	12m to 25m (TD)	fractured dolerite

water struck 8m and 18m, tested yield 0.4l/s, rest level 4.6m bgl.

COLLECTOR WELL SITES - Intermediate Basement

SITE 1a (Willowtree collector well at Hatcliffe)
Geology: epidiorite. A series of 29 exploratory boreholes proved solid bedrock at 15m at well site, shallowing to some 8m over a distance of 20m towards the south east. Lithological section at well shows clay to 0.5m, silt to 4.5m and sand with weathered epidiorite to total depth. Seive analyses of collector well spoil show clay/silt content between 78% and 95% in upper 6m with marked increase in sand content below this level to bottom of well at 10.8m. Calculated transmissivity of 50m^2/day; yield 3.6l/s. Radials show residual bedrock towards the south west. Extensive surface resistivity data indicates apparent resistivity of regolith in range 10ohm.m to 25ohm.m. VES unable to detect the thin more permeable layer immediately above the bedrock (Wright et al, 1985). Present water level 9.03m bgl.

SITE 1b (Windpump collector well at Hatcliffe)
Geology: granite, but apparently very close to contact with host epidiorite; adjacent to south-east trending photo lineament. Bedrock not proved in borehole 26m deep (4m west of well) nor in borehole 15m deep (6m east of well). Upper 6/7m comprised of clay with some sands or sandy clay. Primarily sandy below, becoming coarser with depth and locally including gravel (to 23m). Seive analysis of collector well spoil shows maximum 50% clay/silt at 2m depth reducing to 20% at 9m; conversely sand content increases from 10% at 1m depth to uniform 60% from 5m to bottom of well at 10m. Surface resistivity data indicates suggests lower permeability (increased clay content) in sector north-east to south east of well and enhanced permeability in opposing sector; this broadly confirmed by subsequent radial drilling. Calculated transmissivity 27m^2/day, yield 2.8l/s (Wright et al, 1985). Present water level 3.76m bgl.

COLLECTOR WELL SITES - Karoo basalt

SITE 7a (Machoka Village)
Geology: Karoo basalts interbedded with andesites.
Well log: 0m to 3m clay, 3m to 8m weathered varicoloured basalt with occasional calcrete, 8m to 18m mainly hard less weathered varicoloured basalt with occasional vesicles and calcite-filled veins, some weathering(?) at 18m. In exploration bh at site first water struck at 8m. Pump test in well indicated yield 1l/s.

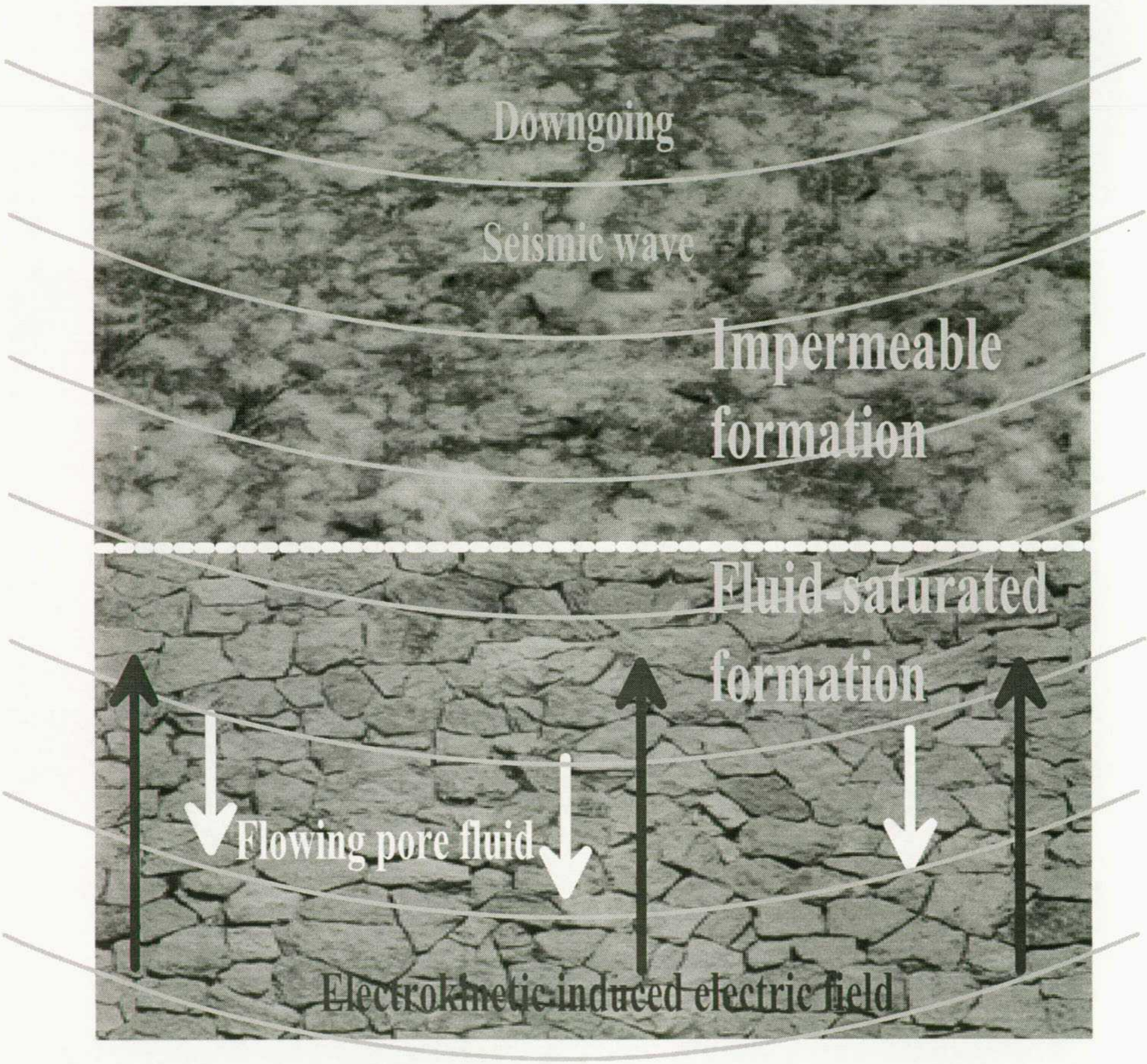
SITE 7b (Masekesa Village)

Geology: Karoo basalts interbedded with andesites

Well log: 0m to 1m sandy/silty soil, 1m to 2m clay, 2m to 18m basalt with occasional shallow calcrete samples above 10m, generally weathered throughout but some harder/fresher horizons. Initial exploration borehole proved hard basalt from 23m to 30m (total depth) with water strike at 18m. Four radials drilled: to the north hard basalt encountered at 9m, no water inflow, to the south, east and west weathered basalt out to at least 14m and strong inflows. Pump test following drilling of four radials indicated yield 1l/s

Figure 3.1. Illustration of the principle of EK sounding

Illustration of the principle of EK sounding



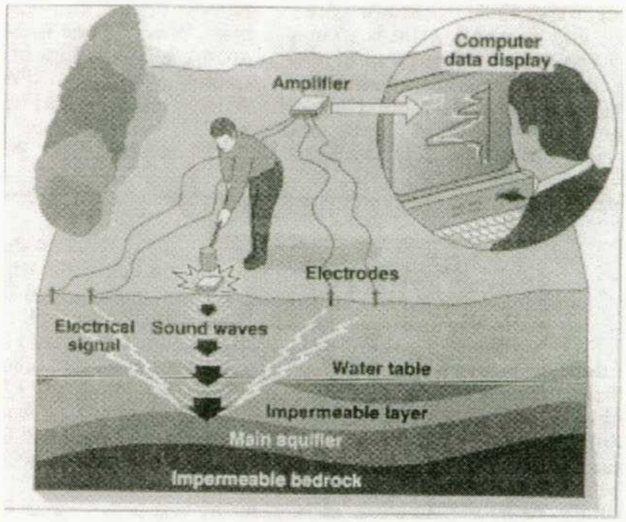
Upper : impermeable formation. Downgoing seismic pulse produces no EK coupling. No EK voltages are observed at the surface.

Lower : fluid saturated formation. Seismic pulse generates relative pore fluid movement. Double layer displacement generates an instantaneous electric field which is observed at surface.

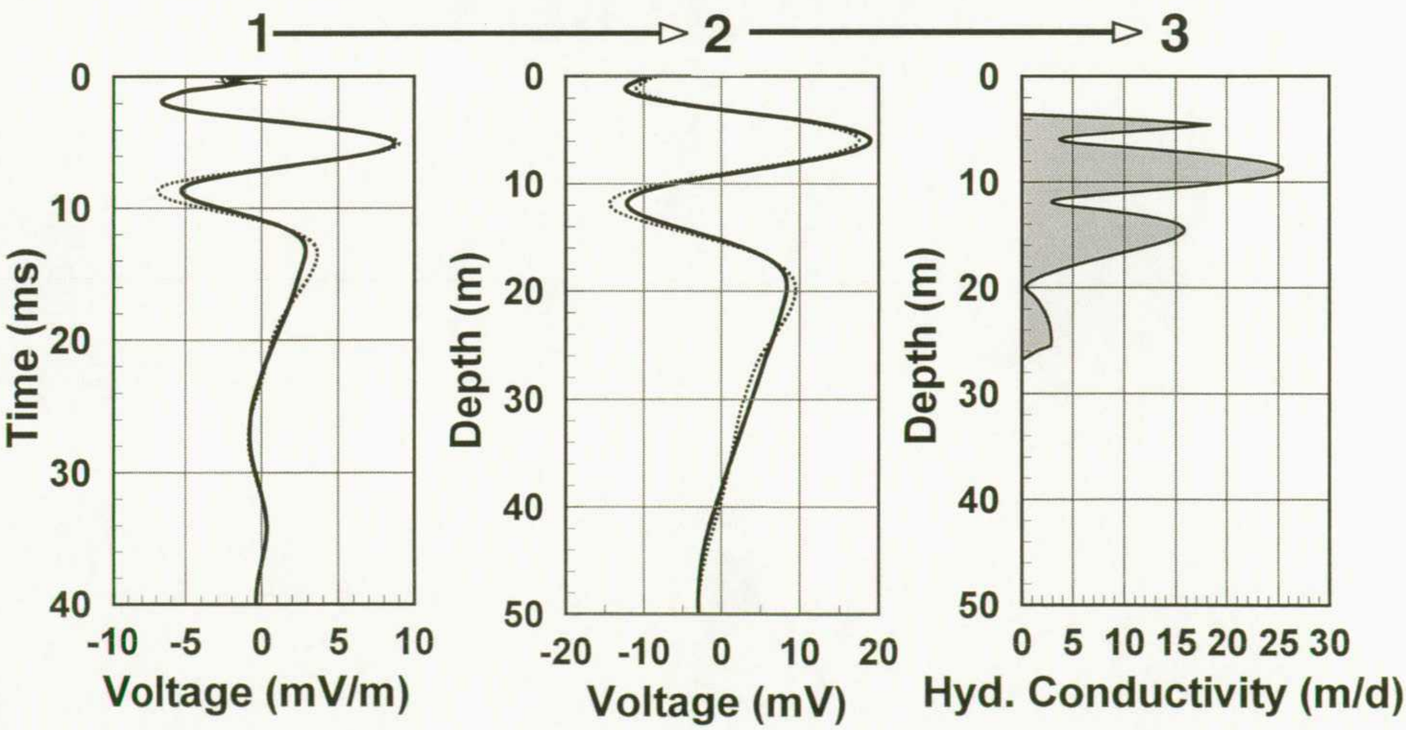
Figure 4.1

Illustration of electrokinetic data acquisition and processing sequence

EKS DATA ACQUISITION .



EKS PROCESSING SEQUENCE .



1) 2-channel voltage/time recording.

2) Time to depth conversion of voltages using a model of the acoustic velocity structure.

3) Voltage/depth converted to an estimate of permeability variation with depth.

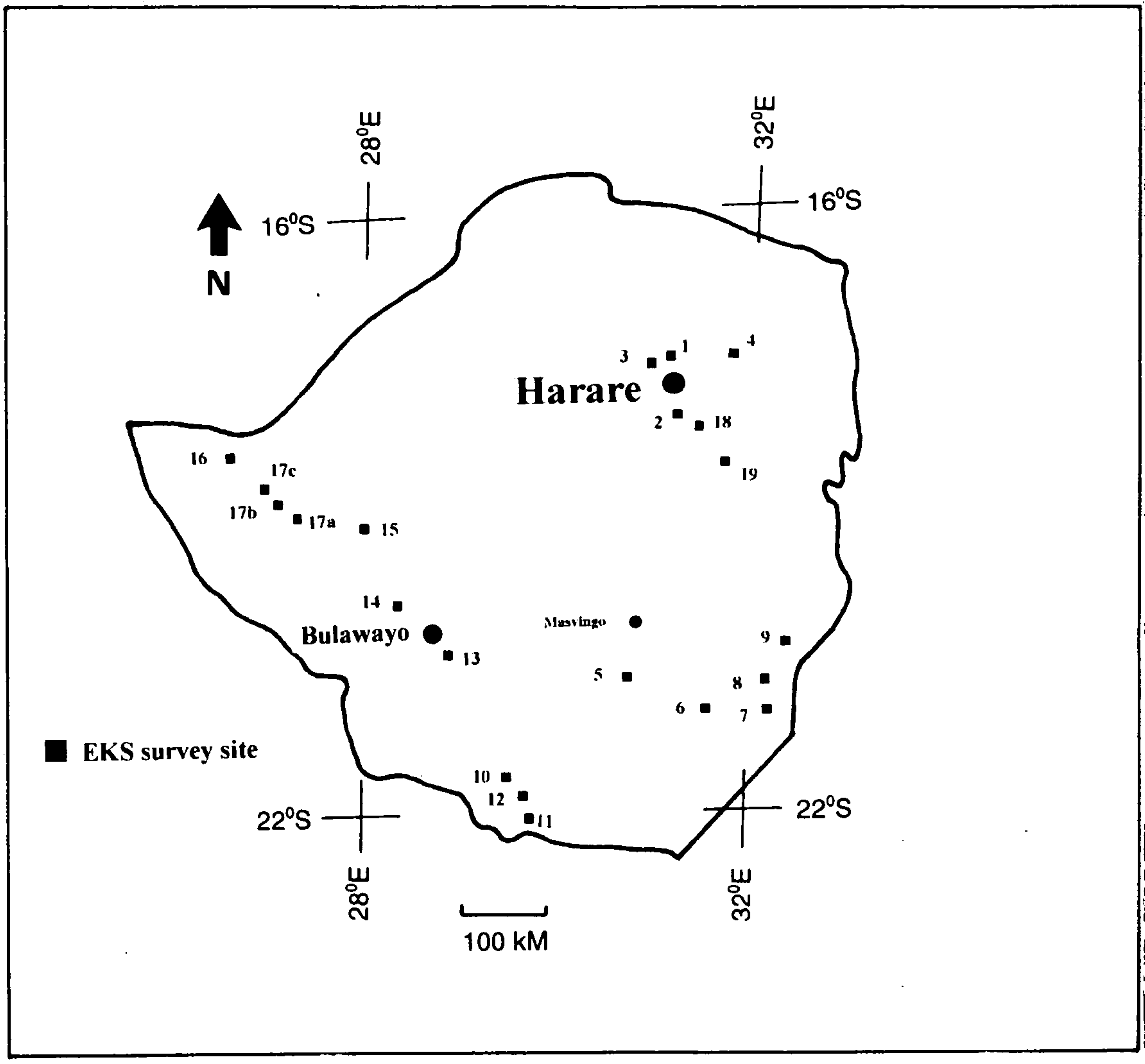


Figure 5.1 Location map showing the sites of the EKS observations

Figure 6.1.
Examples of 2-channel EK-sounding curves in Voltage/time.
All to a common scale

