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WELL AND BOREHOLE SITING BY ELECTRO KINETIC SOUNDING AND ASSOCIATED EXPERIMENTAL OBSERVATIONS IN BIKITA DISTRICT, SOUTHERN ZIMBABWE

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Electrokinetic sounding in progress in a shallow basement area of Bikita District

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1. SUMMARY

The recently developed and still largely experimental electro kinetic sounding (EKS) technique has been used to locate well and borehole sites in the difficult shallow basement terrain of Bikita District, southern Zimbabwe. The sites selected using EKS are due to be further tested, initially with additional geophysical surveys and subsequently by well/borehole construction. The current exercise is thus seen as the definitive test of the EKS technique which we have previously used only in a calibratory sense at existing groundwater sources. Previous overseas surveys involving EKS are described by Peart *et al* (1996a, b) and a fuller description of the technique is given by Beamish and Peart (1996).

In addition to routine well and borehole siting we have made experimental observations, largely relating to field procedure: we describe modified procedures that will result in the collection of improved data. Moveout experiments involving both seismic and electric dipole techniques indicate a disturbing link between the lateral passage of seismic energy and the generation of electrokinetic response. These experimental tests of EK behaviour are described in Section 7.

2. INTRODUCTION

This report describes geophysical field work in Zimbabwe in support of the ODA-funded Bikita Rural Water Supply and Sanitation Project (BIRWSSP) during a two week period in November/December 1996 (the location of the study area is shown in Figure 1). We undertook this work as an extension to our existing ODA TDR Project R6232 "Development of a new well siting technique" which aims to assess to what extent a new, non-invasive surface geophysical technique (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 (R6232) is to improve the efficiency of borehole and well siting in difficult overseas' terrains and hence alleviate water scarcity.

The aims of the present work were threefold:

1) To site wells or shallow boreholes at a selection of Kraals[1] in Ward 22 that currently lack a perennial water supply (ie difficult sites where previous shallow wells and/or boreholes may have failed).

2) To train counterpart staff from the BIRWSSP project and the three Zimbabwean governmental institutions closely concerned with that project in the use of EKS equipment and data intepretation.

3) To further refine and evaluate the infant EKS technique through additional

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[1] A Kraal is defined here as a rural community of less than about ten families

experimental observations and the eventual incorporation of ground truth following well- and borehole construction.

We start with a brief description of the local geology and then give an outline of the EKS technique and the methods of collecting, processing and interpreting EK data. Then we discuss the results of the "routine" well siting component and include recommendations for well or shallow borehole sites. Finally we describe the experimental work undertaken, suggest some improved field procedures and draw conclusions concerning possible limitations of the EK technique as currently employed.

3. OUTLINE GEOLOGY

The dominant rock type of the study area is Younger Granite with subordinate granodiorite; extensive dolerite sills were seen occasionally. The typical soil comprising coarse and pinkish sand suggests generally very shallow weathering, as does the gray silty soil occuring in vlei bottoms. Faults, shown on the geological map and observed on aerial photographs, have dominant north-westerly and northerly trends, and are occasionally of regional extent with strike lengths in excess of 40 km. Two such faults located in the field were found to be intruded by either dolerite or quartz (both standing slightly proud of the country rock) with their exposed contact zones effectively sealed, as with a welded joint, offering no groundwater storage potential. The study area is marginal to the low veld, at about 1000 m elevation, and is generally flat lying with occasional deeply dissected and wooded inselbergs or whale-backs.

4. 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.

5. 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.

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 attempted in the present study by assuming an average seismic velocity of $1500ms^{-1}$ for all the lithologies above unweathered bedrock. This conversion has been made solely to provide an estimate of digging/drilling depths. Departures from this assumed average value are not critical because we are interested primarily in defining the zones of thickest weathering and this can be achieved in a relative sense simply by examination of a series of EK observations.

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. In the present study we have used rise time data (analogue permeability)only to calculate construction depths at the chosen well/borehole sites.

6. ROUTINE WELL AND BOREHOLE SITING

Prior to the present field work, each of the communities had been asked to mark their three most promising/most convenient well sites. These were usually selected on the basis of prior experience, folklore, the recogniton of phreatophytes, aligned termite mounds and occasionally by divining. In the present work the immediate neighbourhood of the three sites at each kraal were tested first with EKS and usually at least one of these appeared suitable. We did not make isolated EK observations but attempted to make short traverses, occasionally linking two or more of the preferred sites. Where none of the preferred sites appeared suitable then recourse was made to an examination of air photographs to locate promising photolineaments etc (see Section 7.13).

6.1 Chitsanga School/Ndoro Kraal

EK sounding at one of the sites chosen by the community and a further apparently promising riverside site (Figure 4) reveal no significant EK signal. Figure 5 shows moderate to high amplitude EK signal (ie both channels in phase) persisting to about 30 ms at and near the first community selected site, occupying flat-lying wooded ground. Observations made near well defined intersecting photolineaments (traditionally a promising site) in a grassy area some 3 m above a neighbouring river proved moderate amplitude EK signal to about 18 ms at Apex 3 (Figure 6).

6.2 Ndazawani Kraal

Two short traverses were made in this gently undulating arable area, both including sites selected by the community. The first of these (Figure 7) indicates a dramatic change in ground conditions between 0 and 25 m (the relatively large, non-EK amplitudes at 100 m being uncharacteristic, reflecting difficult local ground conditions (loose, blocky soil) and consequent electrode shake). At observation points 0 and -25 m the moderate amplitude EK signals persisting to 50 ms suggest the development of deep, saturated permeability. Similar and generally uniform conditions are indicated across Traverse 2 (Figure 8). However, the site at -25m on Traverse 1 was preferred, largely because of its proximity to the base of the inselberg.

6.3 Mapanga Kraal

Similar moderate amplitude EK signatures persisting to about 30 ms were returned at both community selected Sites 3 and 2 (Figure 9). In both cases the orthogonal measurement yielded an almost identical result, implying horizontally isotropic conditions. Site 1 was within a broad gently sloping vlei with gray silty top soil. Two electrodes became stuck here (in shallow decomposed bedrock?) and the EK signature confirms the lack of permeability.

6.4 Gore Kraal

A long (300m) traverse was made here, crossing the sand river that, by virtue of its linearity, was assumed to occupy a fault zone. Soil and outcrop observations support this conclusion, with sparse coarse pink sand overlying fine grey soils to the west and dark reddish/brown soil with occasional patches of very coarse quartz and feldspar rich sands (with highly weathered pegmatitic material between 170 m and 200m). The electrodes were expanded normal to the traverse (ie parallel to the river). The EK responses (Figure 10) indicate a marked divide at about station 110 (the west bank of the river); to the west virtually no signal was recorded while to the east moderate amplitude EK signal was observed to between 18 and 30 ms, apparently persisting progressively longer (ie deeper) towards the east. These subtle variations of EK signal with depth are highlighted by the colour-contoured image of channel 1 amplitude (Figure 11) which confirms the contrasting nature of conditions on either side of the Gore sand river.

The most promising sites on this traverse are between 210m and 250m where moderate amplitude EK signal persists to 30ms. However there was a local dispute concerning the suitability of a borehole in this area and so an alternative site was located at Gore (see Section 7.10 below).

6.5 Tanda Tadious Kraal

The EK responses at the three community selected sites (and the orthogonal measurement at each site) are shown in Figure 12. Moderate amplitude EK signal was observed at both Sites 1 and 2, with, in both cases, the very similar orthogonal responses indicating isotropic conditions. The signal at Site 2 persists to at least 38 ms.

6.6 Maniki Kraal

Measurements were made at and near the three sites chosen by the community: at Site 1 and two further locations within 80 m of this, at Site 2 and at Site 3 and 75 m distant (Figure 13). Similar moderate amplitude signals persisting to between 38 and 42 ms were observed at and near Site 1. Near zero permeability is suggested at Site 3.

6.7 Zvawanda Kraal

Figure 14 shows the EK soundings at three community selected sites and at an existing well site (see Section 7.9 below). Zero permeability is indicated at Site 1 which is characterised in the field by fine gray soil. The existing well site yielded the most persistent EK signal observed during the present study (in excess of 60 ms).

6.8 Recommended well and borehole sites

Following discussions between various community leaders, two of the present authors (RJP and BM) and the rest of the EK survey team, well or borehole sites were agreed and marked with heavy angle iron posts driven at least 1.5 m into the ground. The co-ordinates of these sites, accurate to +/- 50m, were measured using a hand-held GPS device. In most cases at least one of the sites originally selected by the community was shown by EKS to be satisfactory. Where two or more sites appear promising on the basis of EK observations, the site displaying the most persistent signal (suggesting the presence of deeper permeable horizons) has been selected. Alternative sites are given at two kraals: Gore (to avoid a possible political dispute) and Chitsanga (where an additional site was selected for use by the school).

Figure 15 compares the analogue permeability/time (depth) distribution at the chosen sites, derived as outlined in Section 5 above. These data have been used (with the assumed velocity of 1500ms^{-1}) to obtain the recommended construction depths listed in Table 1.

Table 1: Recommended borehole/well sites and depths

Kraal	Site	Co-ords (GPS)[1]	Bh/well	depth (m)
Chitsanga/Ndoro	near Site 1	E36364 S7799.79	Bh	75
Chitsanga/Ndoro	int photolineaments	E36447 S7799.12	Well	35
Ndazawani	25 m from Site 1	E37254 S7804.86	Bh	50
Mapanga	Site 3	E36264 S7798.91	Well	35
Gore	+250 m on traverse	E37027 S7805.07	Bh	60
Gore	c 80m base insel.	E36982 S7804.97	Bh	60
Tanda/Tadious	Site 2	E36348 S7797.61	Bh	50
Maniki	Site 1	E36575 S7804.75	Bh	75
Zvawanda	existing well	E36090 S7803.49	Bh	75

[1] approximate location

7. EXPERIMENTAL WORK

7.1 The effect of watering electrodes

At numerous sites the EK signal was measured both before and after watering the ground in the vicinity of the electrodes. Such watering generally results in reduced contact resistance between electrodes and the ground and, by analogy with galvanic resistivity methods, might be expected to improve both signal strength and consistency. The developers of the EK equipment, however, had originally advised against such action, fearing that percolating water in the vicinity of the electrodes would establish local "noisy" streaming potentials.

The repeated shot records displayed in Figures 16 to 19 show that in every case electrode watering has yielded a more consistent signal from shot to shot. Improved consistency between channels is also demonstrated except at Mapanga Kraal Site 3a (90 degrees) where the responses of channels one and two diverge between 6 and 10ms for the watered electrodes (Figure 19). With watered electrodes the peak to peak amplitude of the first major excursion is also generally increased marginally (say by 10%); this is best seen in Figures 16 and 17.

It should be noted that heavy rains had started locally some two weeks before the present field study and the ground was everywhere fairly damp even before additional watering; thus the signal improvement to be expected by watering electrodes during the dry season would be far more dramatic than described above. On occasion during the present work there was little change in the contact resistance following watering (while on two occasions this resistance actually increased marginally). In such cases signal improvement appears to result from the more "elastic" or mobile electrical connection between the electrodes and ground provided by the wetting, especially in loose, coarse-grained sandy soils.

7.2 Repeated sounding following several hours of heavy rainfall

An example of an EK sounding repeated at exactly the same site after a period of about 19 hours (which included several hours of heavy rainfall) is shown in Figure 20. The gross features of both soundings are the same but the signal measured after rainfall suffers a loss of definition of the inflection between 10 and 16ms. The data acquired on day 2 is also less consistent, apparently at variance with the observations concerning electrode watering made in Section 7.1 above. This may, however, partly reflect the fact that the same (enlarged) electrode holes were used for the repeat measurement. Amplitudes are little changed in the two data sets.

7.3 Comparison of stainless steel and porous pot electrodes

We made a comparison of signals obtained with both the conventional stainless steel stakes and porous pot electrodes at two sites at Chitsanga (Figures 21 and 22) and two sites at Maniki (Figures 23 and 24). The porous pot comprises a copper rod immersed in a saturated solution of copper sulphate contained in a ceramic pot with an unglazed base to allow electrlolytic contact with the ground. It is the favoured voltage-measuring electrode in the induced polarisation exploration technique (since it is non-polarising) and also in hard rock areas (where stakes cannot be implanted easily).

The general form of the measured signals is the same with both electrode types at the first site at Chitsanga (Figure 21) but the amplitude of both channels is significantly increased with the porous pot measurement; there is also a loss of consistency at early times in channel one with the porous pot. At the second Chitsanga site (Figure 22) both amplitude and form are the same but the steel stake observations suffer reduced coherency in both channels at early times.

The relative lack of consistency between repeated observations made with steel stake electrodes is further demonstrated in both channels at both sites at Maniki (Figures 23 and 24). Here again there are significant amplitude variations, with the porous pot measurements displaying relatively enhanced- and reduced excursions at Sites 1A and 2 respectively.

The variability described above probably reflect local soil conditions. At Maniki it was possible to push the steel electrodes their full length into the soft, friable (previously ploughed?) sandy soil, resulting in some degree of electrode shake and loss of consistency. At Chitsanga Site 1 the hard clay surface gripped the steel stakes but probably induced some degree of bounce in the porous pots. The observed signal amplitude variations are less readily explained at this stage.

7.4 90^0 rotation of the electrode array

EK theory dictates that identical signals will be observed above a horizontal water table in an homogenous, isotropic medium, irrespective of the orientation of the measuring array. Hence a comparison of signals obtained with the electrode array rotated through 90^0 provides a simple test of ground conditions and gives added assurance of data quality. Examples of repeated orthogonal measurements (stacked data) at numerous sites are shown in Figures 25 to 28. In almost every case the coincidence of both form and amplitude between the two data sets is good. This has generally not been the case in our earlier experiments in Zimbabwe and elsewhere.

7.5 Dipole and geophone moveout tests

Moveout tests were made in the Gore sand river, at Zvawanda well site and (to a very limited extent) near the Tanda Tadious photolineament. The dipole length was reduced to 1m and EK observations were made at 0.5m interval (Gore) and 1m interval (Zvawanda and Tanda Tadious) from near the central source to about 10m distant. We also measured the seismic velocity moveout at Gore and Zvawanda using a single geophone on each side of the central source, placed consecutively at every electrode position occupied in the dipole experiments. The geophone was coupled to the standard two conductor EK antenna.

The seismic velocity moveouts at Gore are shown in Figure 29. Standard seismic refraction analysis of the first arrivals indicates a three layer arrangement with velocities increasing in the sequence 180/380/1000ms^{-1}, with the thickness of the surface and intermediate layer respectively 0.6m and 1.3m. The apparently unrealistic first velocity (less than the speed of sound in air) reflects the non-elastic ground conditions in the immediate vicinity of the shot point (Jackson, pers comm); velocity measurements are not usually observed at such a fine scale in the field. The second layer is poorly matched by a straight segment; the time/distance graph forms a curve here, indicating uniform velocity increase with depth (reflecting increased water content?). The events following the first break on each geophone trace will indicate both reflected arrivals and direct arrivals of lower frequency seismic waves emanating from the central shot point.

The "EK" moveouts at Gore mimic the seismic events to a large extent (see Figure 30). The apparent velocity of the first three (sloping) coherent disturbances (ie those that extend across the spread) is about 325ms^{-1} while their measured period of about 11.25ms yields a frequency of 89Hz (which is very close to the anticipated dominant frequency of a sledge hammer source). The latest coherent event visible in Figure 30 has an apparent velocity of 180ms^{-1} and may therefore be generated by a Rayleigh wave disturbance. We would expect true EK signal to be observed simultaneously by surface dipoles placed anywhere within the range of detectability. Such an event is seen at about 3ms in Figure 30, this is highlighted by expanding the time scale in Figure 31. Converting the onset time of this signal (say 2.2ms) to depth, assuming an upper layer velocity of 180ms^{-1} , yields approximately 0.4m which is in close agreement with the observed water level in pits dug in the river bed.

The colour-contoured normalised amplitude EK voltages, extended to 100ms, presented in Figure 32 highlight both the coherent- and non-coherent events and reveal subtle assymetry between channel 1 and 2 which presumably reflect very local variations in ground conditions.

The relationship between seismic arrival times and EK signal generation is explored in Figures 33 and 34 where the geophone response at both the outer and inner electrode positions is plotted with the EK signal observed across this dipole. At locations close to the seismic source (Figure 33) the start of the first EK signal occurs at the same time that the seismic arrival is detected at the innermost electrode. At locations more distant from the source (Figure 34) the first seismic arrivals are not associated with an EK response; these first arrivals (in this case) are refractions from the layer of velocity 1000ms^{-1}. The first EK response is now associated with the slow seismic event (330ms^{-1}) and it correlates more closely with the seismic arrival at the outermost electrode location.

The geophone responses at Zvawanda show velocities of 219- and 785ms^{-1} and thickness of the upper layer of 1.24m (Figure 35). Again, several of the seismic events are mimiced by the dipole responses (Figure 36). The first two coherent events indicate a velocity of about 460ms^{-1}. The rest water level at this site (as observed in the well) is 11.5m; thus we might expect to observe a simultaneous arrival (true EK signal) in the time range 14ms to 56ms (calculated assuming velocity extremes of 800ms^{-1} and 200ms^{-1}), however there is no evidence of such an event.

7.6 Triggering delay caused by loose inertia switch

At one stage during the present study the inertia switch attached to the shaft of the sledge hammer worked loose; Figure 37 shows how such a fault can introduce triggering delays into the system (in this case a delay of about 6ms) and highlights the importance of checking the integrity of the equipment at each site.

7.7 The relationship between EK amplitude, electrode contact resistance and spontaneous potential

At numerous sites we have investigated the relationship between EK signal amplitude and electrode contact resistance (CR) and the spontaneous potential (SP) existing across the pair of measuring electrodes for each channel, as measured with a multimeter. CR observations are available for 31 sites while combined CR/SP measurements were made at 19 sites. The polarity of the spontaneous potential observations has been disregarded since we did not follow a sign convention during measurement. The results are tabulated in Appendix 1 while the correlation coefficients derived for the various data sets are listed below:

Table 2: Correlation coefficients derived from 19 sites

	SP1 (mv)	*SP2 (mv)*	*CR1 (ohms)*	*CR2 (ohms)*	*EK (mv)*
SP1 (mv)	*1*				
SP2 (mv)	***0.09***	*1*			
CR1 (ohms)	***0.71***	***-0.16***	*1*		
CR2 (ohms)	***-0.03***	***0.68***	***-0.06***	*1*	
EK (mv)	***-0.17***	***-0.46***	***0.47***	***-0.19***	*1*

Table 3: Correlation coefficients derived from 31 sites

	CR1 (ohms)	*CR2 (ohms)*	*EK (mv)*
CR1 (ohms)	*1*		
CR2 (ohms)	*0.06*	*1*	
EK (mv)	*0.50*	*-0.14*	*1*

There is significant positive correlation between EK signal amplitude and CR1 and negative correlation between EK signal amplitude and SP2. Significant positive correlation is also displayed between both SP1/CR1 and SP2/CR2. The apparent lack of correlation between both SP1/SP2 (implying that the measured SP has a very local origin) and CR1/CR2 (suggesting rapid local variations in soil conditions) is unexpected. Ideally this experiment should have been restricted to porous pot (non-polarising) electrodes, a sign sonvention should have been employed and the steel source plate should have been isolated from the ground.

7.8 The effect of lightning

Local thunderstorm activity occasionally hampered our field work, particularly in the late afternoon. Figure 38 shows, at left, the stacked traces at Site 1, Mapanga and at right, a single record (shot number 12) at the same site (excluded from the stack) that is dominated by lightning responses. Lightning strikes are manifested as relatively large amplitude spikes of very short duration. These appear out of phase since one channel is reversed in the display, but in reality are in-phase since the source is remote from the antennae set-up. The signal cross-over following the initial large excursion and the subsequent slow decay to zero volts is noteworthy.

