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ELECTRO KINETIC MEASUREMENTS IN VARIOUS HYDROGEOLOGICAL ENVIRONMENTS OF EGYPT

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Discussion of the electro kinetic technique in the field at El Bustan, Artificial Recharge Project, Egypt

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1. SUMMARY

BGS used the recently developed and still largely experimental electro kinetic sounding (EKS) technique in Egypt in April 1996. The purpose of this work, our third overseas EKS programme, was to investigate and possibly calibrate the EK sounding methodology in a variety of Egypt's hydrogeological environments which included some existing groundwater sources. The aquifers currently tested are all unconsolidated and comprise the Nile Delta- and Nile Aquifer fluviatile deposits and thick (high energy) wadi deposits.

In broad terms we obtained a variety of conflicting results. At one site, large amplitude EK signals were clearly generated in only partially saturated sediments, with no response evident from the underlying fully saturated aquifer. Elsewhere large amplitude EK signal was recorded at sites where thick clays had been proved while no recognisable signal was yielded over shallow, high permeability saturated aquifers. On the positive side, however, the absence of EK signal in a waterlogged zone may indicate the presence of a shallow aquiclude on which excess irrigation water is pooling, while a detailed traverse of observations at another site has revealed in remarkable detail what may be a shallow depositional feature.

The methodology of the EK technique (as originally stated by Groundflow Ltd, suppliers of the equipment used in this study) 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 that numerous seismic waves have to be 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 present survey is likely to be grossly in error. For this reason we have made little attempt to process/interpret the current 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 a short programme of fieldwork conducted in collaboration with the Egyptian Research Institute for Ground Water (RIGW) during April 1996 in support of the ODA TDR Project R6232 "Development of a new well siting technique". This project aims to assess to what extent a recently developed, 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.

This is our third overseas programme of EKS observations; details of earlier studies may be found in Peart *et al*, 1996a, Peart *et al*, 1996b and Beamish *et al*, 1997) while our early investigations of EKS in the United Kingdom are summarised in Beamish and Peart, 1996.

During the present work we demonstrated the EKS equipment and technique to our Egyptian collaborators and subsequently made field observations at several sites of particular concern to the RIGW (see Figure 1). These sites comprised:

a) two desert reclamation projects in the West Nile Delta (Bustan, the site of the first artificial recharge experiment in Egypt and New Nubaria where large scale irrigation has led to a rising water table and consequent waterlogging and salinisation problems)

and

b) the Bimban area some 70km north of Aswan where the groundwater potential of wadi deposits and Nile Aquifer sediments is being investigated as part of a major re-settlement scheme.

We start this report with an outline of the EKS technique and the methods of collecting, processing and interpreting EK data. We then describe the results of the present field work on a site by site basis, preceding each section with a brief description of the geological- and hydrogeological setting. Finally we draw conclusions as to the apparent effectiveness of EKS in the various environments tested.

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 2. 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 3. 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 below (Figures 5 and 11).

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. Stage 2, the conversion of time to depth, has been largely omitted in the present study. We have, very occasionally, estimated a possible EK signal source depth by assuming typical seismic velocities for the lithologies involved.

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

5.1 BUSTAN RECHARGE EXPERIMENT

At Bustan, about 120km north of Cairo, RIGW/IWACO have constructed an artificial recharge pond (155m by 135m), excavated to a depth of 2m in Nile Delta alluvials. These Pleistocene heterogeneous fluviatile sediments comprise dominant fine to coarse sands with occasional gravels and clay lenses and attain a thickness of about 130m. The site for construction of the experimental recharge pond was chosen following exhaustive tests (including surface geophysics, shallow trenching and auguring and numerous deeper boreholes) that indicated the absence of shallow clays and cretes that would hinder the percolation of recharge water. Borehole 17, near the centre of the pond, proved an alternation of fine to coarse sand with occasional gravels and very minor clay to a total depth of 51m. It is noteworthy that the column extending beneath the pond base to the water table at a depth of about 22m (through which recharge is occurring) is not fully saturated. This was demonstrated by the manual construction of a shallow, hand-sized adit beneath the base of the pond which did not immediately fill with water. The estimated vertical permeability at this site is about 10m/d. Water from a nearby irrigation canal is introduced to the pond by a narrow lined channelway.

The EK observations were made about 2m from the water's edge (about 5cm above the pond surface) along the north side of the pond at an interval of 5m (Figure 4). The electrodes were aligned parallel to this edge of the pond (ie W-E) after initial tests showed this orientation to give the most consistent response between the two channels coupled with the maximum signal and minimal noise pick-up.

Characteristic EK responses at Bustan are shown in Figure 5; signal repeatability from shot to shot is good and there is close correlation between channels 1 and 2. The response at 50m starts at negative potential and rapidly saturates the amplifiers (at +5V) between about 0.5 and 4.5ms, thereafter returning slowly to 0V at about 50ms. The response at 25m is more subdued, comprisng essentially a small positive excursion and return to datum within 2.5ms. Signal rise times (analogue permeability) for the entire EK traverse, gridded and colour contoured (Figure 6), indicate a narrow zone of enhanced permeability extending to some 20ms centred at about 50m. If we assume a seismic velocity through partially saturated sands of 1200ms^{-1}, this time equates to a depth of about 24m. The overall shape of this feature suggests that it may represent an ancient channelway (a high-energy depositional environment) while the fine detail revealed by the colour contours may indicate both slump bedding and upward coarsening of deposits. (It should be noted here that it was not possible to collect EK data at 60m (due to the presence of the inflow canal) and this absence of data accounts for the rather abrupt contour pattern in this vicinity). The highest permeabilities revealed (in excess of 10md^{-1}) are in accord with the estimates yielded from local pump tests etc. It is noteworthy that fine pebbles can be observed in the sand beside the recharge pond at about 40m.

Analogue permeability (the voltage time derivative) analysis of the stacked data from 50m (Figure 7) confirms the absence of significant permeability (rise-time excursion) below 375 data points, equivalent to approximately 19ms or a depth of about 23m (assuming the seismic velocity referred to above). Thus it appears that the EK signal observed at Bustan has been generated entirely in the partially saturated sediments above the water table.

5.2 NEW NUBARIA WATERLOGGING PROBLEM

New Nubaria, approximately 150km north of Cairo, lies immediately west of the Nile Delta proper, and like Bustan (above) is an area being reclaimed from the desert. Here again the shallow lithology comprises Pleistocene fluvial deposits, up to 80m thick. The main water table lies between 15m and 20m bgl and in addition there is frequently a shallow (3m) perched water table supported on a calcrete or clay aquiclude. Extensive crop irrigation has resulted in waterlogging problems, especially in topographic depressions (inter-dune areas) and in the subsequent deposition here (following evaporation) of white salts and orange iron oxides.

EK measurements were made at approximately 100m interval near the edges of cultivated fields extending between a drainage canal and the main road (Figure 8); three additional soundings were also completed. The electrodes were aligned parallel to the track bordering the fields (SW-NE). EK observation number 6 was made in a field, much of which was occupied by a swampy depression; a shallow water filled pit some 20m from the EK site proved the presence of calcrete.

Figure 9 shows the observed EK response at site 6 and neighbouring sites. The waterlogged zone is apparently characterised by antiphase (non EK) behaviour of the two channels (in reality the two channel responses are moving in phase) while immediately neighbouring observations (at stations 5 and 7) display responses that are intermediate between that at station 6 and the more typical EK signatures of stations 3, 4, 8 and 9. This short profile of EK observations thus supports the assertion that the cause of waterlogging is the presence of a shallow impermeable horizon (that does not generate an EK response) upon which occurs the ponding of excess irrigation water.

5.3 BIMBAN RESETTLEMENT SCHEME

A schematic east-west geological section of the Bimban area (after RIGW), derived from projected borehole and surface geophysical data (vertical electrical sounding, VES) is shown as Figure 10. Here, some 700km south of Cairo, the Nile Aquifer (of similar composition to the Nile Delta fluviatile sediments) is overlain by up to 14m of low permeability flood deposits (silt and clay). Consolidated rocks, largely sandstone and shales, of Nubian age (early Cretaceous) underlie the Quaternary deposits.

We made EK observations at the sites of boreholes tapping the Nile Aquifer at Ababda, Raquaba and Sabkhaya. We also investigated the Wadi deposits (here comprising up to 40m of coarse sands and gravels deposited in ephemeral river courses) in the vicinity of VES22 in the desert, some 6km west of the River Nile, and again at Kopania, some 20km south of the projected section of Figure 10.

Ababda (Borehole D10/No 4)

Log (m) observation borehole:	0-1	fine sand
	1-2	sandy clay
	2-20	clay

RWL 1.5m.
2m screen placed at 15.5m.
Production well reported about 3km distant.

EK soundings were made at three sites here: numbers 1 and 2 were linked (ie shared a common electrode), oriented east-west and centred some 15m north-east of the borehole in a cultivated field. Number 3, on the edge of a track only 4m south-west of the borehole, was oriented north-south. Figure 11 demonstrates the excellent repeatability (of even the minor inflection at about 3ms) typically achieved in this area. All three sites yielded similar low amplitude (0.5mv) EK sounding curves (with a suppressed signature at site 2) with moderate in-phase behaviour between about 3 to 15ms (Figure 12). The analogue permeability graphs (Figure 13) indicate the absence of permeable horizons below about 7ms (corresponding to a depth of about 8m), in general accord with the observed (shallow) geology.

Raquaba (Borehole D13/No 5)

Log (m) observation borehole:	0-1	fine sand
	1-19	clay

RWL 1.9m
2m screen placed at 15m

EKS were made at five sites here: numbers 1 to 3 were linked, oriented north-south and centred about 8m north-east of the borehole. Numbers 4 and 5 were also linked, located some 15m west of the borehole and oriented east-west.

The stacked EK data and analogue permeability at these five sites are shown in Figures 14 and 15. Again the EK responses are small and do not persist beyond about 16ms. Individual sites demonstrate some weak in-phase behaviour (eg site 2). However, the linked sites 1 to 3 show quite different characteristics indicating the dominance of very local/shallow effects. The analogue permeability section indicates the complete absence of coherent permeability at this site.

Sabkhaya (Production well C1)

Log (m) production borehole:

0-6	clay
6-19	sand
19-31	clay

RWL 6.9m
Yield 12l/s

Orthogonal EK soundings were made some 3m south-west of the production borehole at this culturally noisy site. Exceptionally low amplitude (<0.2mv) and largely out of phase signal was recorded with both electrode orientations and there is no indication of enhanced permeability in the aquifer zone between 6m and 19m (Figures 16 and 17).

VES22 (Wadi deposits)

At this site we experimented with increasing dipole lengths: the innermost electrodes were fixed 0.5m from the central source while the outer electrodes were moved between observations to 2.5m, 5.5m and 10.5m (giving dipole lengths of 2m, 5m and 10m). Orthogonal measurements were made with electrode orientations at both 35^0 and 125^0. Similar complex, moderate amplitude responses were yielded in both orientations and with all dipole lengths (Figures 18 and 19). Increased signal amplitudes are obtained with the 35^0 orientation while, contrary to expectations, there is no increase in signal amplitude in direct proportion to the dipole length. Figures 21 and 22 show both channel responses overlaid for the increasing dipole lengths in the two orientations. It is noteworthy that at 125^0 the channel 2 responses remain at about equal amplitude for all separations while the channel 1 amplitudes increase with greater separations. Conversely, with the 35^0 orientation, channel 1 amplitudes remain about equal while channel 2 amplitudes increase with increasing dipole length.

The analogue permeability presentation (Figure 20) suggests enhanced saturated permeability down to about 18ms which could reflect the presence of about 40m of wadi deposits overlying non-permeable shales.

Kopania (Well No 1)

Log (m) observation borehole:

0-2	fine sand
2-6	clay
6-9	sandy clay
9-13	coarse sand
13-15	gravel/coarse sand
15-19.5	coarse sand

RWL 4.6m
2m screen placed at 9m

Here again we experimented with 2m, 5m and 10m dipoles, at a site some 40m from a disused borehole. Very low amplitude (<0.2mv) and largely anti-phase responses were returned with all dipole separations in the north-south orientation (Figure 23). Following electrode rotation to east-west orientation, an improved shallow EK response was obtained using 2m dipole length (the centre graph of Figure 24). However, after about six shots in this orientation, both channel responses spontaneously diminished in amplitude by a factor of about two (right hand graph of Figure 24). Since both channels were affected we conclude that this reduction in amplitude did not reflect poor electrode/ground contact. Analogue permeability analysis indicates enhanced permeability (east-west orientation only!) to about 7ms which must be above the proved aquifer level of between 9m and 19.5m.

6. CONCLUSIONS

Our results are largely confusing while the general lack of correlation between our EK observations and hydrogeological control is disappointing. We have observed large amplitude signal that is clearly generated in zones of only partial saturation while an underlying high permeability aquifer at a depth of only 22m yielded no visible response. At other sites we have recorded both relatively strong signals above clay-rich units and a complete absence of signal above shallow and thick saturated aquifers.

On a more positive note we observed that a waterlogged area was characterised by the absence of EK signal which may support the conclusion that such problems are caused by the pooling of excess irrigation water on shallow aquicludes (impermeable strata). Also, a detailed traverse at an experimental site (believed, following earlier exhaustive investigations to occupy relatively homogeneous fluviatile sediments) revealed what may reflect very fine detail of a shallow depositional feature.

Experiments with increasing dipole lengths showed that the measured signal generally does not increase in direct proportion to the dipole separation and also highlighted some asymmetry conditions about the central source. The implication is that we are not measuring a uniform and symmetric electric field generated at depth.

The current field work confirms our earlier conclusions concerning EK data quality:

- Data stacking (of repeated shots) to identify/reject poor quality data and to confirm the validity of a response should be used routinely.
- High electrode contact resistances result in degraded 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.

We have made little attempt to assess the present data 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.