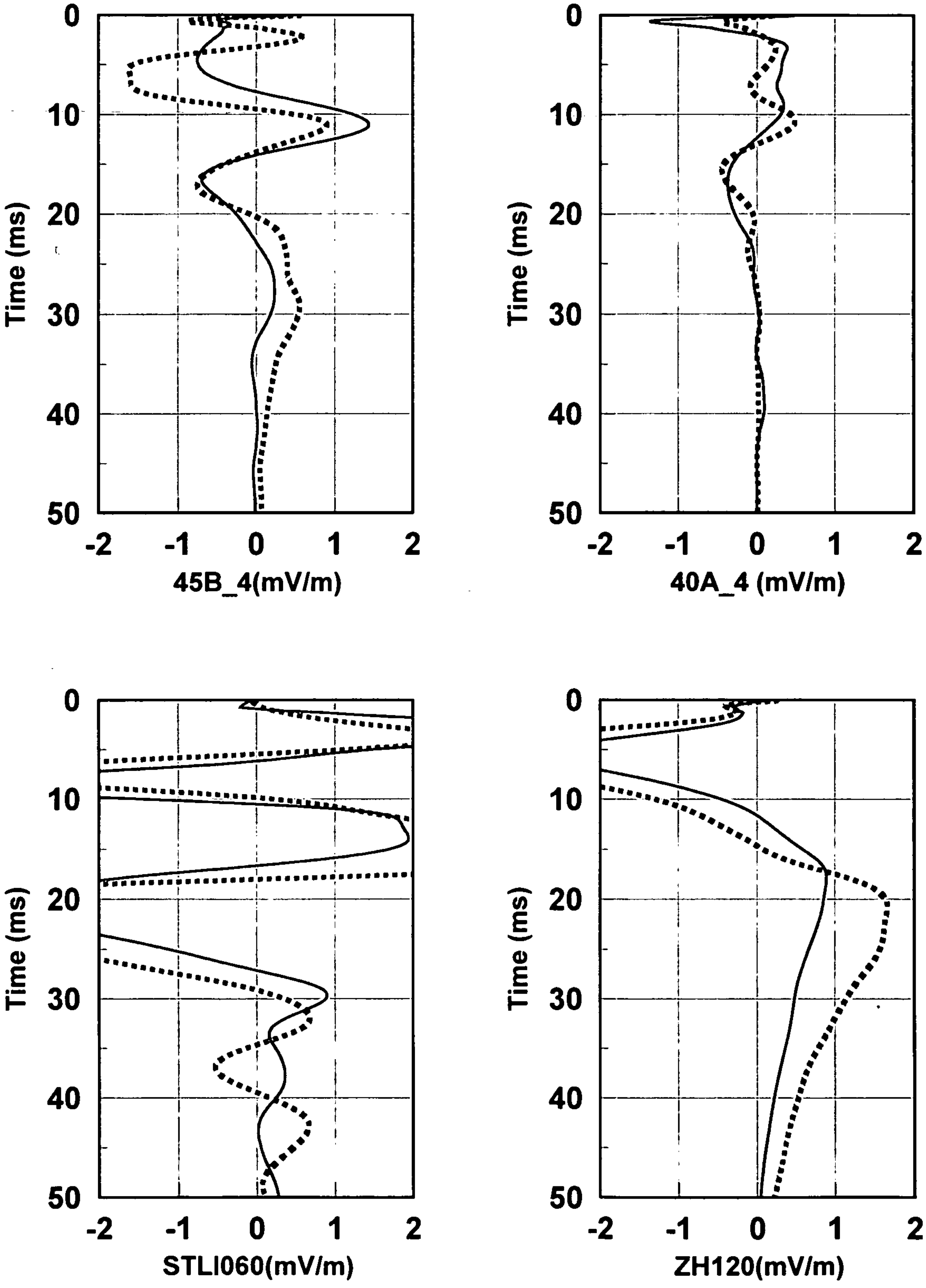
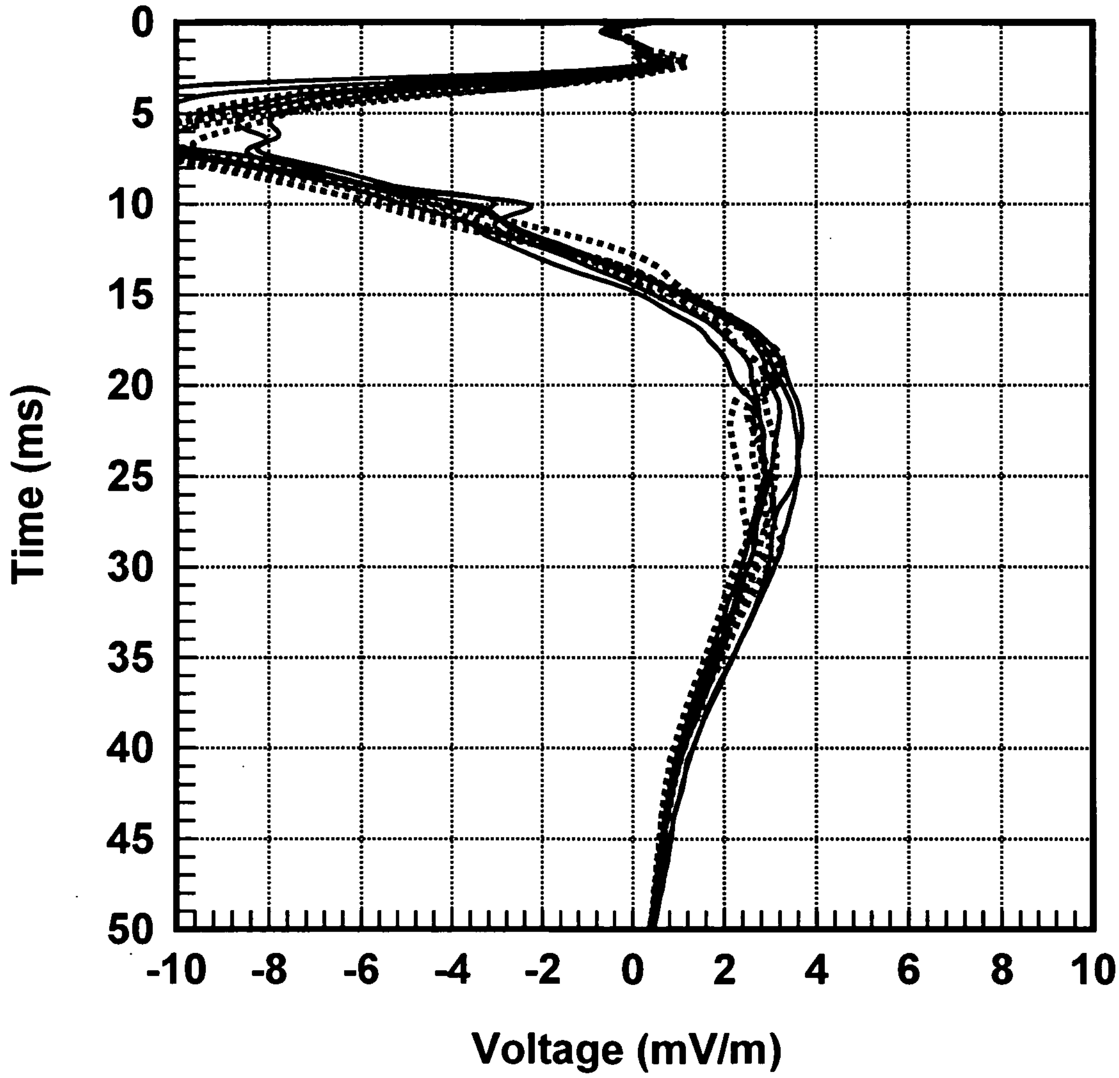
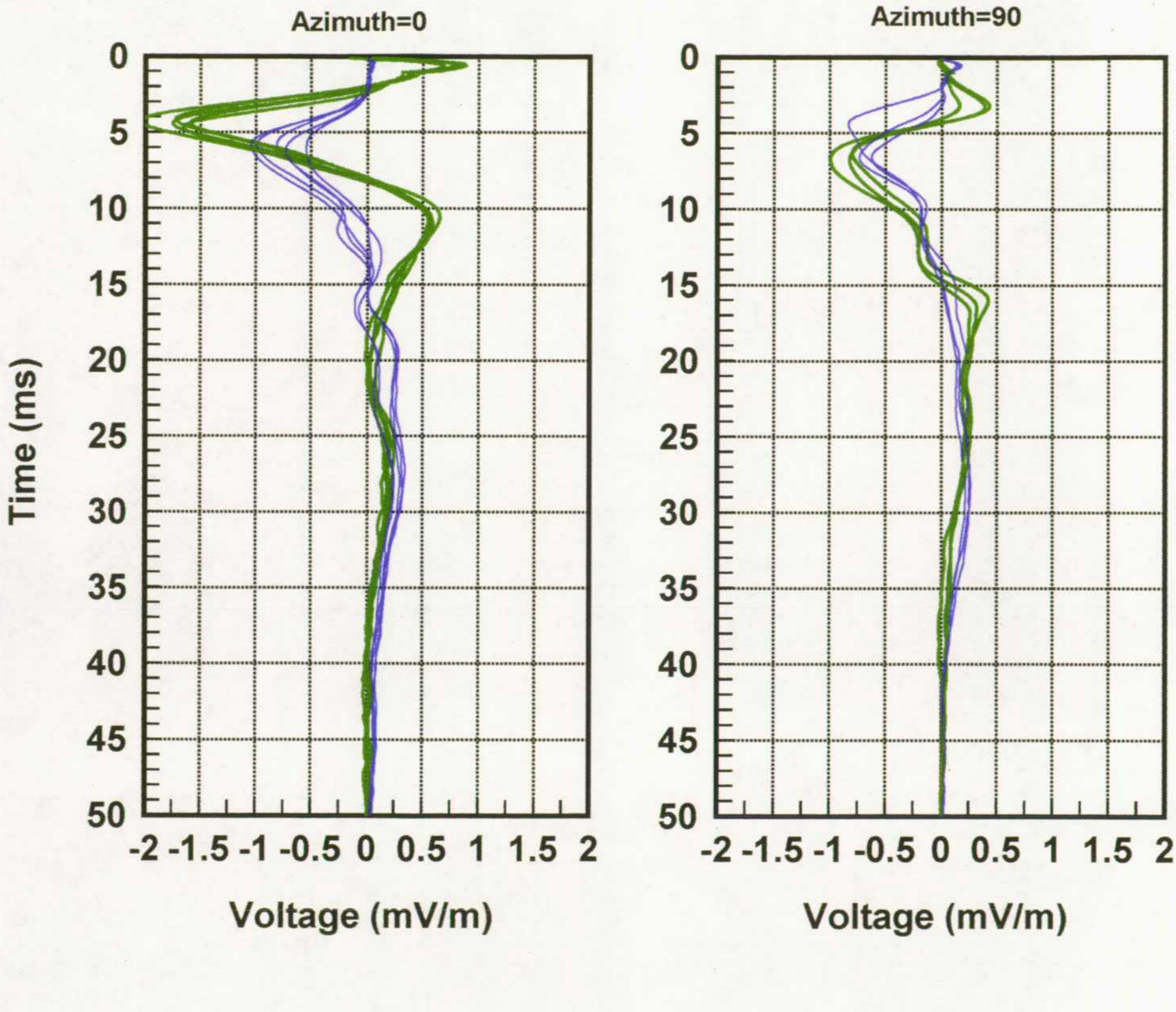


Figure 6.2
Example of EKS data repeatability
5 repeat shots - 2 data channels
CH-1 (solid), CH-2 (broken)



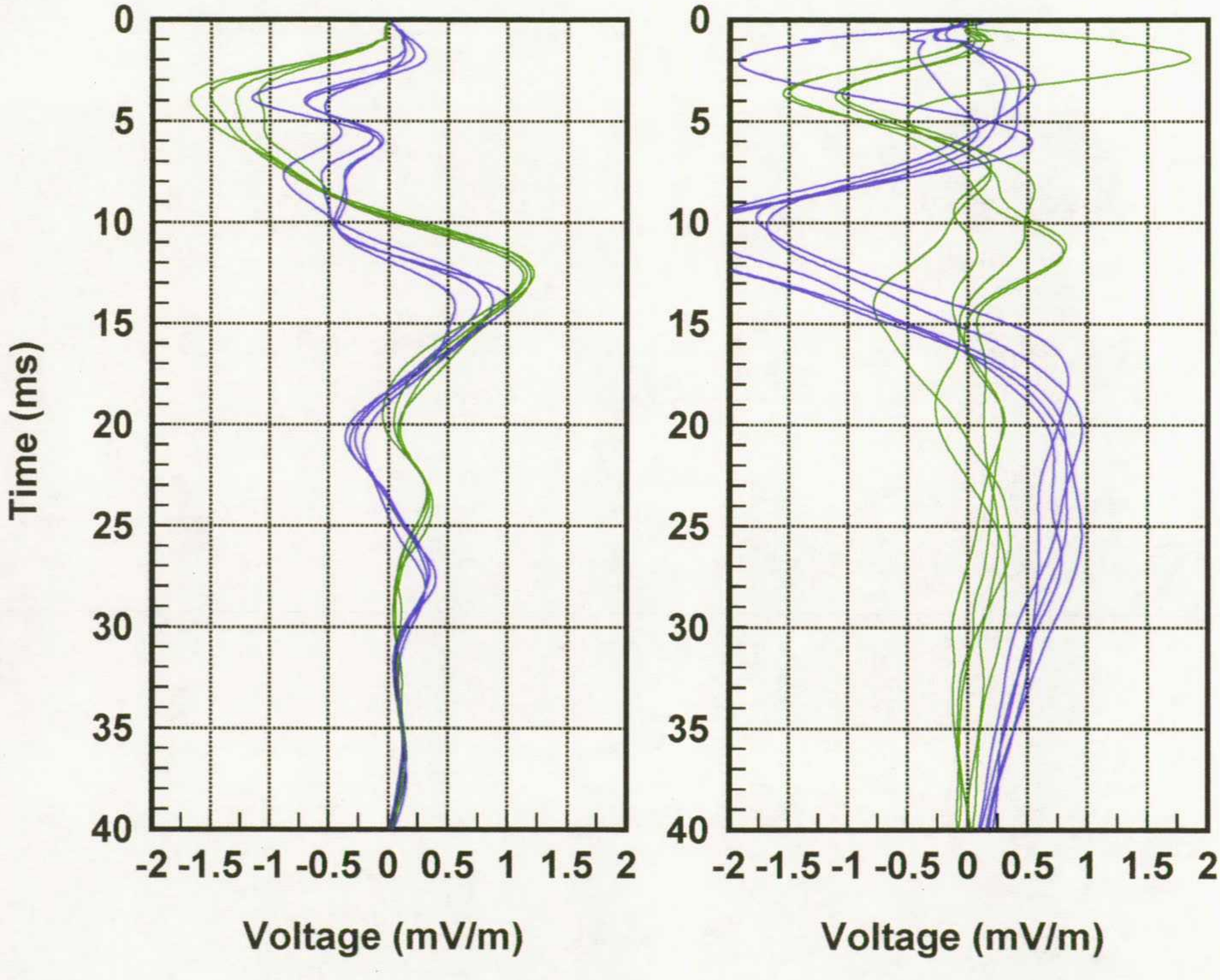
LOCATION : Zhovu Dam, Umzingwane Sand River, Zimbabwe.
SITE : 60E
Fluviatile sediments above Karoo Basalt.
Imains=0, Ifilt=0

Figure 6.3
Example of EKS data repeatability
5 repeat shots - 2 data channels.
Orthogonal, same centre, soundings.



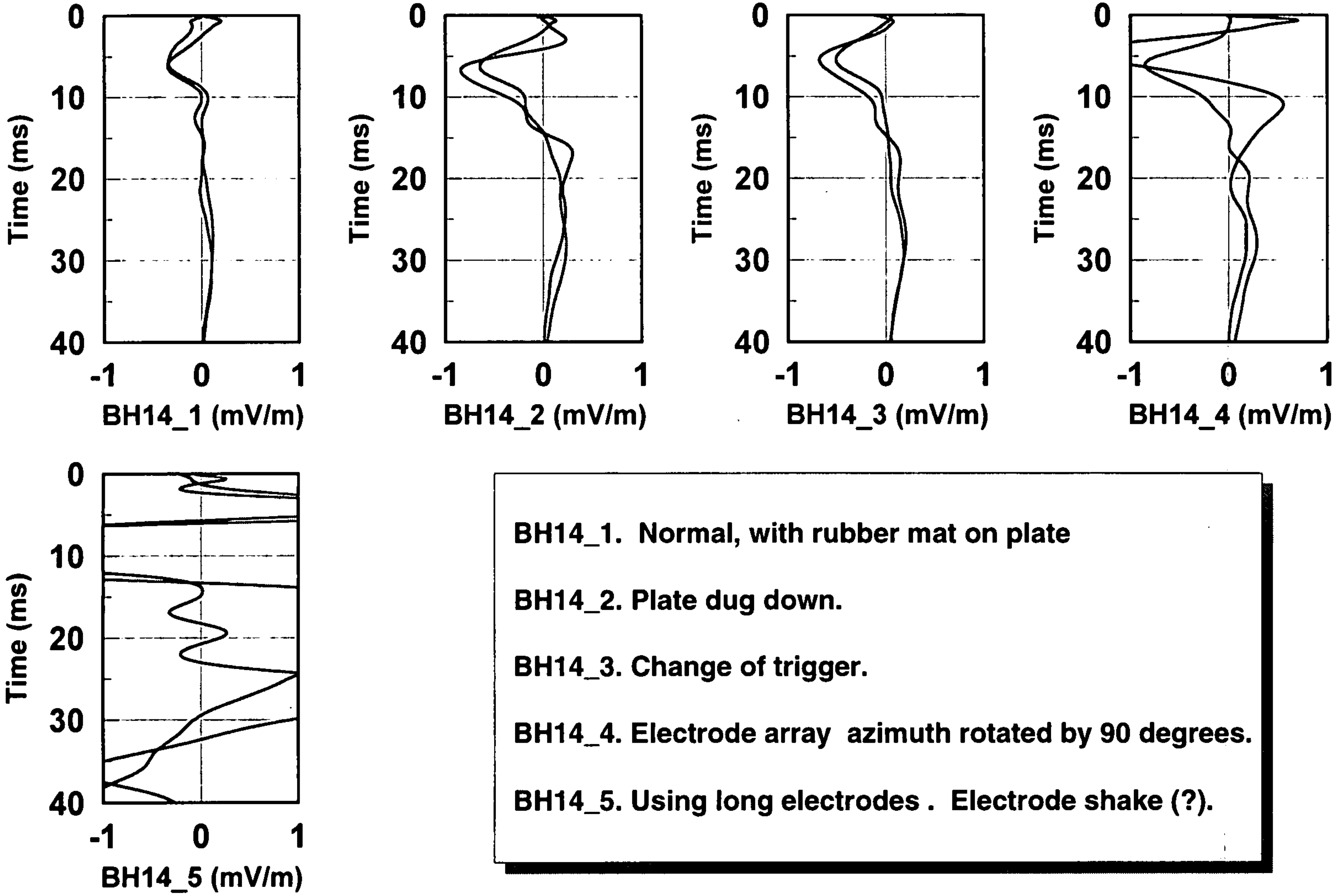
LOCATION : BH14, Save Valley, Zimbabwe.
SITE : BH14
Fluviatile sediments in down-faulted trench.
Water level 9.5 m. Main supply 31 m yielding
70-80 l/s, fresh.
Imains=0, Ifilt=1

Figure 6.4
Example of EKS data repeatability
5 repeat shots - 2 data channels.
Parallel soundings. 1m offset.



LOCATION : Ndamuleni School, CW, Zimbabwe.
SITE : NDA CW 200 m S
Lupani river flood plain (Kalahari sand alluvium).
Water level 3 m.
Imains=1, Ifilt=1

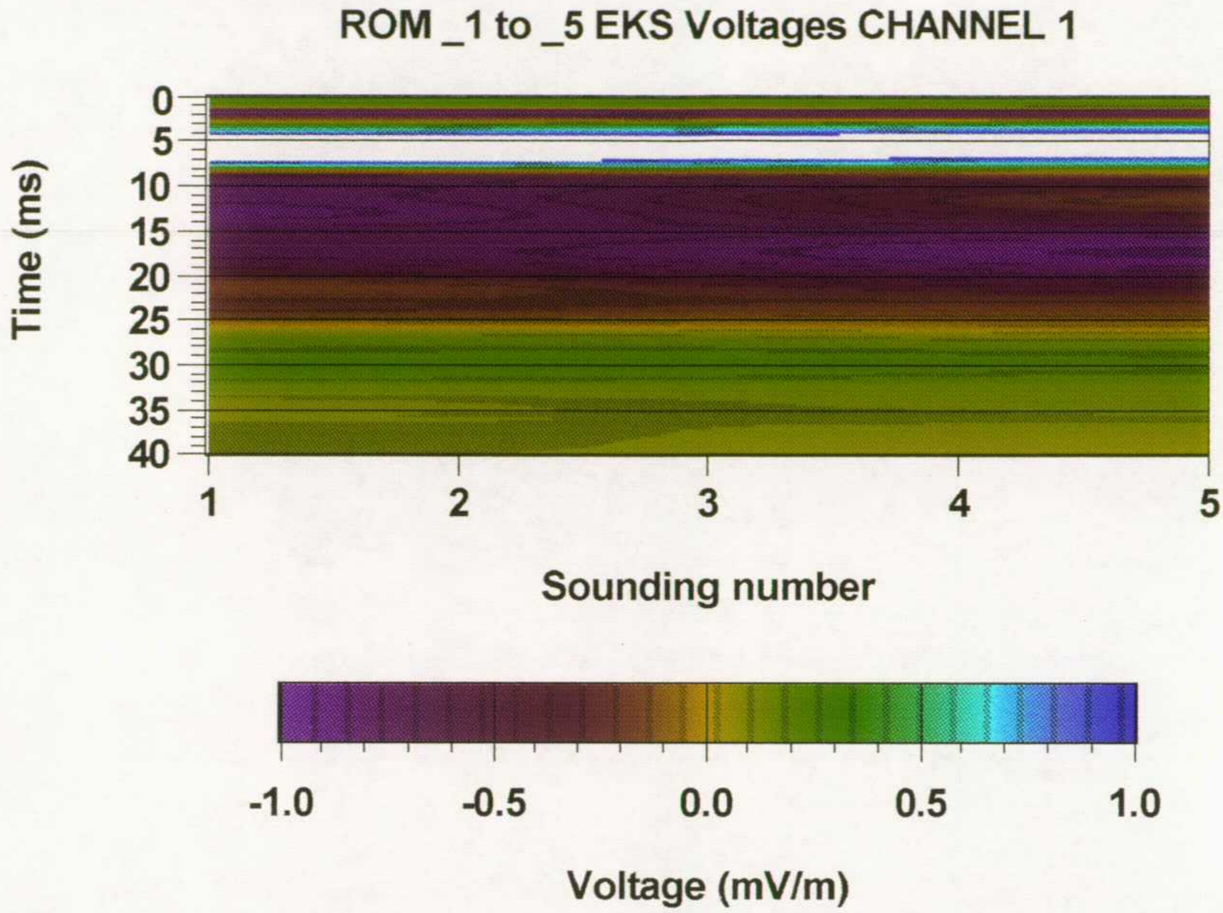
Figure 6.5
Examples of EK-sounding curves in Voltage/time, at one site. Plate and electrode tests.



Location : BH14, Save Valley. Zimbabwe. Water table at 9.5 m.

Figure 6.5

Figure 6.6
Colour-contoured voltages from 5 close-proximity soundings.
ROM_1 to _5. CW in granite/gneiss basement.