7.9 EKS at existing well sites

EKS were made at five existing well sites displaying a wide range of rest water levels (from between 1.8m and 11.5m), yield and yield reliability; the results are displayed in Figure 39. Fresh granite was proved at about 3m depth at Chitsanga (Mrs Makumbe's well) while massive outcrop occured some 40m distant. This site did yield low amplitude EK signal (c 0.3mV peak to peak), but similar low amplitudes were also recorded at Gore (Mrs Tumbe's well) and Tanda Tadious where much thicker regolith occurs. There appears to be no correlation between water level and onset (in terms of time) of EK signal.

7.10 EKS near the base of inselbergs

During an extensive programme of geo-electrical surveying in southern Zimbabwe, Barker *et al* (1992) commonly observed a zone extending to between 100 and 200m from the base of inselbergs where, it was postulated, concentrated run-off had resulted in the development of relatively thick regolith. The porosity/permeability of this fringing zone is likely to be further enhanced due to the accumulation here of scree deposits resulting from exfoliation. In the present work we occasionally made EK observations at regular intervals approaching inselbergs in the attempt to confirm the existence of such fringes.

There is some indication of increasing regolith thickness between about 175m and 225m from the inselberg base on the first traverse at Ndazawani Kraal (Figure 7). At Gore three EK measurements indicate the greatest depth to unweathered basement at about 80m from the base (Figure 40) while regular increasing thickness of regolith from near the base of inselberg to about 150m away is suggested by the four EKS at Tanda Tadious (Figure 41).

7.11 EKS at divined sites

Mr Dube of Bikita, a recognised diviner employed occasionally by the Lutheran church, accompanied us in the field on one occasion; in addition, one of the present authors (BM) had also demonstrated some divining ability. Both men used freshly cut forked sticks. Figures 42 to 45 compare EKS at divined sites with EKS at adjacent, random sites some 10 m to 100 m distant, at Gore, Chitsanga and Zvawanda respectively.

The four divined sites on the Gore traverse (Figure 42) are characterised by out of phase behaviour following an initial very shallow EK signature. The first divined site in the garden at Gore does suggest some late EK signal but of very low amplitude (Figure 43). At Chitsanga the divined site (only 1 m distant form the community selected site) returned one of the most promising EK signals observed during the present study (Figure 44), with moderate amplitudes to times in excess of 40ms. This site was chosen for a borehole. Again, at Zvawanda, the divined sites show largely anti-phase character with no significant permeability at depth (Figure 45).

7.12 EKS at well sites selected following earlier geophysical surveys

During the present study the local communities at three locations showed us sites that had been pegged following geophysical surveys (presumably resistivity sounding), but that had never been tested. We made EK measurements at these sites (Mapanga, Gore and Zvawanda) but very low amplitudes were returned and no site appeared suitable in terms of EKS (see Figure 46).

7.13 EKS in the vicinity of photolineaments (possibly indicating faulting)

Photolinears commonly indicate faulting and traditionally such features, and in particular the zone around the intersection of photolineaments, are promising borehole and well sites in shallow basement terranes. Three EK measurements near such an intersection at Chitsanga yielded the returns seen in Figure 6 (Apex 1 to Apex 3), the two accompanying soundings being from locations about 100m distant. The EKS at Apex 3 indicates permeability extending to 48 ms (75m) and a well was sited here, on a grassy knoll some 3m above the adjacent river. A further photolineament was investigated near Tanda Tadious. The EK signal measured here (the leftmost in Figure 41) shows low amplitude signal, not persisting below about 13ms.

8. CONCLUSIONS AND RECOMMENDATIONS

Routine siting:

Nine boreholes or wells have been sited at seven Kraals (as detailed in Table 1); in most cases at least one of the three sites chosen initially by the community has been shown by EKS to be suitable for further testing by conventional geophysical techniques and borehole- or well construction. Where none of the chosen sites appeared suitable, recourse has been made to an examination of air photographs to locate lineaments (possibly representing faulting) that were subsequently tested in the field.

The selected sites are to be tested with other more conventional hydrogeophysical techniques prior to drilling. It is important that all data subsequently obtained (including ground truth) at the sites investigated with EKS be made available to allow further calibration and evaluation of the technique.

The four counterpart staff involved with the present study agreed that the EKS technique is rapid and straighforward in operation; any initial problems experienced with operating the computer and subsequent data processing are soon overcome with practice.

Experimental observations:

Electrode watering results in the collection of more consistent data, both from shot to shot and between channels; there is also some indication of increased signal amplitude following watering. Such watering during the dry season can be expected to yield even more dramatic improvements in data quality. The much improved consistency between orthogonal data sets observed during the present study probably results largely from electrode watering.

The use of porous pot electrodes generally resulted in more consistent (and occasionally larger amplitude) recordings. It appears that porous pots are more suitable than steel stake electrodes in loose, sandy conditions and where large, shallow cobbles etc hinder stake placement. On hard pan surfaces the pots are liable to bounce and in this case the stake electrodes are to be preferred.

Weak relationships between EK signal amplitude, electrode contact resistance and the earth's natural potential are suggested. These could be investigated further using improved experimental techniques.

EKS were made at five existing well sites that display strongly contrasting yields, yield reliability and rest water levels. These soundings show no consistent correlation with any of the observed variables.

EKS have yielded limited evidence of increasing regolith thickness near the base of inselbergs. Similarly, measurements in the vicinity of intersecting photolineaments suggest the presence of deeper weathering.

EKS generally failed to confirm the suitability of groundwater sites located by divining. Similarly three sites chosen using alternative geophysical techniques (which have not been tested) yielded no significant EK response.

Seismic and electric dipole moveout experiments show a disturbing relationship between the lateral passage of seismic energy and the generation of "EK" signal, extending to at least 100ms in one example. It appears that refracted arrivals (unlike direct arrivals or body waves) may not generate "EK" signal, possibly because of their steep return path to surface. In only one case of dipole measurements have we seen an instantaneous arrival that may be true "EK" response.

The concept introduced by the suppliers of the equipment is that the voltage returns observed on the two shot-symmetric dipoles can be interpreted *entirely* by Fresnel zone coupling directly beneath the shot point. This is well explained in the user manual that accompanies the equipment. The modus operandi is one of equating time to depth and thus obtaining a vertical sounding of voltage characteristics.

The examples of non-simultaneous moveout effects shown in the previous Section provide unequivocal evidence that the 'simple' concept stated in the user manual is flawed. The moveout experiments conducted during this survey were preceded and postdated by other experiments conducted in the UK. These experiments confirm the pervasiveness of additional horizontal and sub-horizontal modes of acoustic wave propagation, and resulting voltage coupling, that are recorded near the shot point. In our opinion the routine use of only two channels does not provide sufficient objective discrimination. Again, in our opinion, the routine use of the equipment and the modus operandi established in the manual is likely to:

- provide insufficient information into the nature of EK coupling at the site
- provide a false interpretation under the assumptions stated in the manual

9. ACKNOWLEDGEMENTS

We thank Mr Robin Cadwallader (ODA, Harare) for his initiation and continued support of the present field work. We also gratefully acknowledge the invaluable assistance and local insights provided throughout the fieldwork period by our counterpart staff (Messrs James Mukarudzi (BIRWSSP), Eliah Mafunga (Department of Water Affairs), Omaly Magura (District Development Fund) and Handy Mlambo (Agritex)). We also thank Mr Peter Greenwood of the BGS for his preparation of the figures accompanying this report.

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10. REFERENCES

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Peart, R J, Beamish, D and Davies, J. 1996b. Electrokinetic soundings to locate zones of enhanced porosity/permeability in man-made sediment traps at the former Empress Nickel Mine, Zimbabwe. British Geological Survey Technical Report **WC/96/18C.** A report prepared for RTZ.

APPENDIX 1

Spontaneous potential, contact resistance and EK amplitudes observed at various sites

DATE	RECORD	SP1 (mv)	SP2 (mv)	CR1(ohm)	CR2(ohm)	EK (mv)		
28/11	s3a_3.stk	4	30	10500	5700	2.33		
28/11	s3a_4.stk	23	12	10500	6200	1.67		
28/11	s2a_1.stk	22	33	7500	2500	2.17		
28/11	s2a_2.stk	16	112	6600	18200	2.17		
28/11	s2a_3.stk	69	13.6	12500	5600	2.33		
28/11	s2a_4.stk	0	8.2	5800	5700	1.93		
28/11	s1a.stk	33.9	40.7	2400	4600	0.33		
29/11	s132.stk	230	70.2	17000	6700	0.36		
29/11	s1140.stk	120	74.8	11800	7800	0.26		
29/11	s1144.stk	41	132	2600	9300	0.27		
29/11	s1160.stk	18.2	3.7	2300	1890	2.33		
30/11	s1240.stk	22	1.3	3460	2330	1.33		
2/	makww.stk	53.5	10.2	7650	3500	1.1		
3/	nw.stk	31.3	2.5	1980	9900	0.5		
3/	90w.stk	26.5	16	2320	3490	2		
4/	zva1.stk	54	43	2300	5620	0.27		
5/	ch2.stk	118	5.6	20000	3800	4		
6/	bk.stk	5	117	870	12600	0.53		
28/11	s1u.stk	7	61.8	500	2600	0.5		
26/11	1.stk			1000	1000	0.53		
27/11	0m.stk			11000	4500	3.13		
27/11	75m.stk			700	6000	0.13		
27/11	nw.stk			4600	4500	1.73		
27/11	w.stk			1200	2500	2.33		
28/11	s3a_1.stk			11600	5000	3.6		
28/11	s3a_2.stk			4230	7670	2		
29/11	s100.stk			7600	2500	2.67		
4/	man3a			1190	1290	0.33		
5/	zva3c			7970	10140	0.33		
5/	zvaws2			8700	7800	3.33		
6/	gto.stk			7580	2500	1.53		

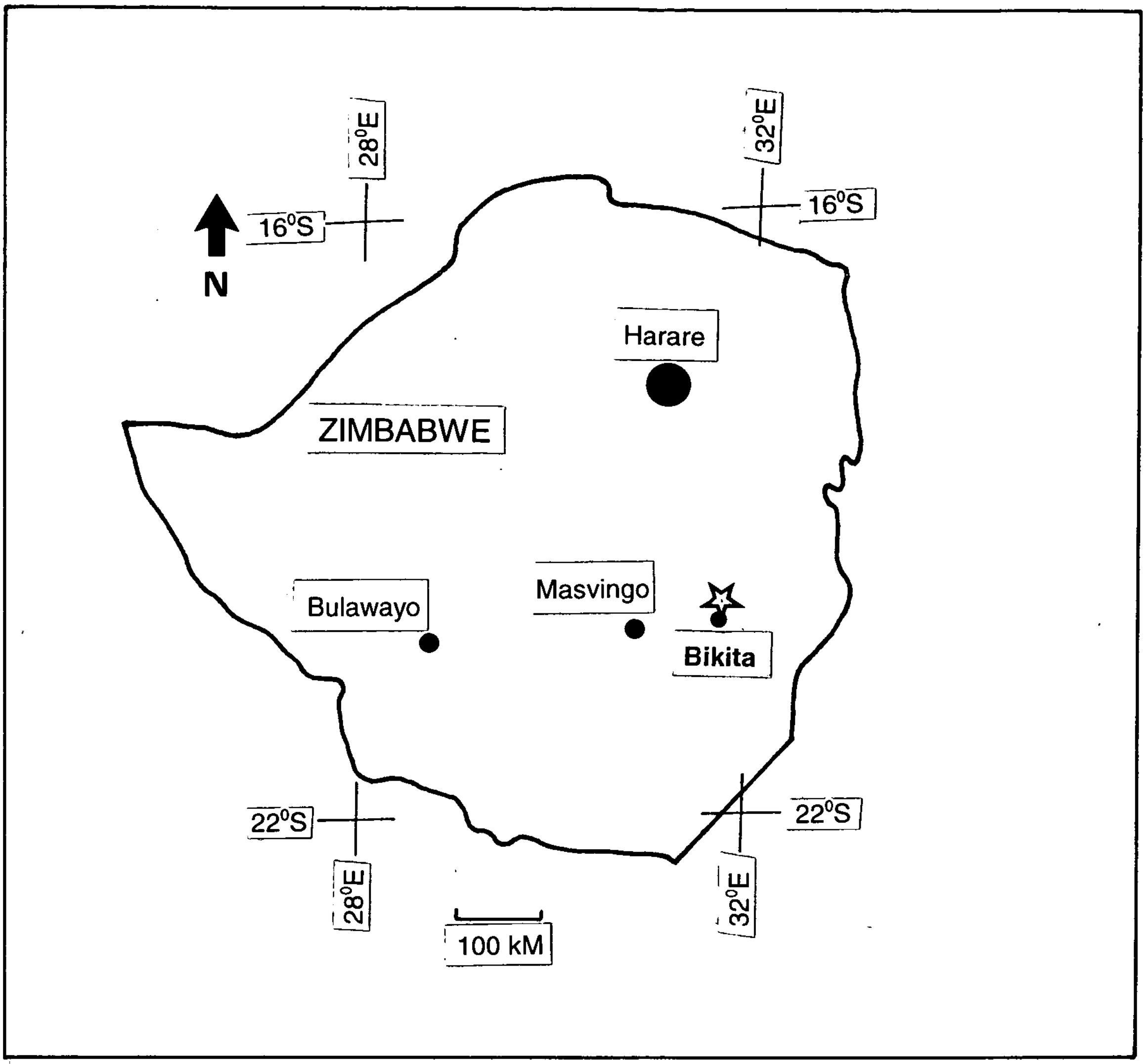
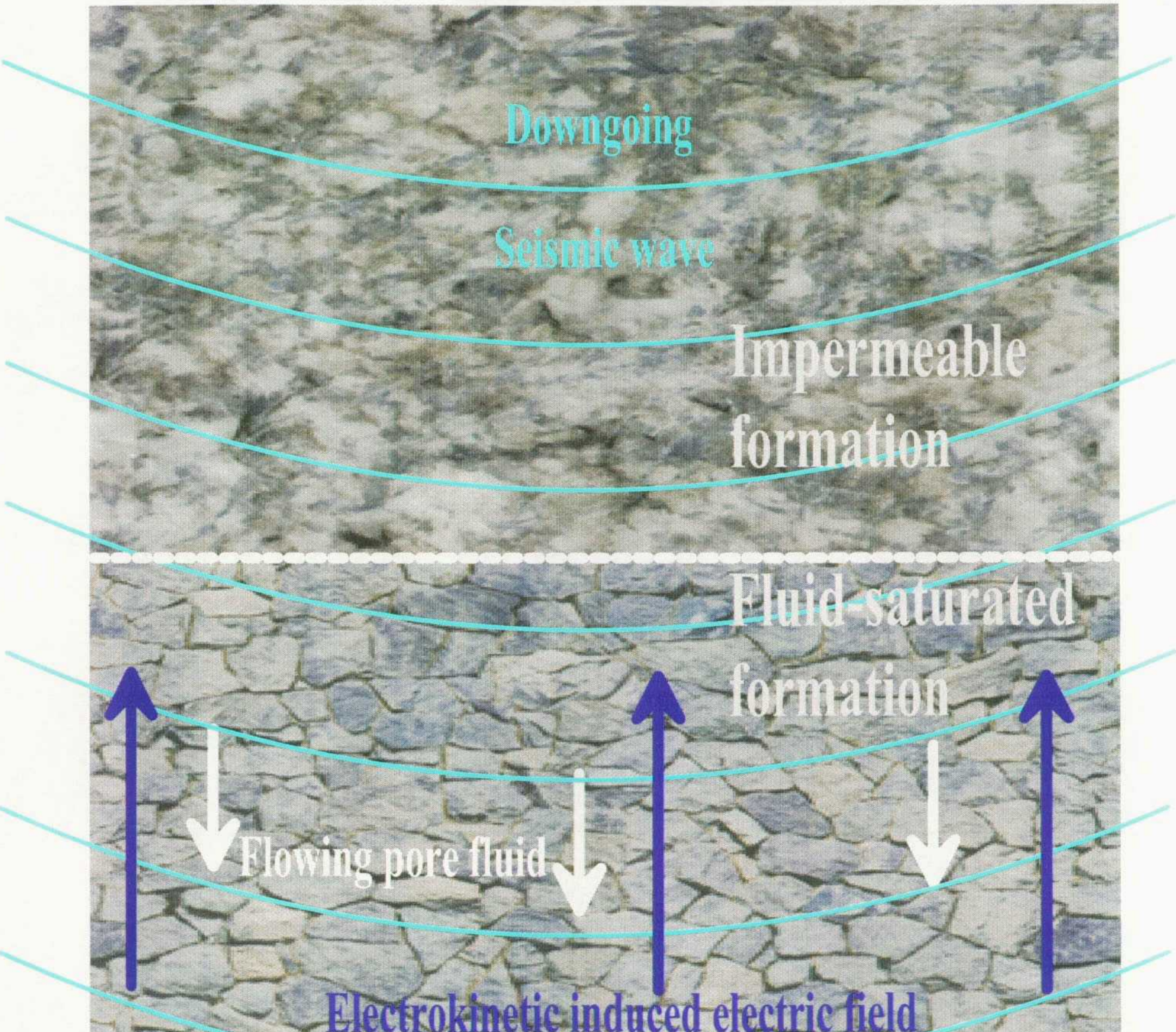


Figure 1 Location diagram

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

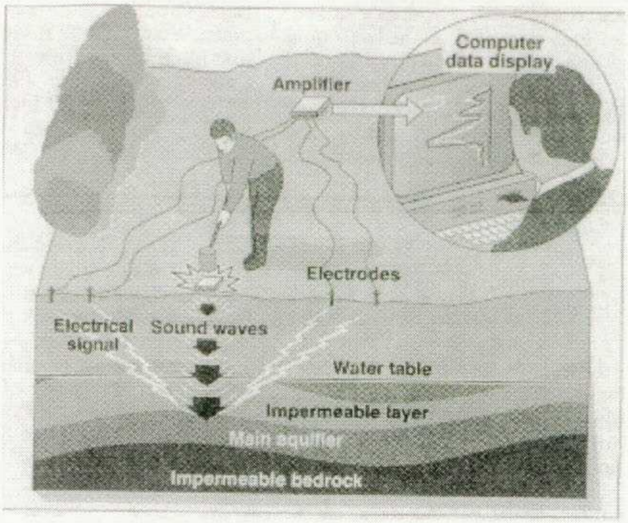


Lower : fluid saturated formation. Seismic pulse generates relative pore fluid movement. Double layer displacement generates an instantaneous electric field which is observed at surface.