7. ACKNOWLEDGEMENTS

We gratefully acknowledge our warm reception by Dr Fatma Attia (Director RIGW) and her senior colleagues: Drs Nahed el Sayed el Araby (Head of Nile Basin Hydrogeology) and Madiha Mostafa (Head of Bustan reclamation project), Eng Youssef George Youssef (Head of Dissemination), Mohamed Thabet Ali (Hydrogeologist, West Aswan Project) and Eng Ahmed Ragab Allam (Researcher, Bustan Project) and their unstinting efforts to ensure the success of the present visit. Ebel Smidt of IWACO provided additional useful information and discussion on the Bustan recharge experiment. Bertil Vendel and Sami M Kamel of DANIDA (Aswan) are thanked for their invaluable logistical support in the Bimban area and their interest in the EKS technology. In the UK we thank our colleague Mr Peter Greenwood of the BGS for the preparation of the figures accompanying this report.

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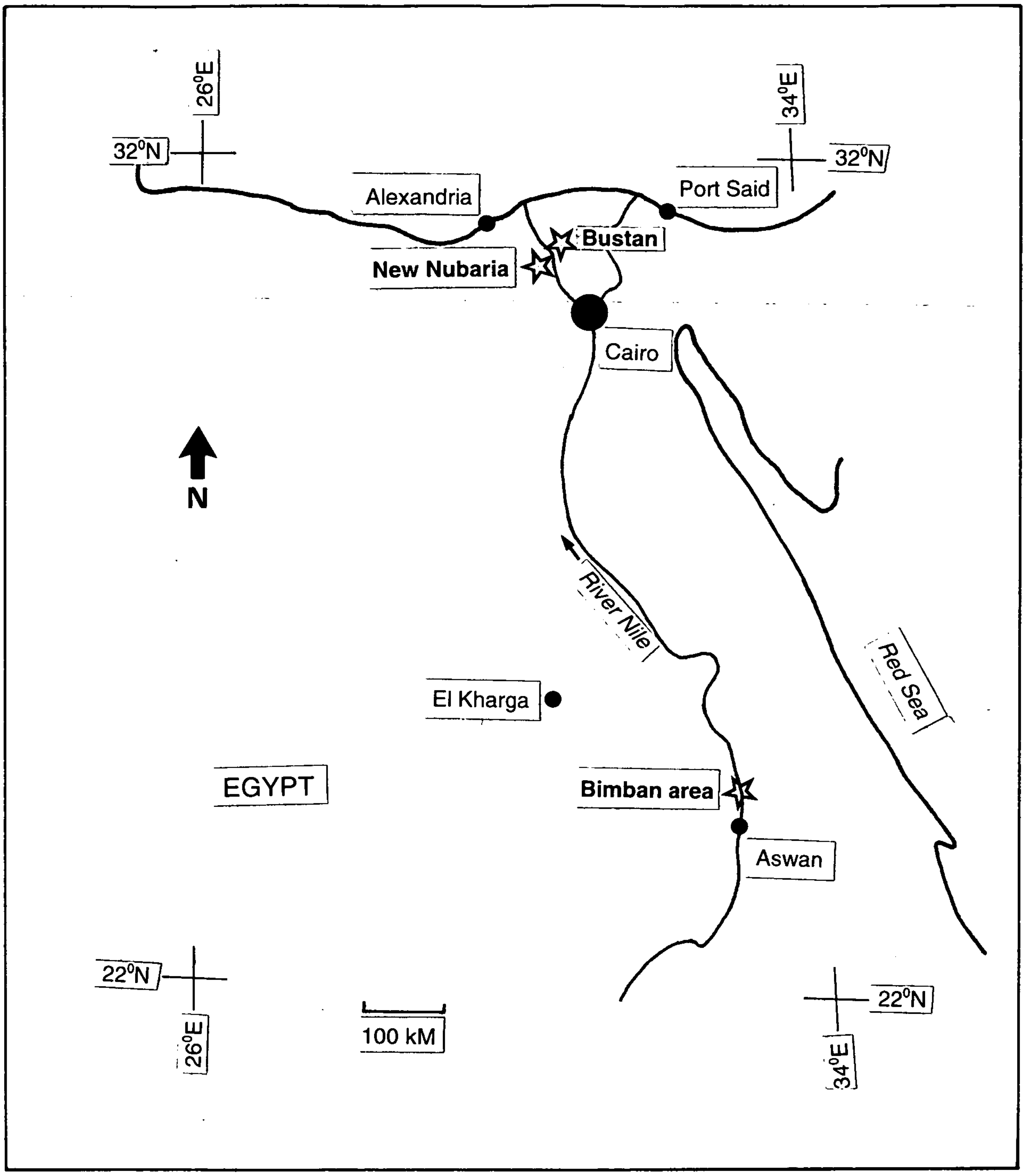
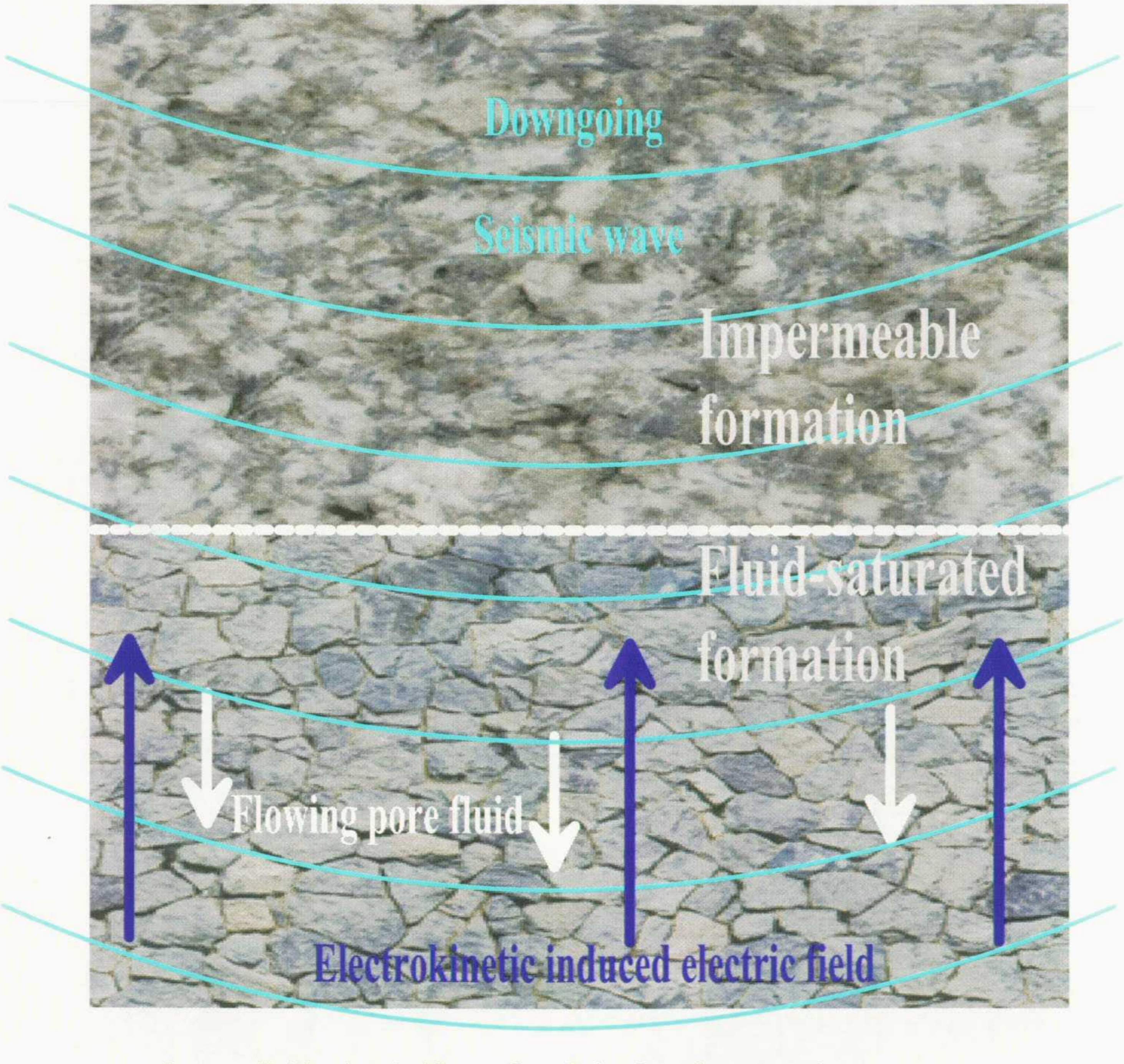


Figure 1 Approximate locations of the sites investigated

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

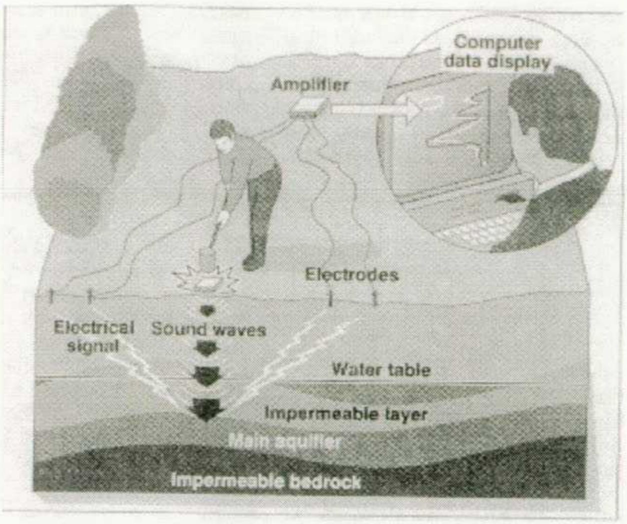


Lower : fluid saturated formation. Seismic pulse generates relative pore fluid movement. Double layer displacement generates an instantaneous electric field which is observed at surface.

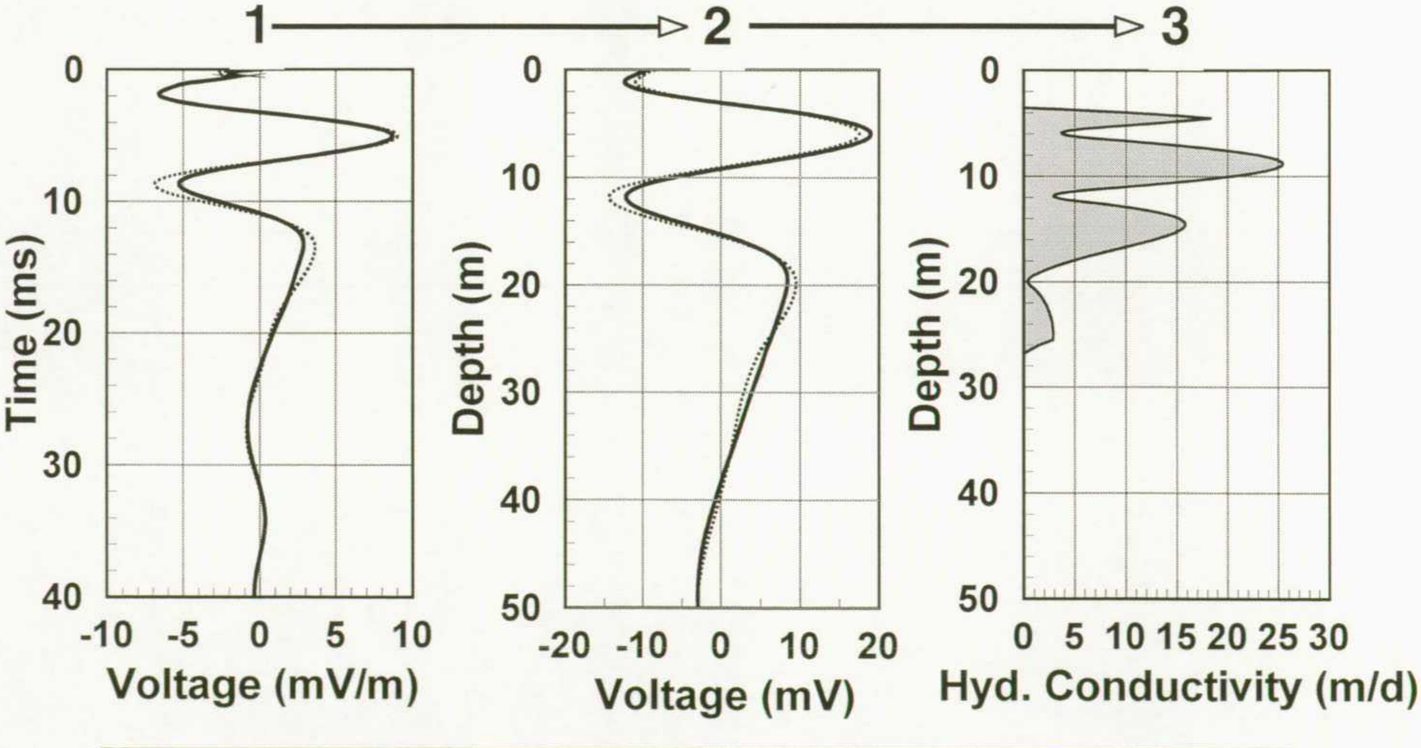
Figure 2. The principle of EK sounding

Figure 3. EK 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.