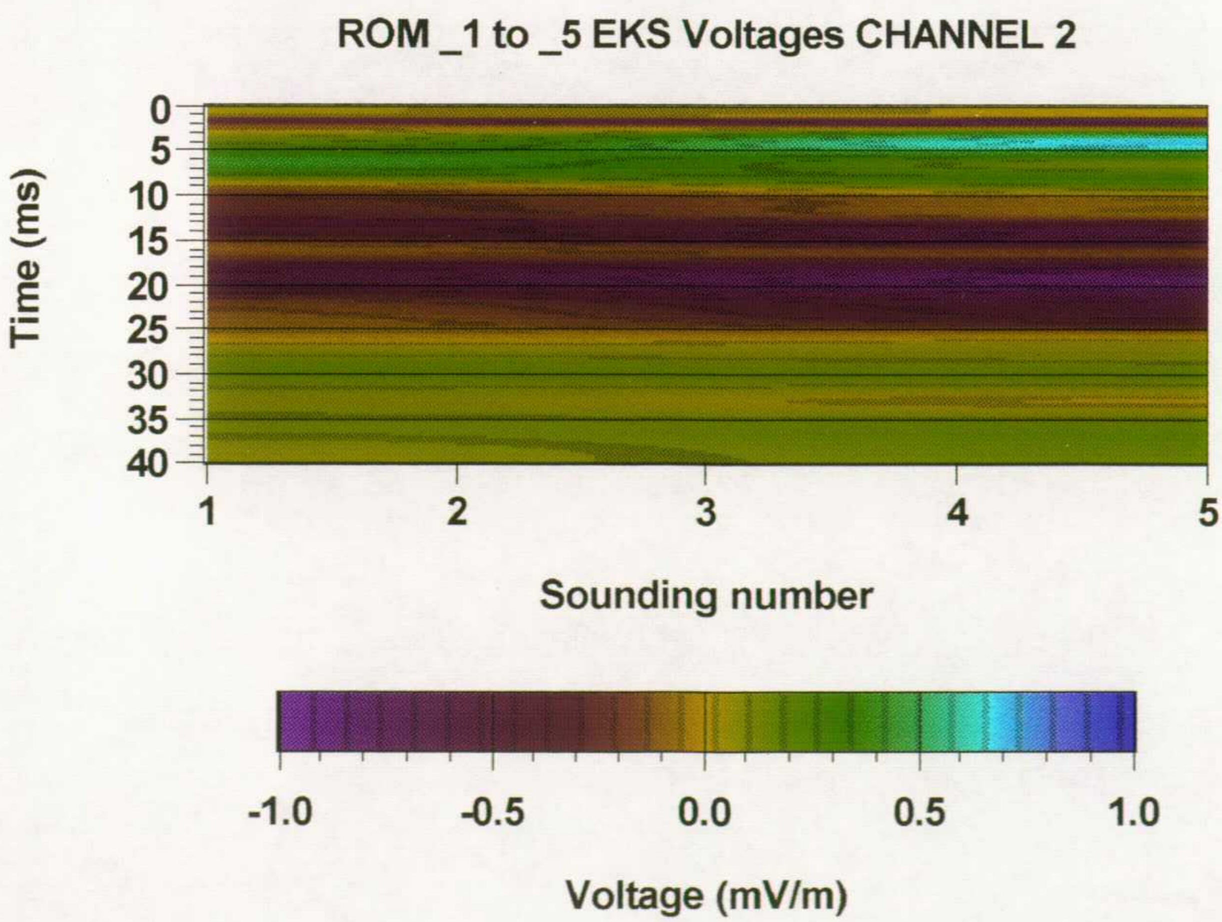


Figure 6.7
Colour-contoured voltage rise-times from 5 close-proximity soundings. Logarithmic scale..
ROM_1 to _5. CW in granite/gneiss basement.

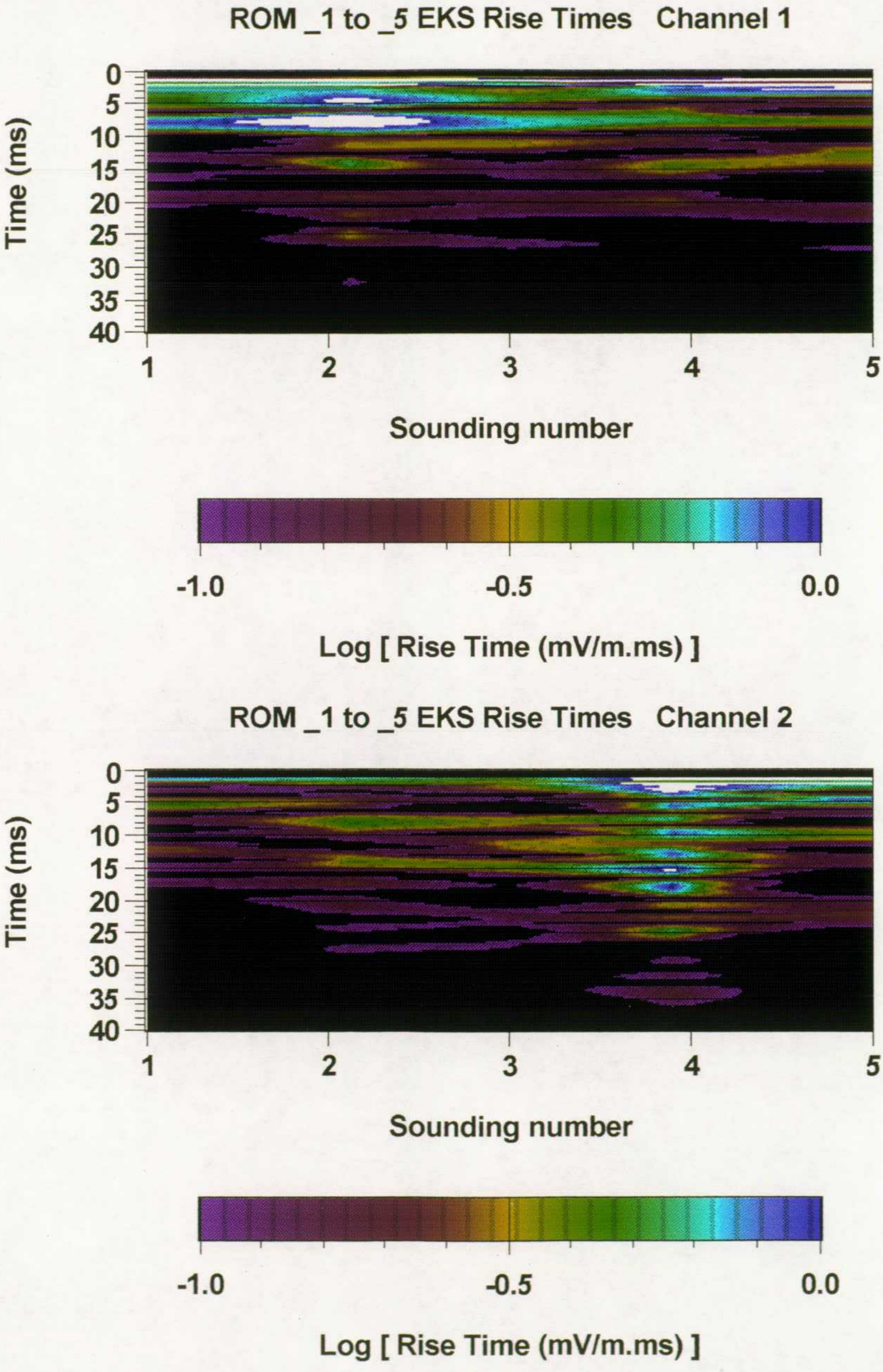


Figure 6.8

3Box presentation of 3 soundings at Site 3a, Stamford Farm BH14.

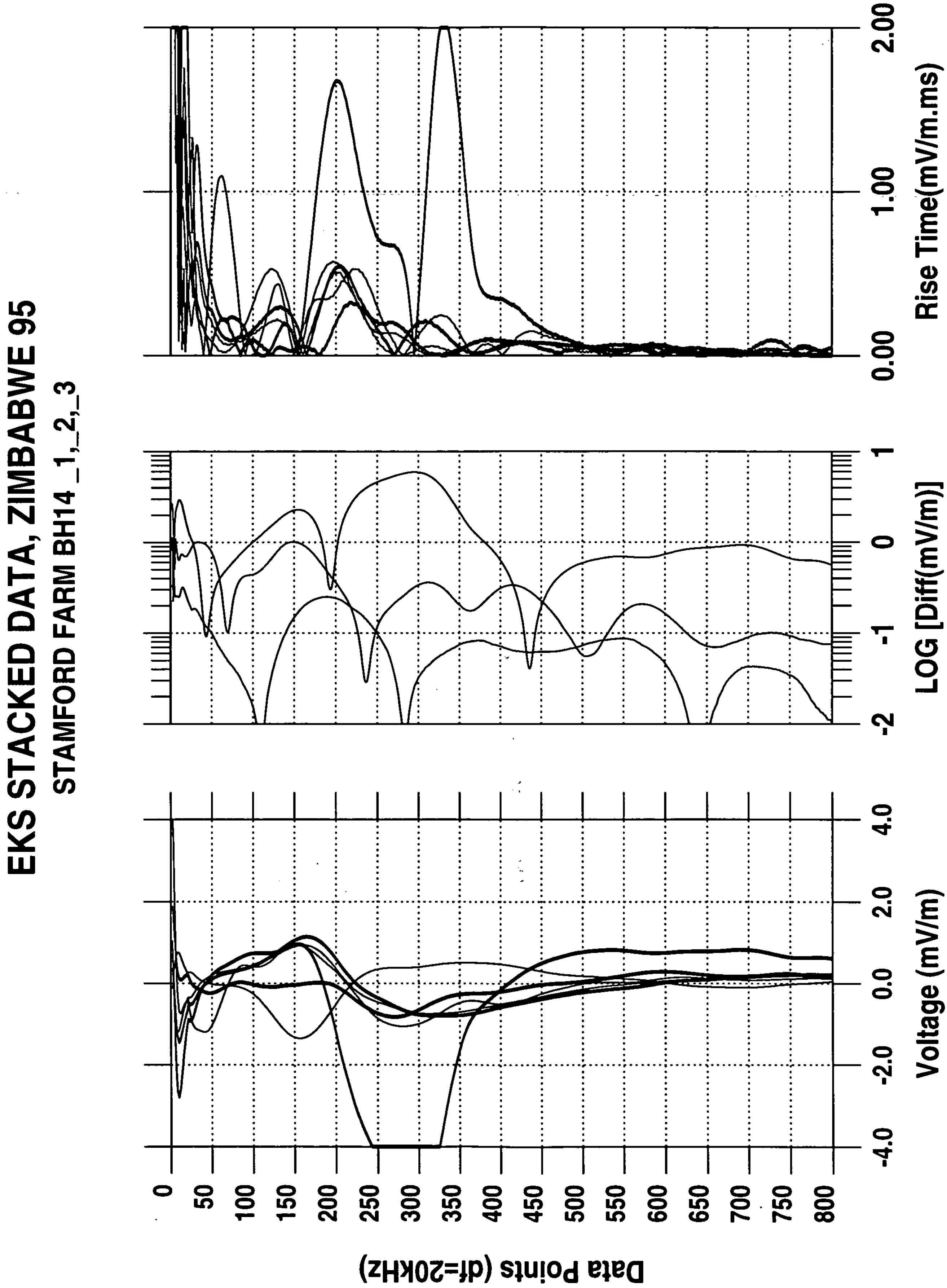


Figure 6.9

3Box presentation of 3 soundings at Site 3b, Stamford Farm BH15.

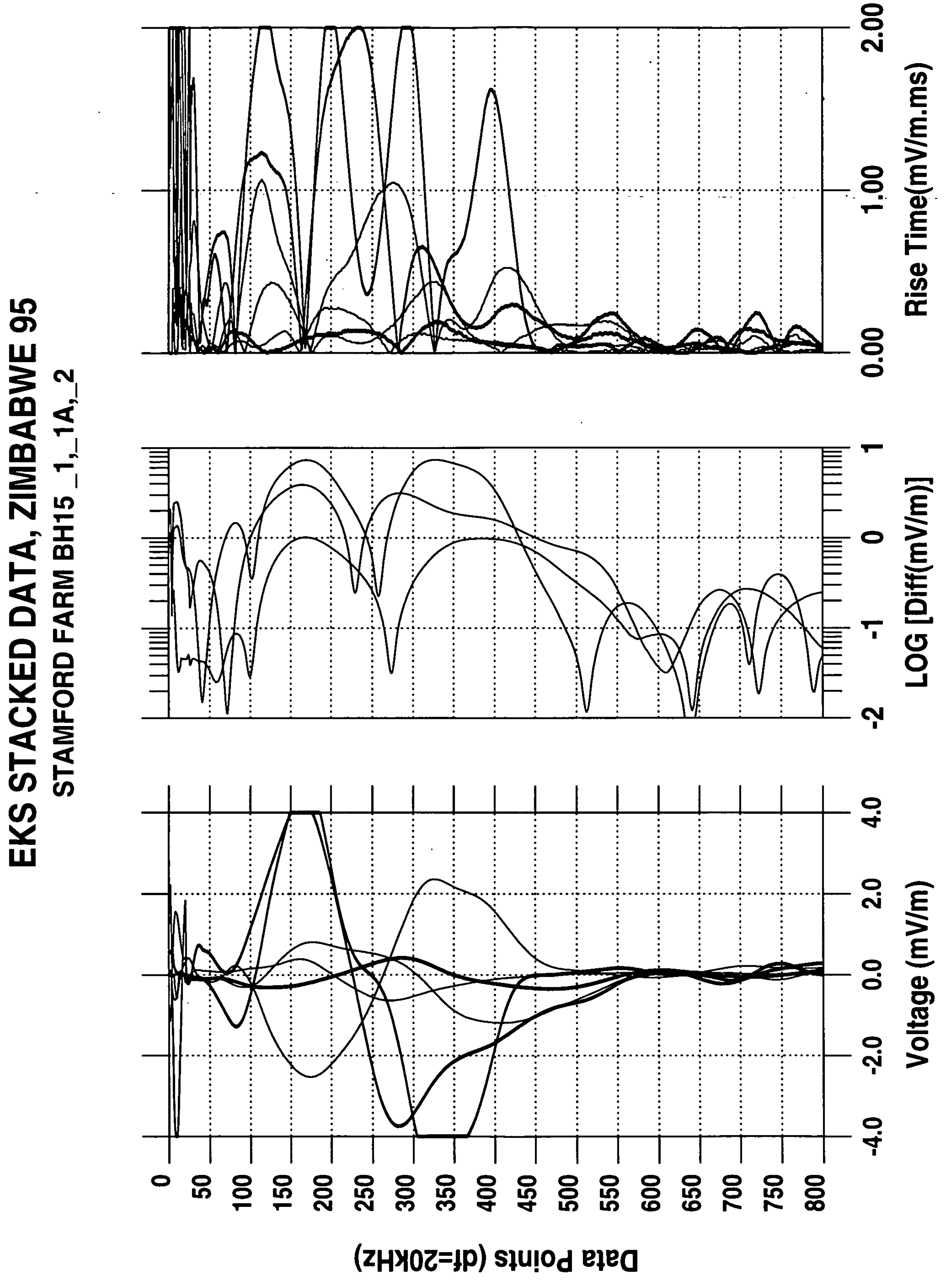


Figure 6.10

3Box presentation of 3 soundings at Site 3c, Stamford Farm BH17.

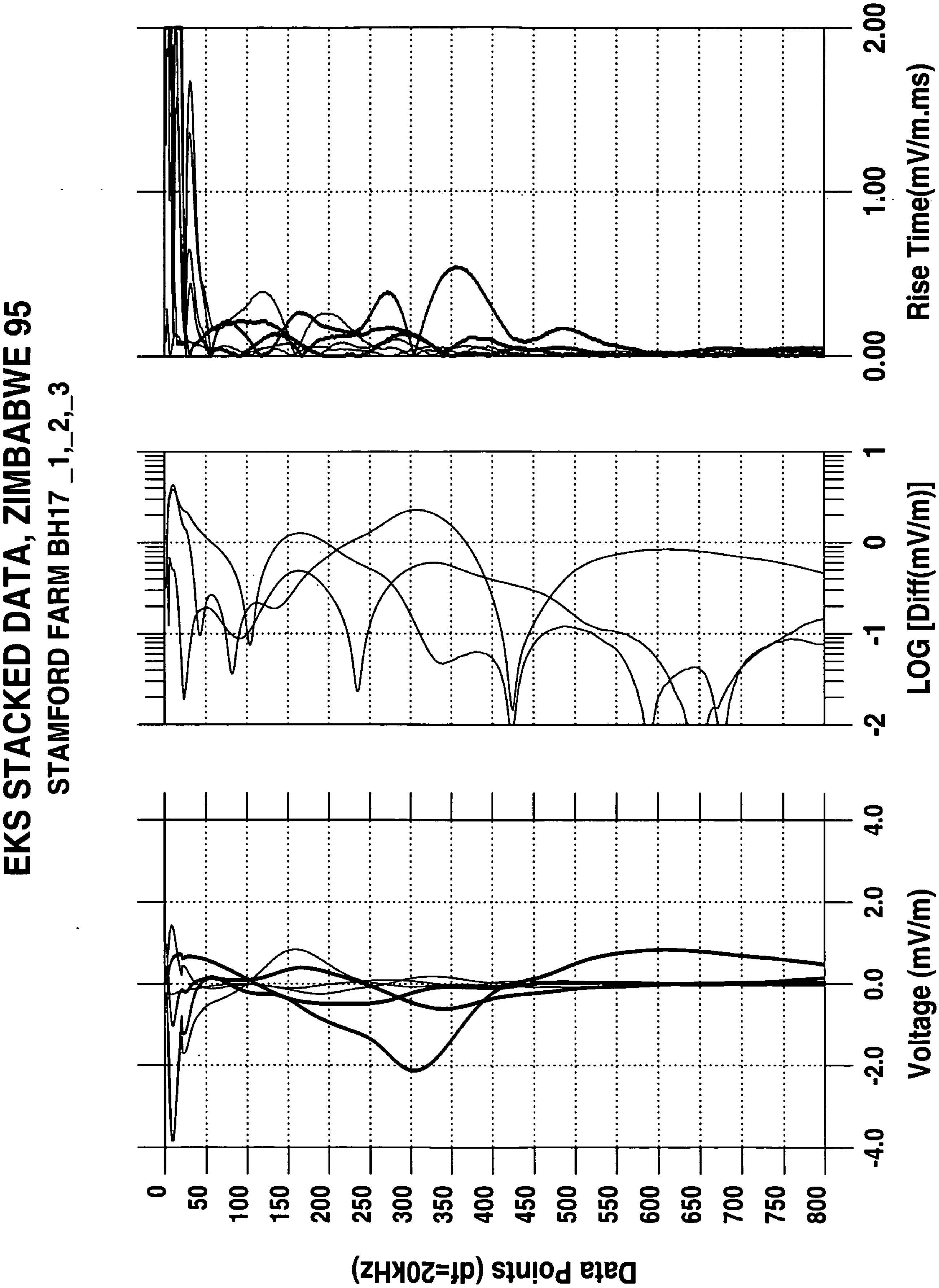


Figure 7.1
Colour-contoured voltages from 5 profile soundings.
Habani Township BH. 3-21 m (weathered peg. granite)