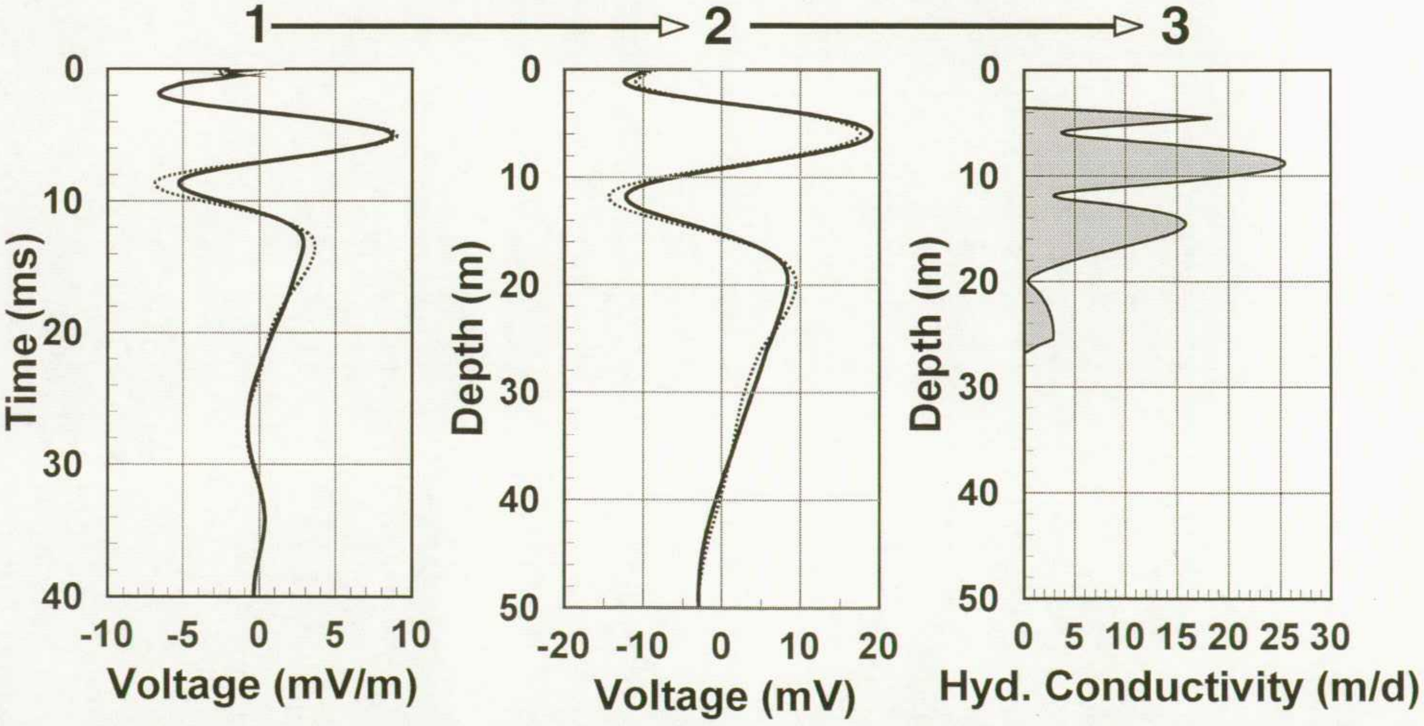
Figure 2. The principle of EK sounding

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.

Chitsanga/Ndoro Kraals

Community site (L); near river crossing (R);

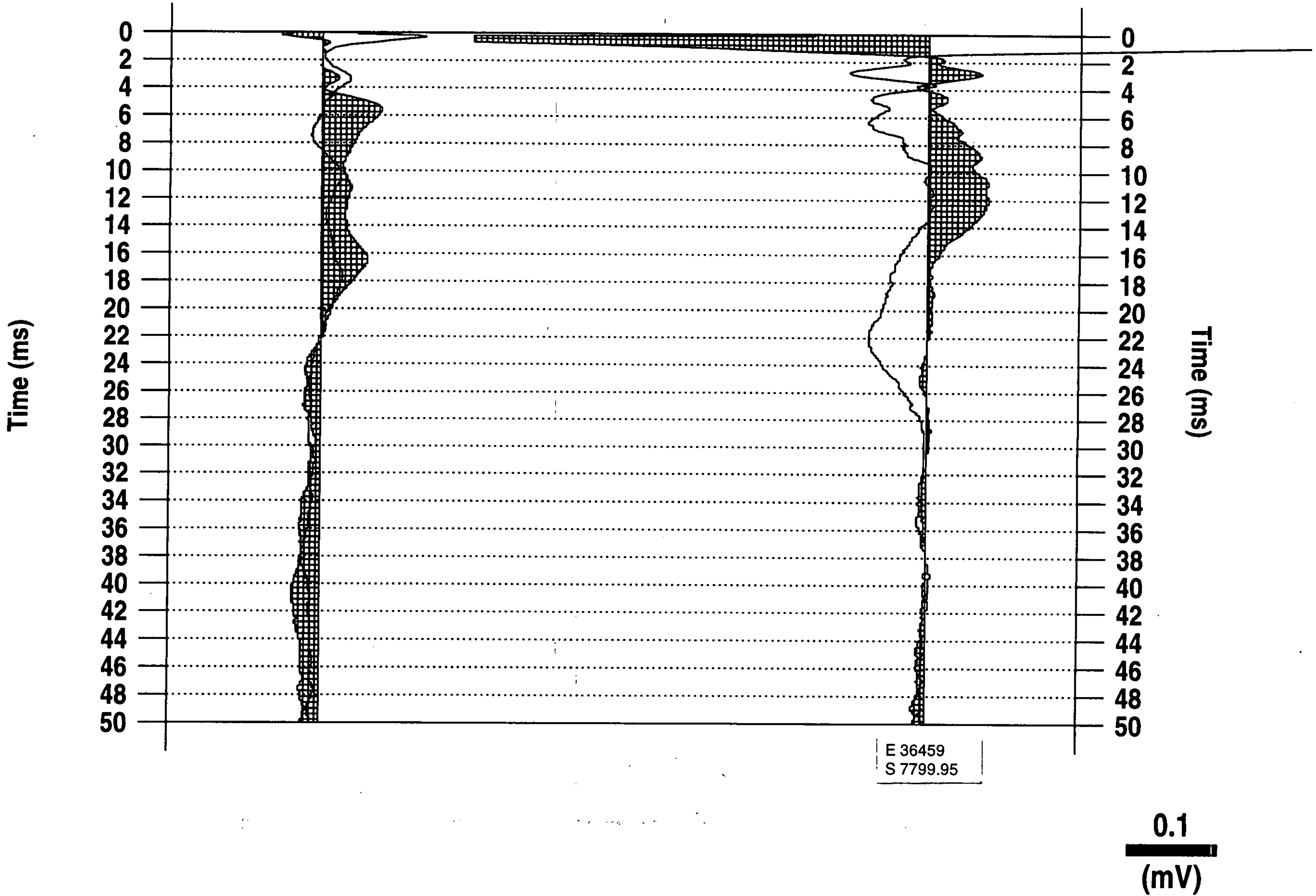


Figure 4 EKS plots from Chitsanga/Ndoro kraals

Chitsanga

EKS at and near site 1

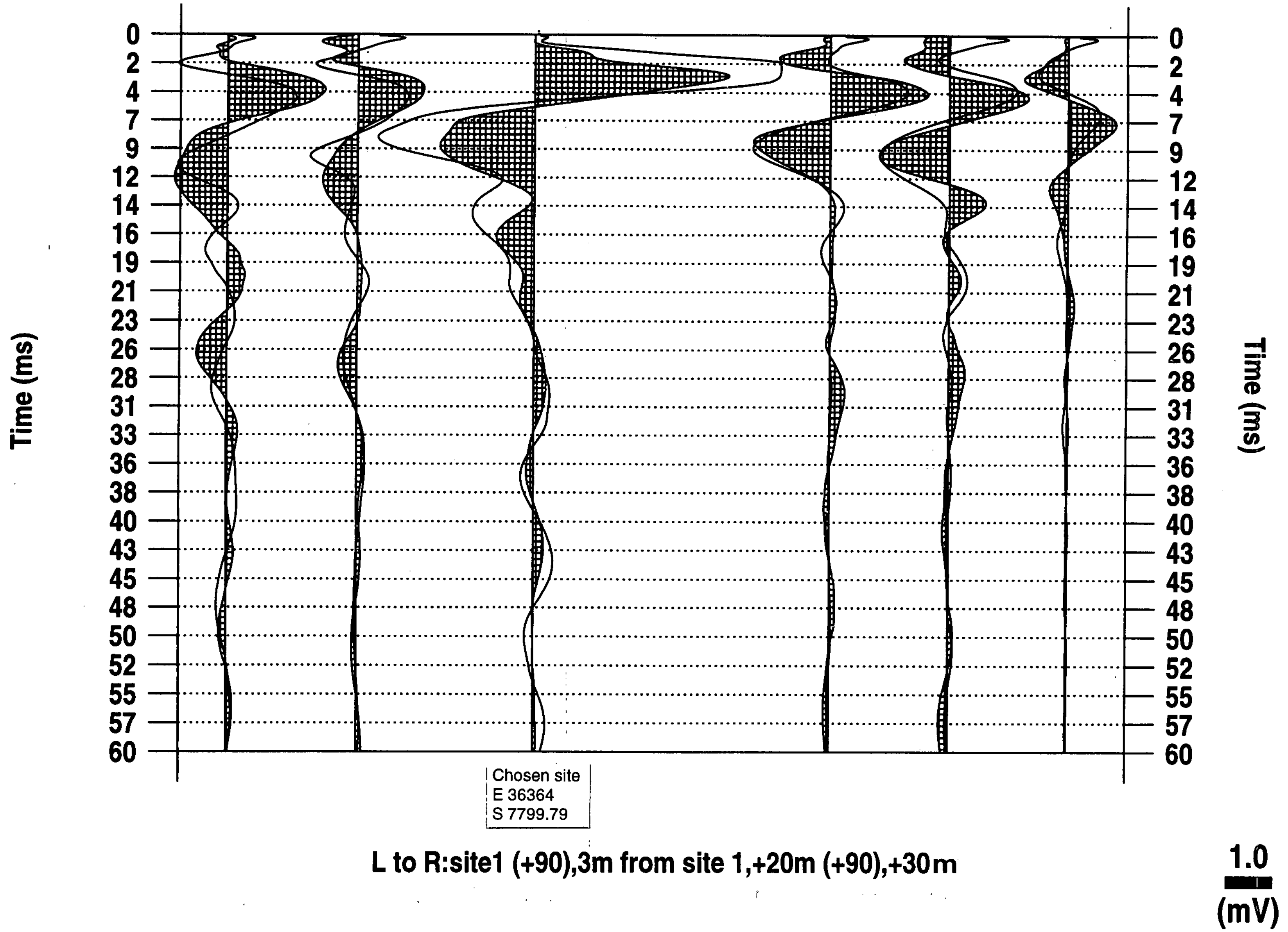


Figure 5 EKS plots from Chitsanga Site 1

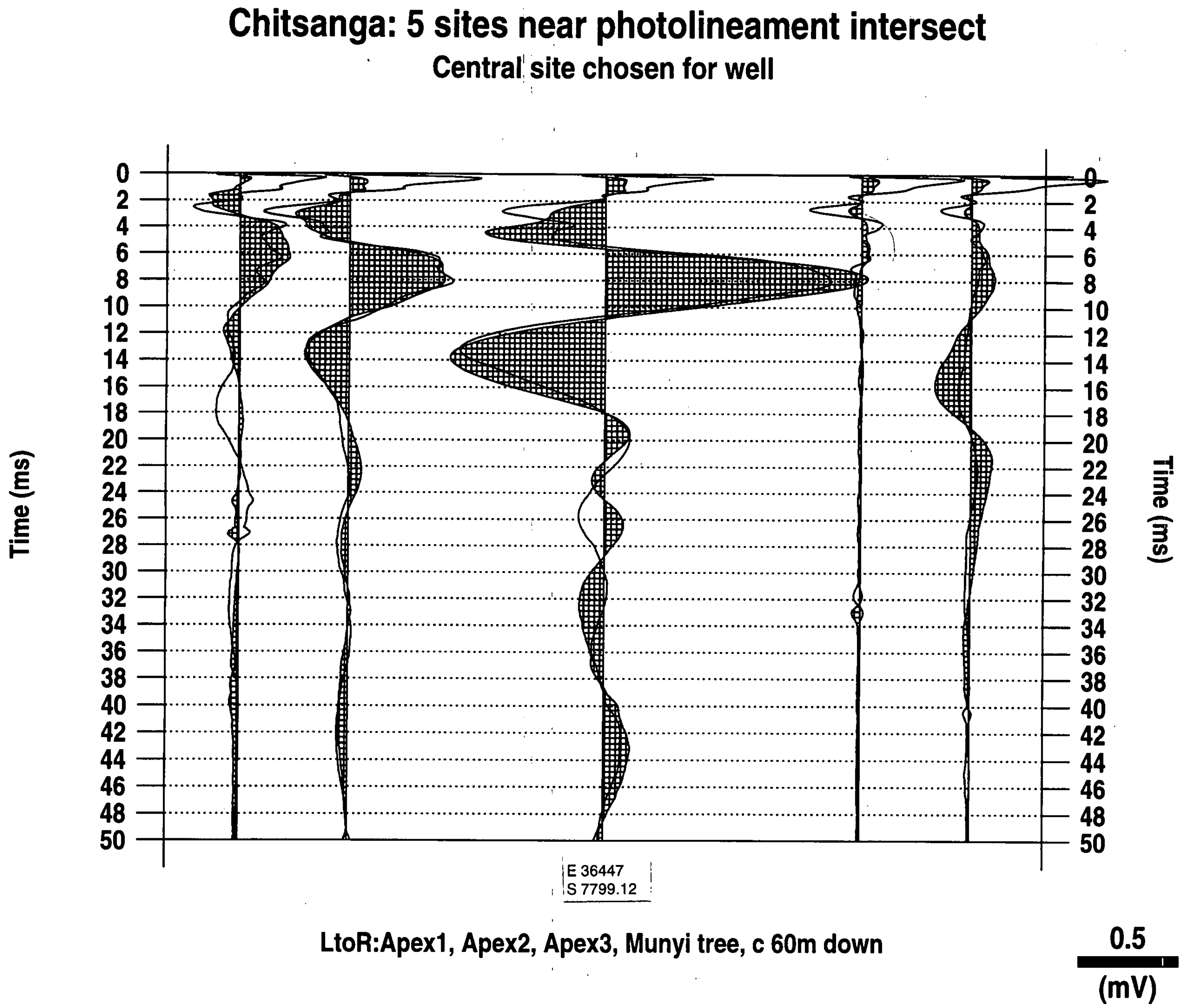
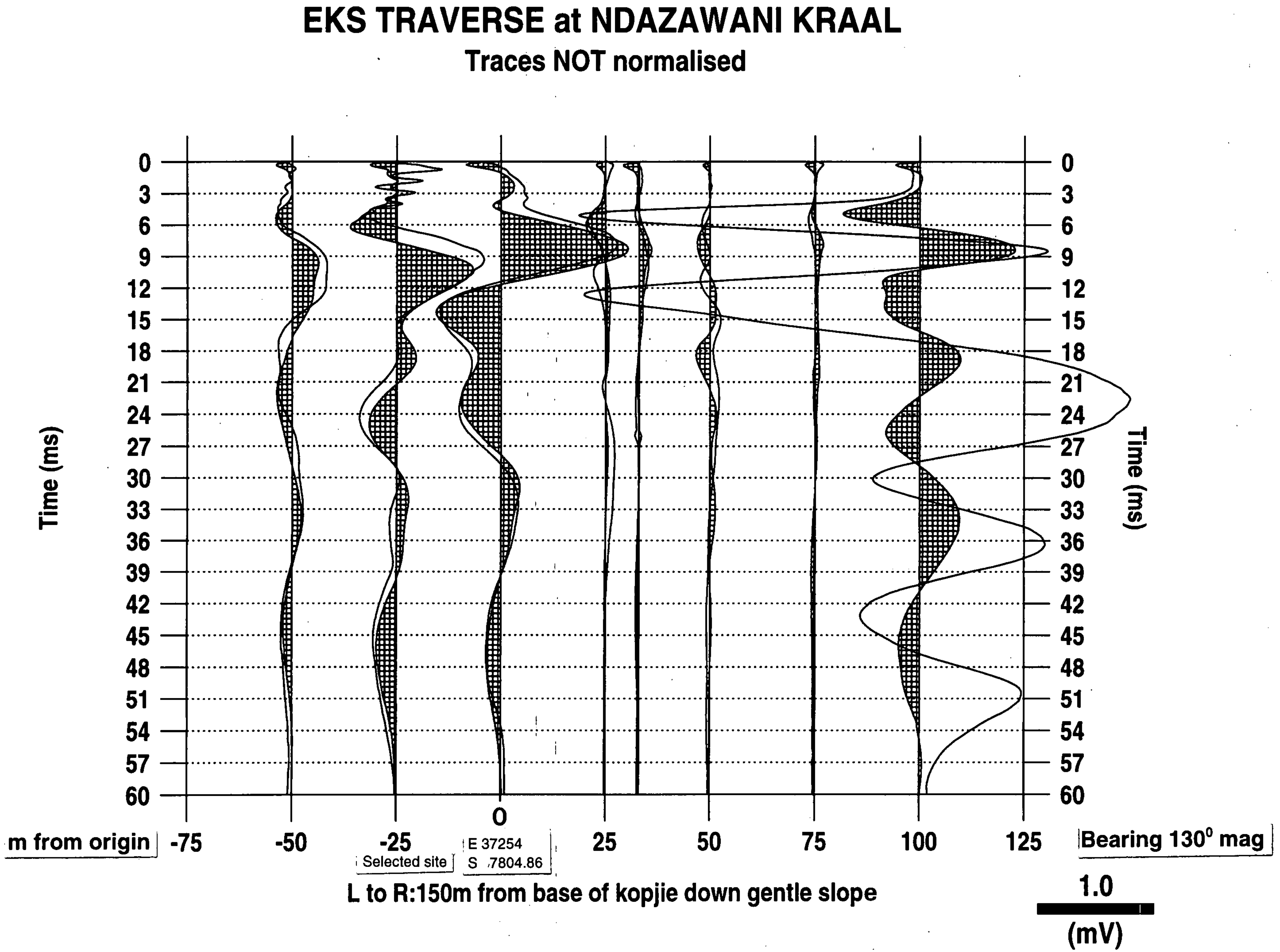


Figure 6 EKS plots from Chitsanga photolineament intersection



EKS TRAVERSE at NDAZAWANI KRAAL

Traces NOT normalised

Figure 7 EKS traverse one at Ndazawani Kraal

EKS TRAVERSE (2) at NDAZAWANI KRAAL

Traces NOT normalised

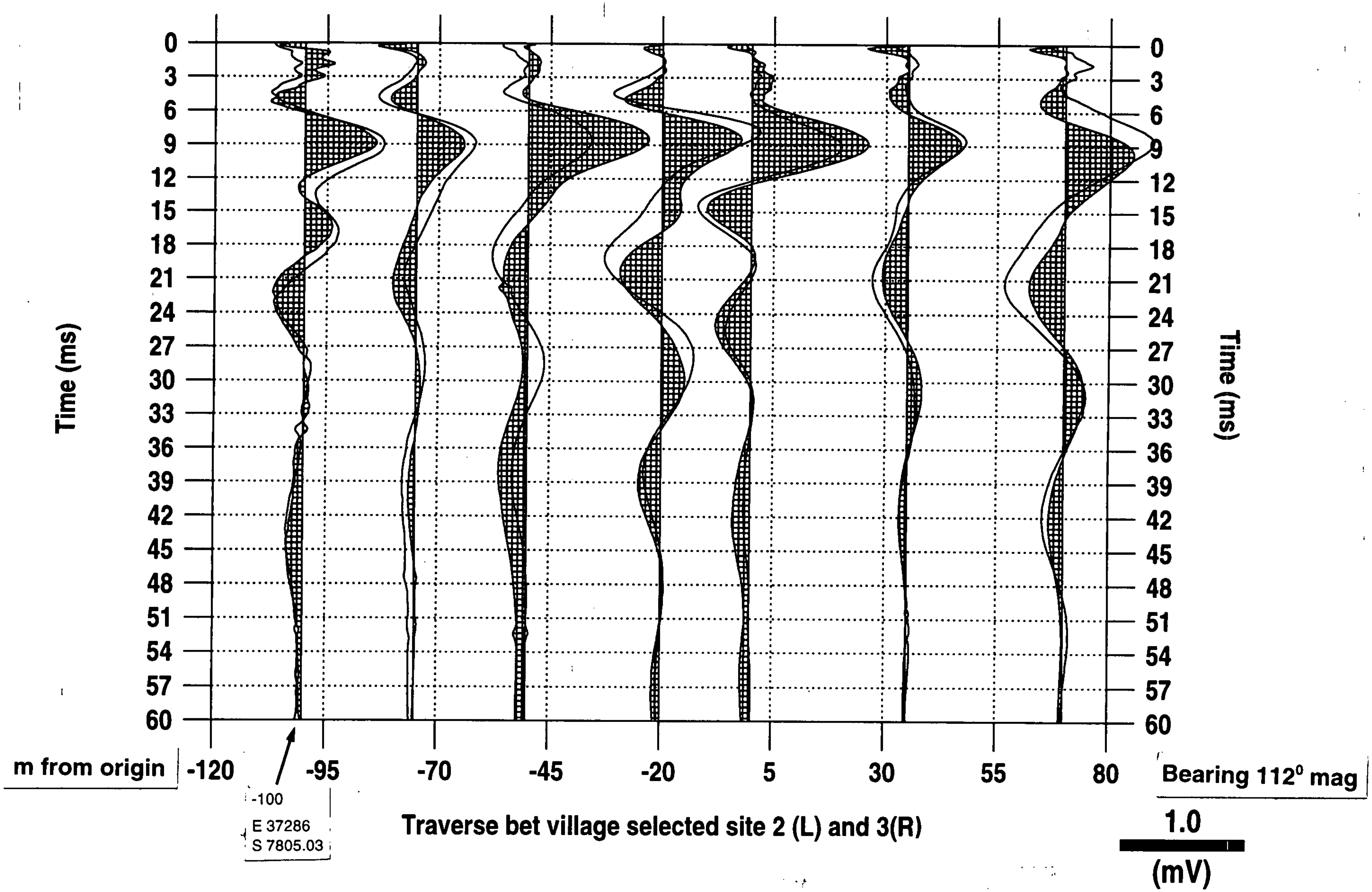


Figure 8 EKS traverse two at Ndazawani Kraal

Mapanga Kraal - sites chosen by the c ommunity
L to R:Site 3 (+90),Site 2 (+90), Site 1