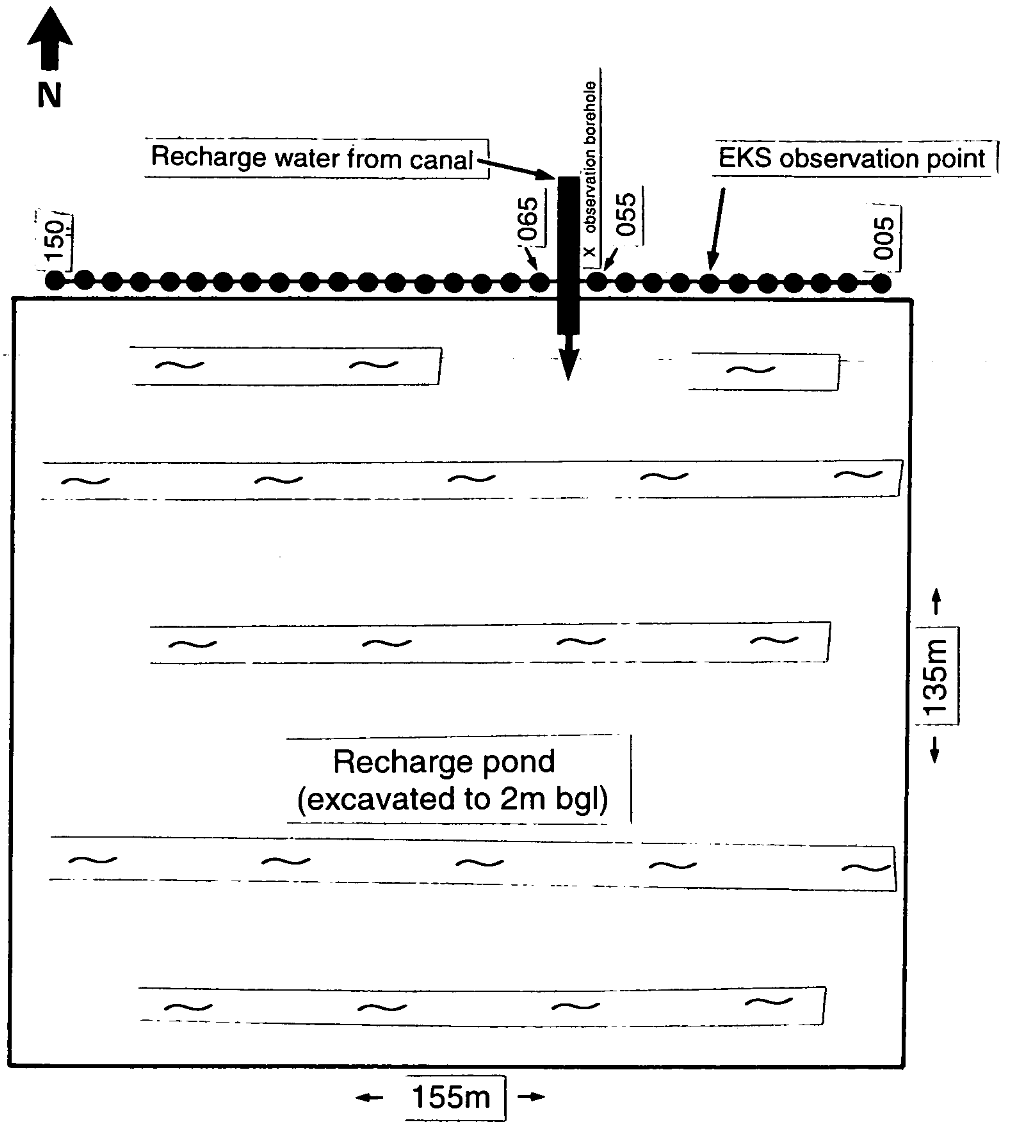


Figure 4 Layout of the EK traverse at the Bustan Recharge Pond

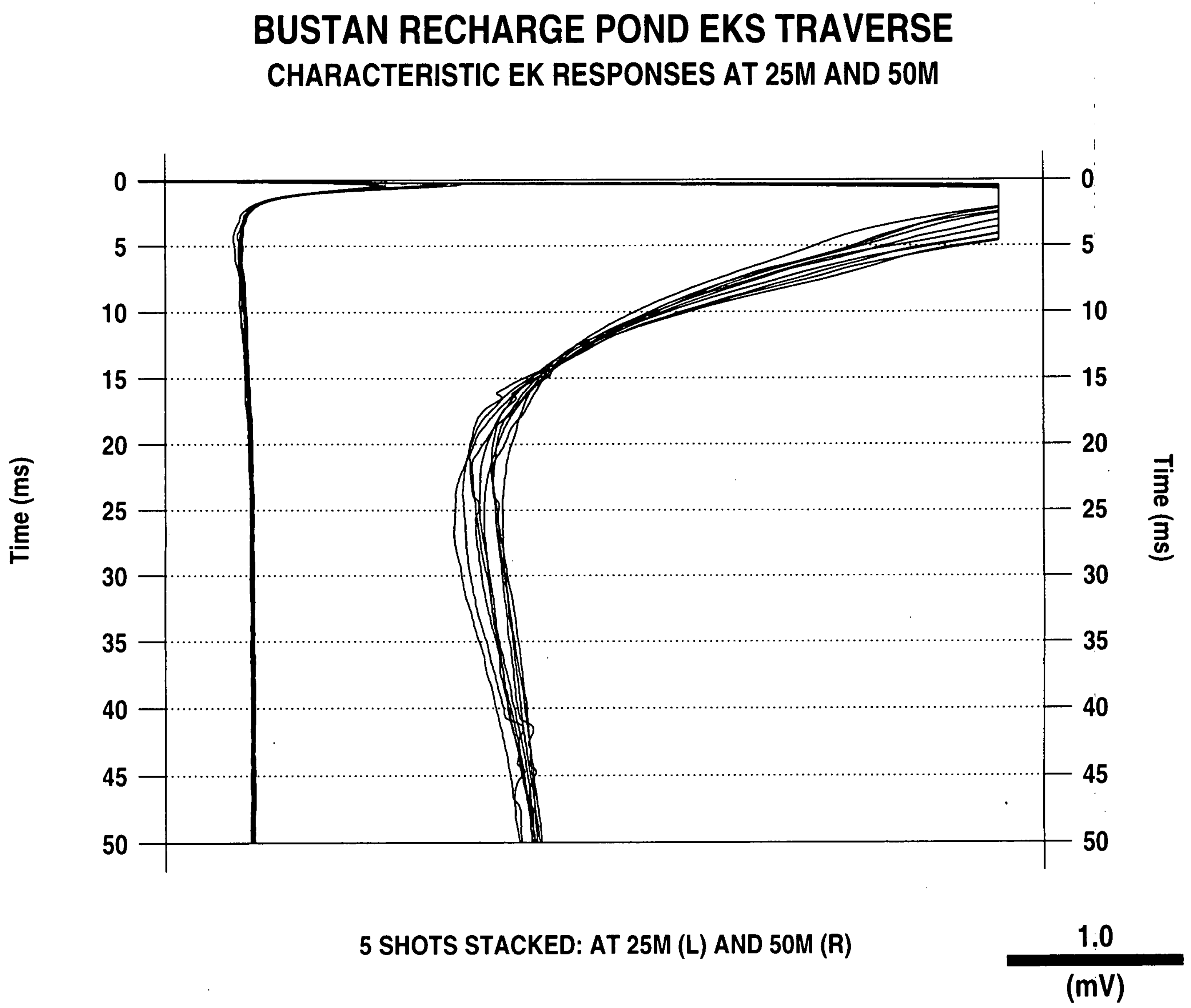


Figure 5 Characteristic EK responses from the Bustan traverse

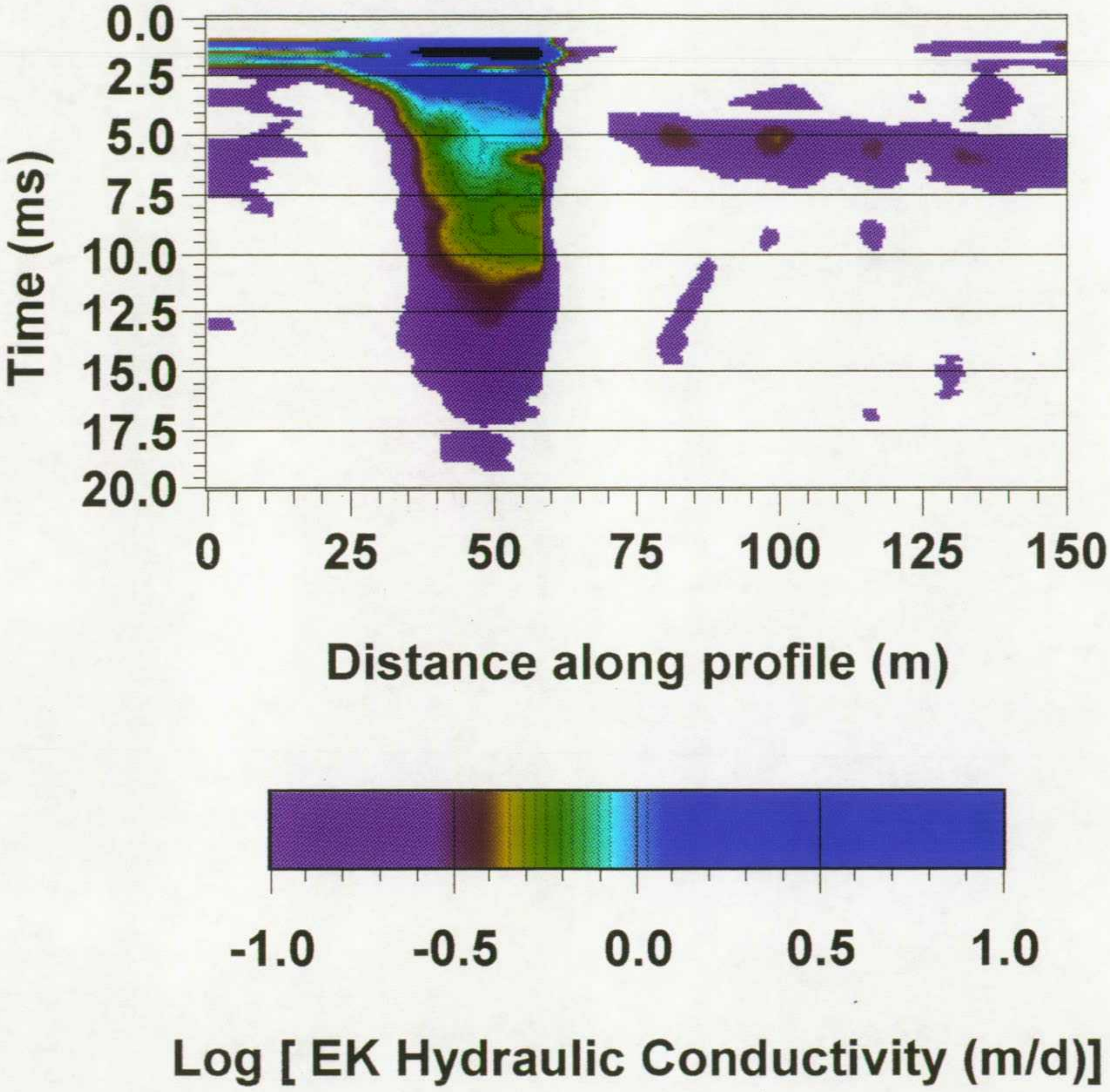
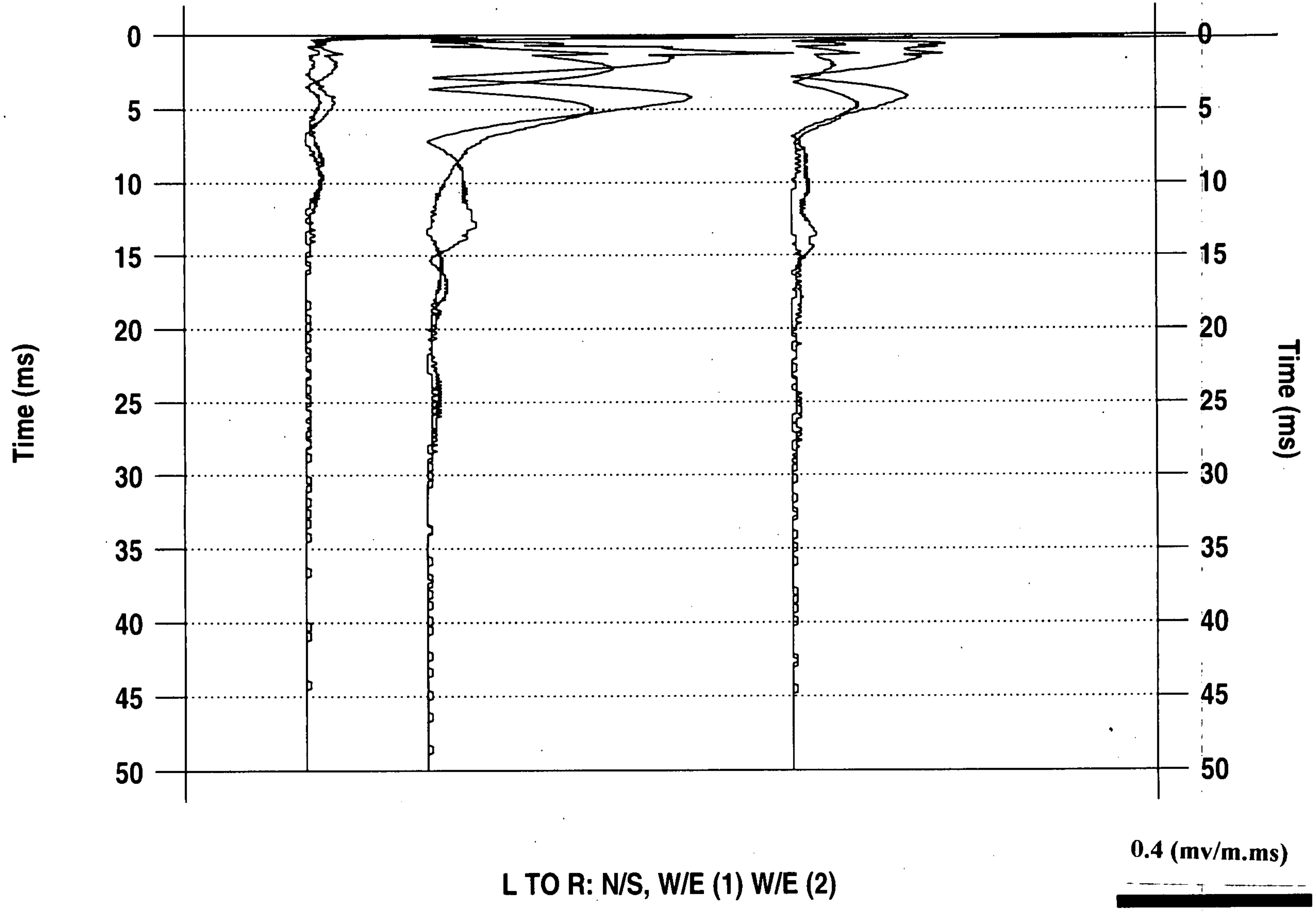