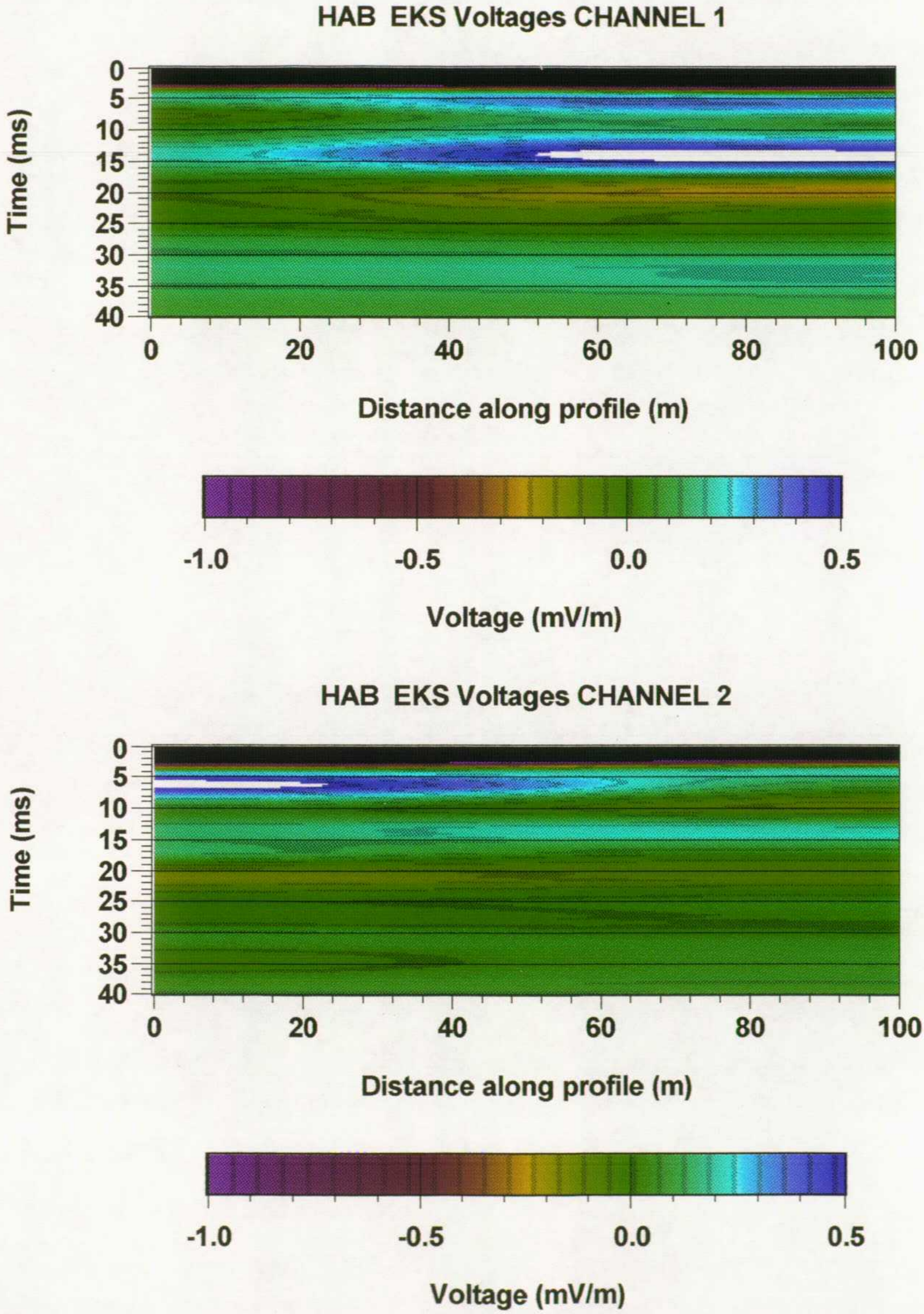
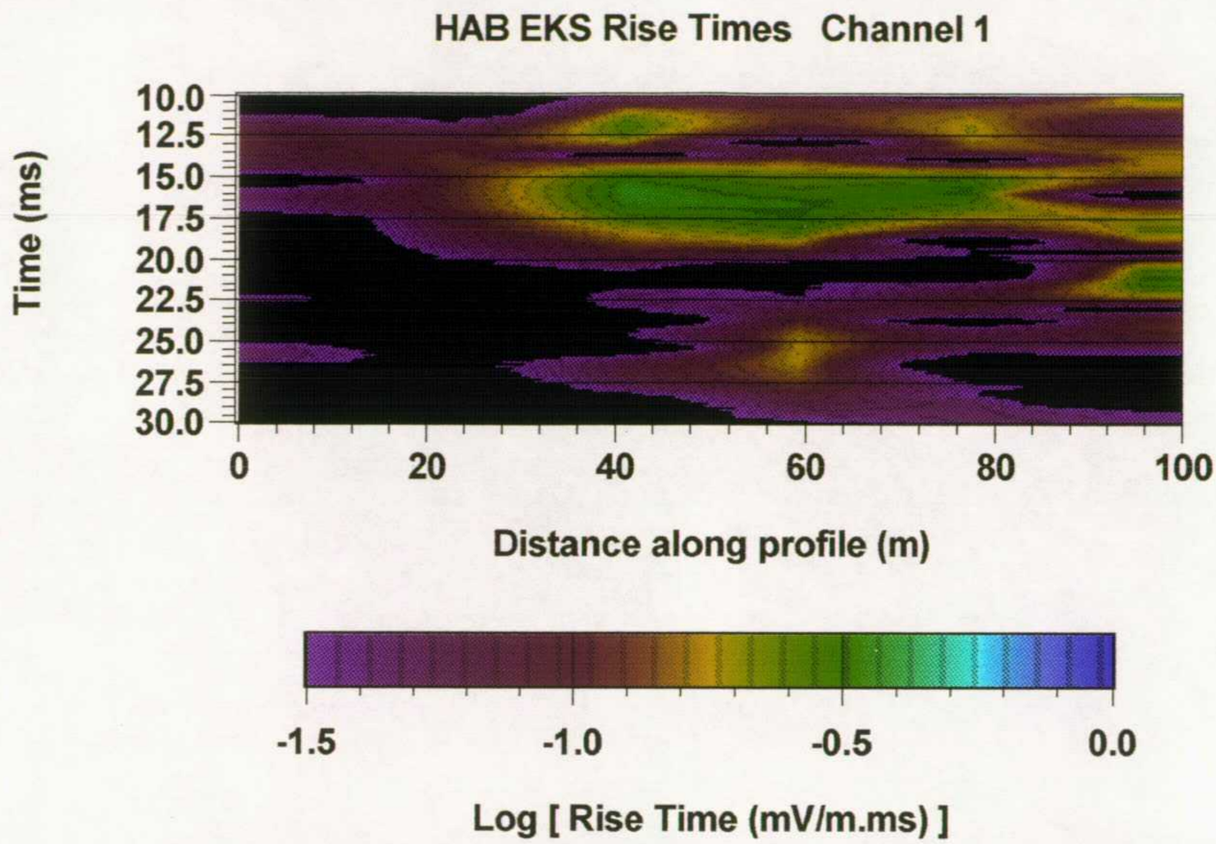


Figure 7.2
Colour-contoured voltage rise-times from 5 profile soundings. Logarithmic scale.
Habani Township BH. 3-21 m (weathered peg. granite)



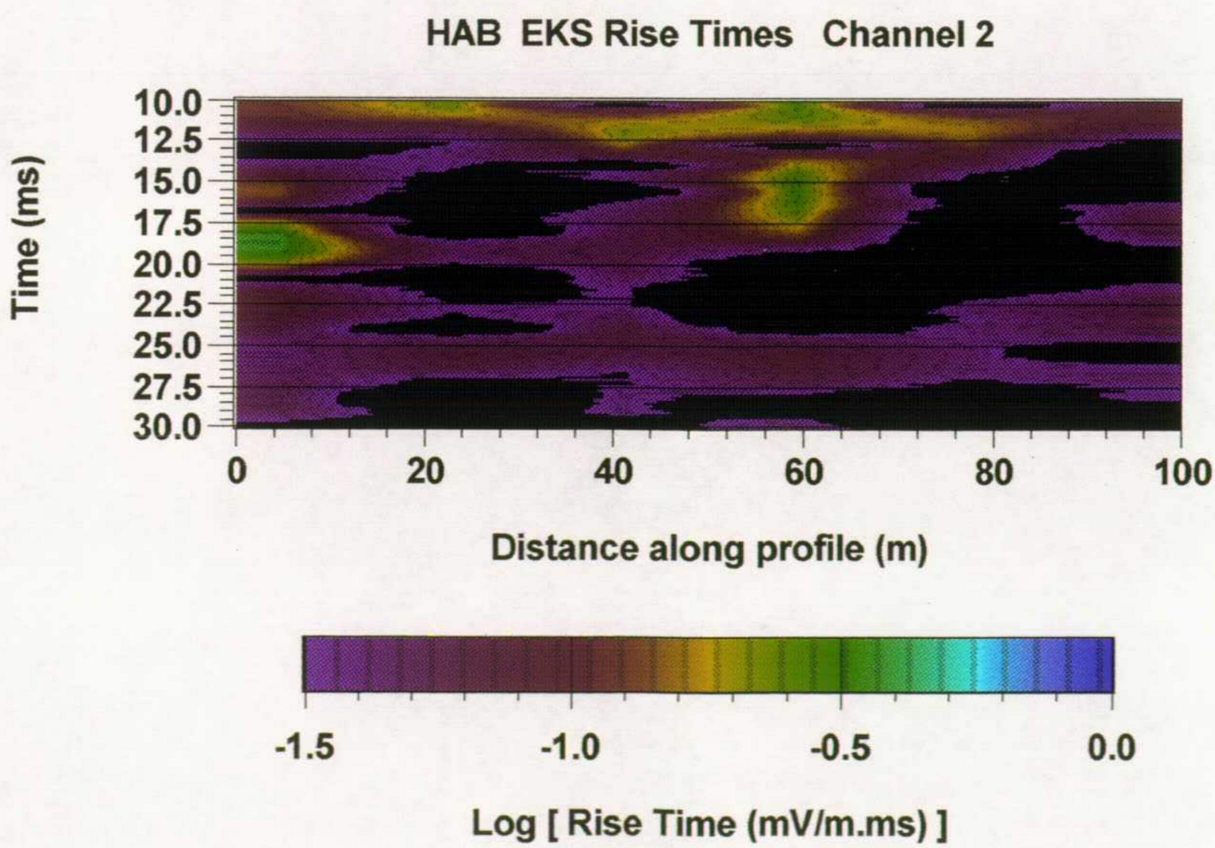
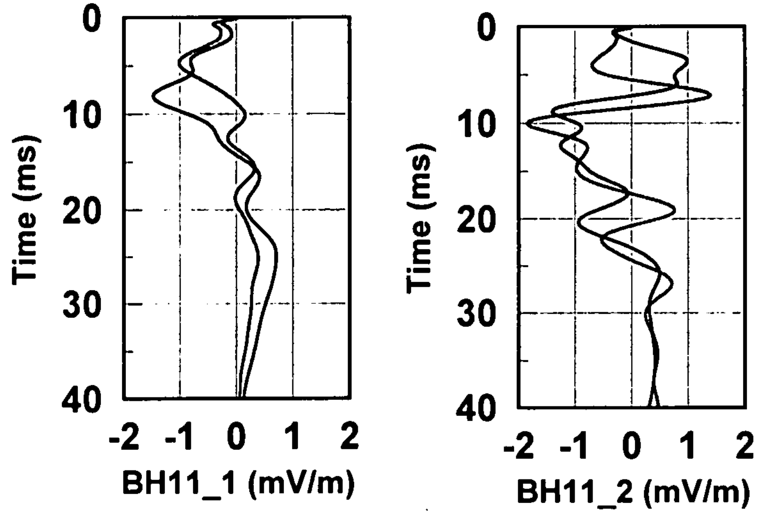


Figure 7.3
Examples of EK-sounding curves in Voltage/Time. In vicinity of a borehole.



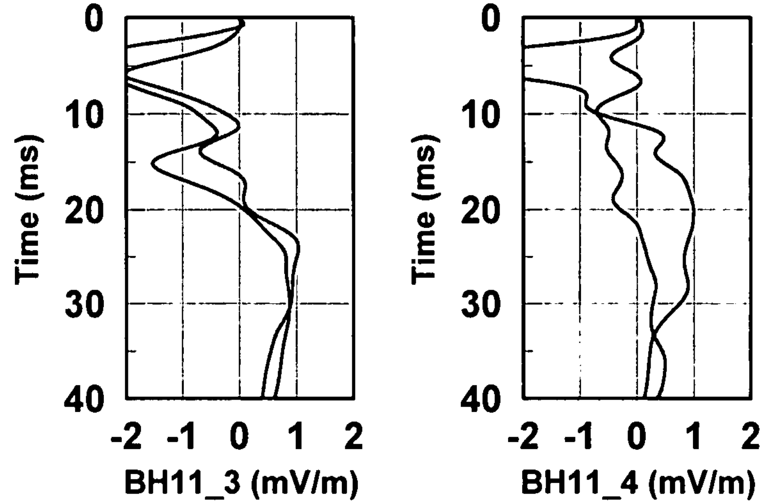
BH11_1 and BH11_2.

Same sounding centre.

Perpendicular dipole azimuths.

35 m SE of BH11.

IN TREES



BH11_13 and BH11_24

Same sounding centre.

Perpendicular dipole azimuths.

30m , NW of BH11.

IN OPEN GROUND

Location : BH11, Save Valley. Zimbabwe. Water table at 11.6 m.

Figure 8.1
Colour-contoured voltages from 5 profile soundings.
Mukumba School CW (~70m) in granite/gneiss basement.

Sands over Gneiss/granite basement

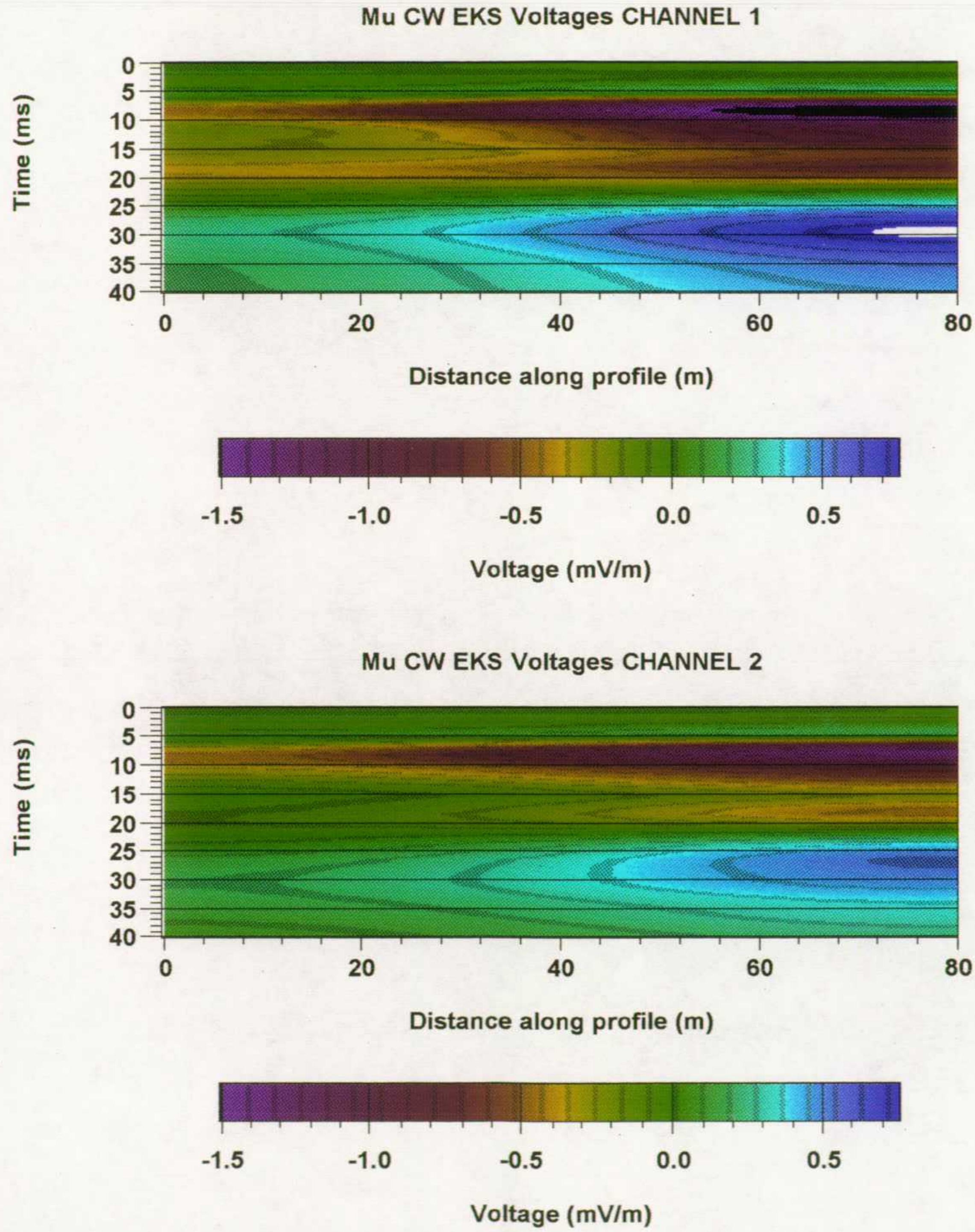
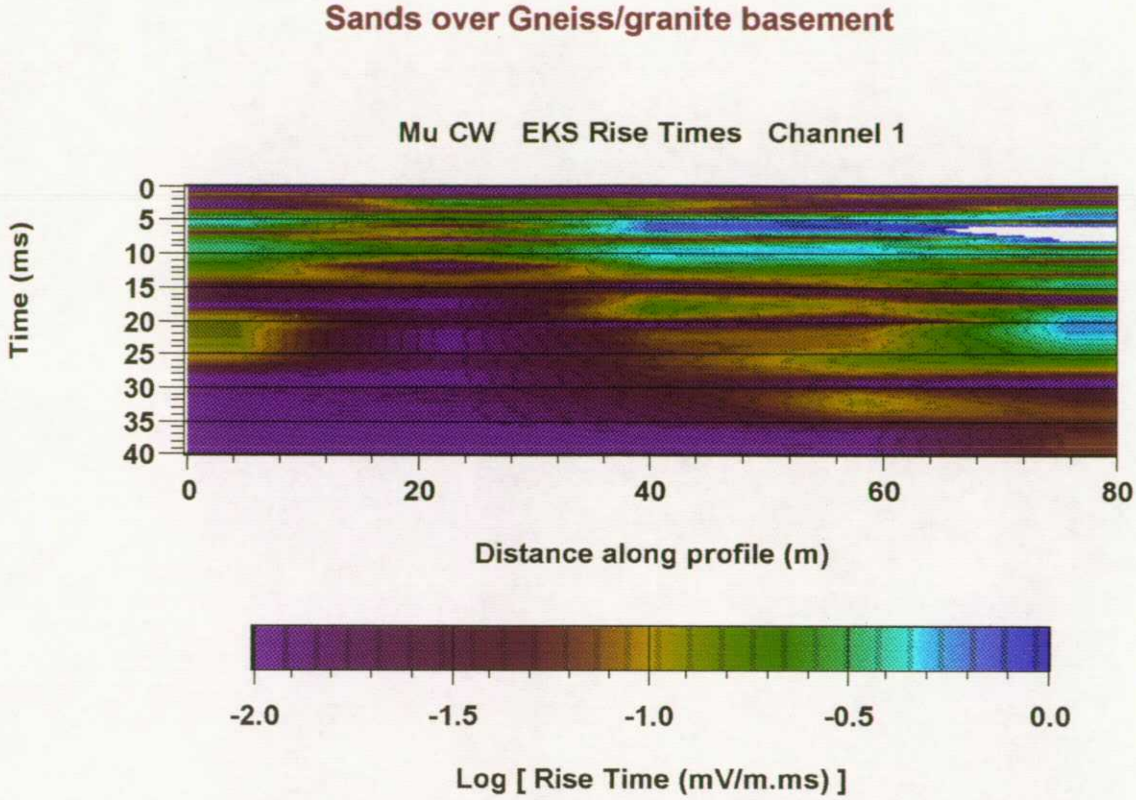


Figure 8.2
Colour-contoured voltage rise-times from 5 profile soundings.
Mukumba School CW (~70m) in granite/gneiss basement.



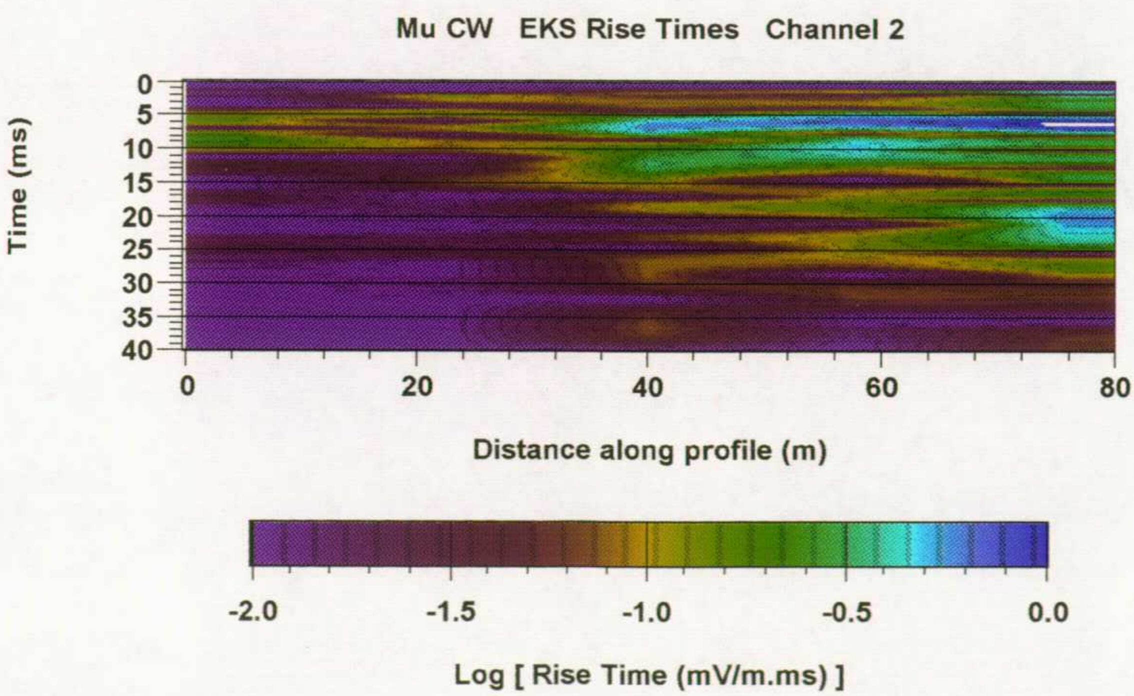


Figure 8.3
Colour-contoured voltages from 8 profile soundings.
St. Lioba's school CW in granite/gneiss basement.