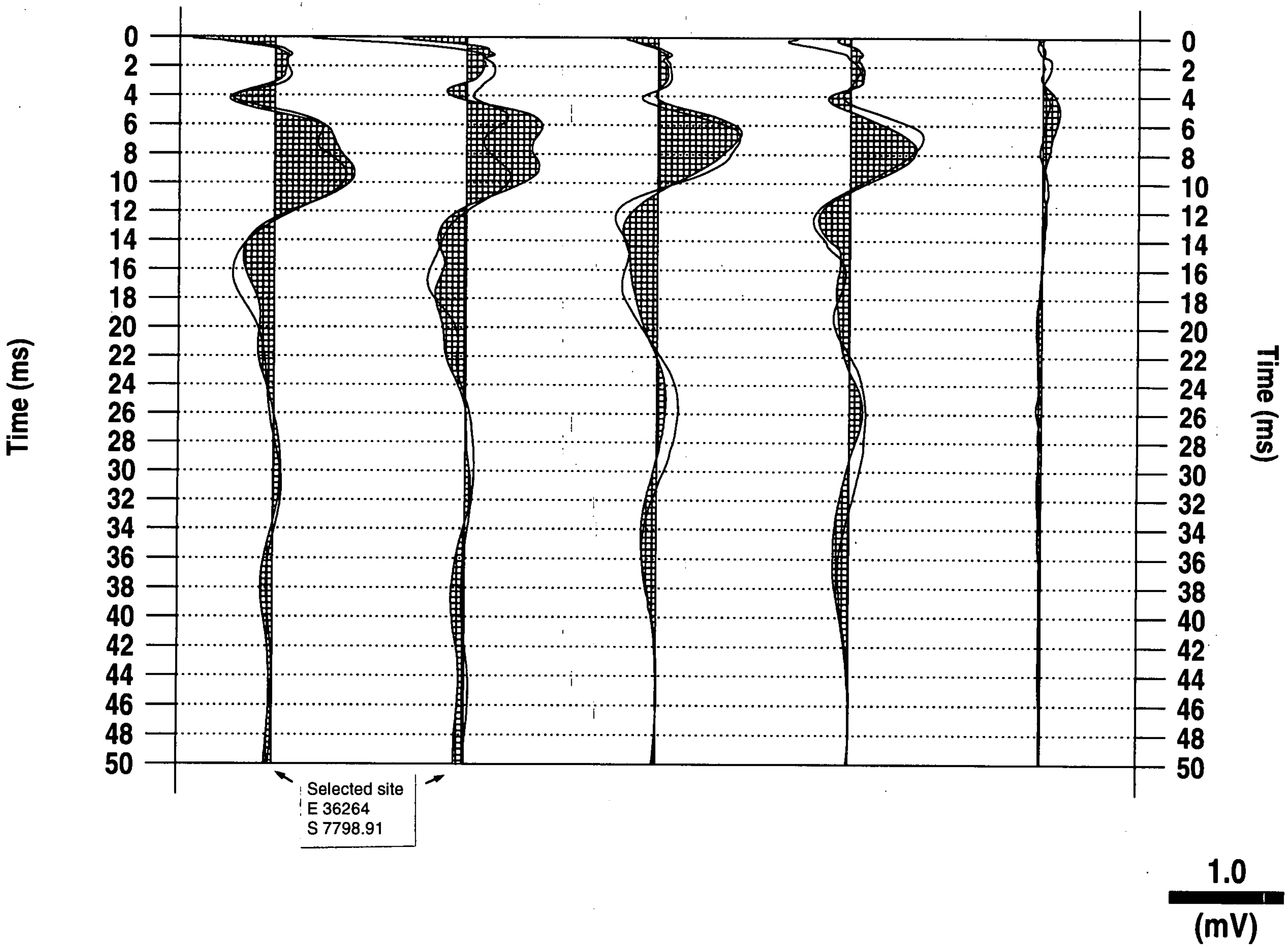


Figure 9 EKS plots from Mapanga Kraal (Sites 1, 2 and 3)

GORE SAND RIVER TRAVERSE

the river occupies possible fault zone

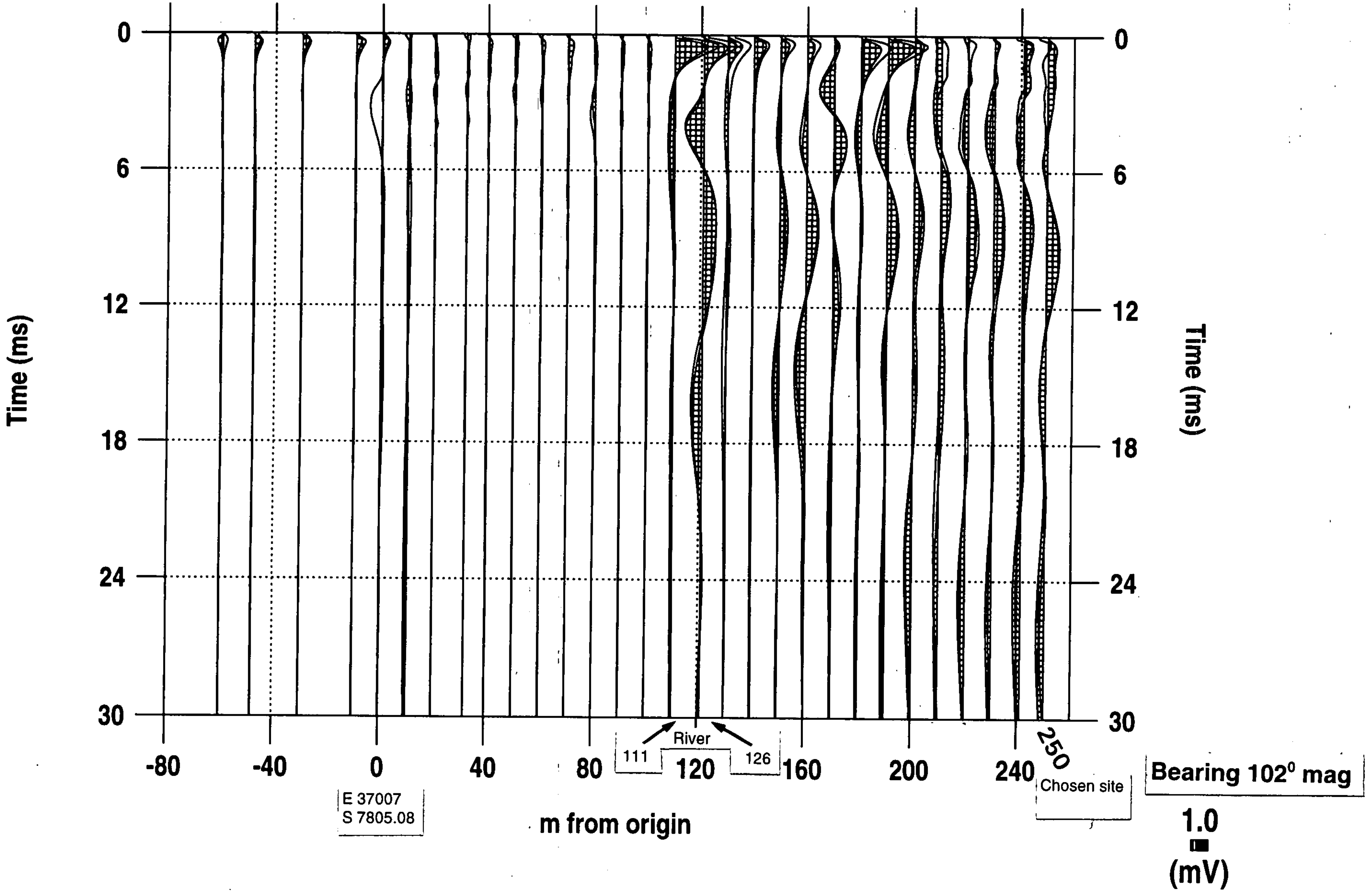


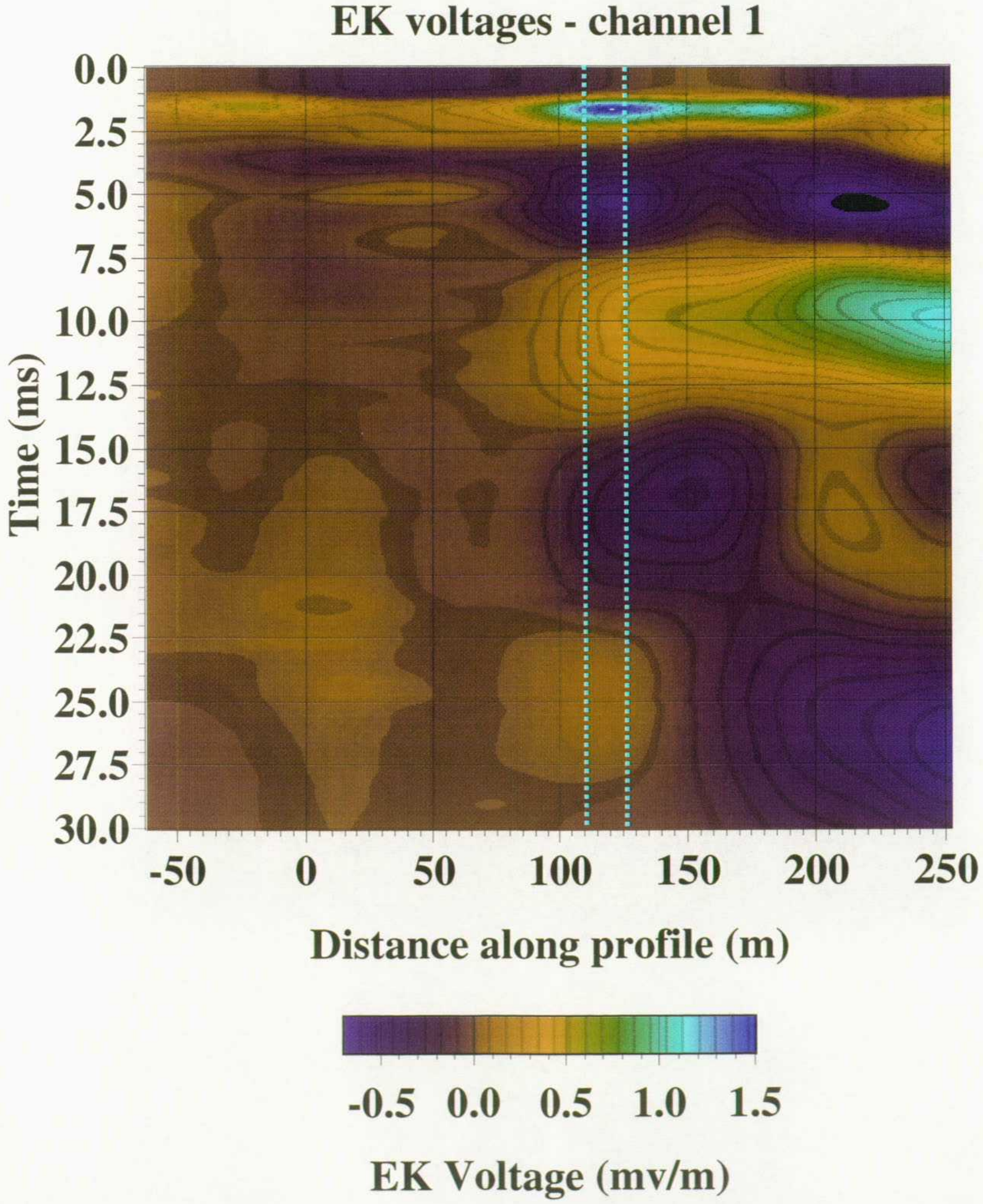
Figure 10 EKS traverse across Gore sand river

Figure 11. Gore sand river EKS traverse: channel 1 voltages colour contoured

Gore Sand River, Bikita, Zimbabwe

EK traverse at 10 m intervals. No normalisation.