Figure 6 Analogue permeability variations along the Bustan traverse

EL KUBANIA OBS BH 1   RWL 4.6M

ANALOGUE PERM 2M DIPOLE



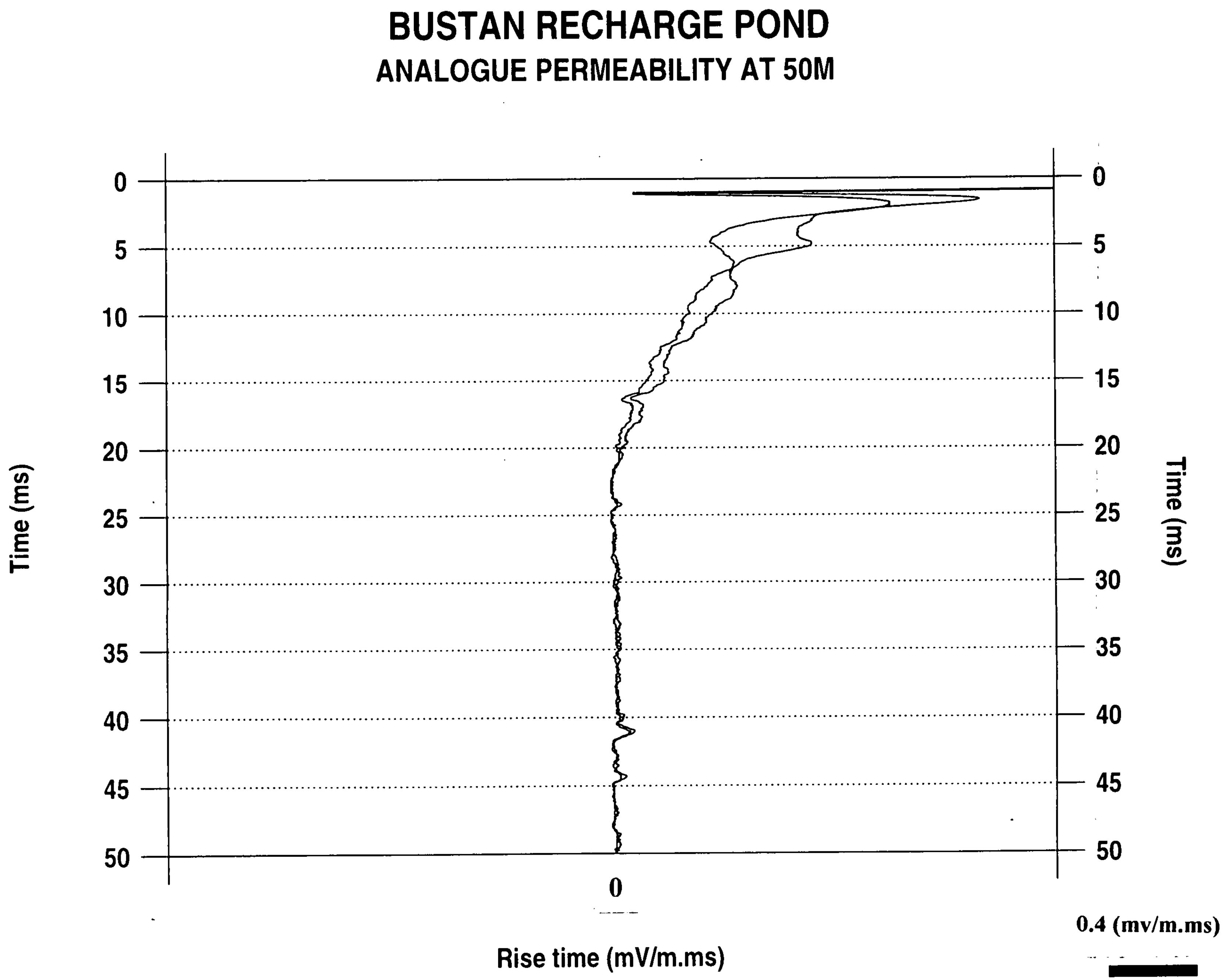


Figure 7 Analogue permeability of stacked EK data at 50M (Bustan traverse)