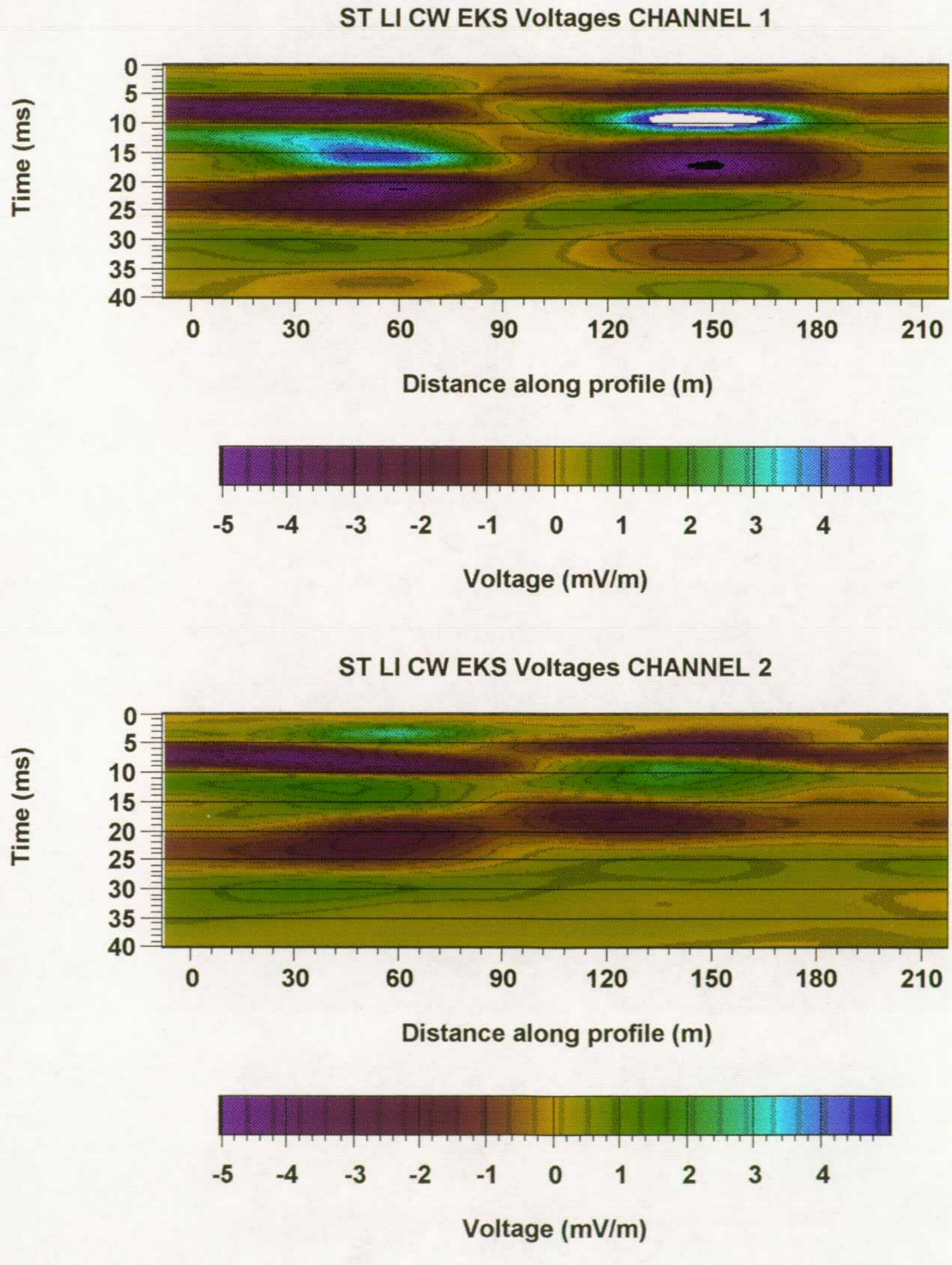
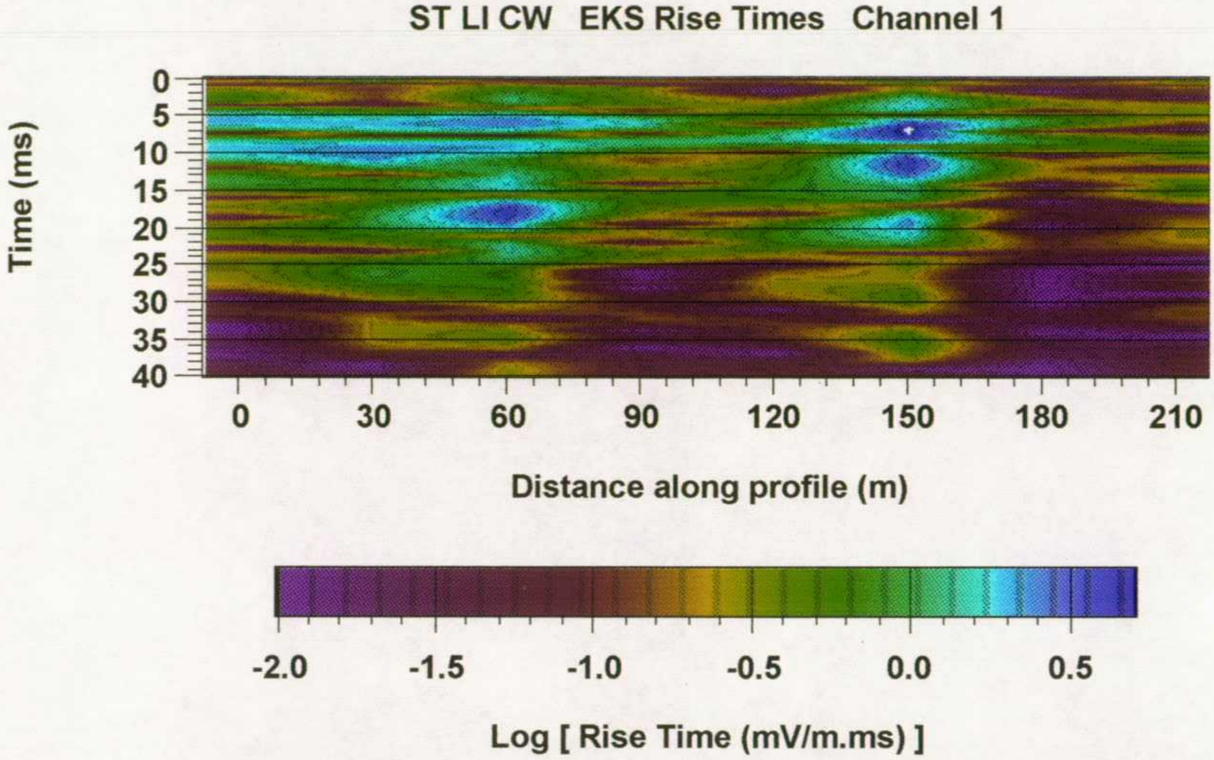


Figure 8.4
Colour-contoured voltage rise-times from 8 profile soundings. Logarithmic scale.
St. Lioba's school CW in granite/gneiss basement.



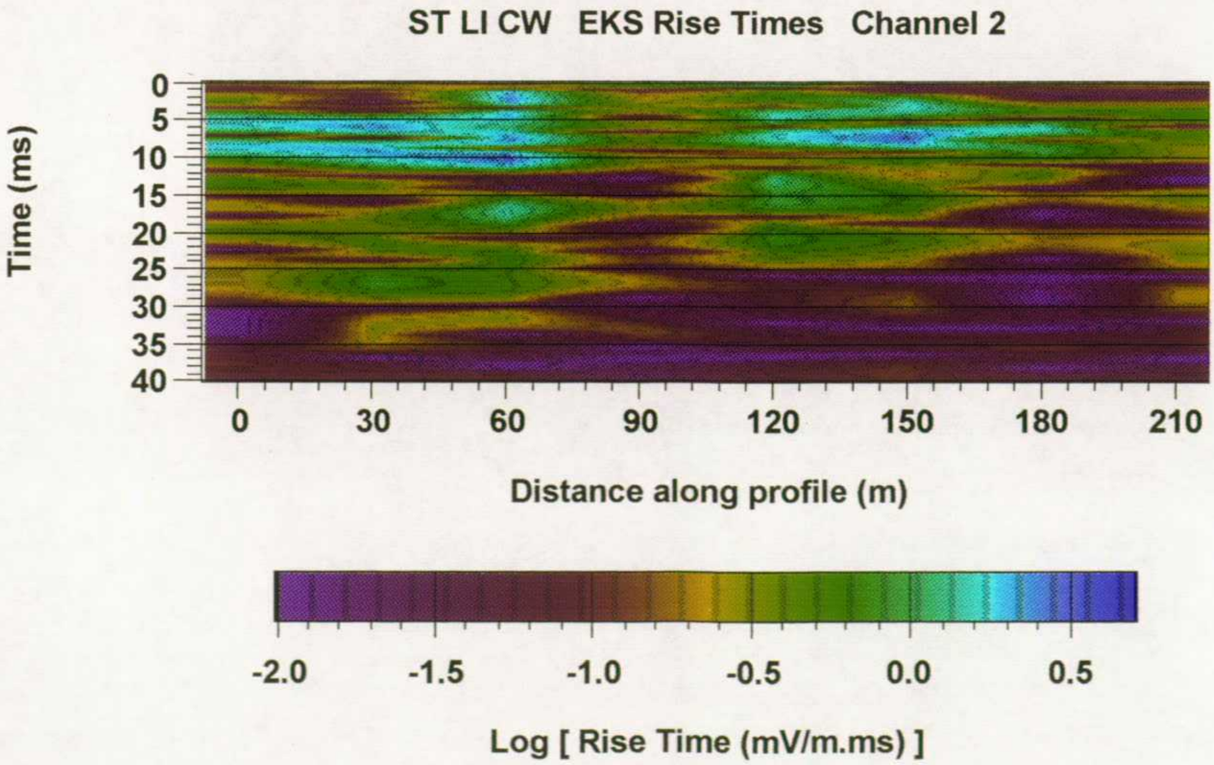
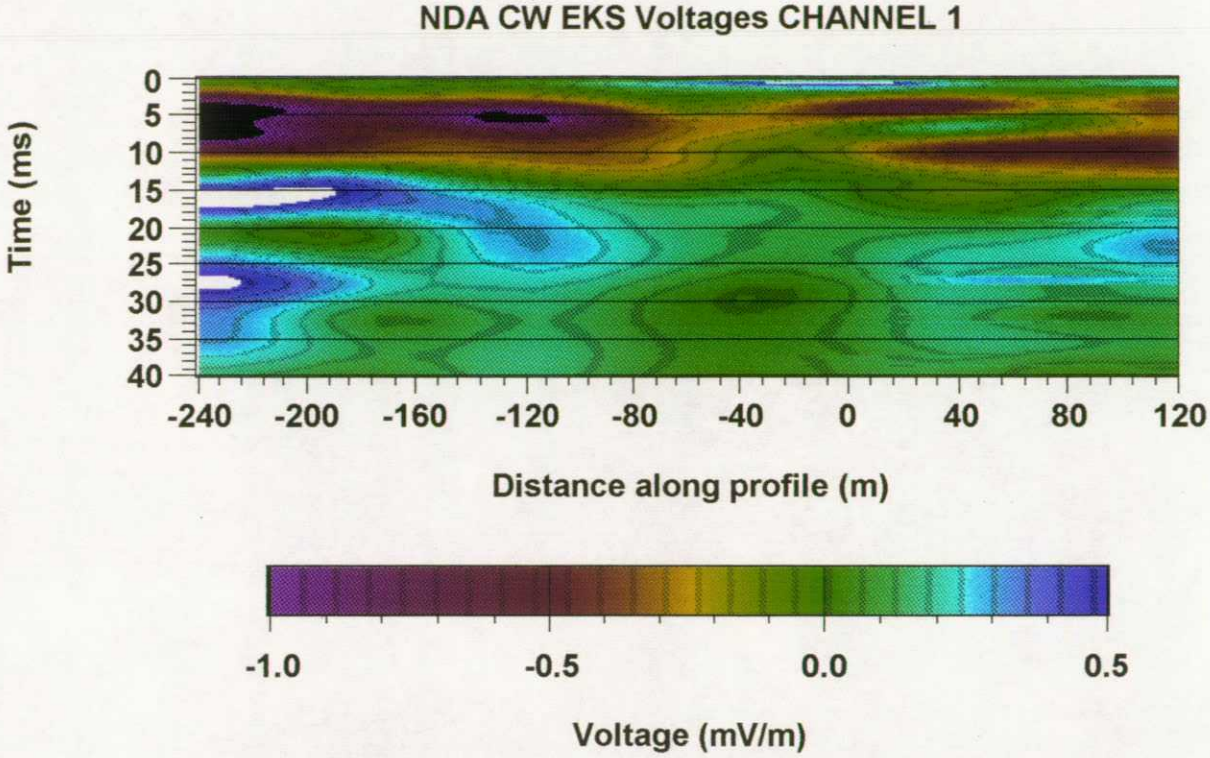


Figure 8.5
Colour-contoured voltages from 11 profile soundings. Ndamuleni School CW in Kalahari deposits (Lupani River flood-plain).



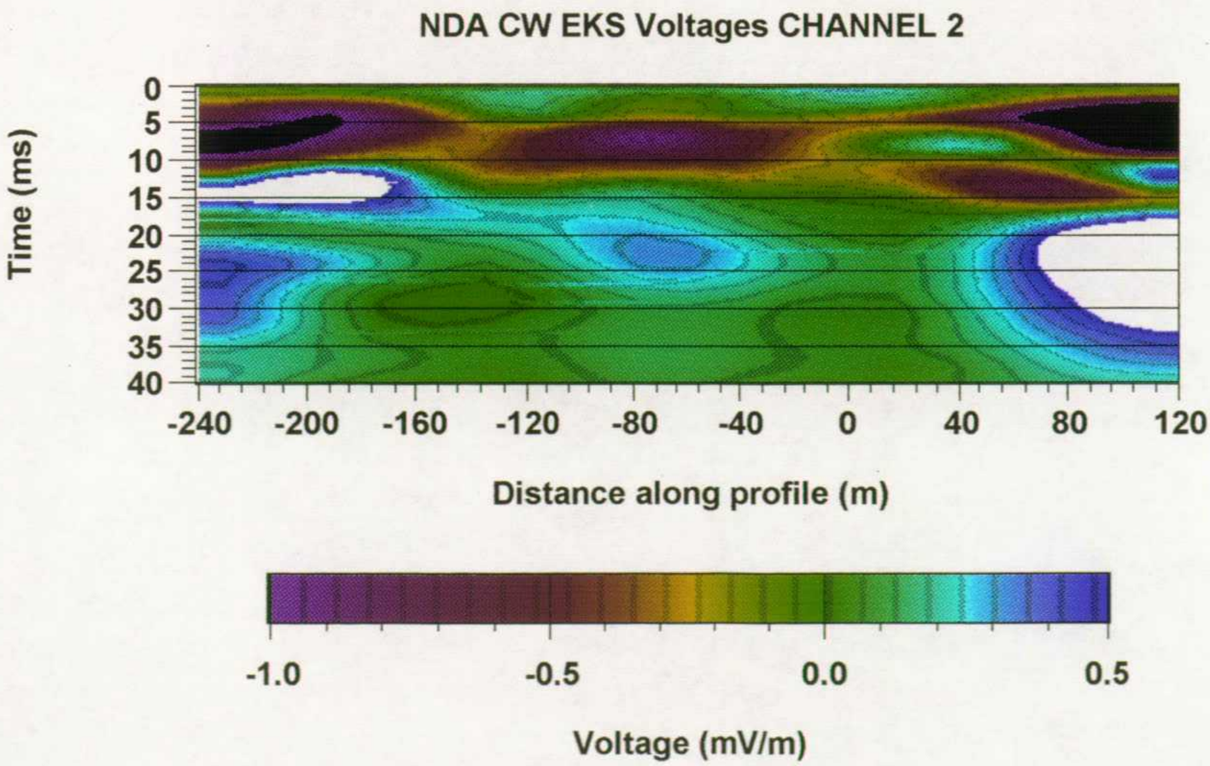
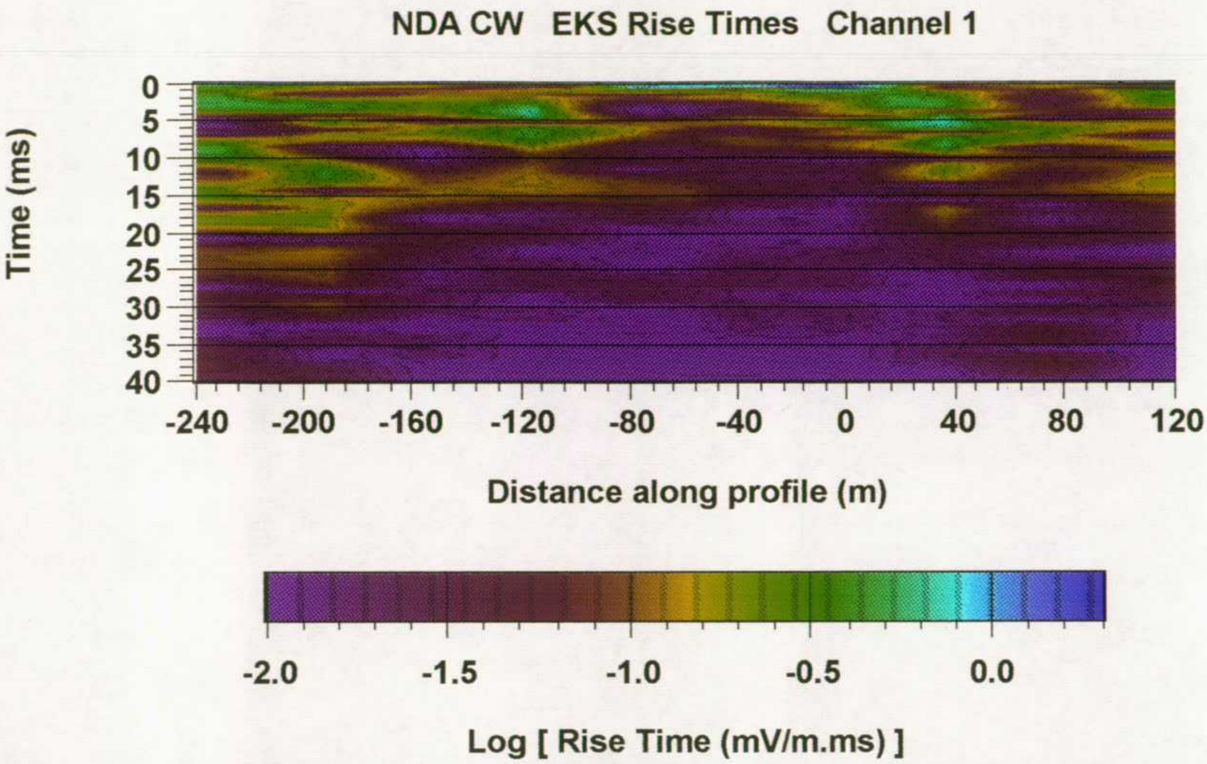


Figure 8.6
Colour-contoured voltage rise-times from 11 profile soundings. Logarithmic scale.
Ndamuleni School CW in Kalahari deposits (Lupani River flood-plain).