River (111 to 126 m) occupies a possible fault zone



Tanda/Tadious

3 sites chosen by the community

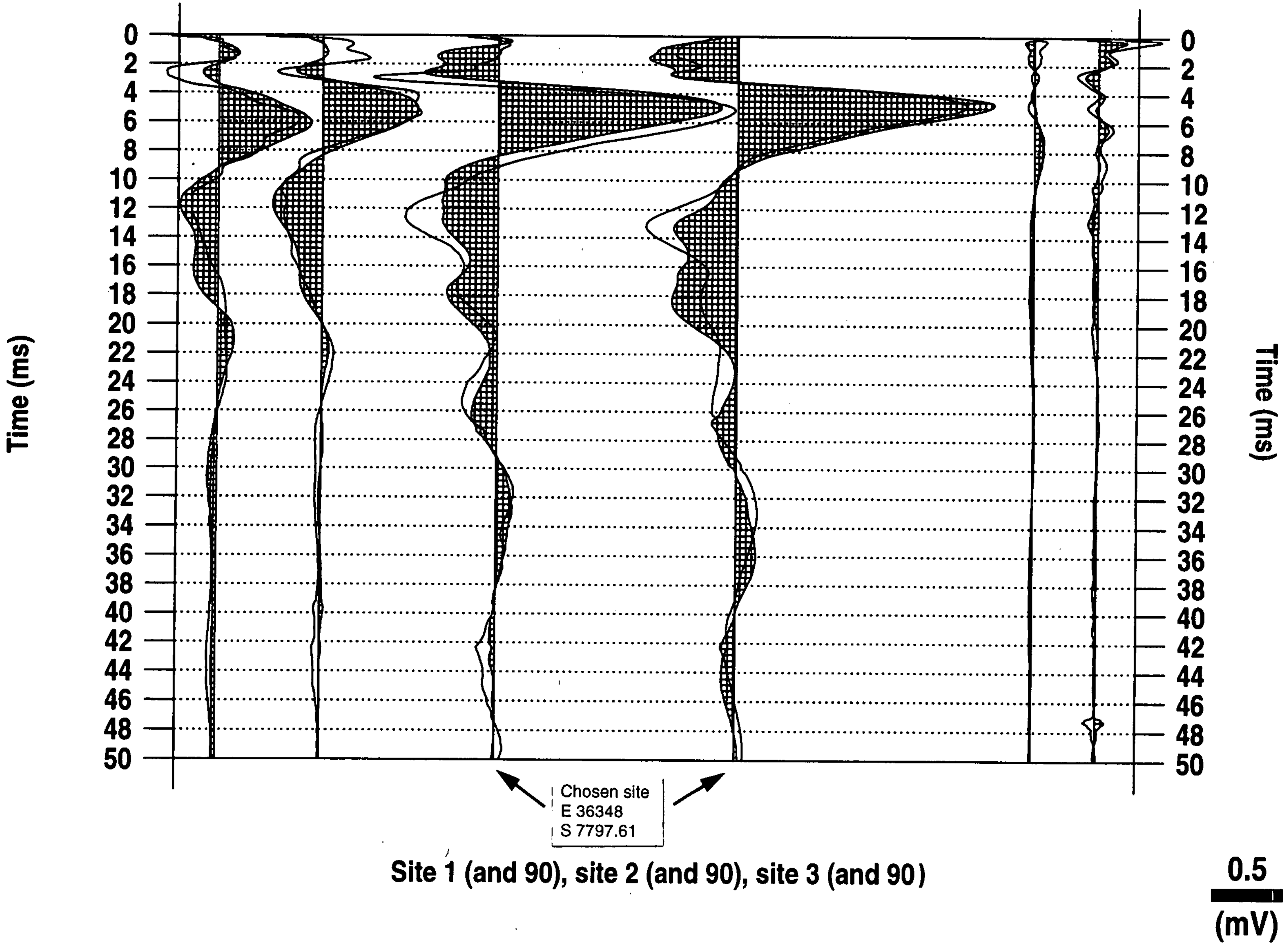


Figure 12 EKS plots from Tanda Tadious, Sites 1, 2 and 3

Maniki

3 sites chosen by the community

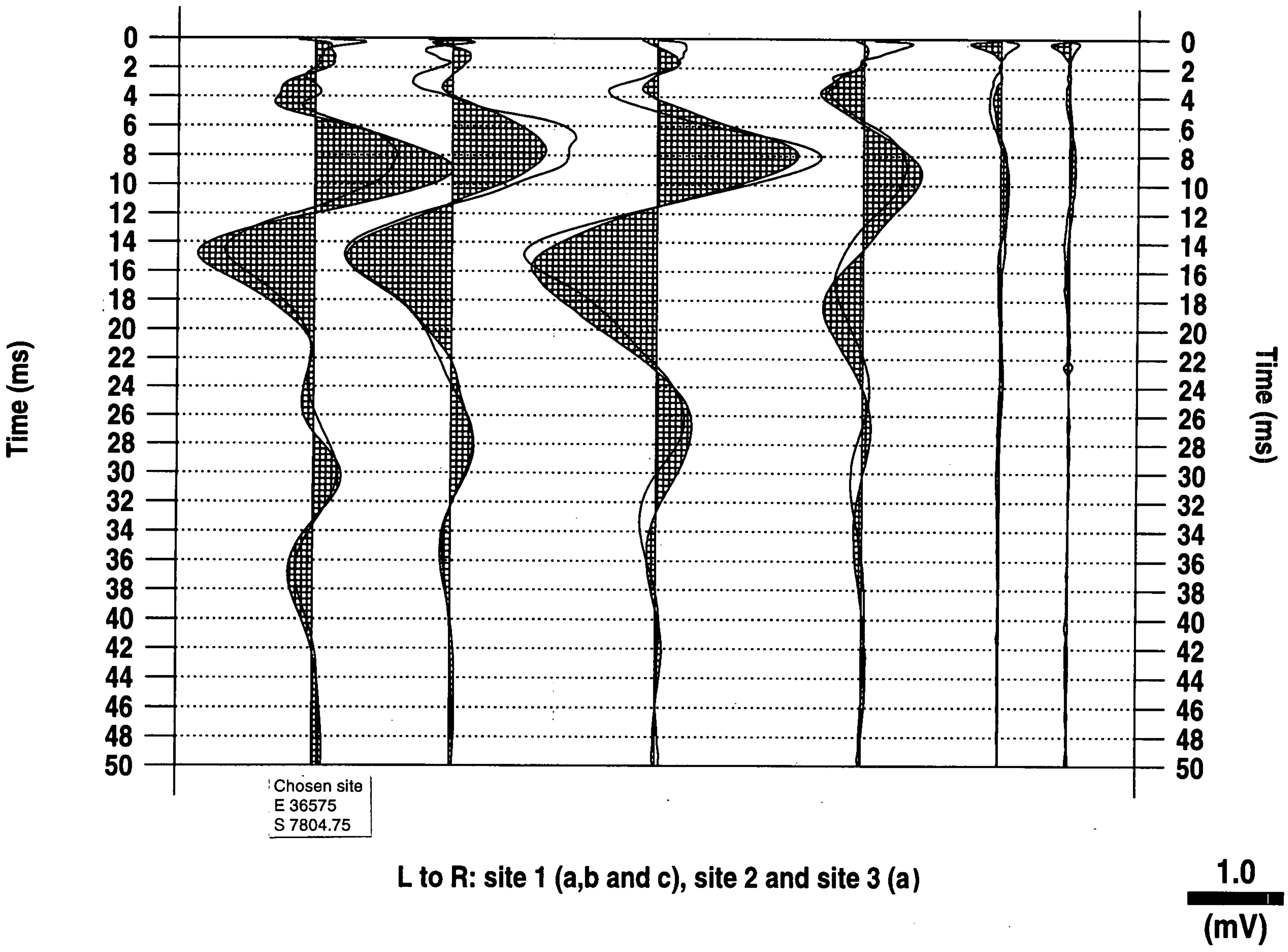


Figure 13 EKS plots from Maniki, Sites 1, 2 and 3

Zvawanda
3 sites chosen by community and existing well

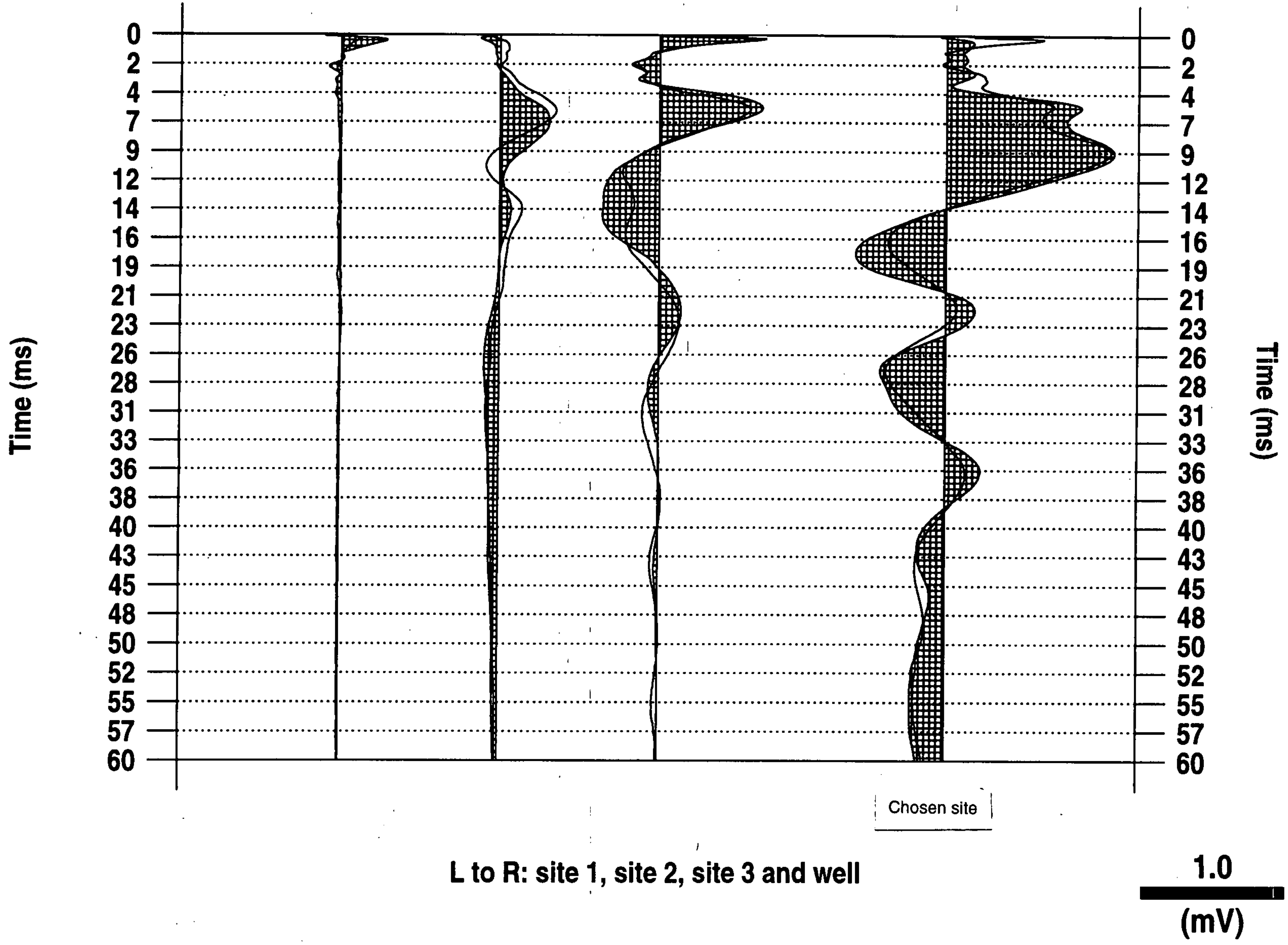


Figure 14 EKS plots from Zvawanda, Sites 1, 2 and 3 and existing well site

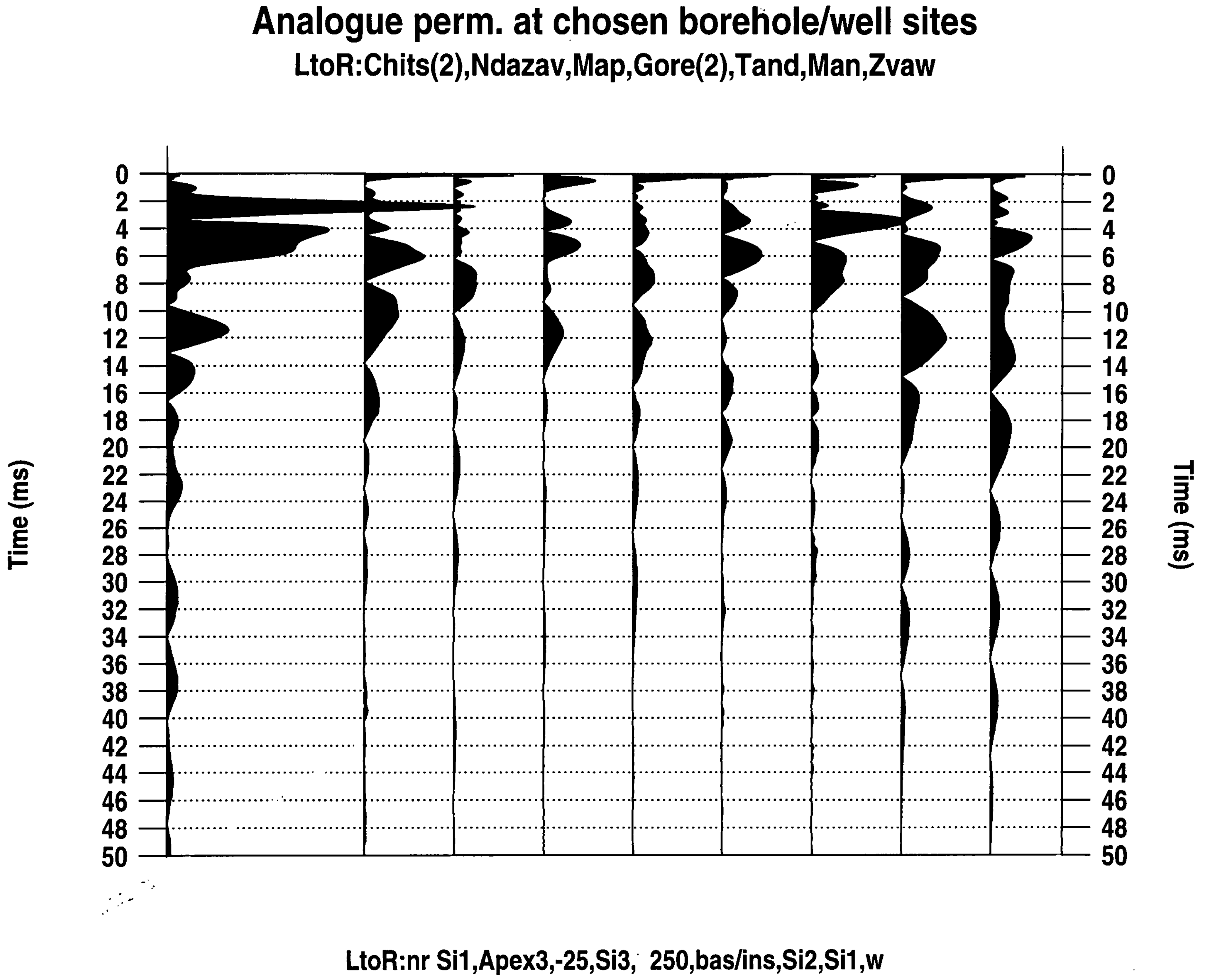


Figure 15 Analogue permeability/time section for chosen well and borehole sites

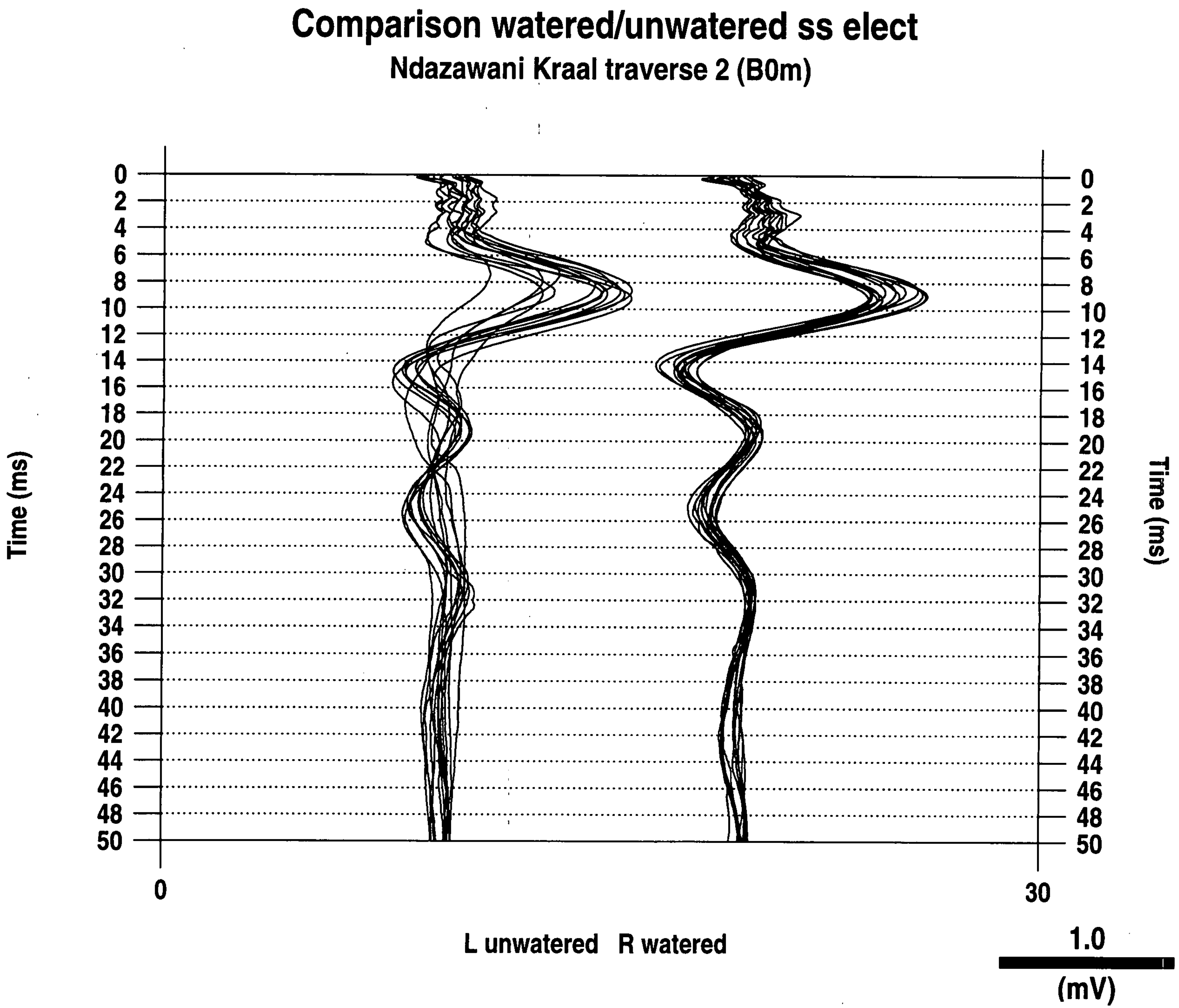


Figure 16 Comparison of EK responses with watered/unwatered electrodes (Ndazawani)

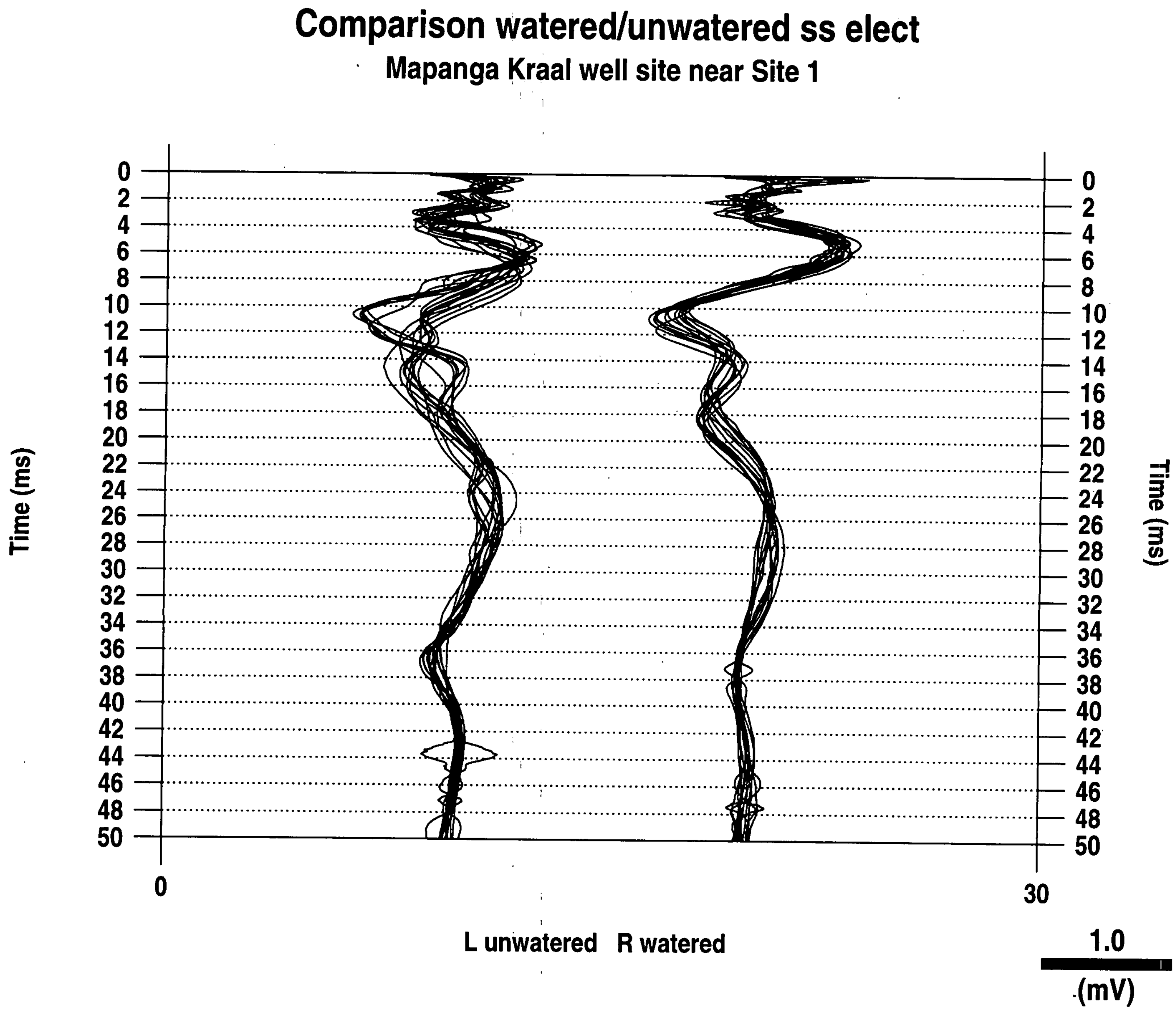


Figure 17 Comparison of EK responses with watered/unwatered electrodes (Mapanga 1)

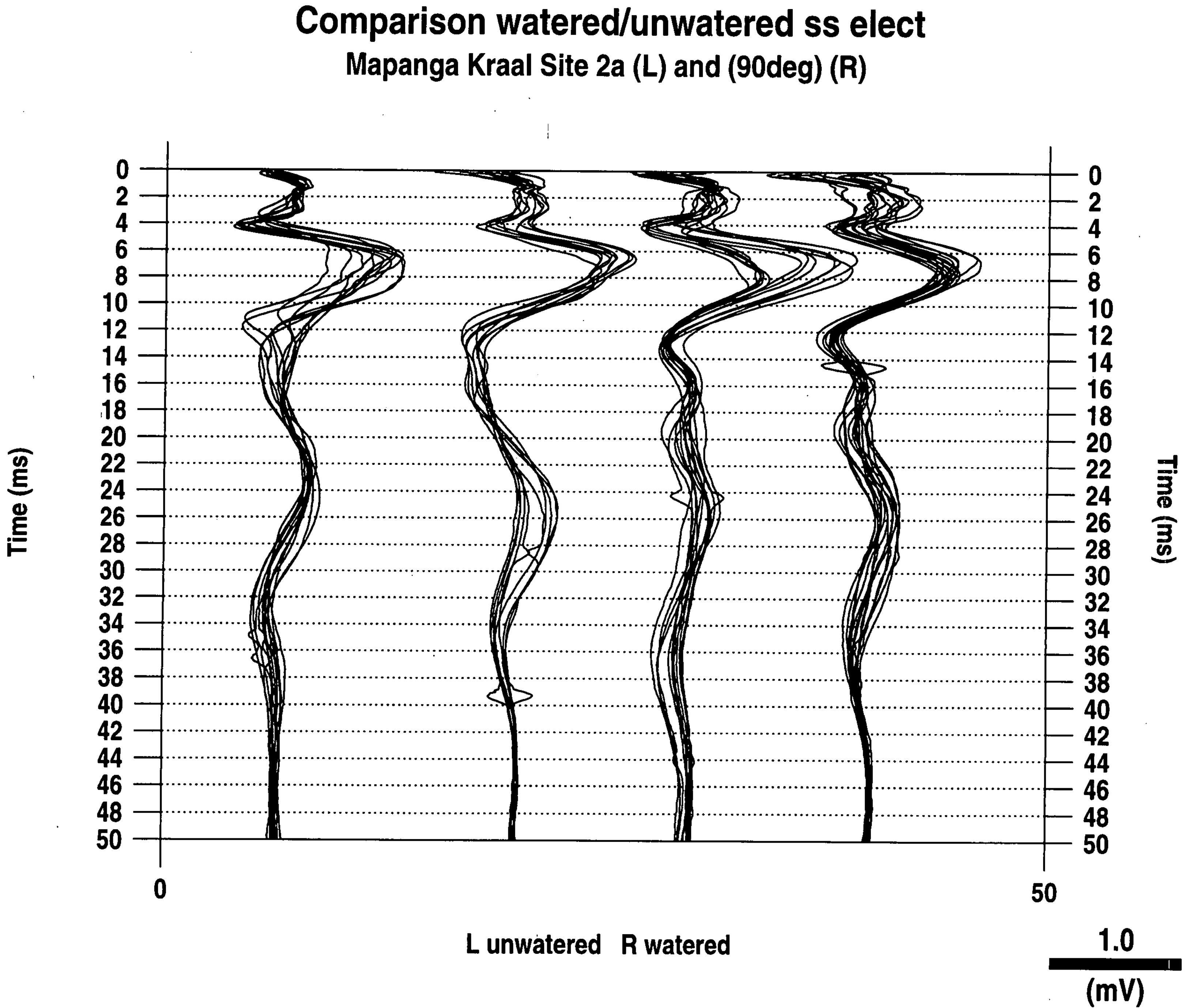


Figure 18 Comparison of EK responses with watered/unwatered electrodes (Mapanga 2)