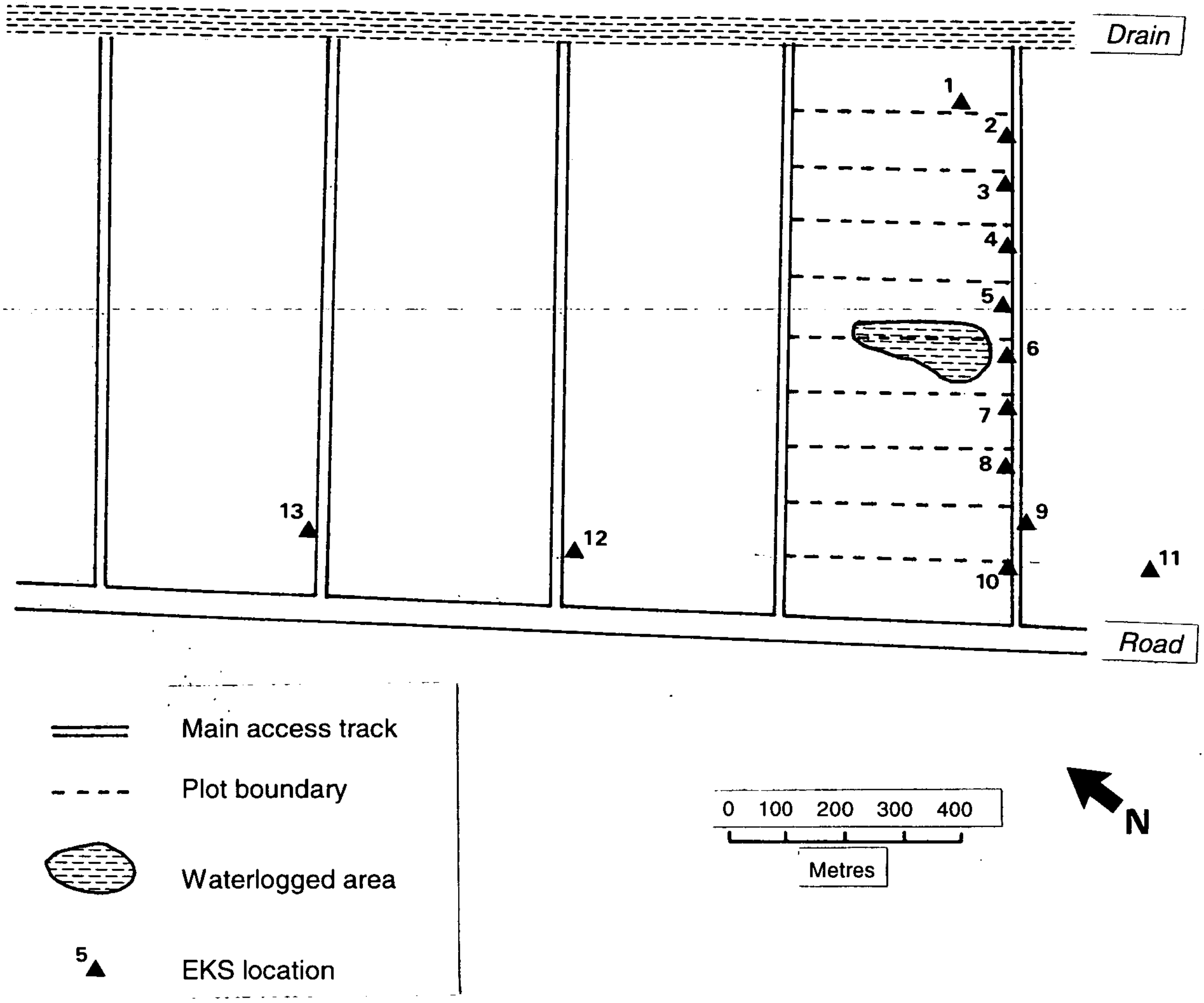


Figure 8 Location of the EK observations at New Nubaria

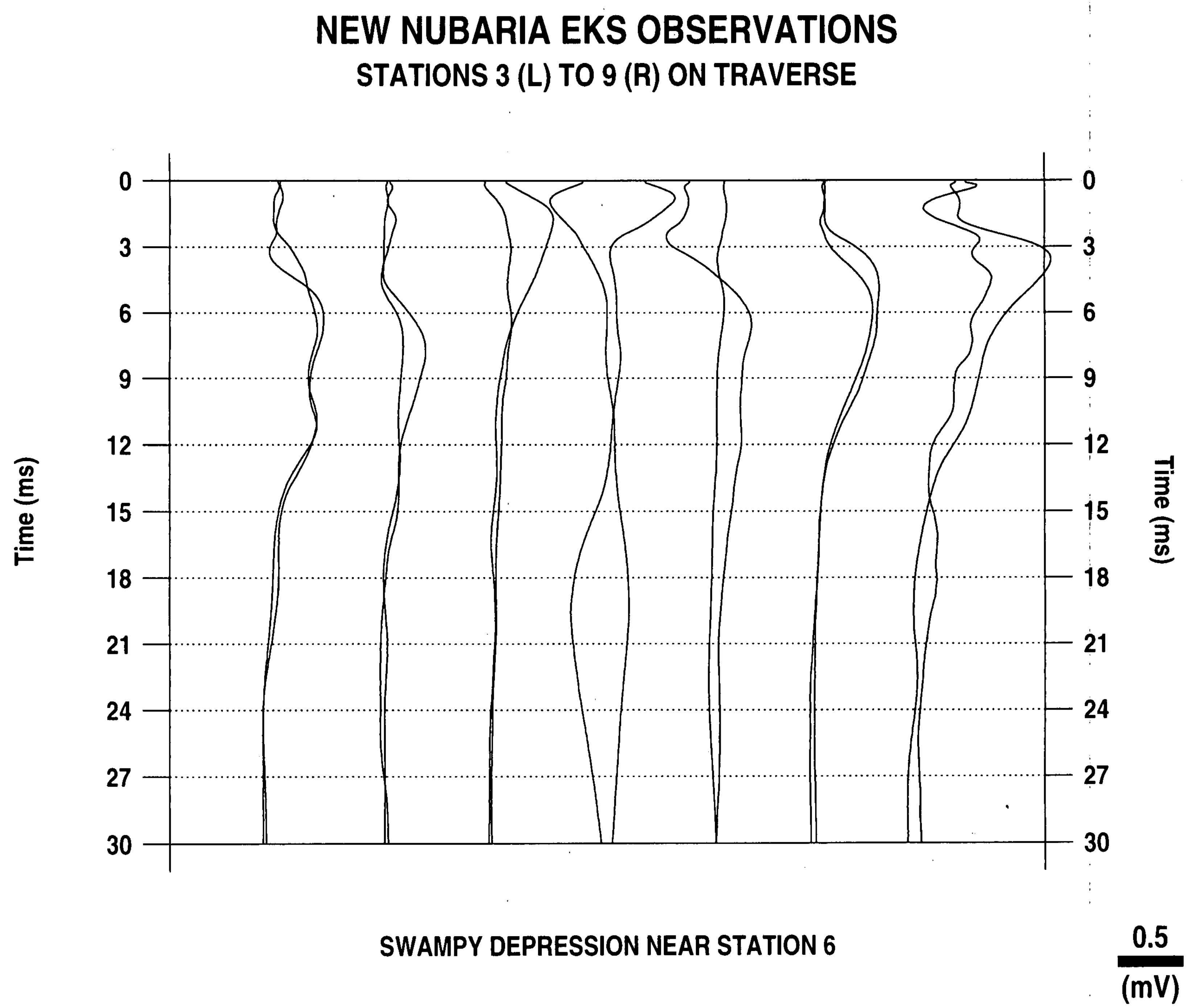


Figure 9 Stacked EK data centred near the water-logged area at New Nubaria

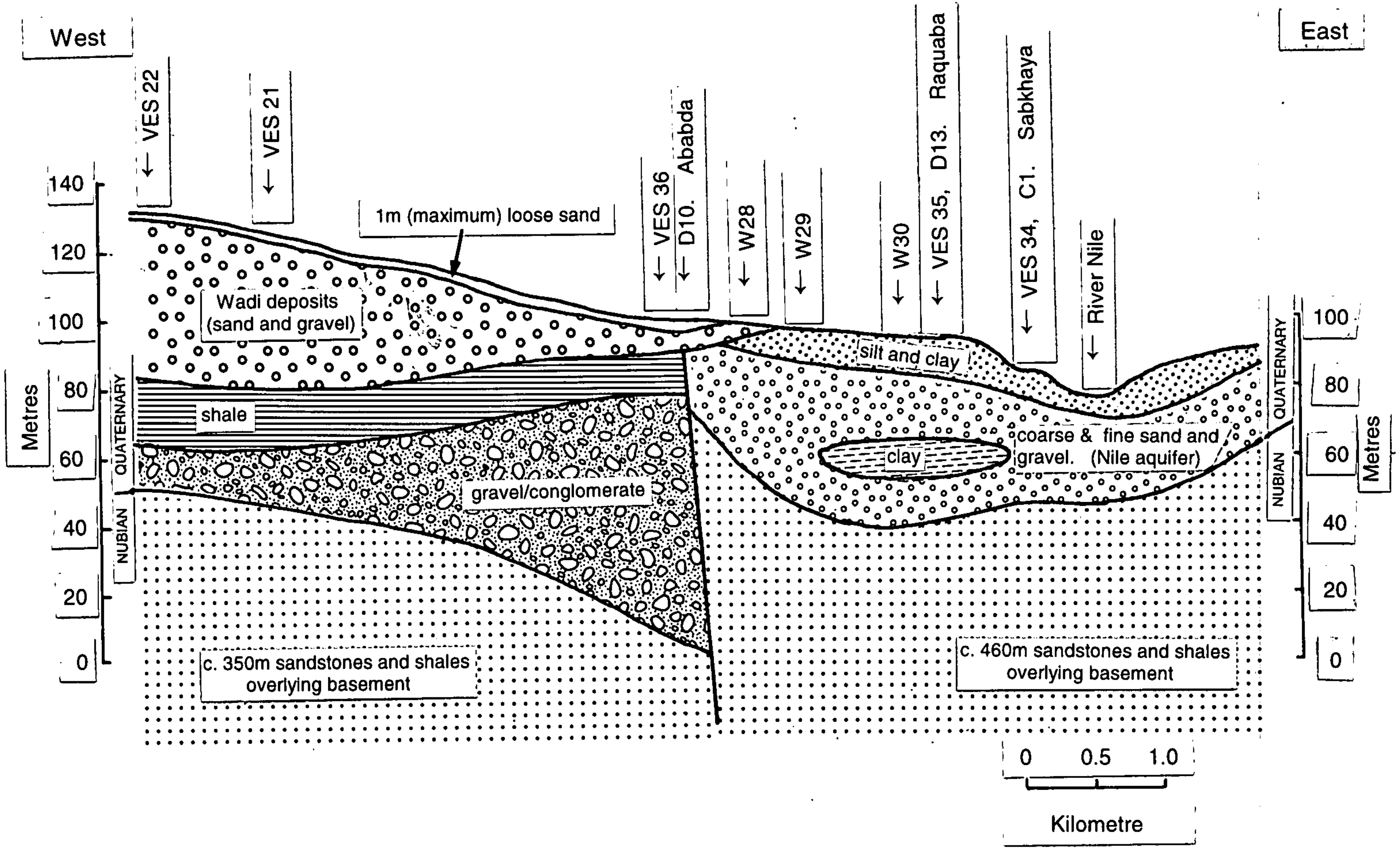


Figure 10 Schematic geological cross section of the Bimban area

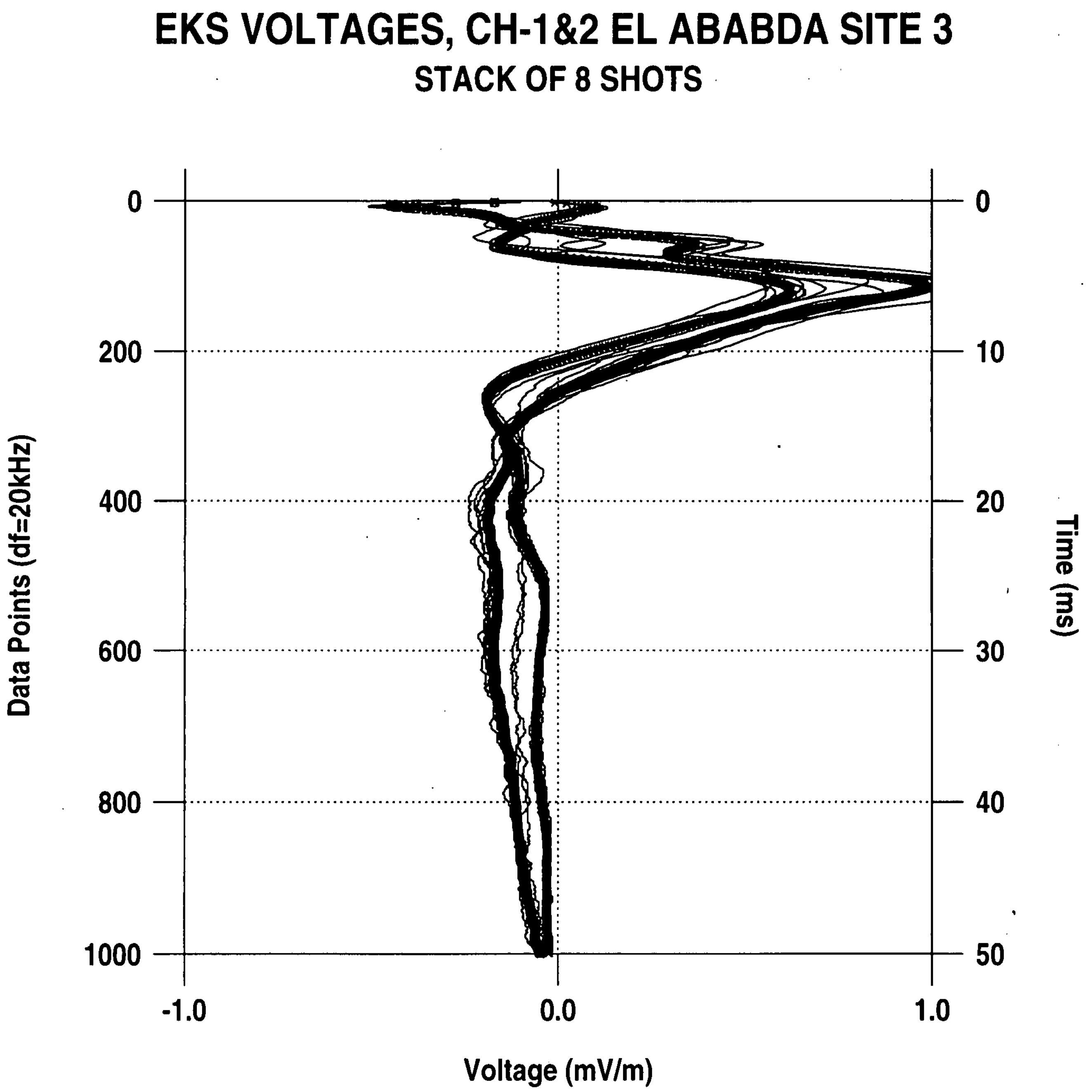


Figure 11 EK data repeatability, site 3 near El Ababda observation borehole

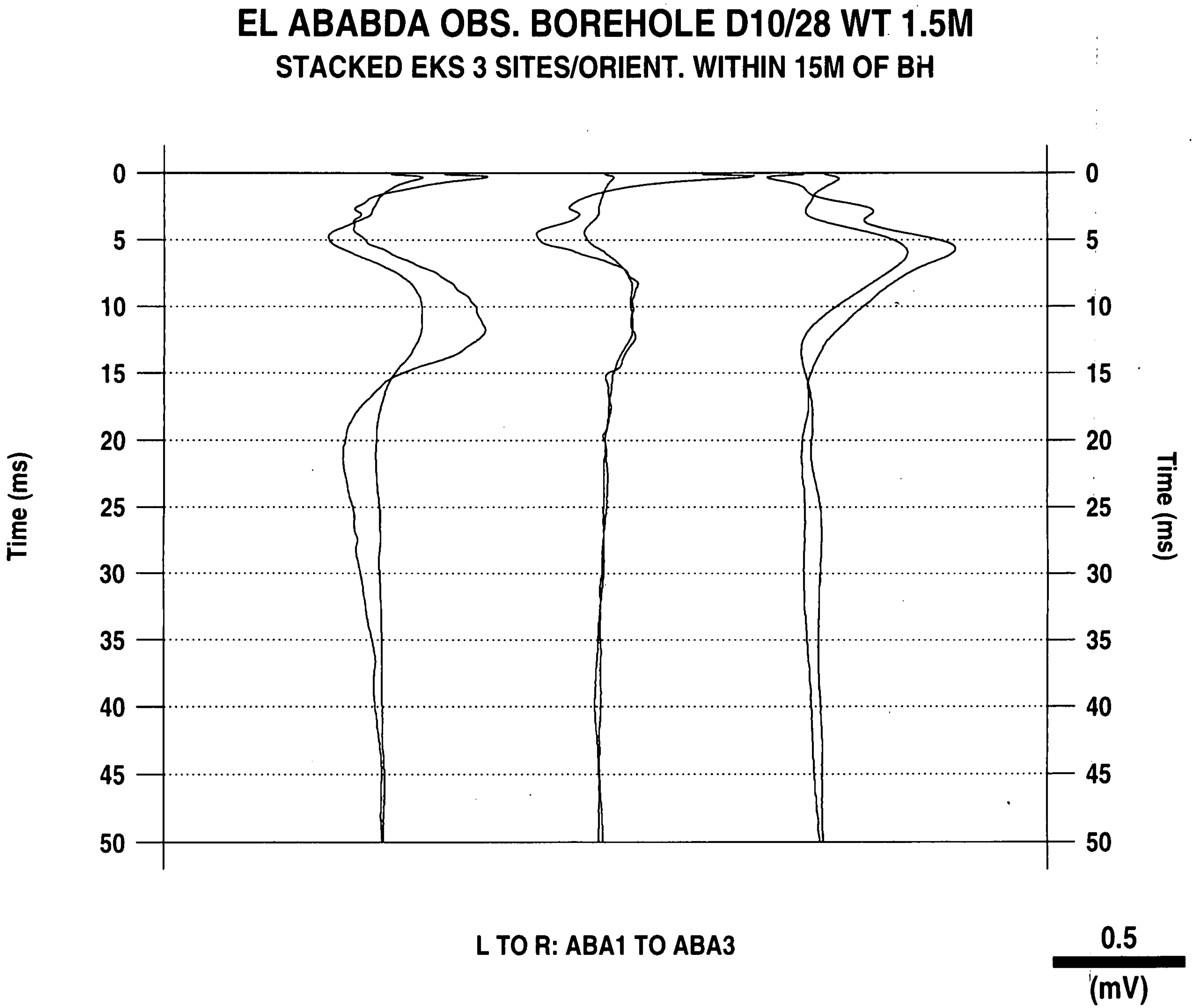


Figure 12 Stacked EK responses at 3 sites near El Ababda observation borehole

EL ABABDA OBS. BOREHOLE D10/28 WT 1.5M

ANALOGUE PERM. 3 SITES/ORIENT. WITHIN 15M OF BH

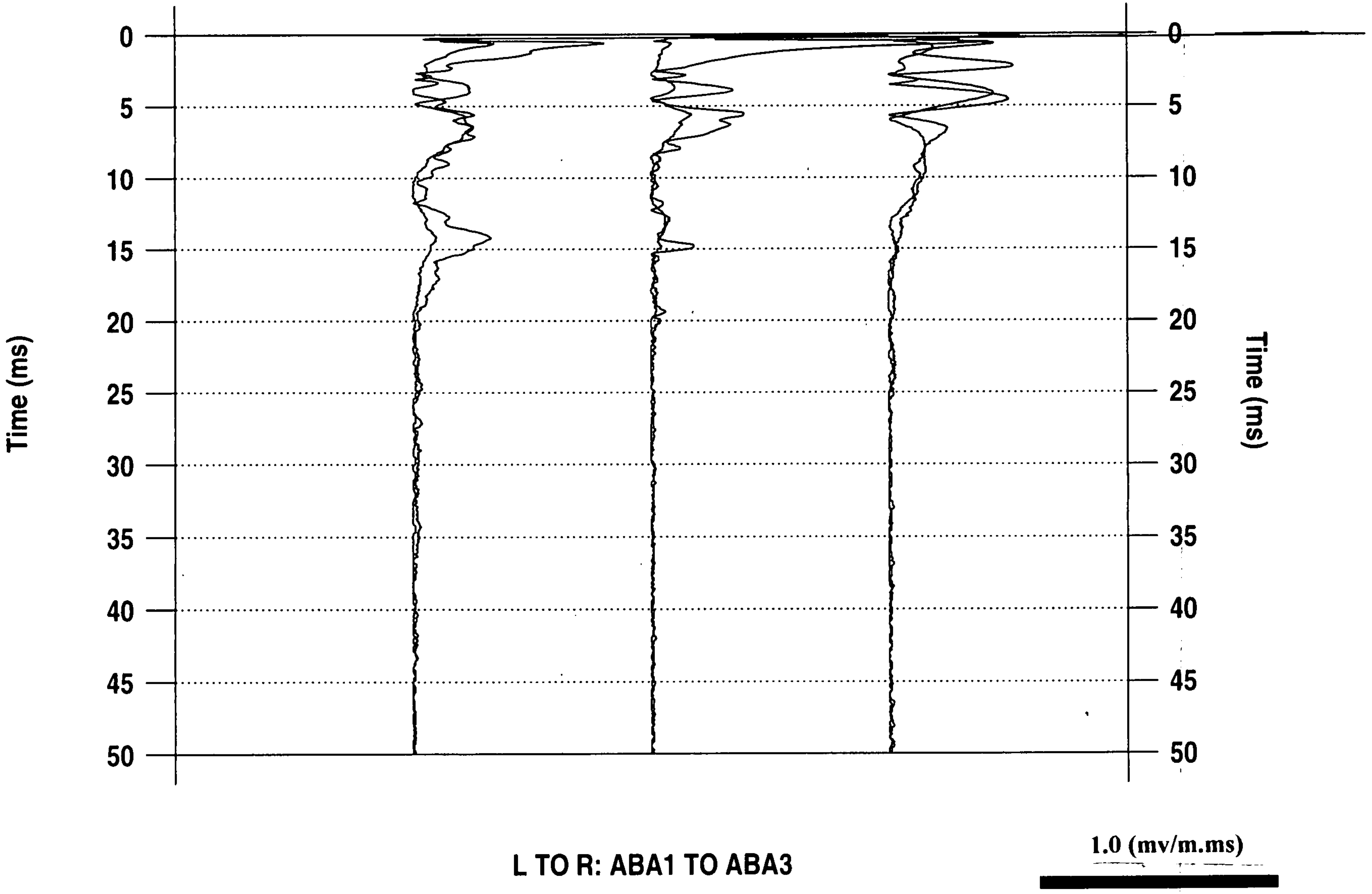


Figure 13 Analogue permeability at 3 sites near the El Ababda observation borehole.