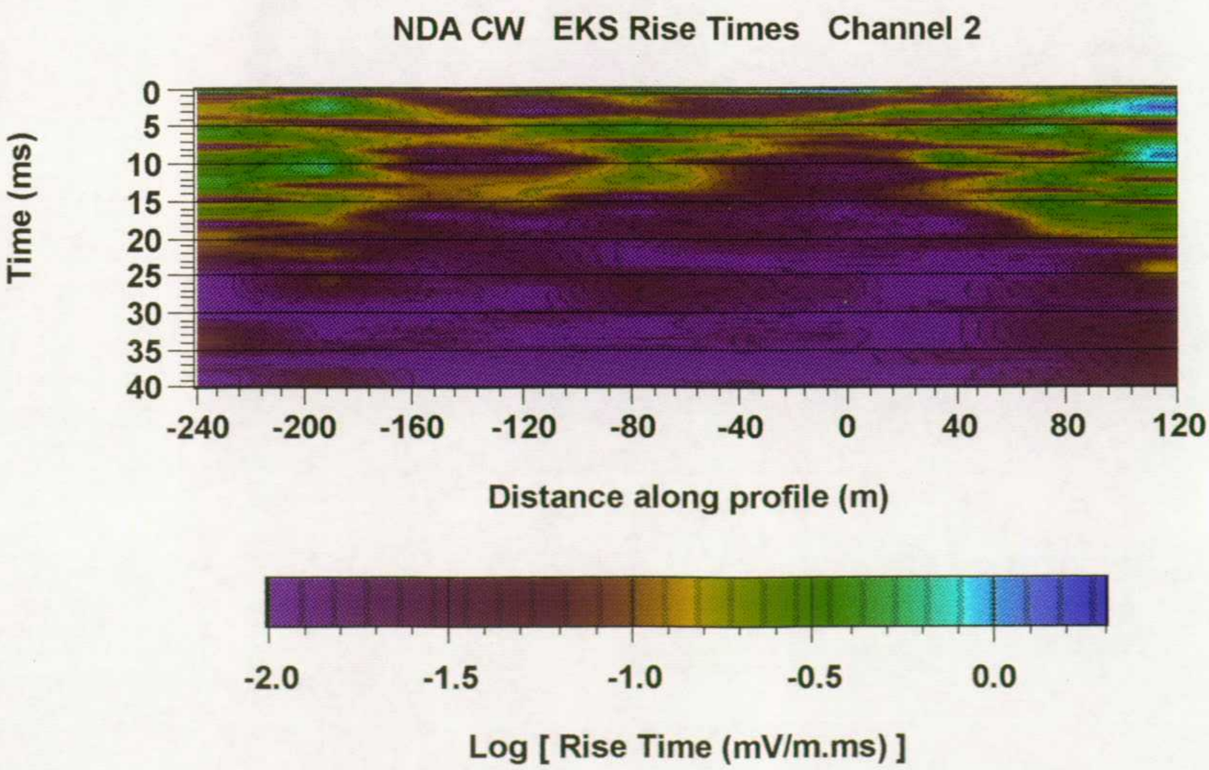
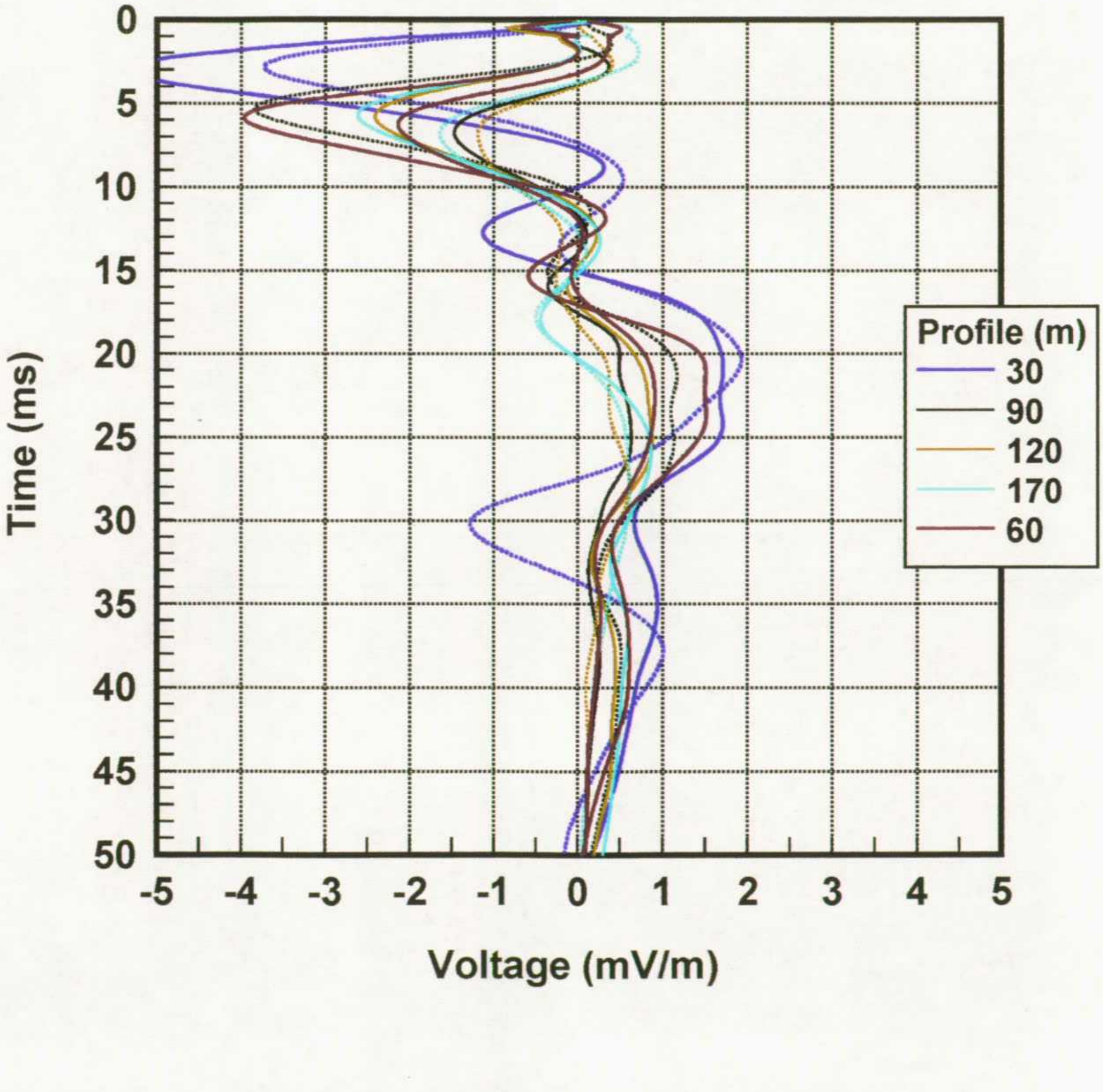


Figure 9.1
Overlay of 5 EK Soundings along a sand river profile.
Channel 1 (solid), channel 2 (broken line).
Bwemula School (UN North), Umzingwane River.
Fluviatile deposits over acid basement.



LOCATION : UN, Umzingwane Sand River, Zimbabwe.
SITES : NE [30, 60, 90, 120, 170 m] SW
Fluviatile sediments above Granite/gneiss basement.
Water Level ? < 3m.
Imains=0, Ifilt=0

Figure 9.2
Colour contoured voltages from 5 profile soundings.
Channel 1 (upper), channel 2 (lower).
Bwemula School (UN North), Umzingwane River.
Fluviatile deposits over acid basement.

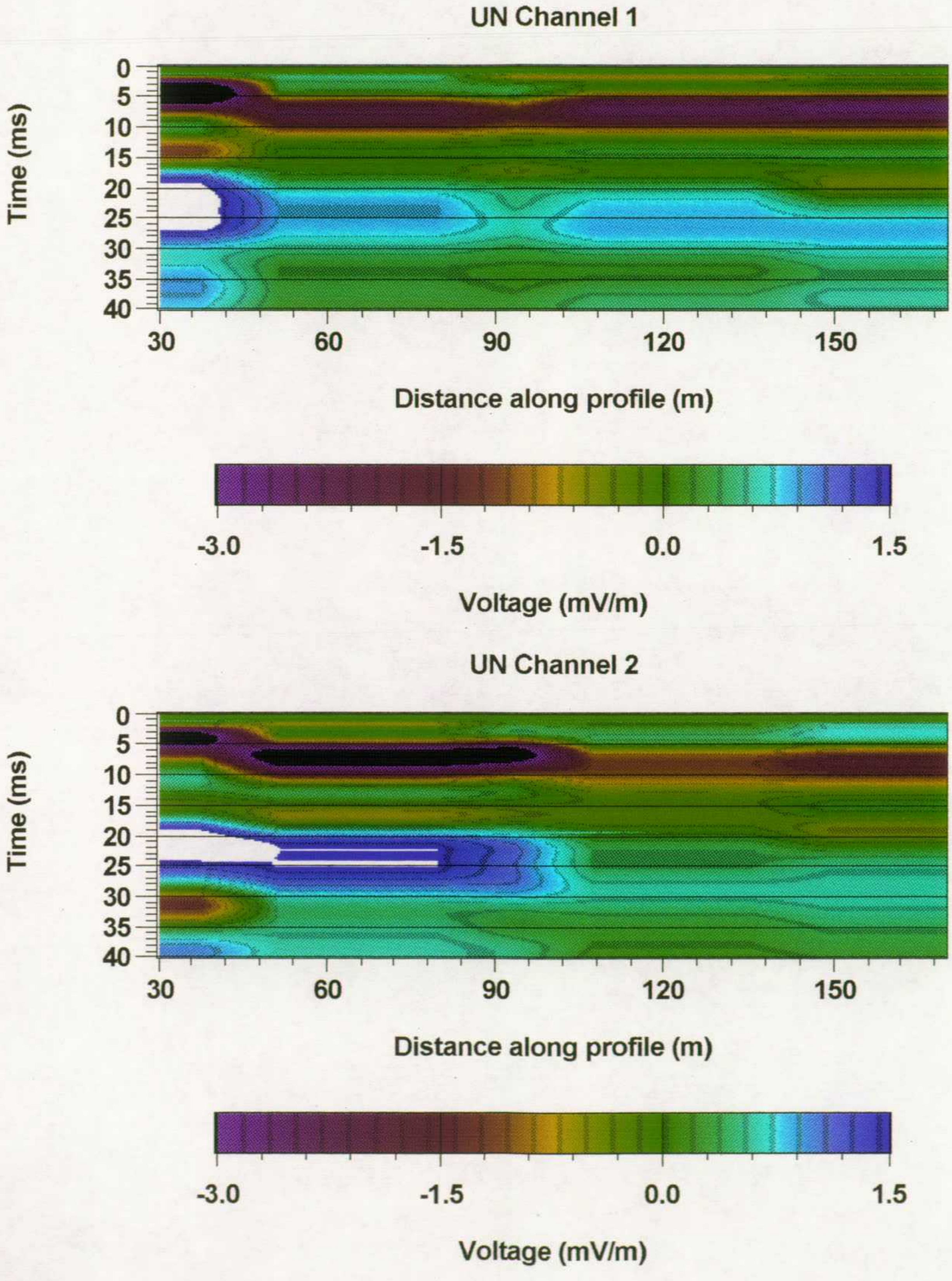
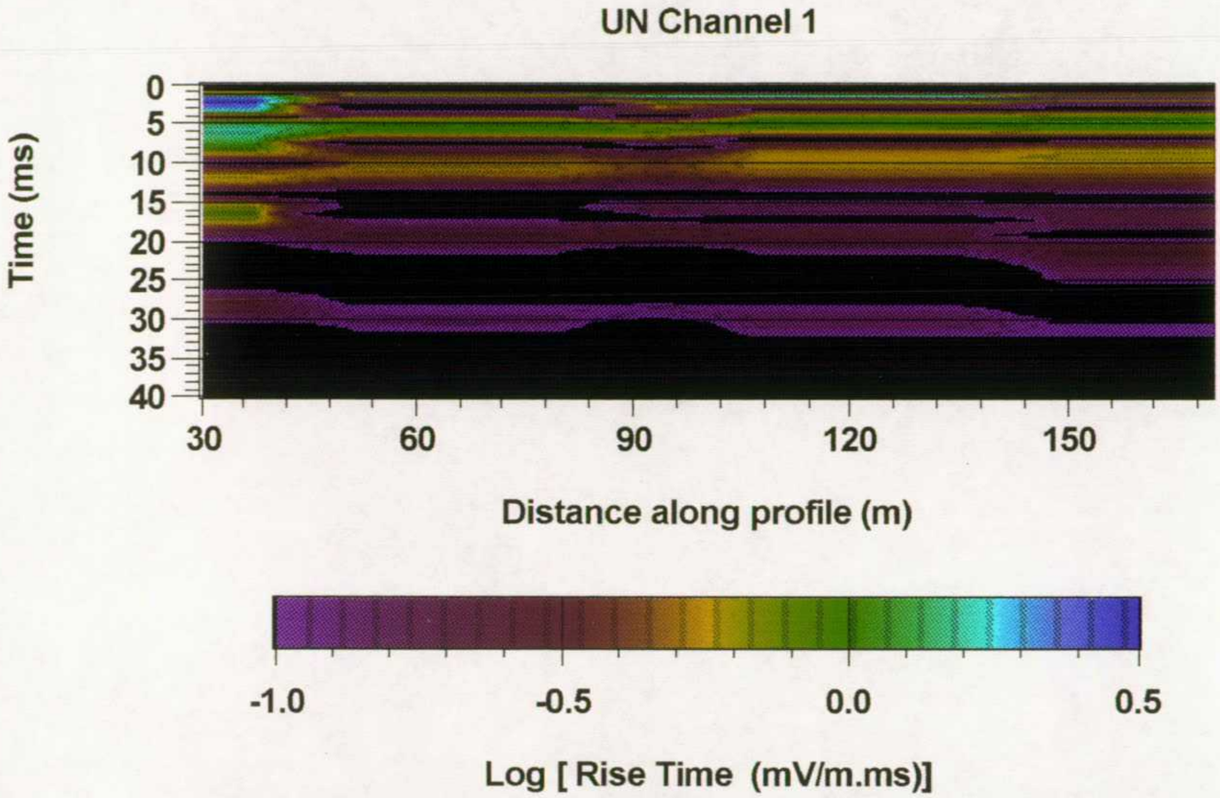


Figure 9.3
Colour-contoured voltage rise-times from 5 profile soundings. Logarithmic scale.
Channel 1 (upper), channel 2 (lower).
Bwemula School (UN North), Umzingwane River.
Fluviatile deposits over acid basement.



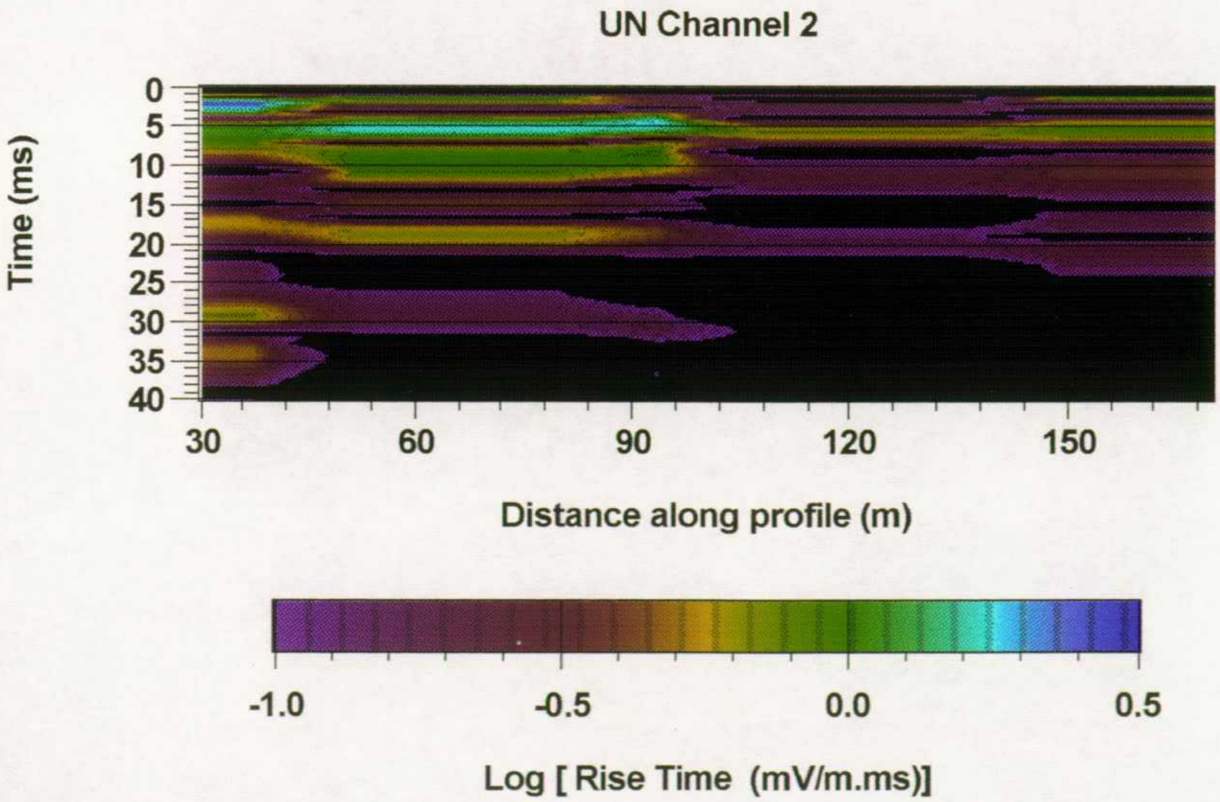
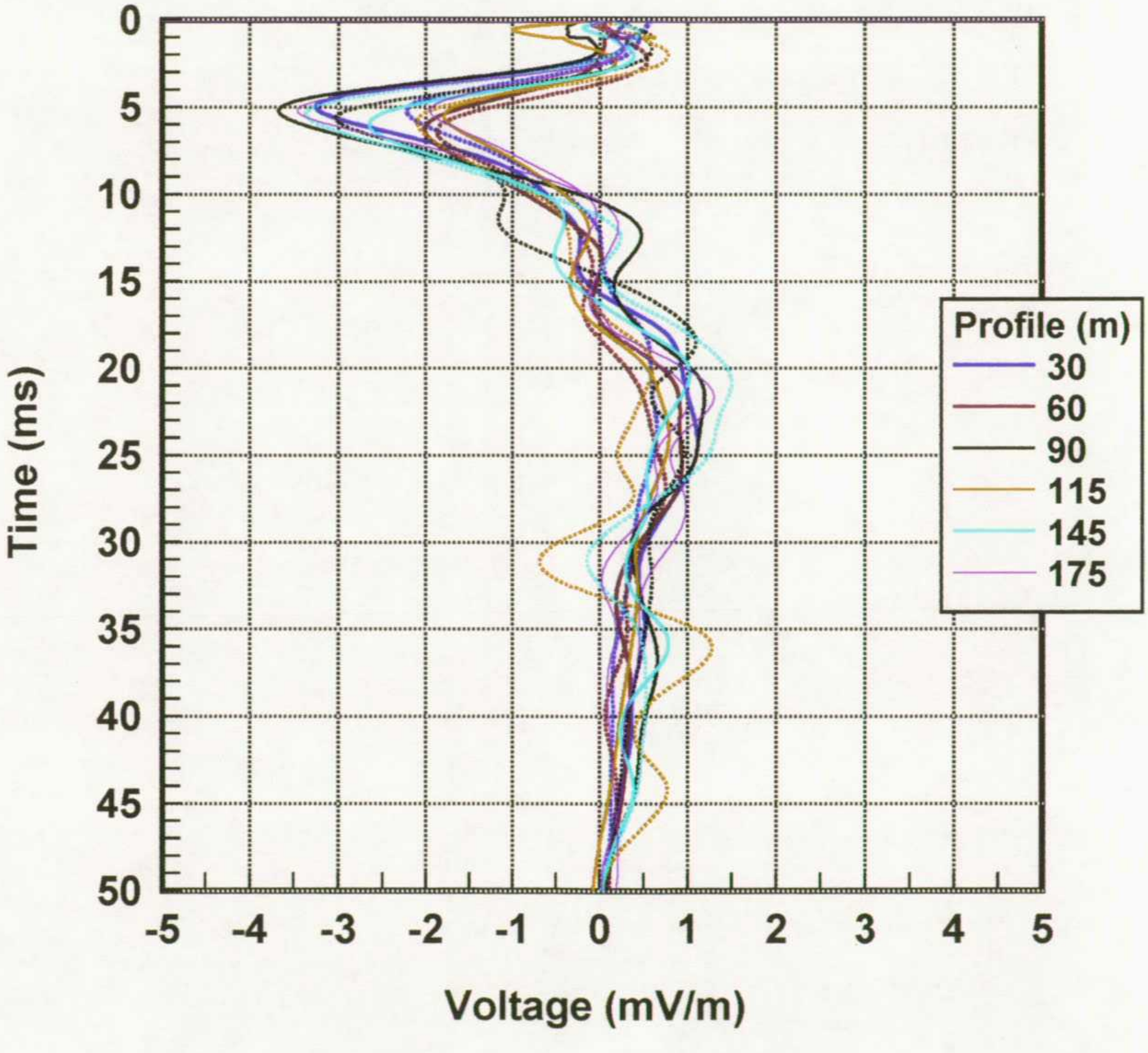


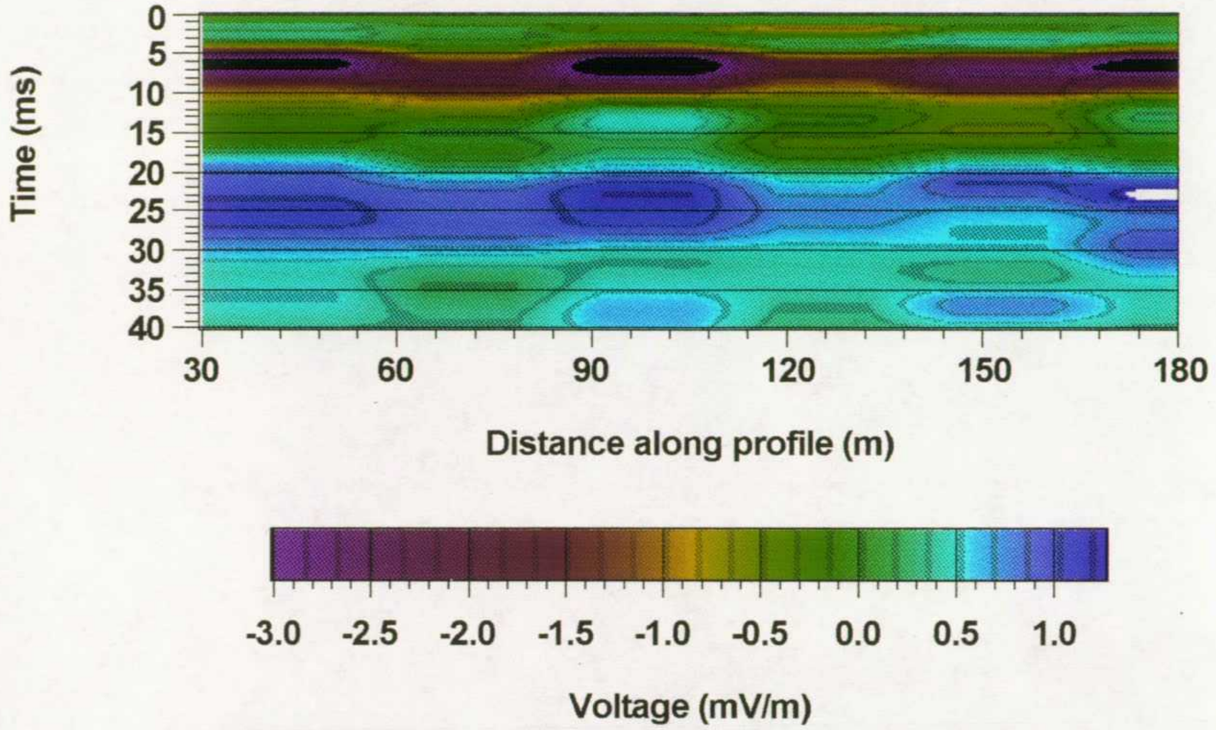
Figure 9.4
Overlay of 6 EK Soundings along a sand river profile.
Channel 1 (solid), channel 2 (broken line).
Bwemula School (BWS, South), Umzingwane River.
Fluviatile deposits over acid basement.