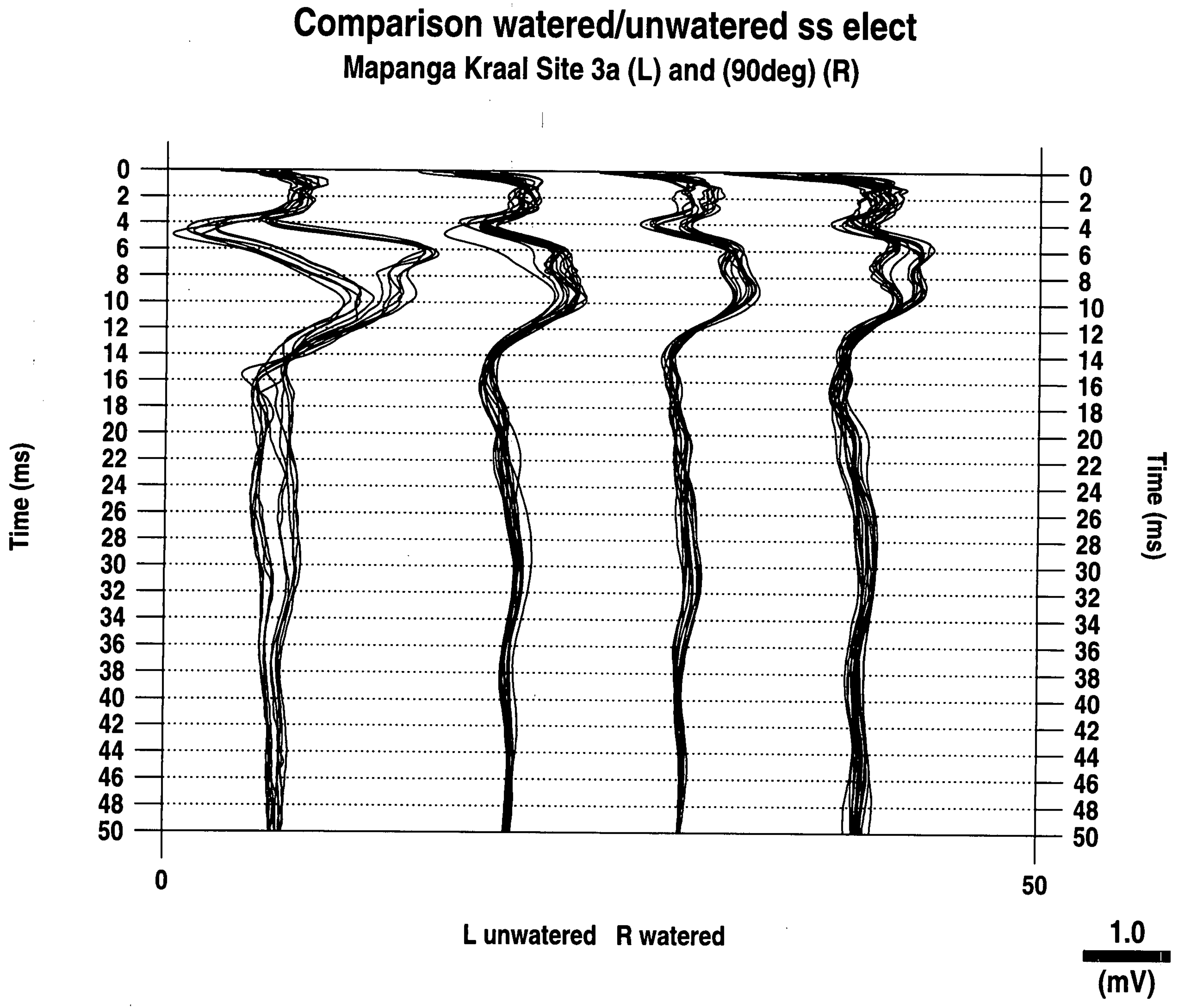


Figure 19 Comparison of EK responses with watered/unwatered electrodes (Mapanga 3)

Repeat EKS (next day, following heavy rain)

Gore traverse at 200m

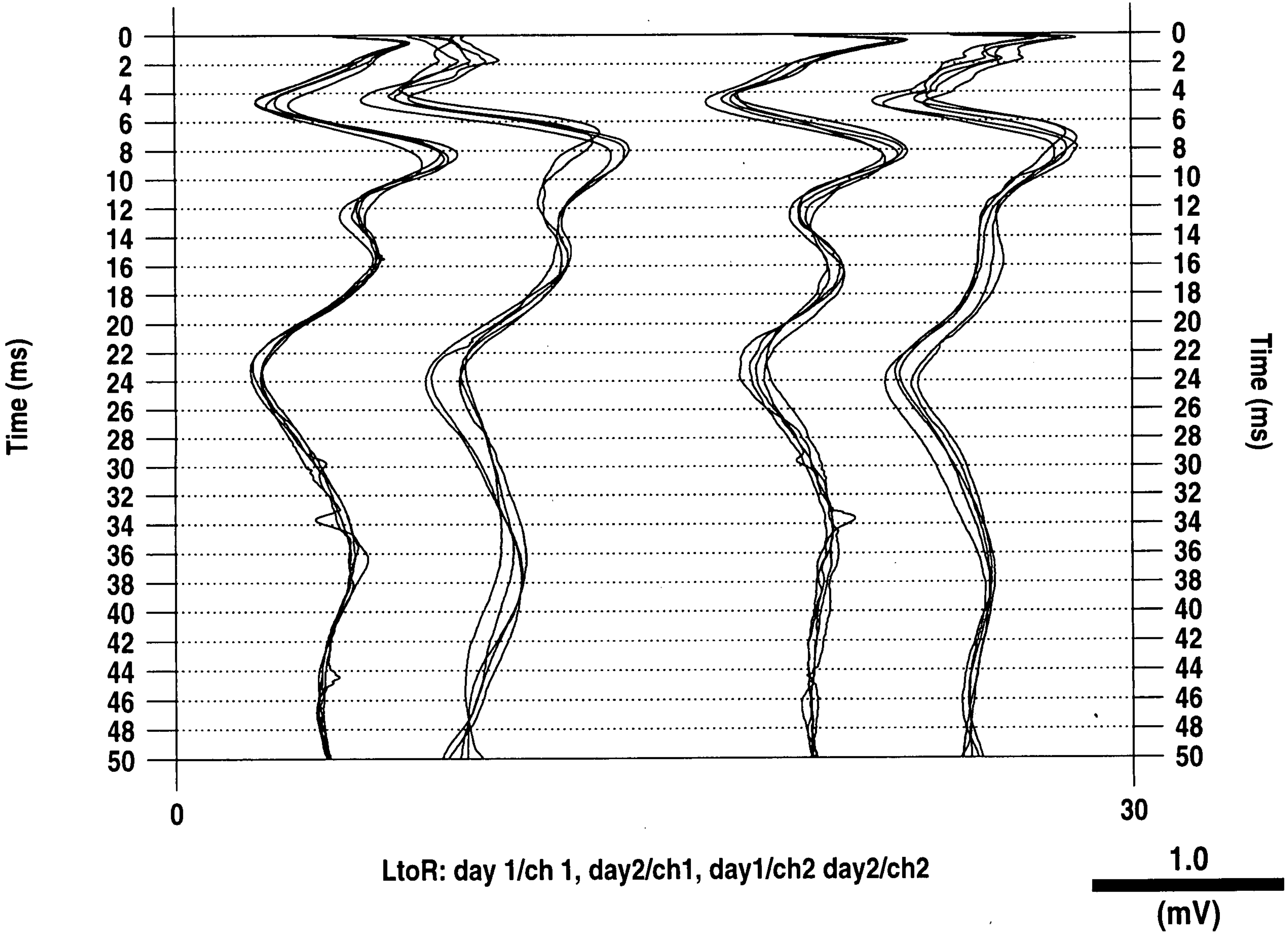


Figure 20 Comparison of repeated EKS (following heavy rain)

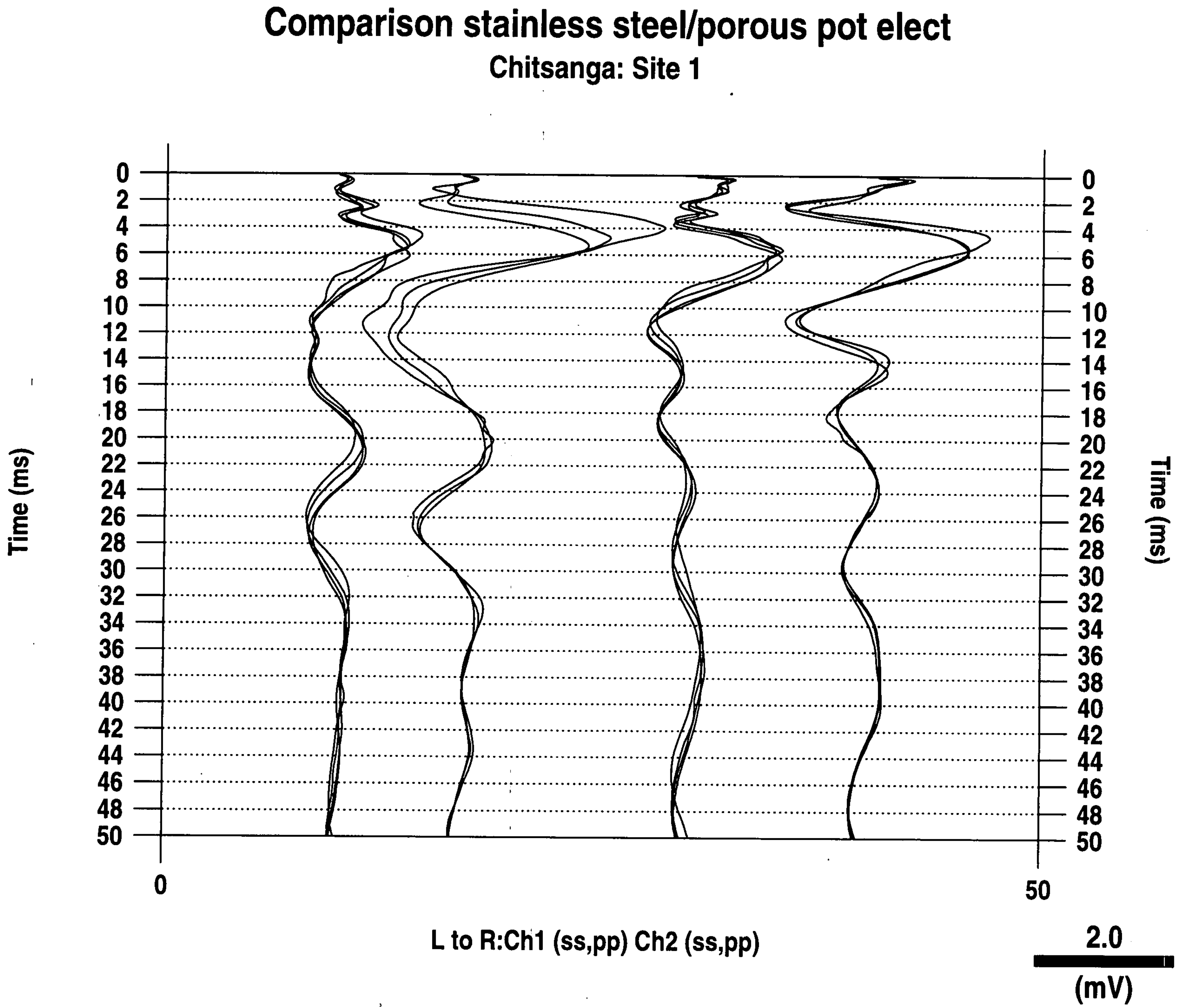


Figure 21 Comparison of EK data obtained with stainless steel and porous pot electrodes

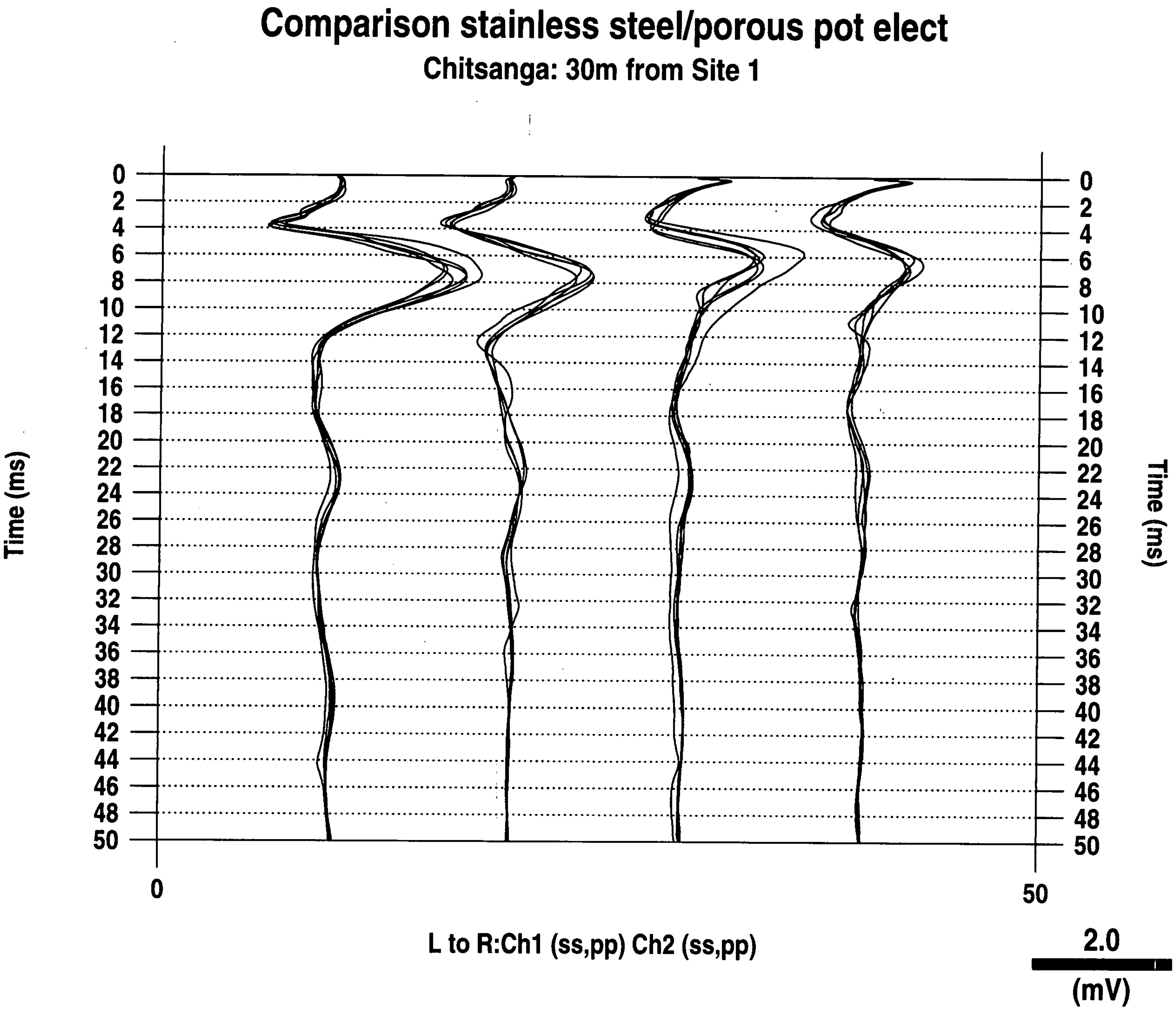


Figure 22 Comaprison of EK data obtained with stainless steel and porous pot electrodes

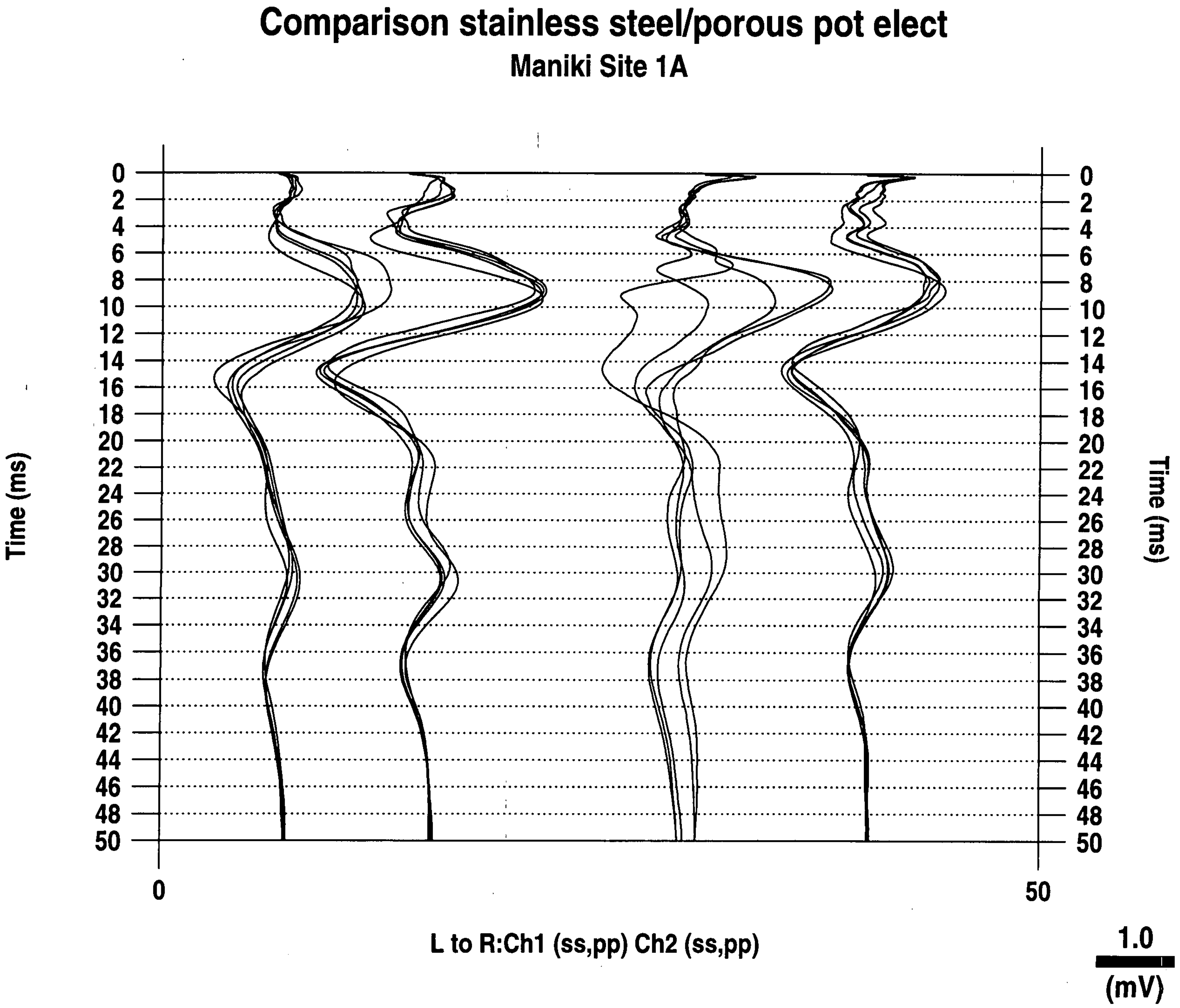


Figure 23 Comparison of EK data obtained with stainless steel and porous pot electrodes