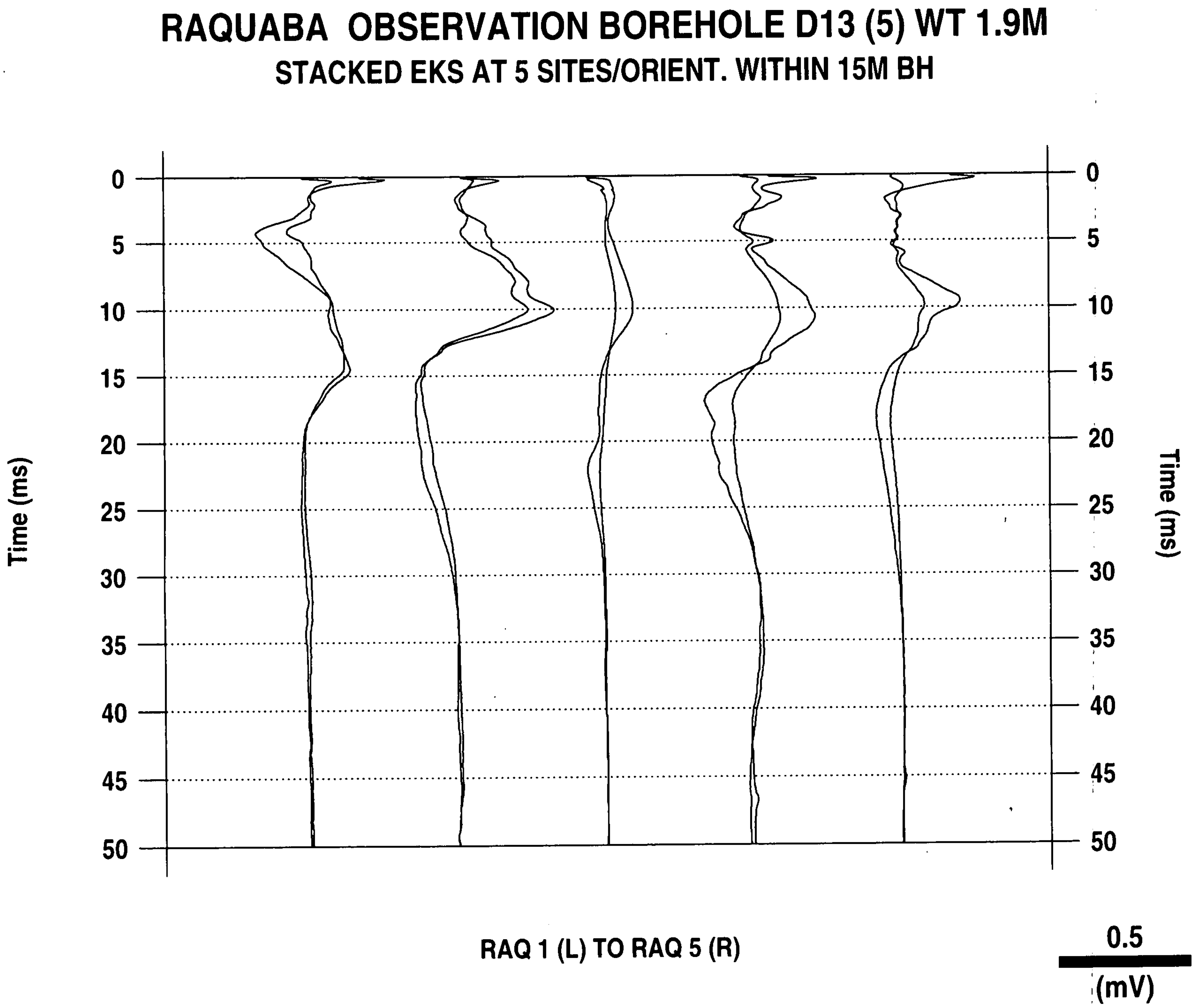


Figure 14 Stacked EK responses at 5 sites near Raquaba observation borehole

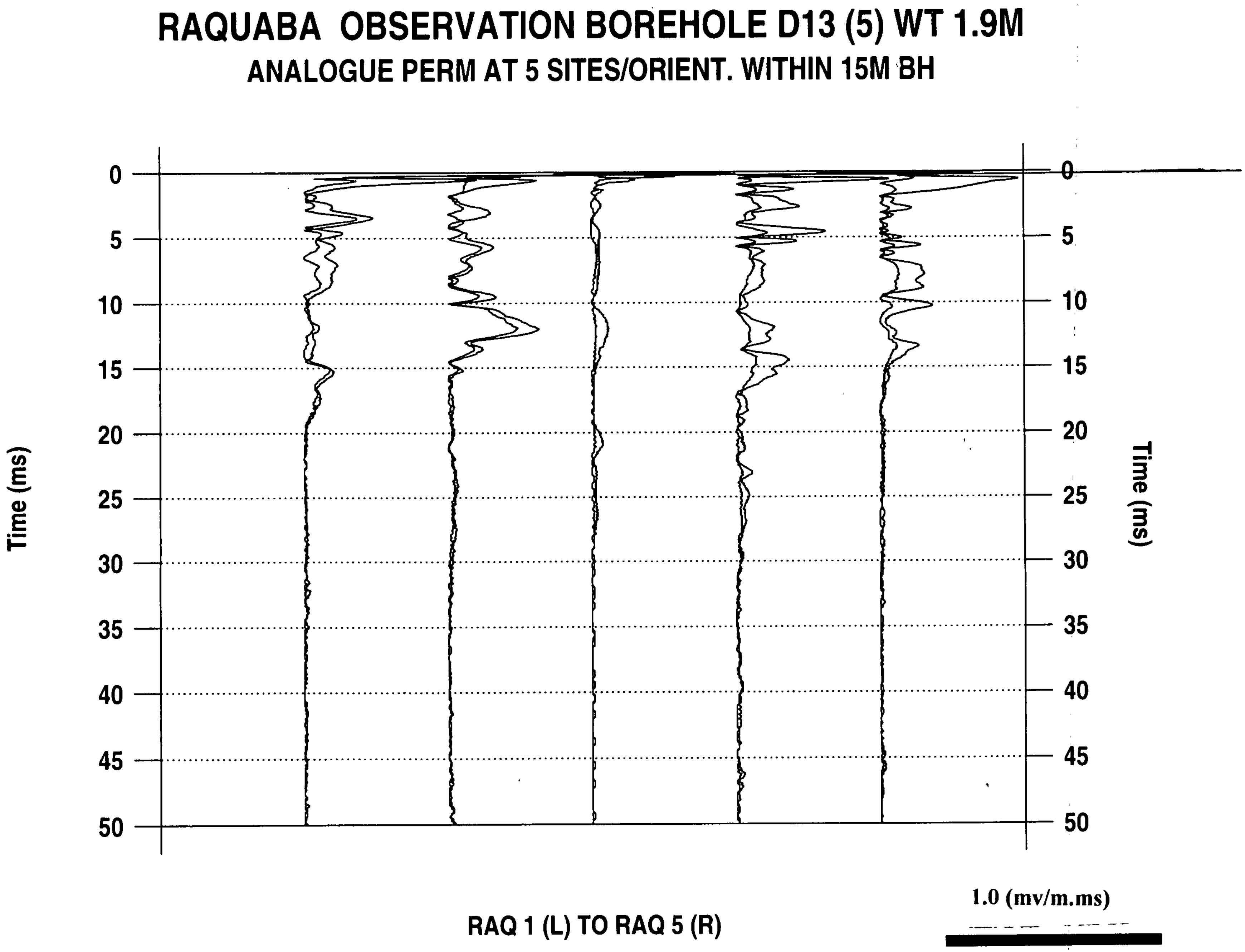


Figure 15 Analogue permeability at 5 sites near the Raquaba observation borehole

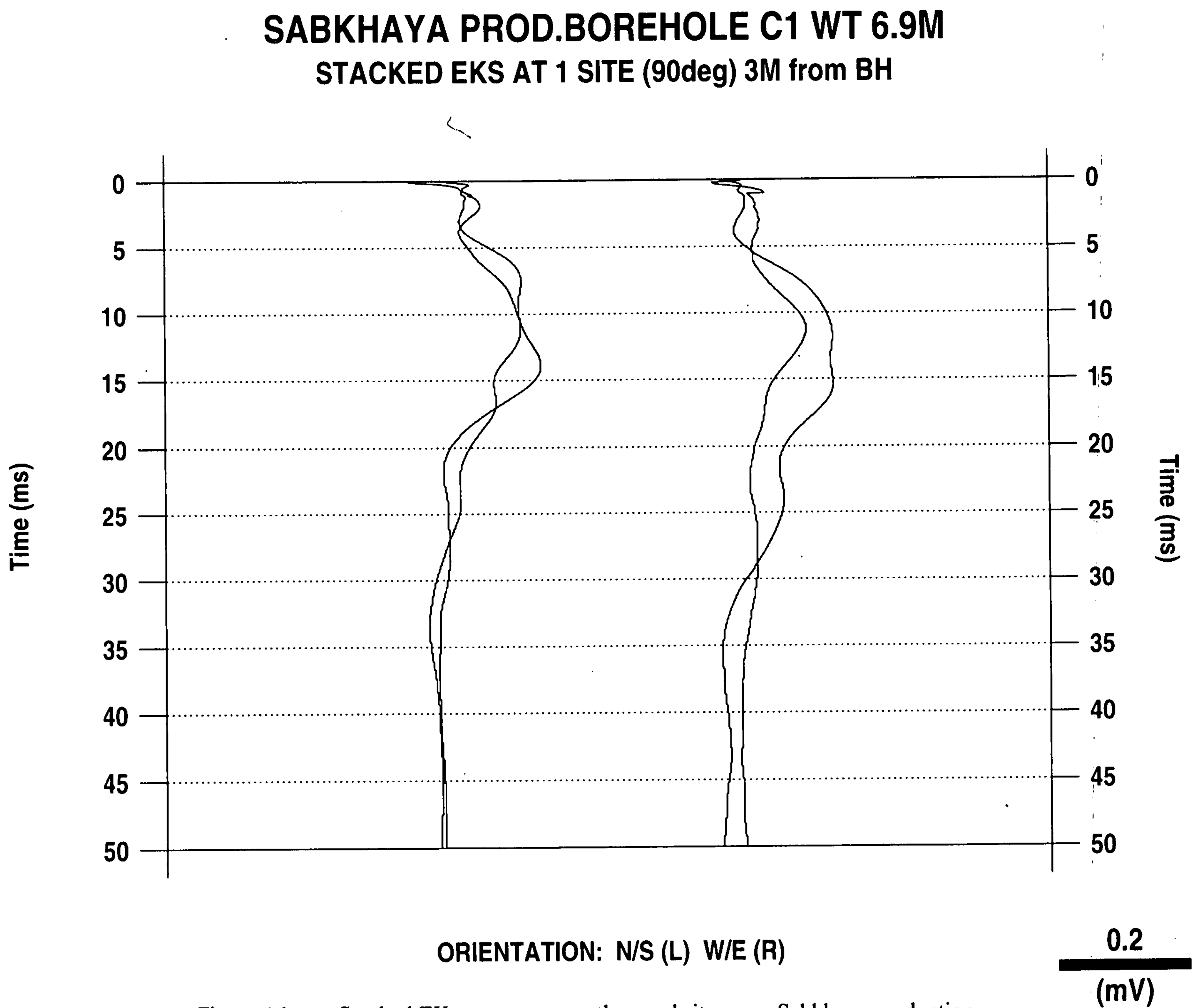


Figure 16 Stacked EK responses at orthogonal sites near Sabkhaya production borehole

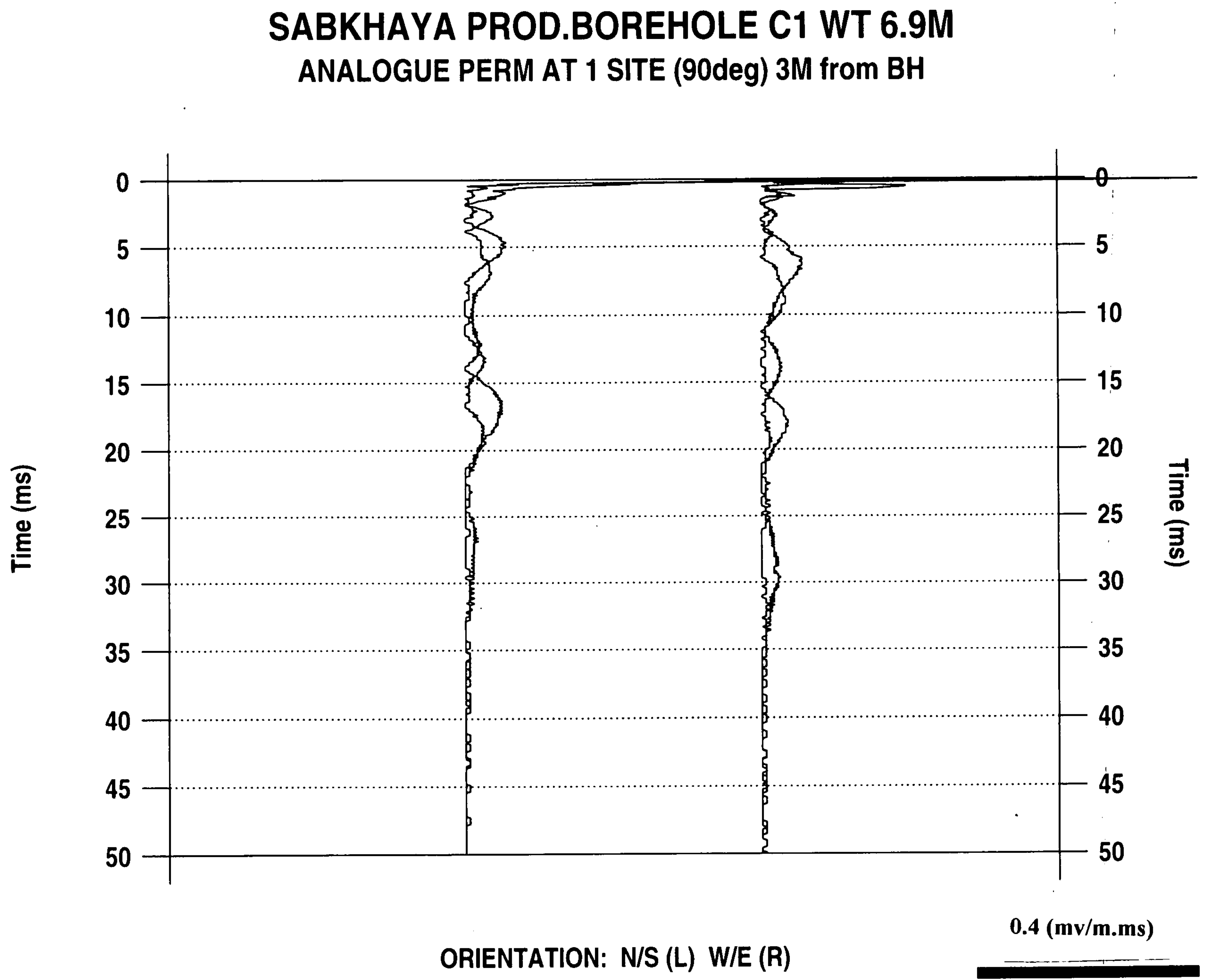


Figure 17 Analogue permeability near Sabkhaya production borehole

SITE VES 22 (50M THICK WADI DEPOSITS ON SHALE)