LOCATION : Bwemula school, Umzingwane Sand River, Zimbabwe.
SITES : NE [30, 60, 90, 115, 145, 175 m] SW
Fluviatile sediments above Karoo Sandstone.
Water Table = ?< 3m.
Imains=0, Ifilt=0

Figure 9.5
Colour contoured voltages from 6 profile soundings.
Channel 1 (upper), channel 2 (lower).
Bwemula School (BWS, South), Umzingwane River.
Fluviatile deposits over acid basement.

BWS Channel 1



BWS Channel 2

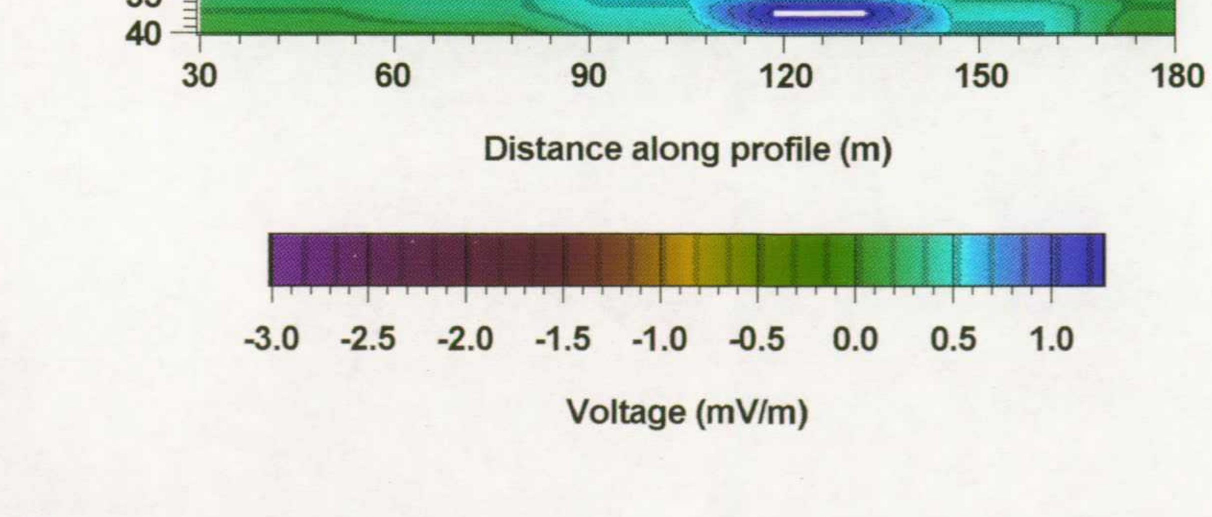


Figure 9.6
Colour-contoured voltage rise-times from 5 profile soundings. Logarithmic scale.
Channel 1 (upper), channel 2 (lower).
Bwemula School (BWS, South), Umzingwane River.
Fluviatile deposits over acid basement.

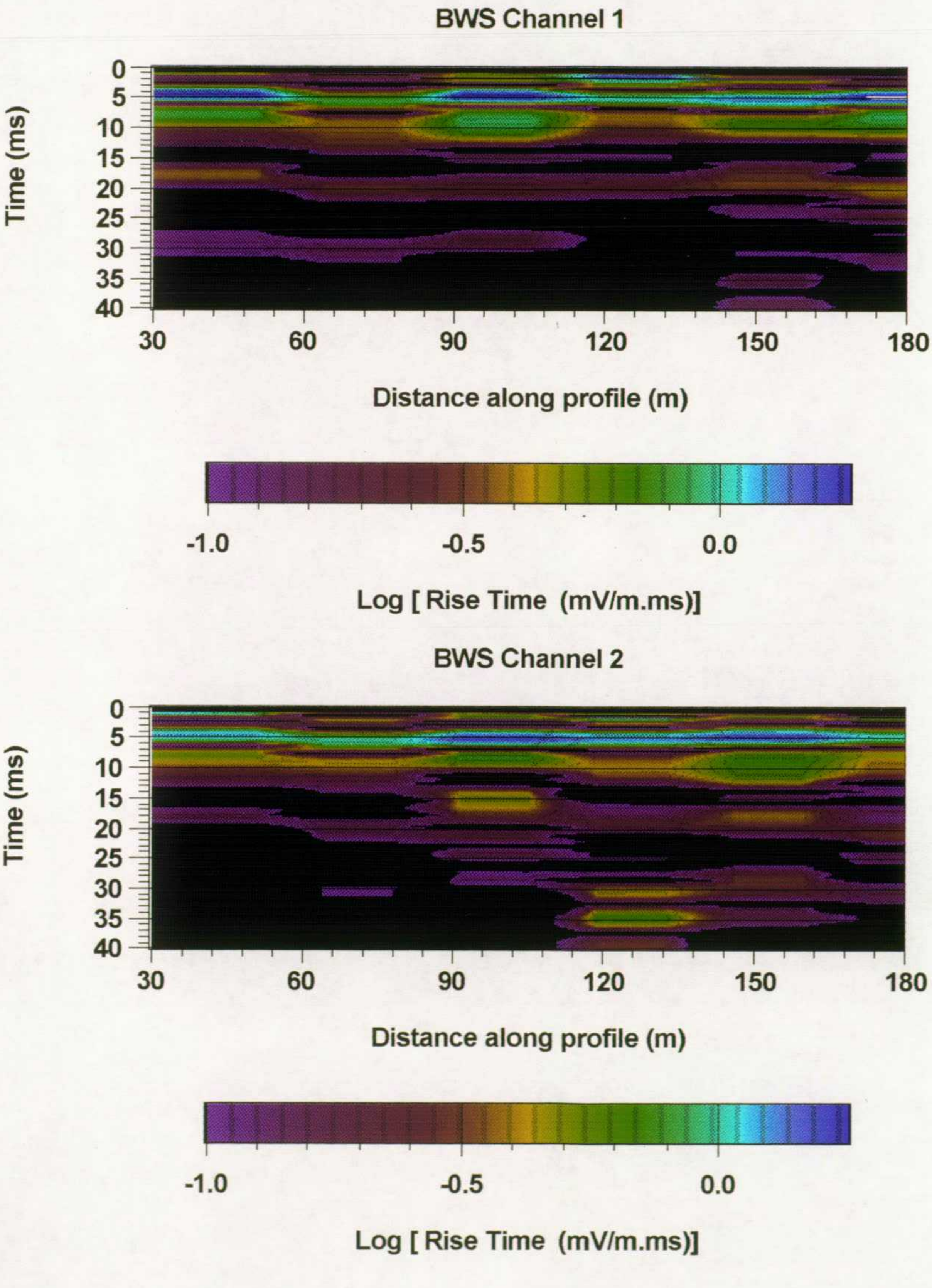
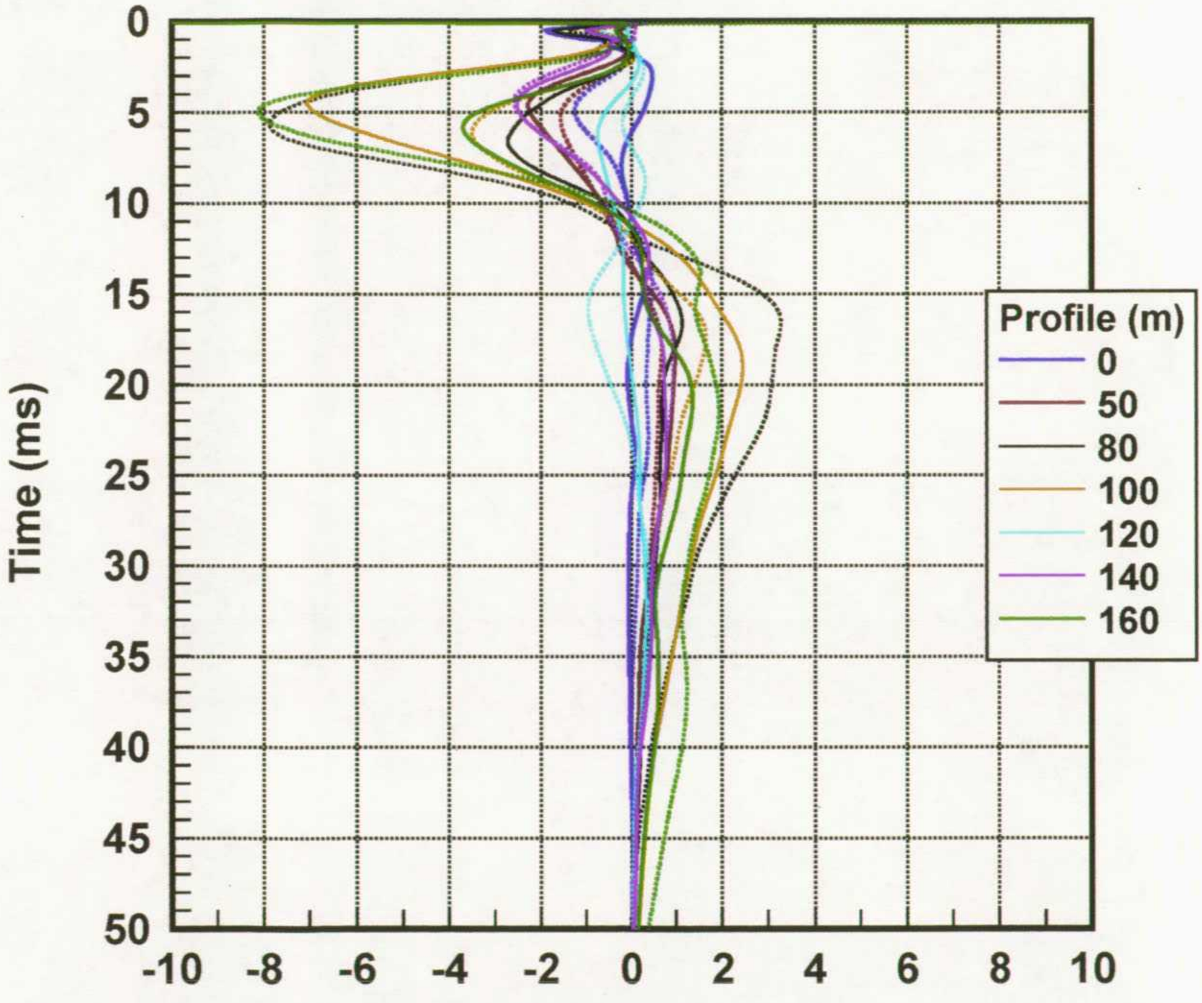
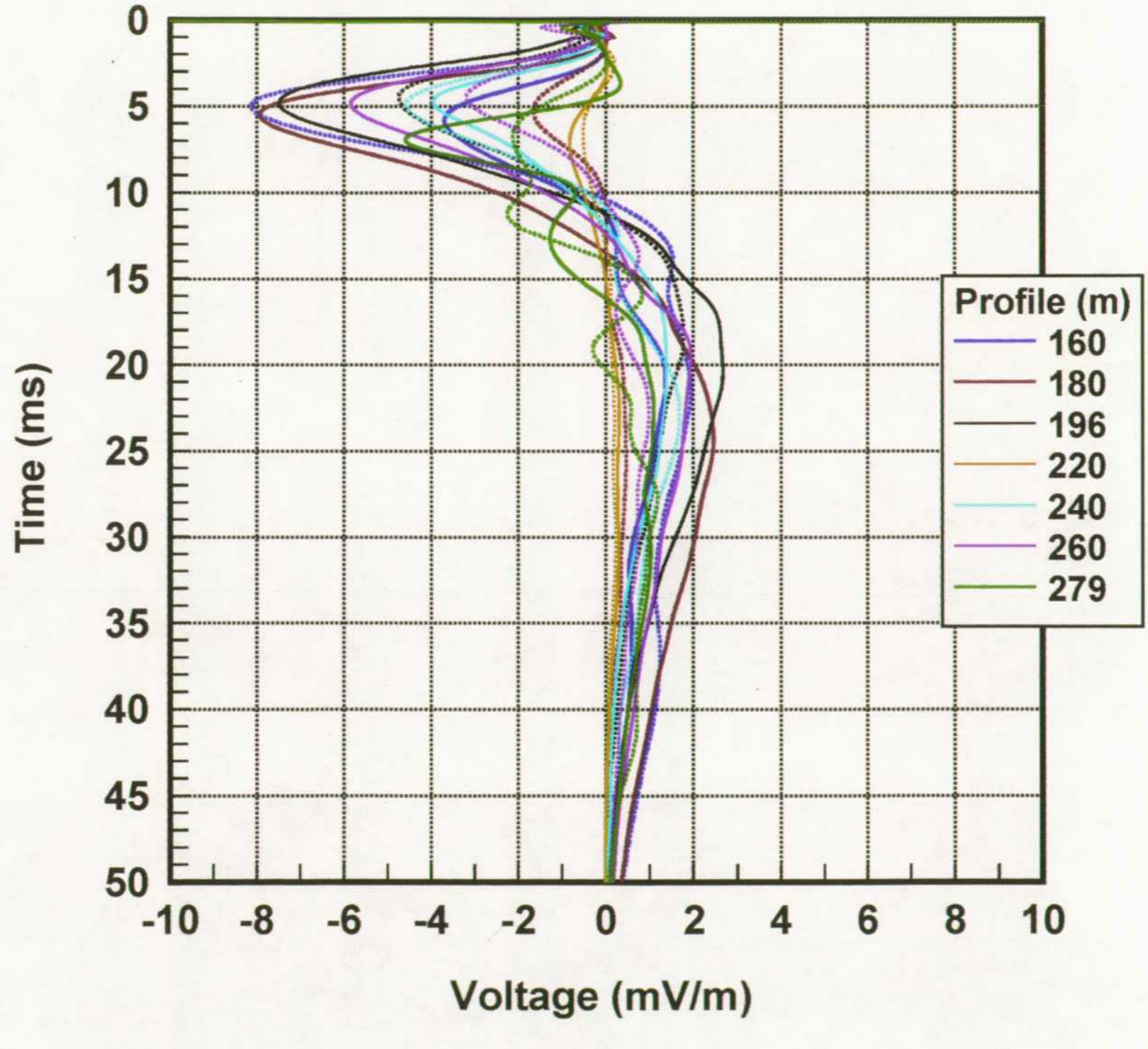


Figure 9.7
Overlay of 7 EK Soundings along a sand river profile.
Channel 1 (solid), channel 2 (broken line).
Cawood Ranch (CAW), Umzingwane River.
Fluviatile deposits over Karoo Basalt.



LOCATION : Cawood Ranch, Umzingwane Sand River, Zimbabwe.
SITES : NE [0, 50, 80, 100, 120, 140, 160 m] SW
Fluviatile sediments above Karoo Basalt.
0m (flank) is 6m above river.
Water table (BH) = 8 m, yielding 28 l/s from typically 17m depth.
Boreholes 3m apart display highly variable yields.
Imains=0, Ifilt=0

Figure 9.8
Overlay of 7 EK Soundings along a sand river profile.
Channel 1 (solid), channel 2 (broken line).
Cawood Ranch (CAW), Umzingwane River.
Fluviatile deposits over Karoo Basalt.



LOCATION : Cawood Ranch, Umzingwane Sand River, Zimbabwe.
SITES : NE [160, 180, 196, 220, 240, 260, 279 m] SW
Fluviatile sediments above Karoo Basalt.
279m (flank) is 2m above river.
Water table (BH) = 8 m, yielding 28 l/s from typically 17m depth.
Boreholes 3m apart display highly variable yields.
Imains=0, Ifilt=0

Figure 9.9
Colour contoured voltages from 13 profile soundings.
Channel 1 (upper), channel 2 (lower).
Cawood Ranch (CAW), Umzingwane River.
Fluviatile deposits over Karoo Basalt.

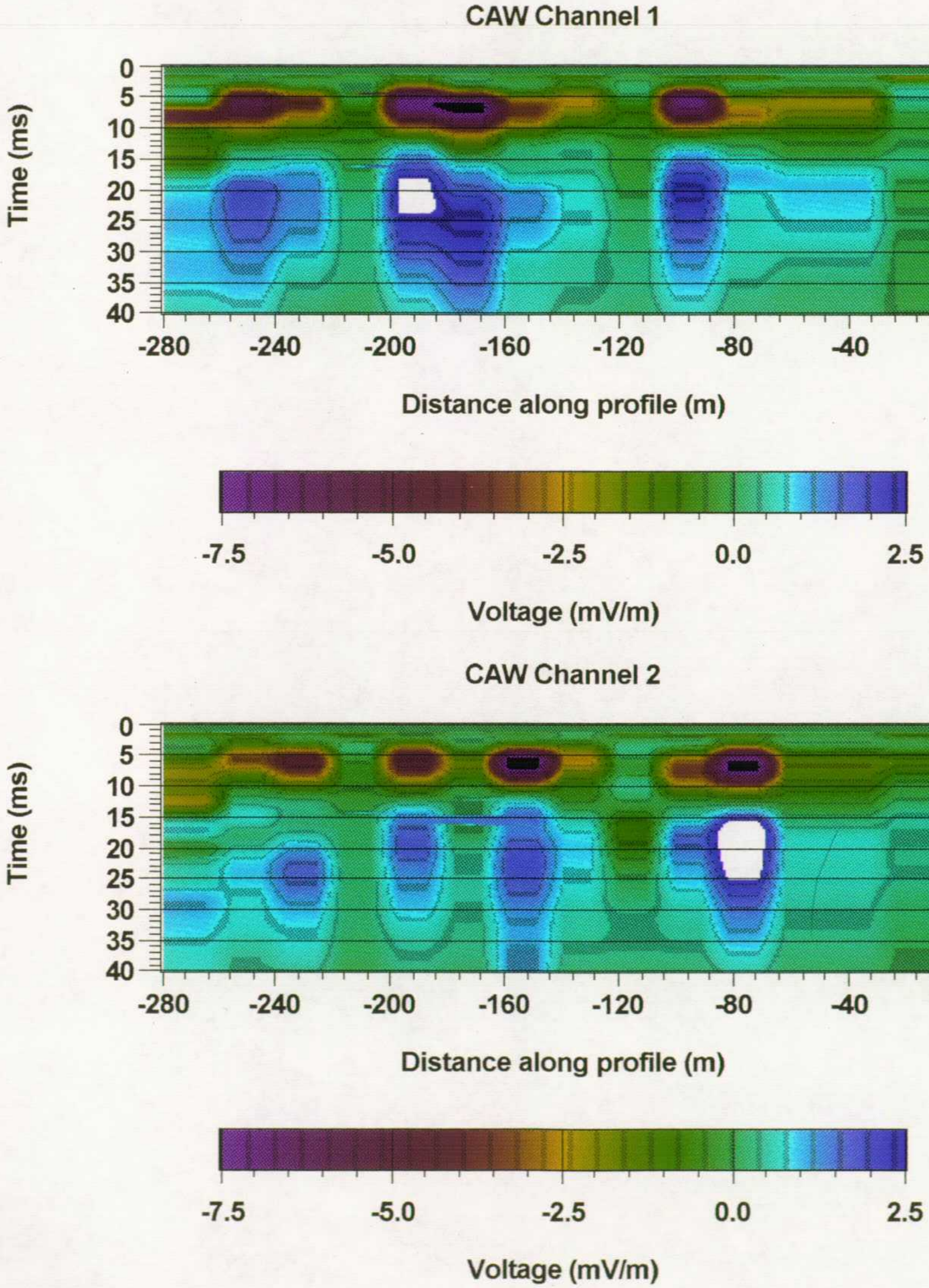


Figure 9.10
Colour-contoured voltage rise-times from 17 profile soundings. Logarithmic scale.
Channel 1 (upper), channel 2 (lower).
Cawood Ranch (CAW), Umzingwane River.
Fluviatile deposits over Karoo Basalt.