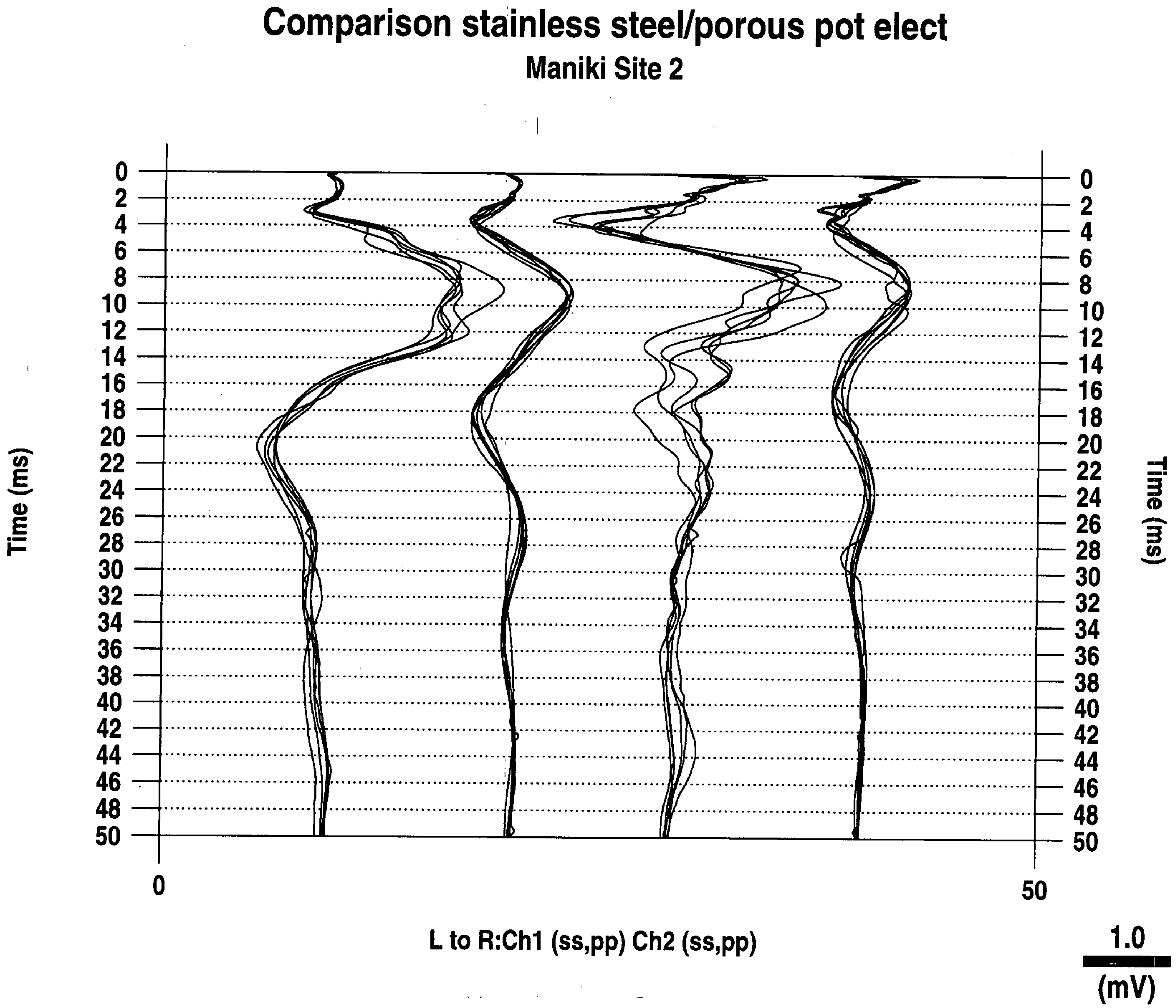


Figure 24 Comparsion of EK data obtained with stainless steel and porous pot electrodes

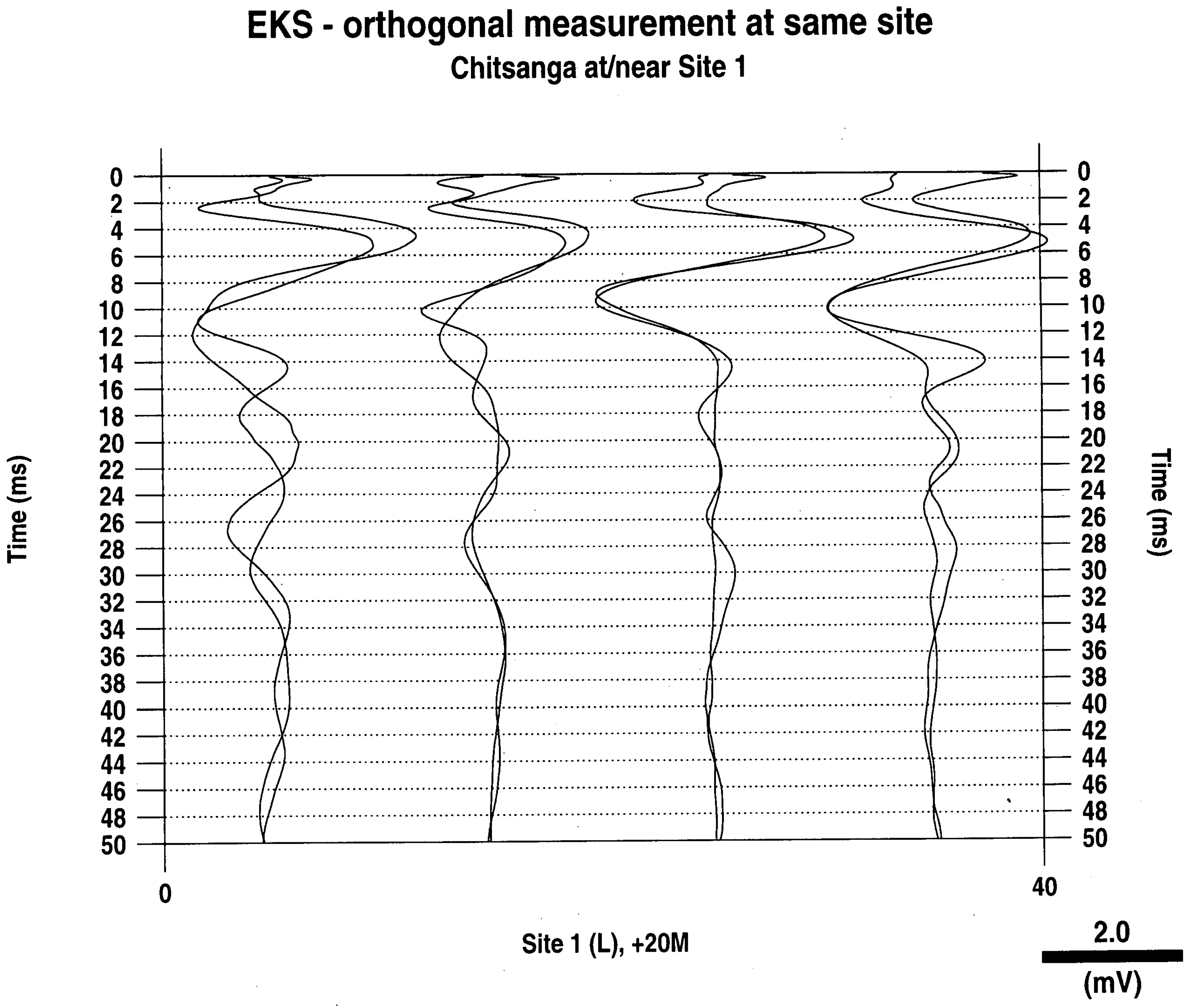


Figure 25 Comparison of orthogonal EK data (Chitsanga Site 1)

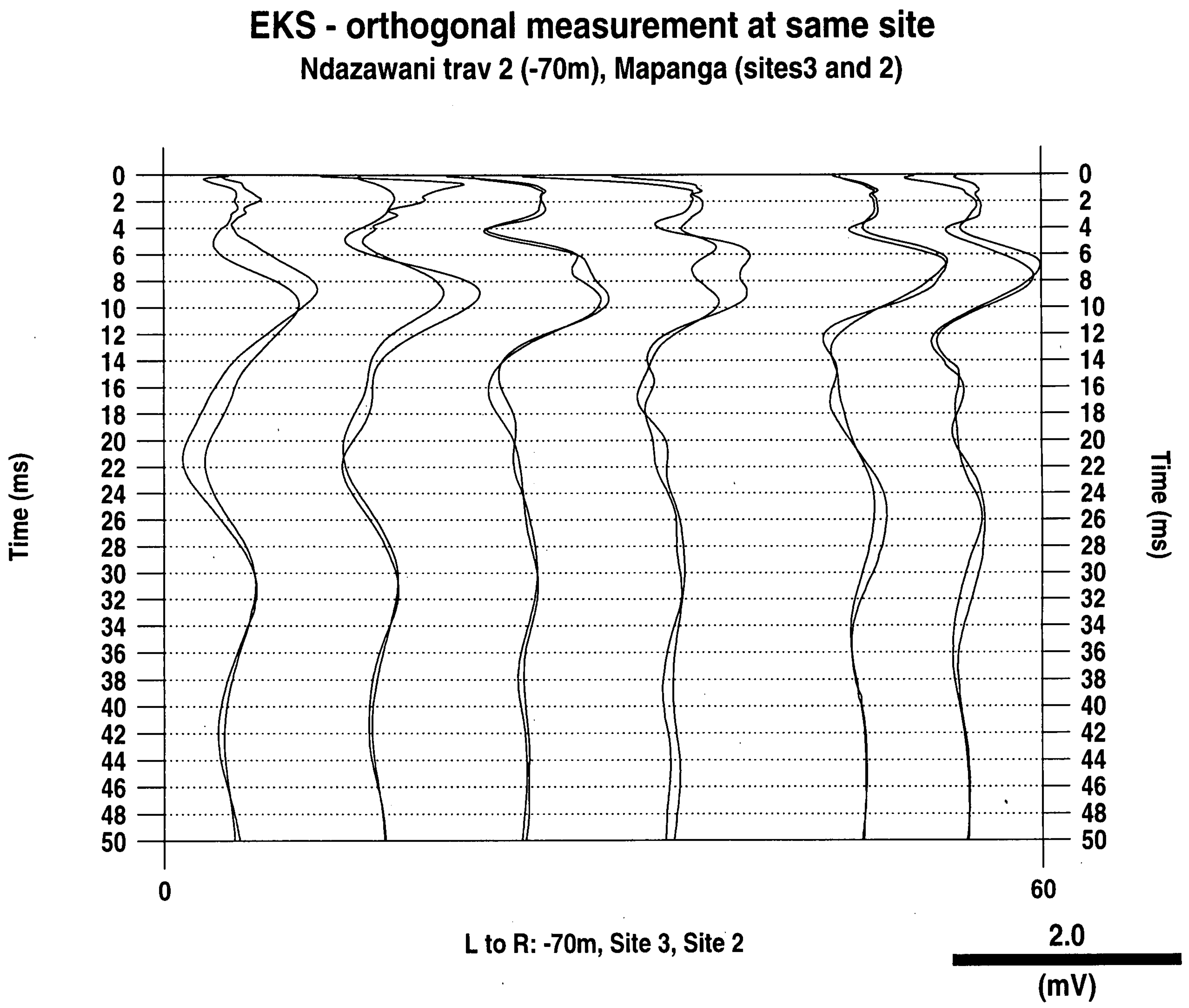


Figure 26 Comparison of orthogonal EK data (Ndazavani Traverse 2 and Mapanga)

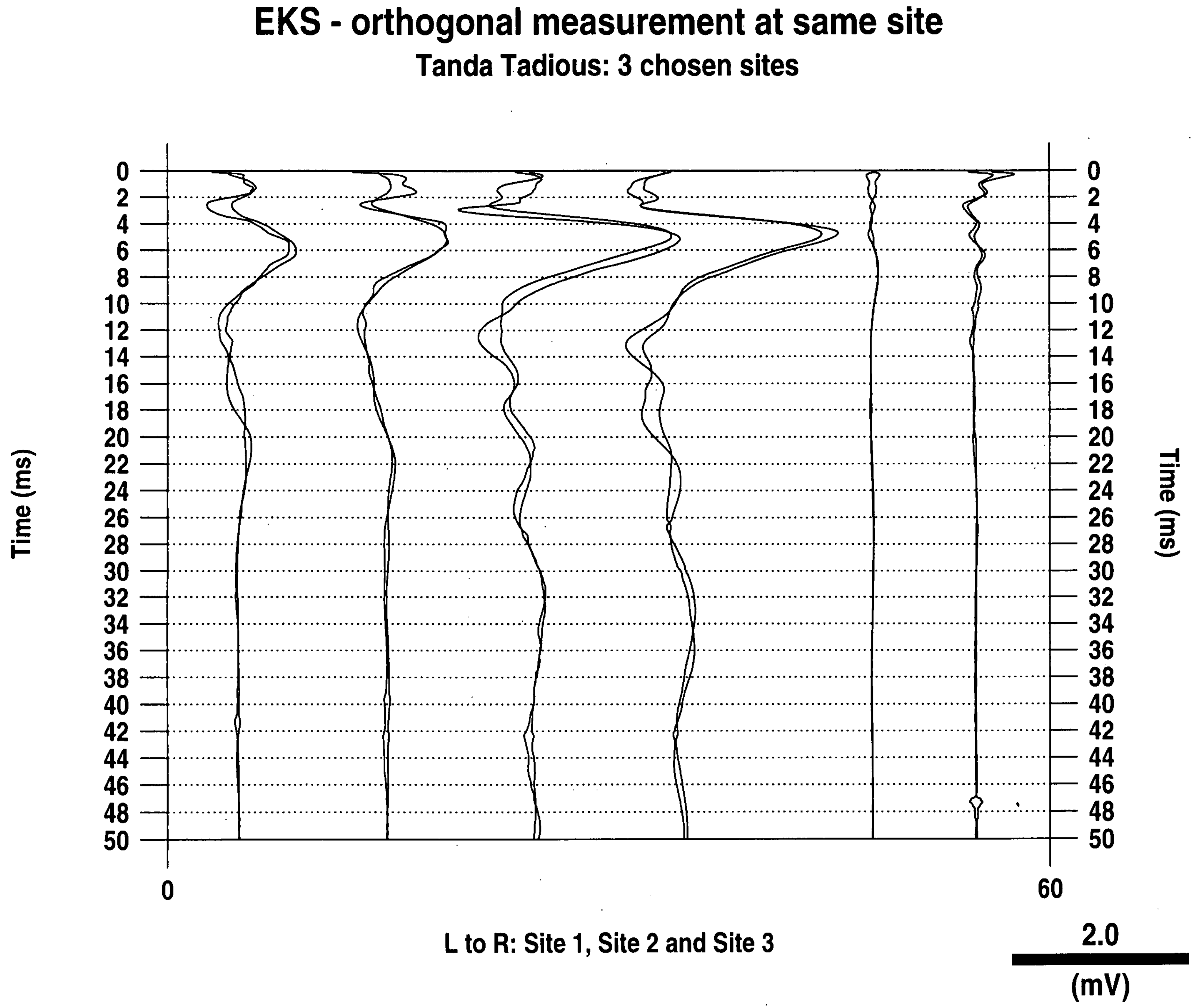
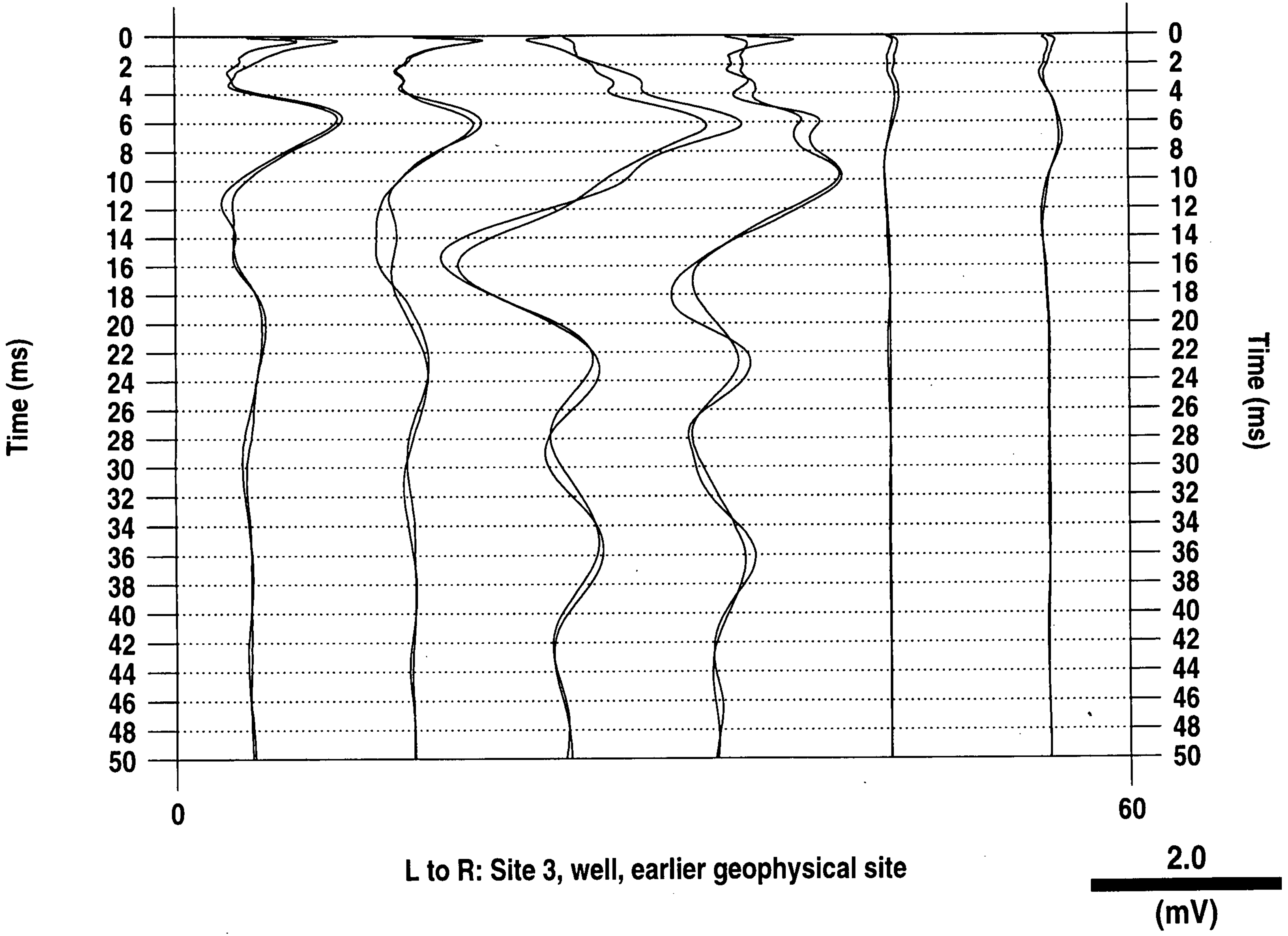