STACKED EKS 1 SITE (2M,5M,10M DIPOLES) ORIENT 35

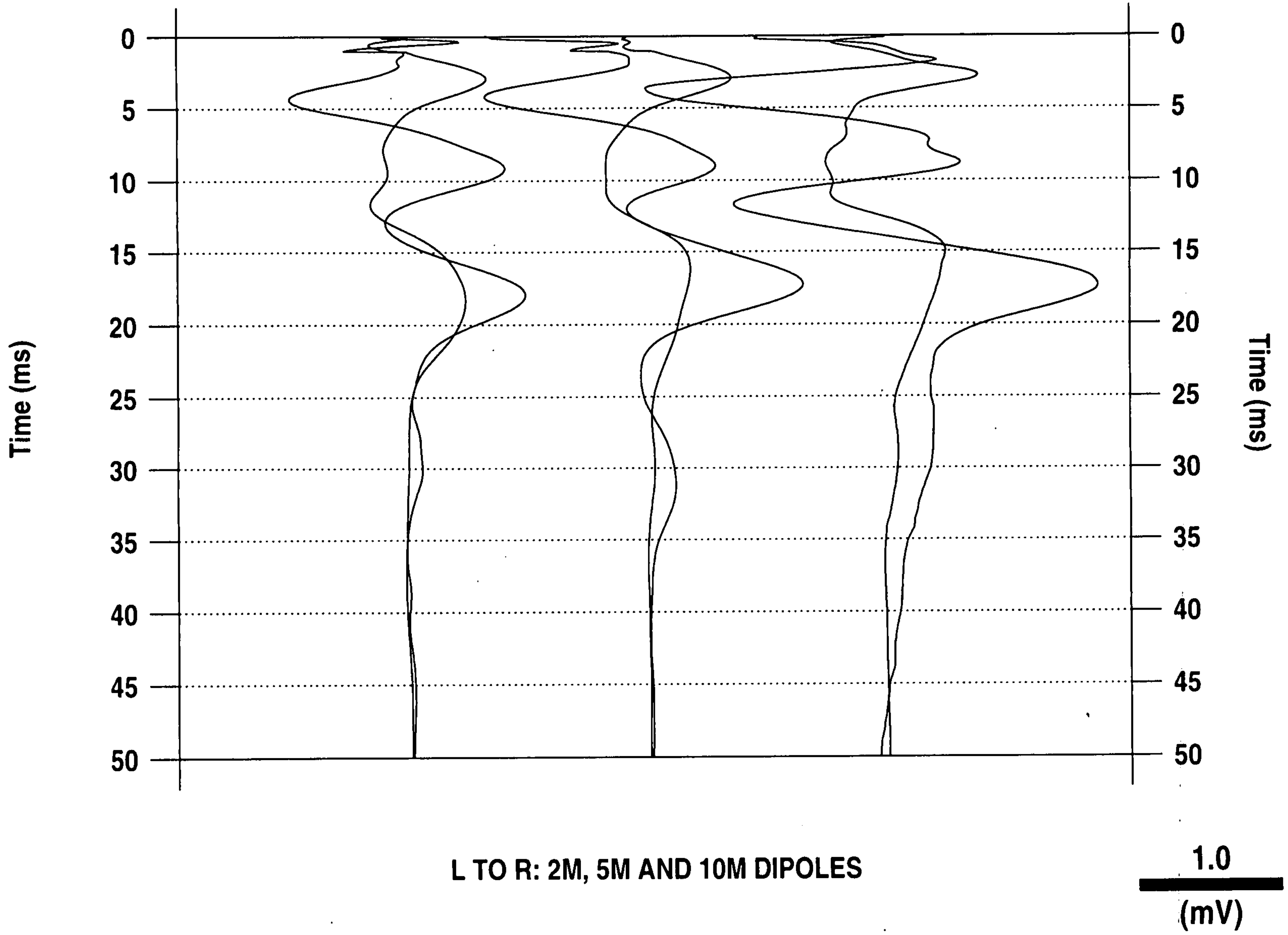


Figure 18 Stacked EK responses using 2-, 5- and 10M dipoles, Site VES22 (35 deg)

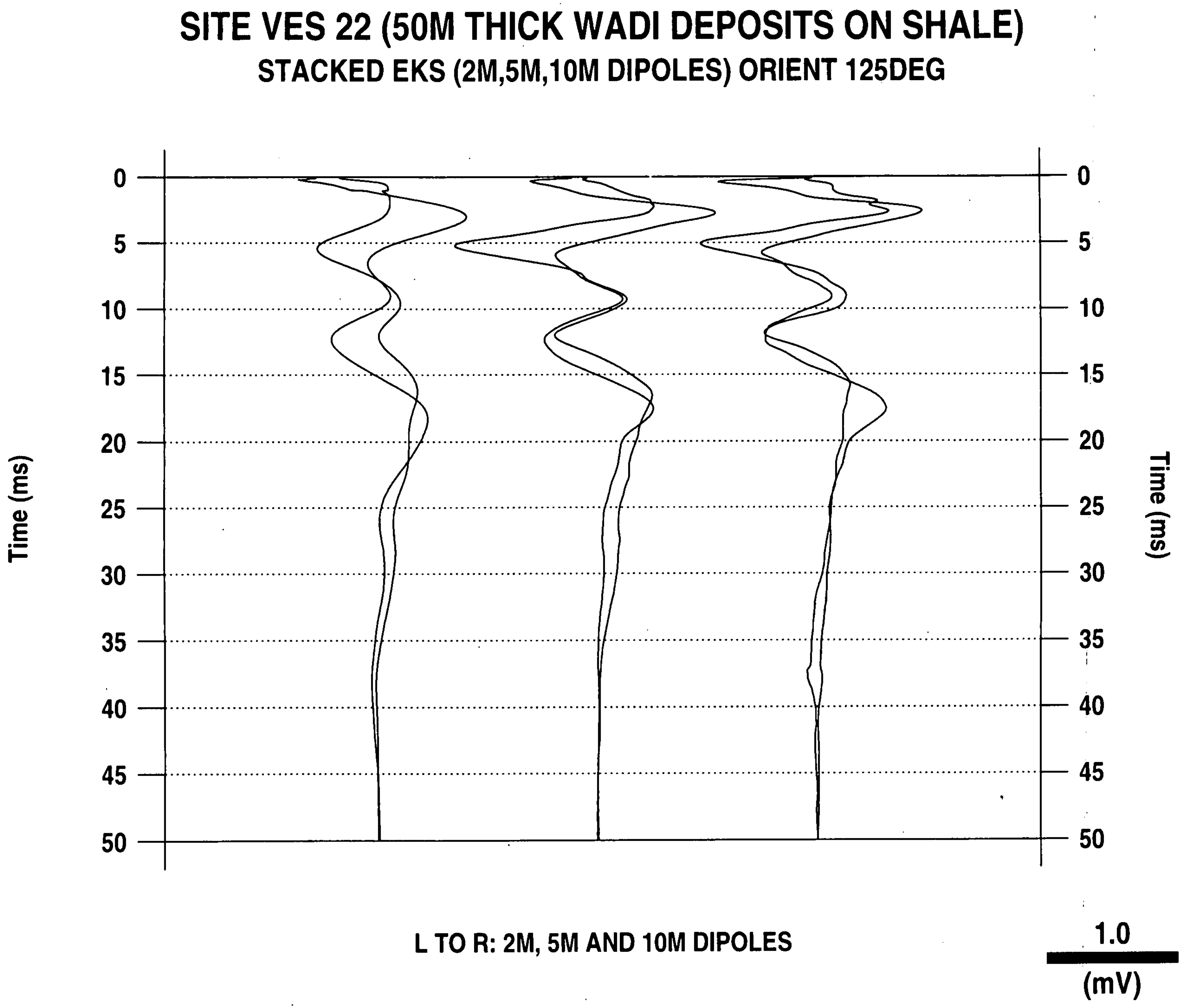


Figure 19 Stacked EK responses using 2-, 5- and 10M dipoles, Site VES22 (125 deg)

SITE VES 22 (50M THICK WADI DEPOSITS ON SHALE)

ANALOGUE PERM.(2M,5M,10M DIPOLES) ORIENT 125DEG

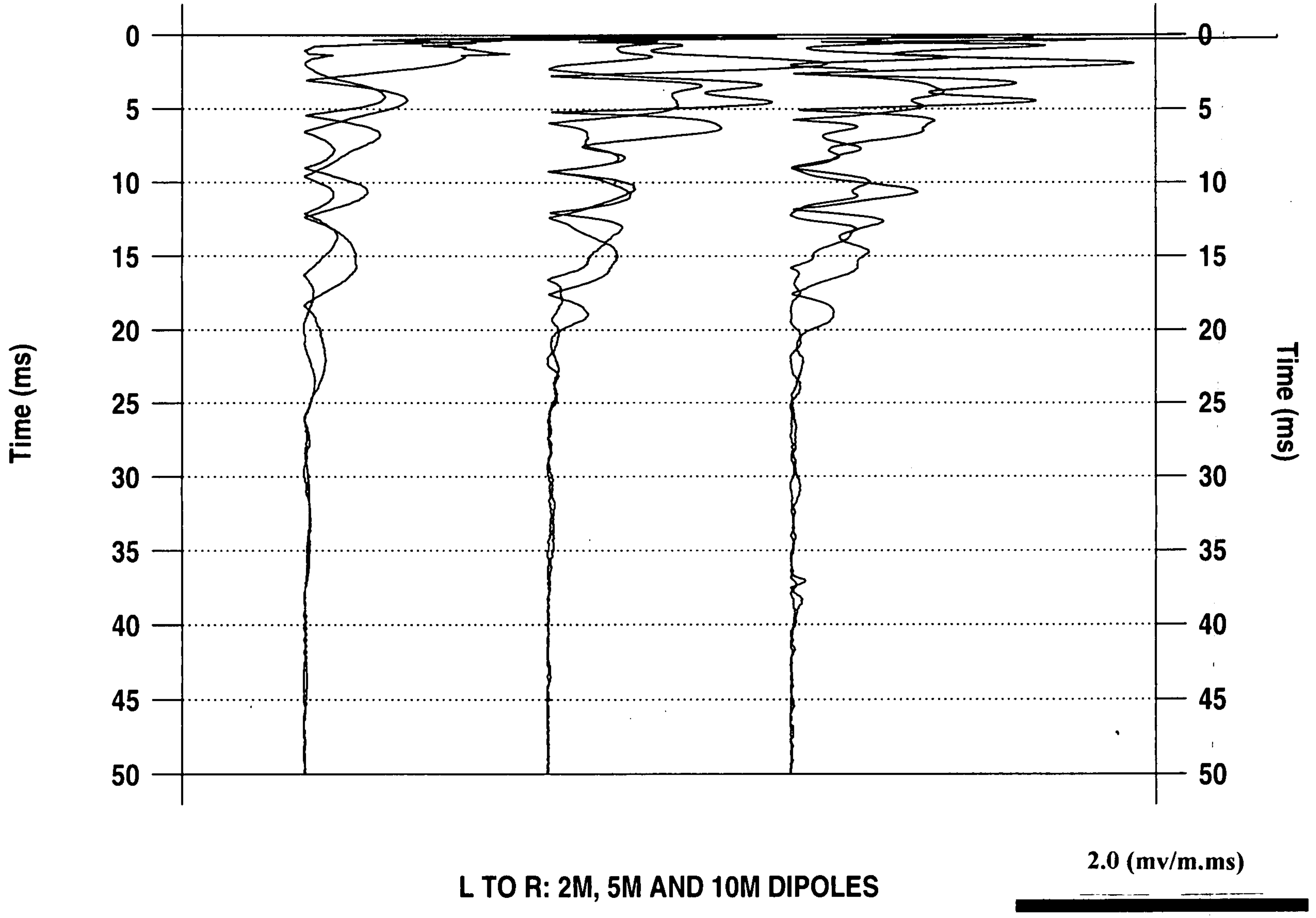


Figure 20 Analogue permeability (2-, 5- and 10M dipoles), Site VES22 (125 deg)