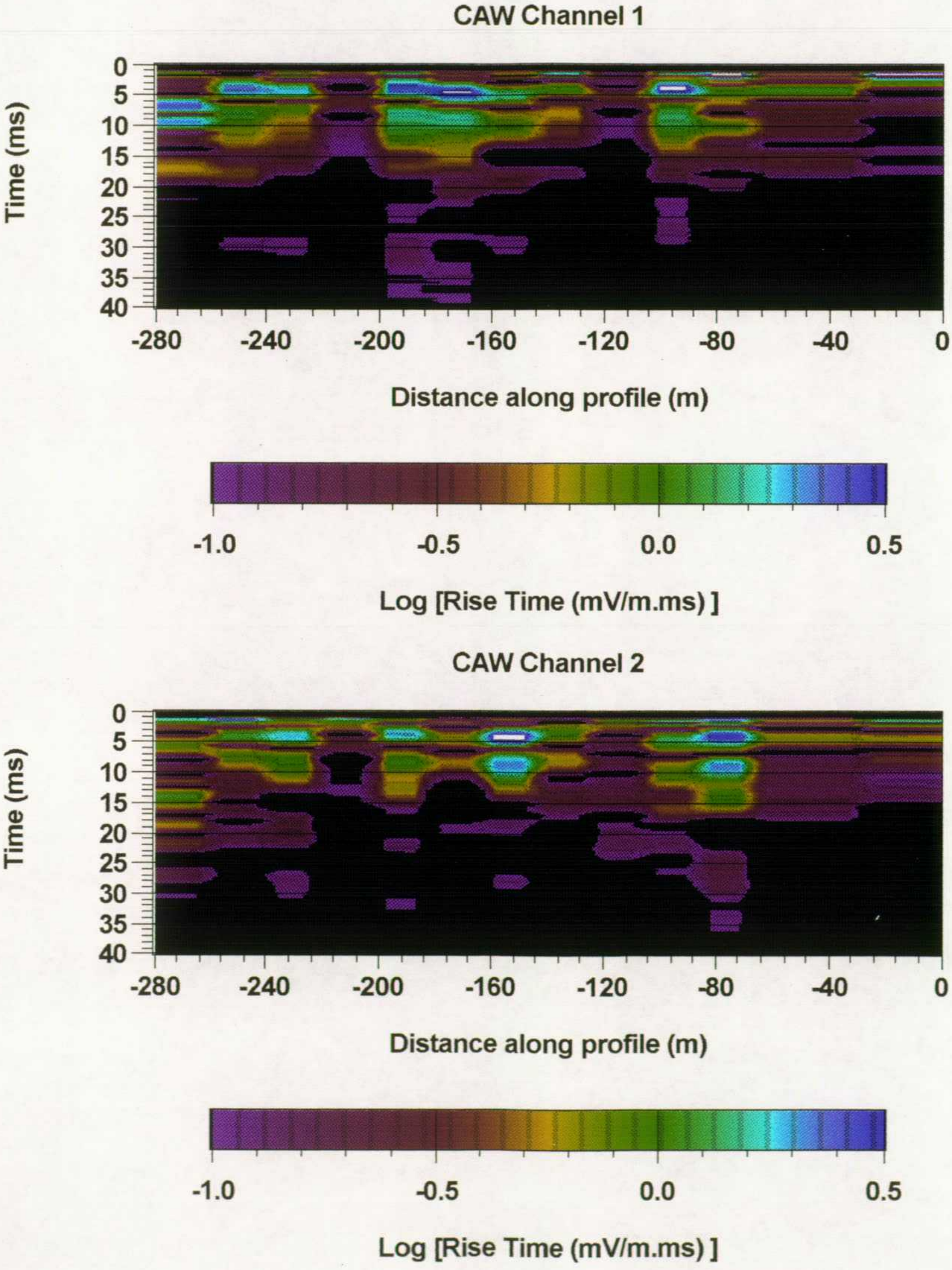
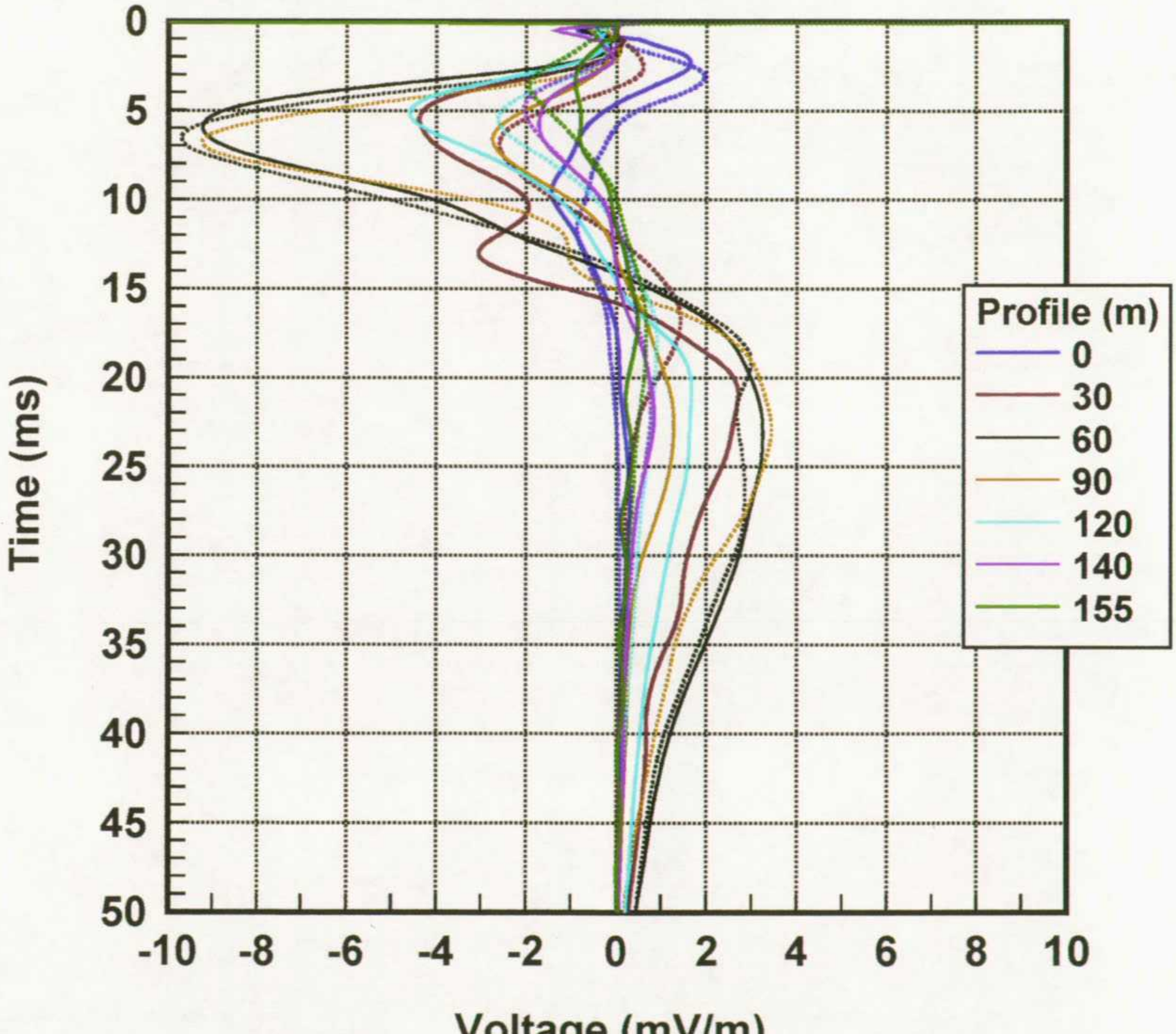


Figure 9.11
Overlay of 7 EK Soundings along a sand river profile.
Channel 1 (solid), channel 2 (broken line).
Zhovu Dam (ZH), Umzingwane Sand River.
Fluviatile deposits over Karoo Basalt.



LOCATION : Zhovu Dam, Umzingwane Sand River, Zimbabwe.
SITES : SW [0, 30, 60, 90, 120, 140, 155 m] NE
Fluviatile sediments above Karoo Basalt.
0m on flank (2m relief). 155m on basalt flank (3m relief).
Water level = 0.5m
Imains=0, Ifilt=0

Figure 9.12
Colour contoured voltages from 7 profile soundings.
Channel 1 (upper), channel 2 (lower).
Zhovu Dam (ZH), Umzingwane Sand River.
Fluviatile deposits over Karoo Basalt.

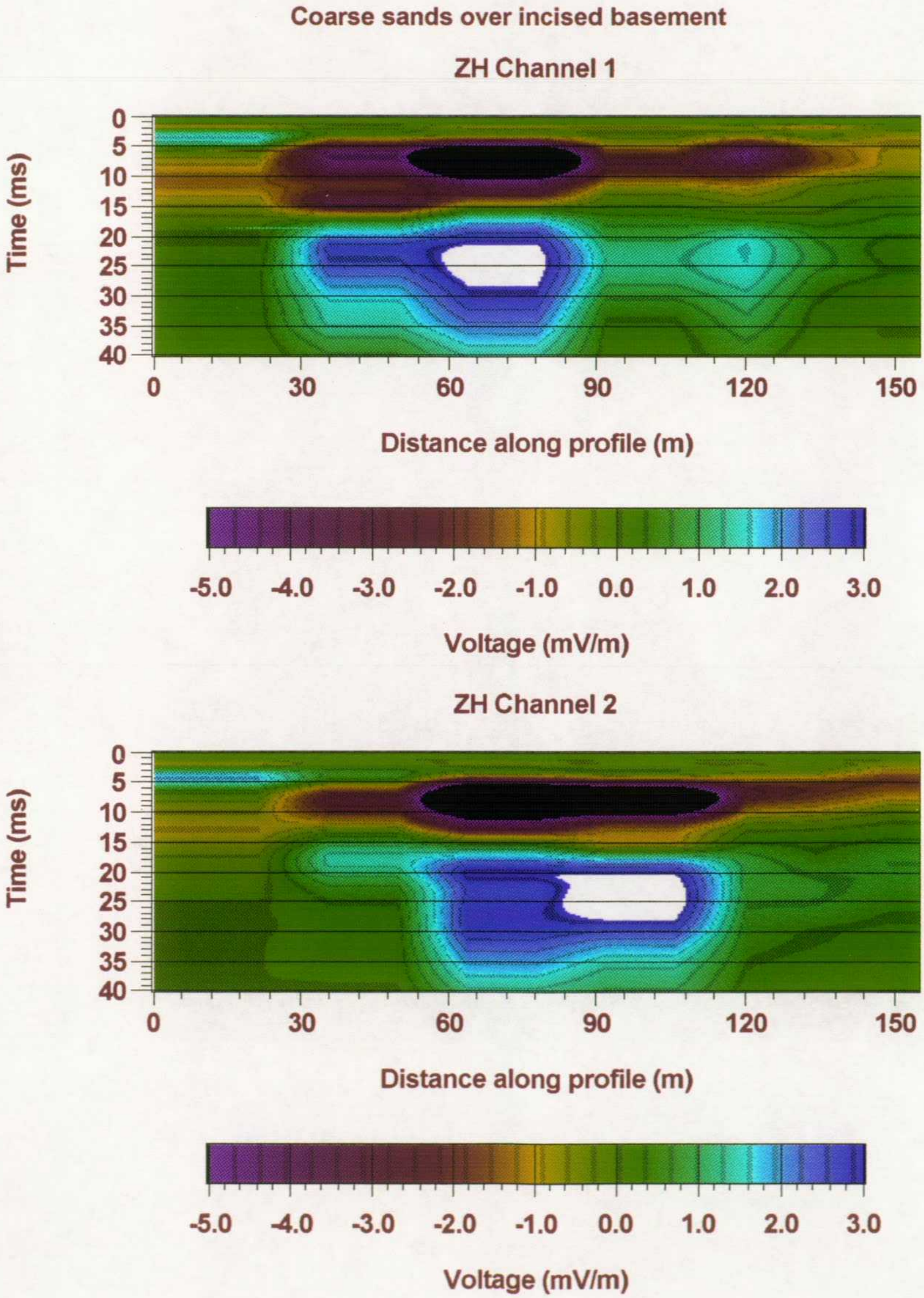
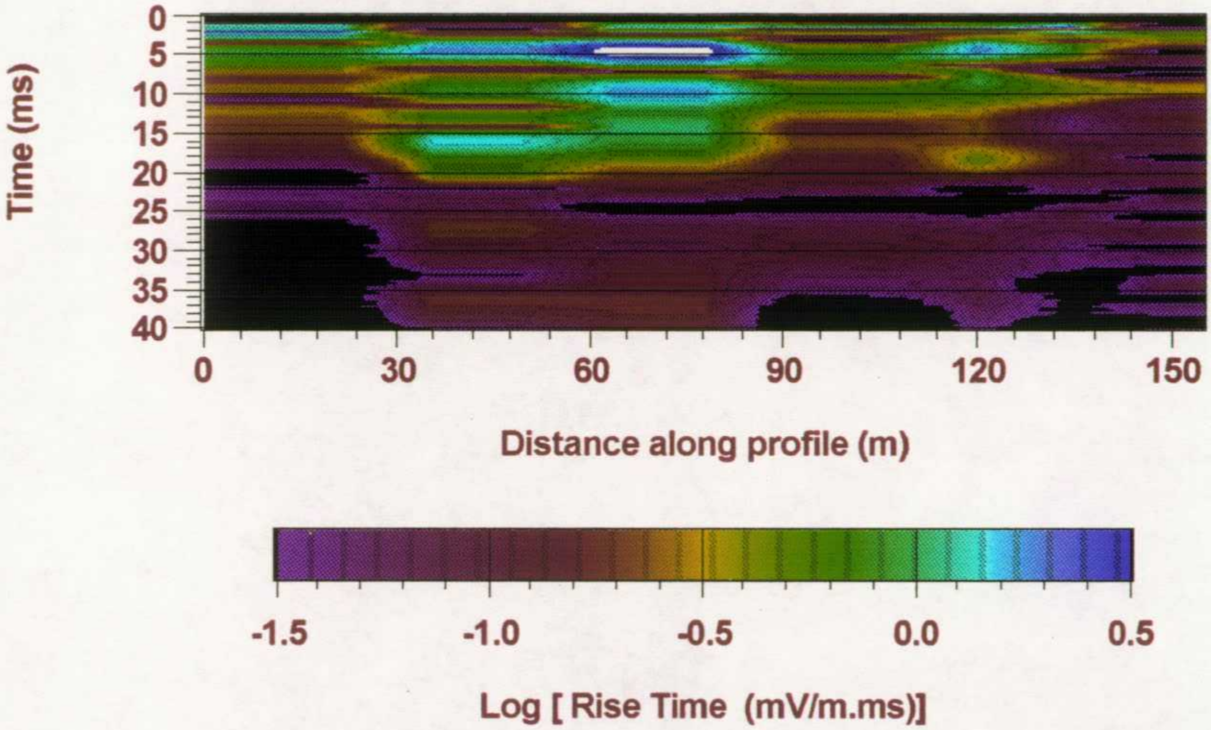


Figure 9.13
Colour-contoured voltage rise-times from 7 profile soundings. Logarithmic scale.
Channel 1 (upper), channel 2 (lower).
Zhovu Dam (ZH), Umzingwane Sand River.
Fluviatile deposits over Karoo Basalt.

Coarse sands over incised basement

ZH Channel 1



ZH Channel 2

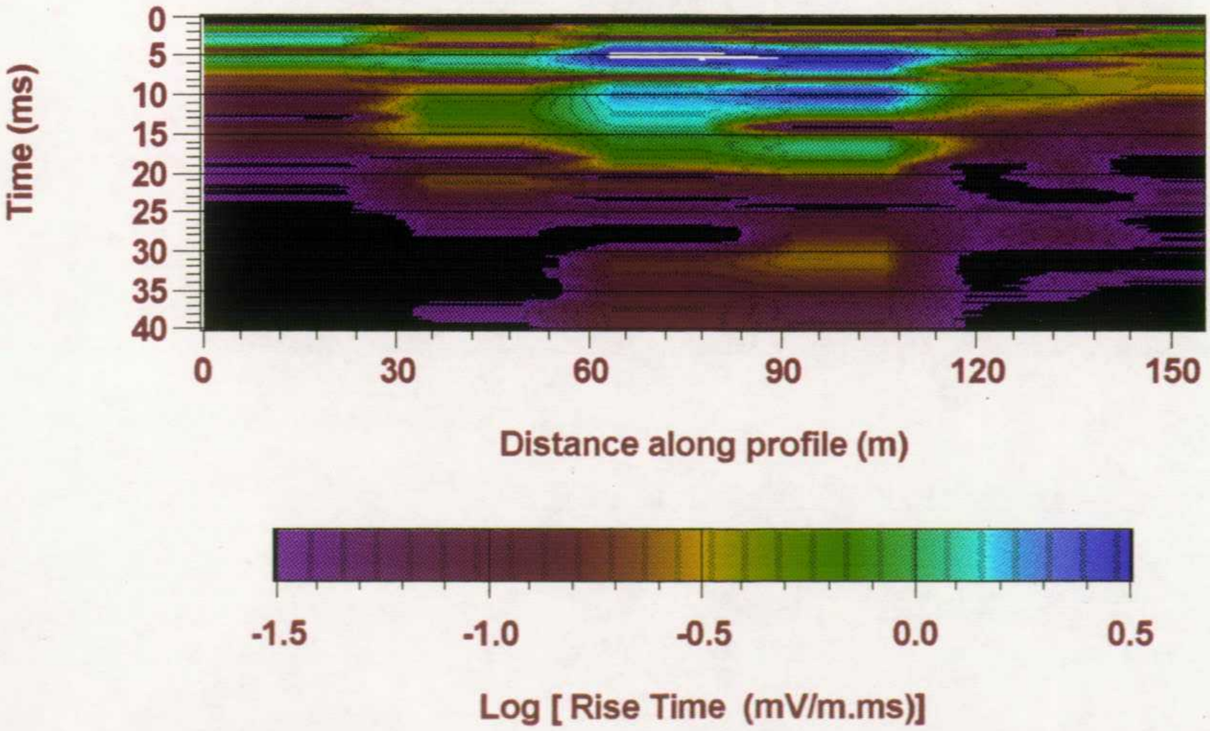


Figure 9.14
Colour-contoured voltage rise-times from 7 profile soundings. Logarithmic scale.
Depth conversion using seismic velocities.
Broken line = basement (4000 m/s).
Sandstone velocity = 1500 m/s.
Zhovu Dam. Umzingwane Sand River.