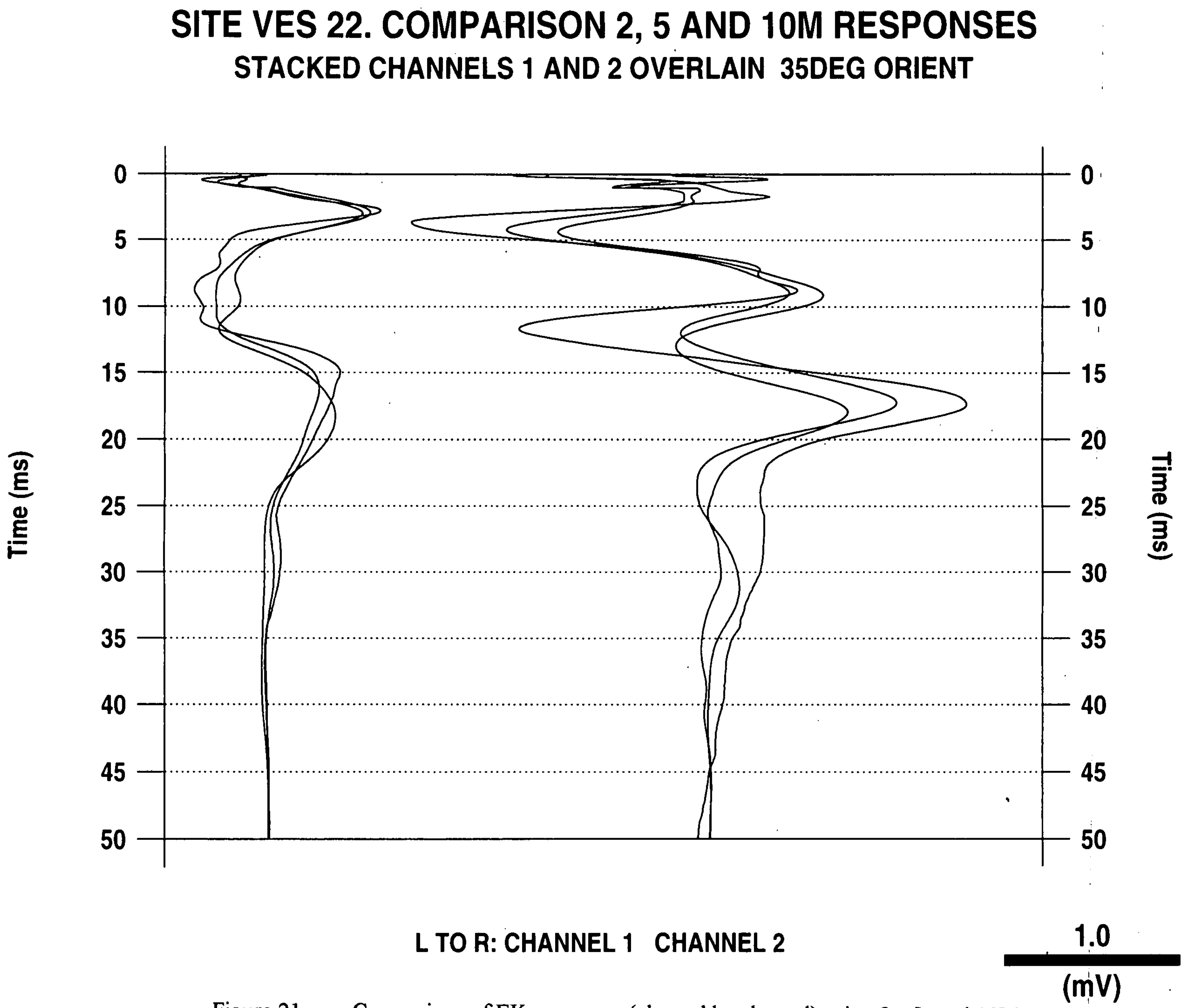


Figure 21 Comparison of EK responses (channel by channel) using 2-, 5- and 10M dipoles, Site VES22, 35 deg orientation

SITE VES 22. COMPARISON 2, 5 AND 10M RESPONSES

STACKED CHANNELS 1 AND 2 OVERLAIN 125DEG ORIENT

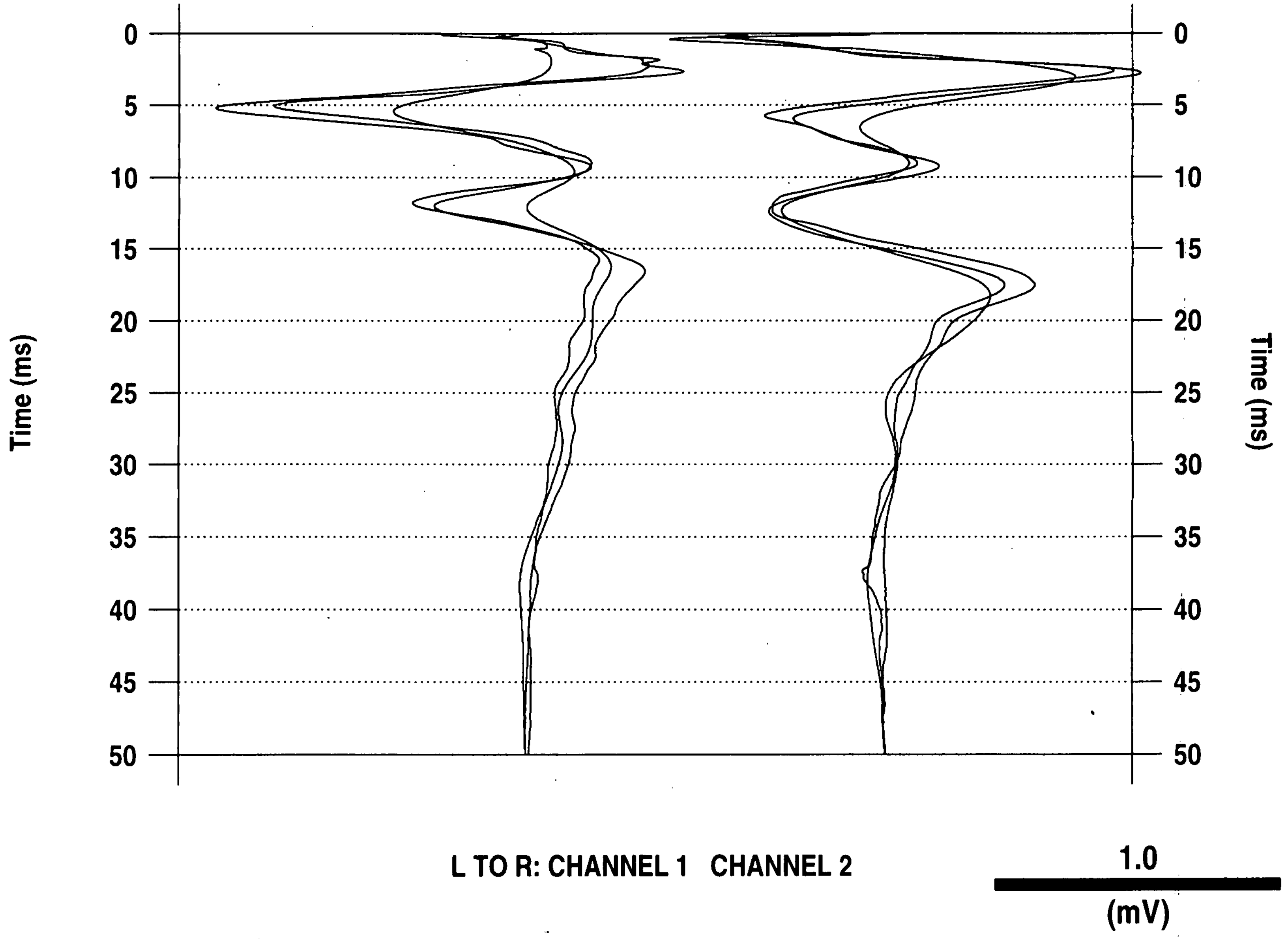


Figure 22 Comparison of EK responses (channel by channel) using 2-,5- and 10M dipoles, Site VES22, 125 deg orientation

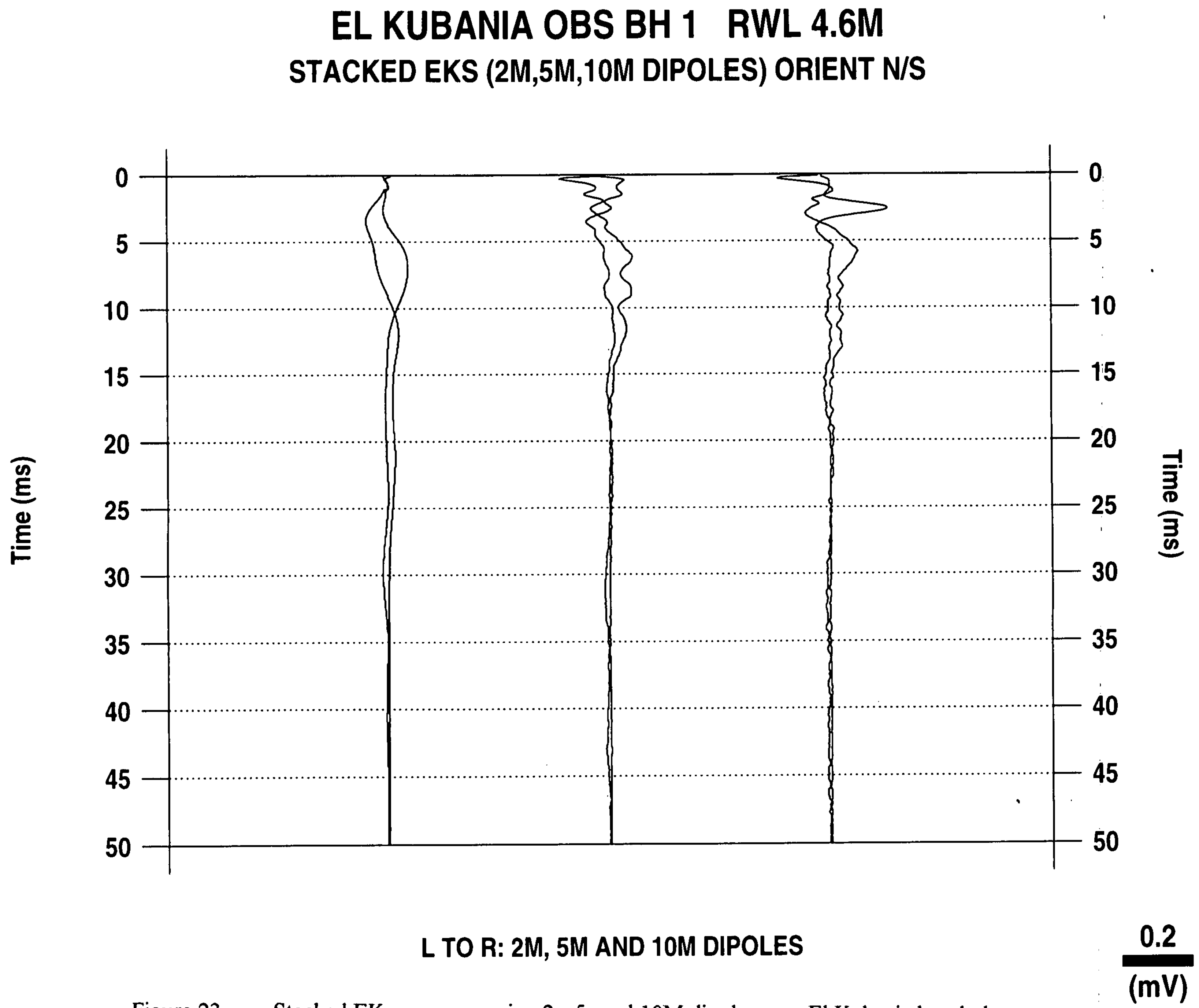


Figure 23 Stacked EK responses using 2-, 5- and 10M dipoles near El Kubania borehole (N-S orientation)

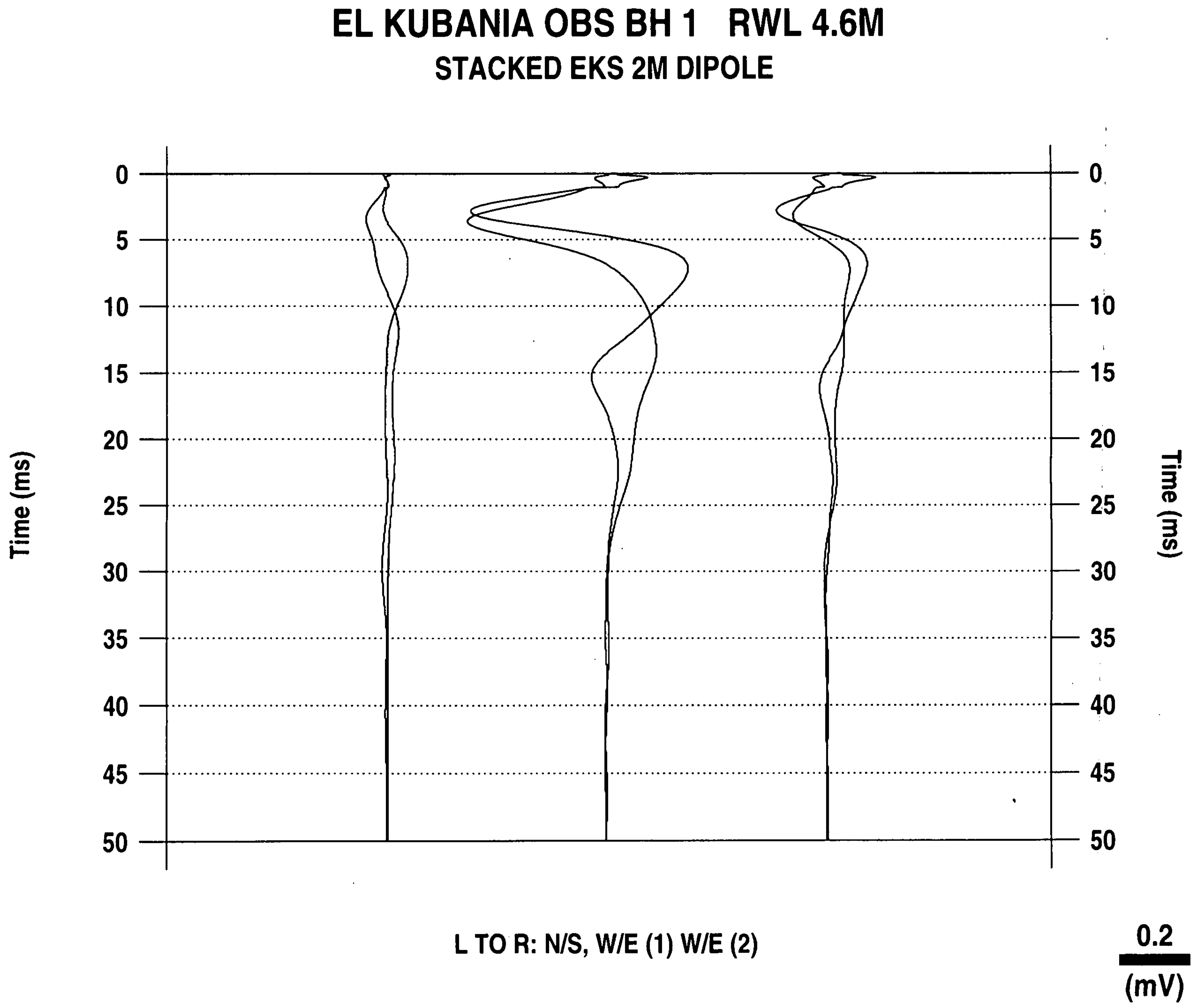


Figure 24 Stacked EK responses (2M dipole), orientation N-S and W-E, near El Kubania borehole