Figure 27 Comparison of orthogonal EK data (Tanda Tadious Sites 1, 2 and 3)



EKS - orthogonal measurement at same site

Zvawanda: Site 3, well site and earlier geoph

L to R: Site 3, well, earlier geophysical site

Figure 28 Comparison of orthogonal EK data (Zvawanda: Site 3, well site and other)

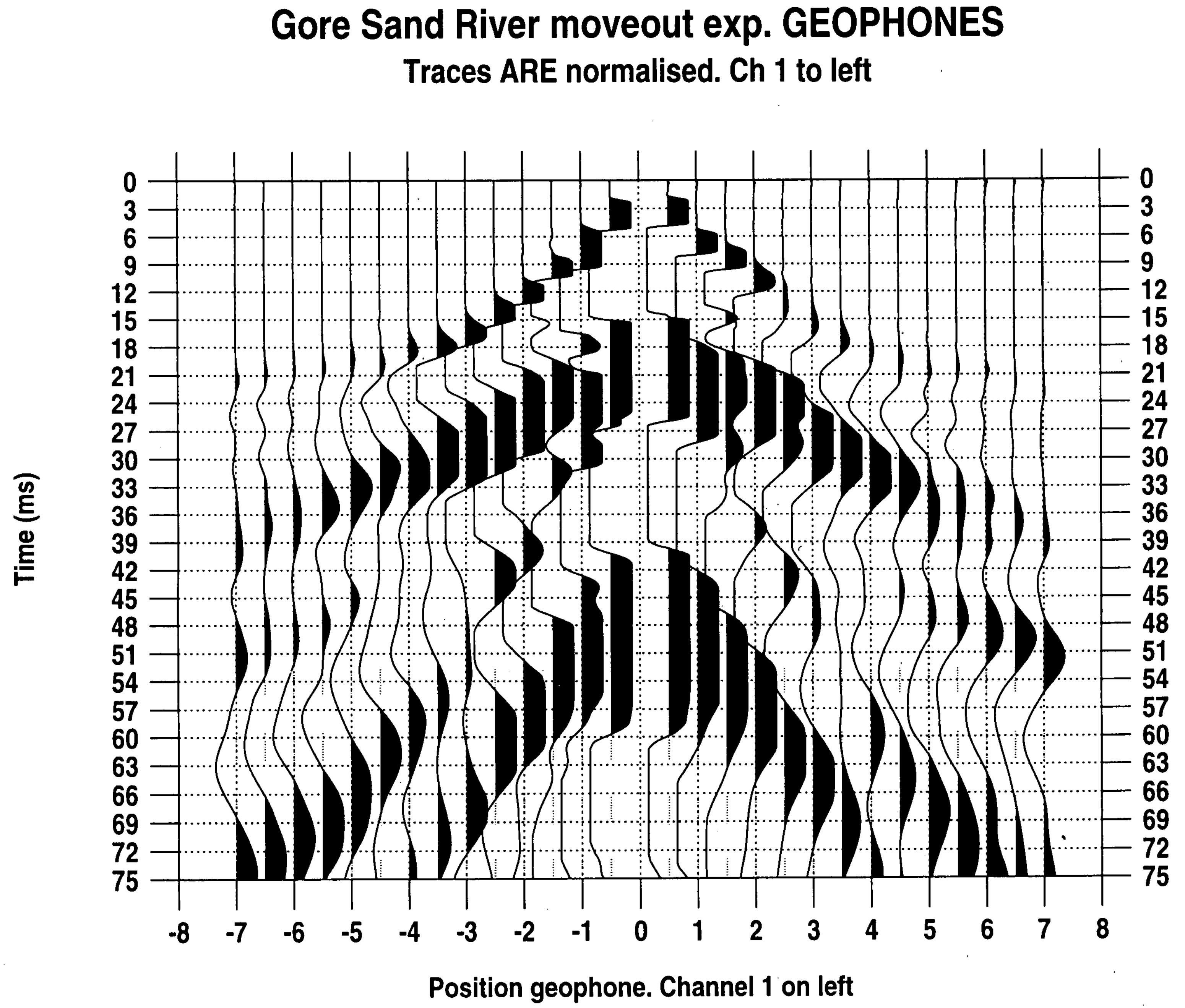


Figure 29 Geophone moveout experiment at Gore sand river

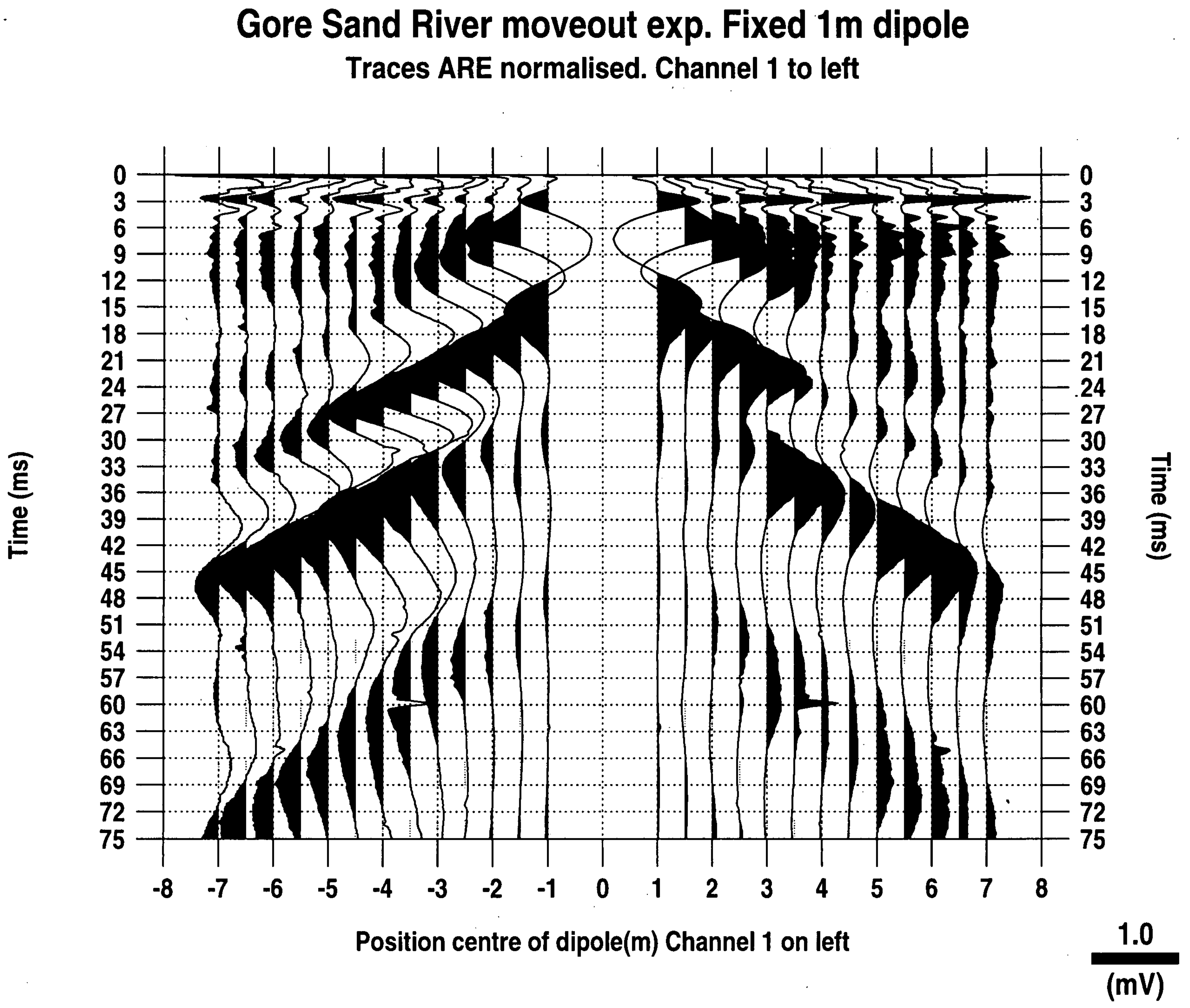


Figure 30 Dipole moveout experiment at Gore sand river

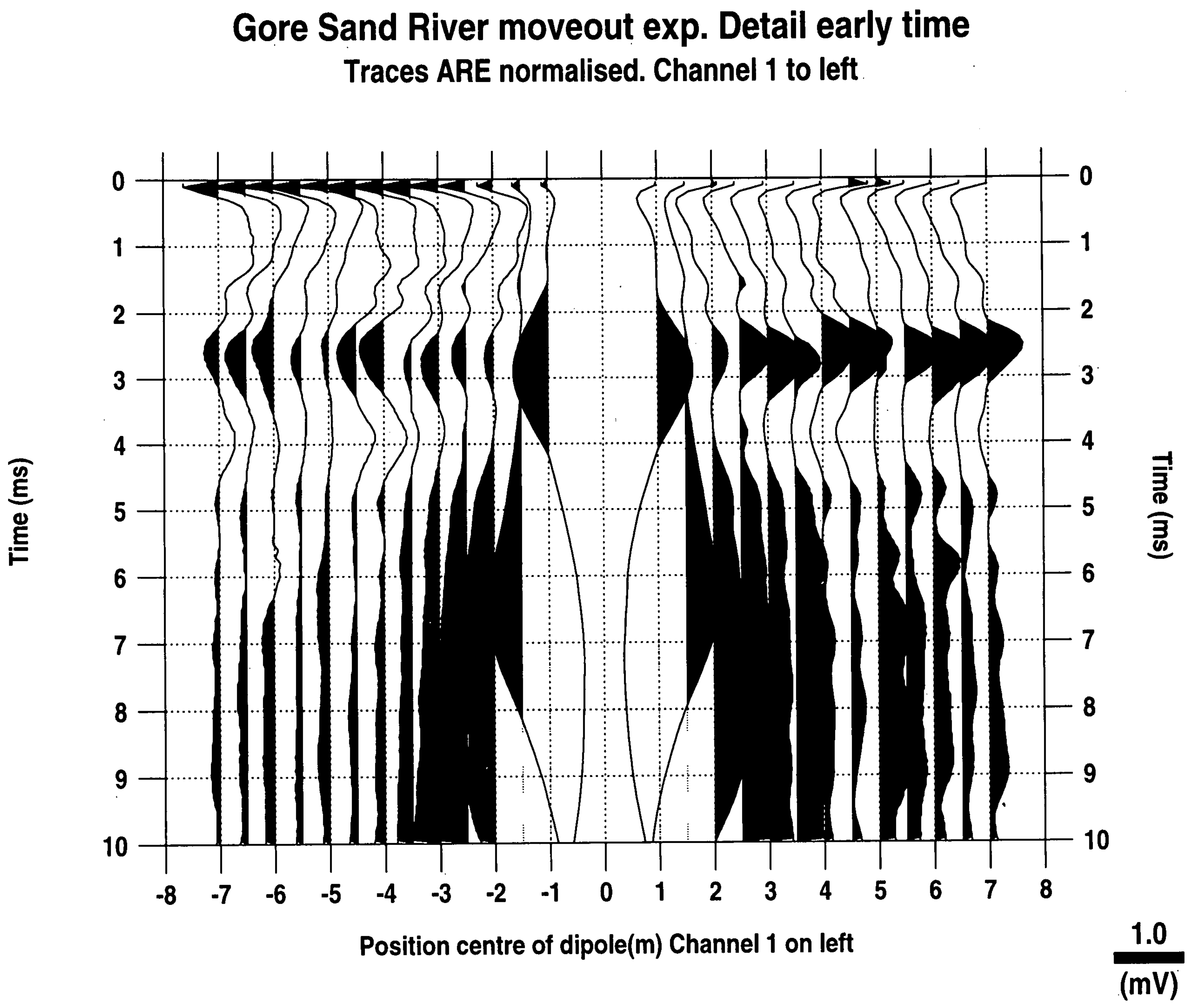


Figure 31 Early time detail of Gore sand river dipole moveout experiment

GORE Sand River, Bikita, Zimbabwe. EK moveout experiment

Trace normalisation. 1 m dipoles at 50 cm offsets

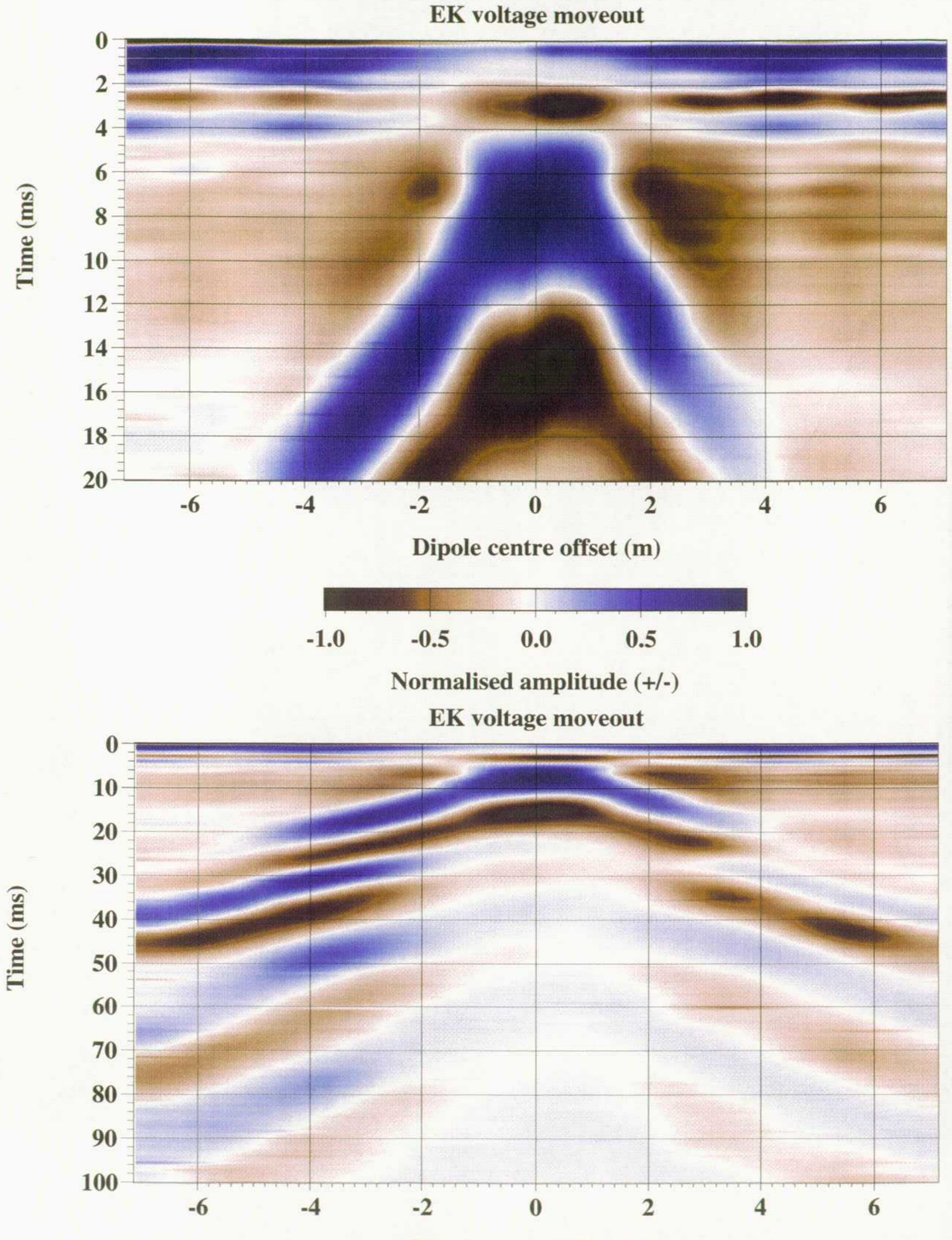


Figure 32. Gore sand river dipole moveout data : channel 1, voltages colour contoured

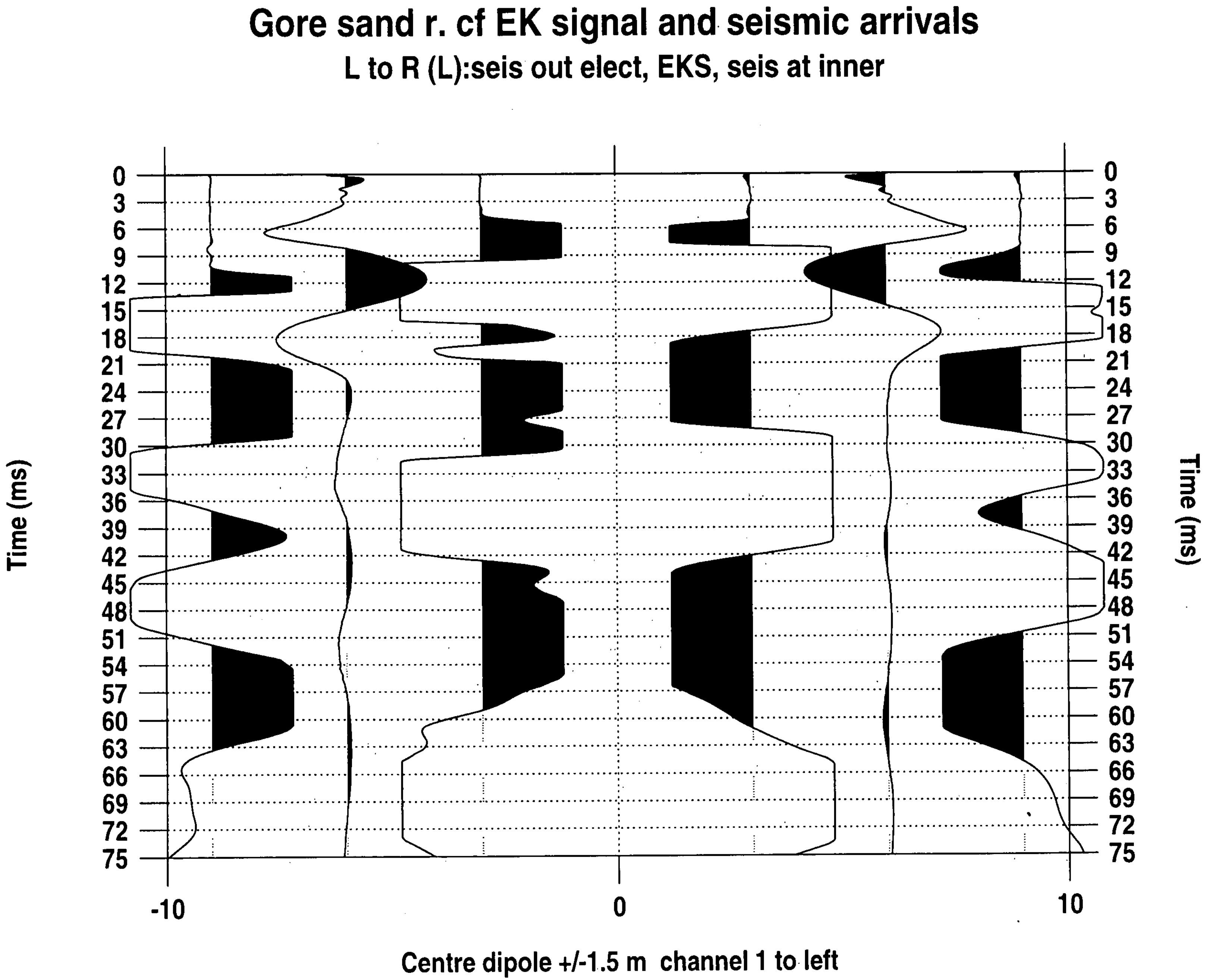


Figure 33 Gore river: comparison EK signal and seismic arrivals at electrodes (+/- 1.5m)

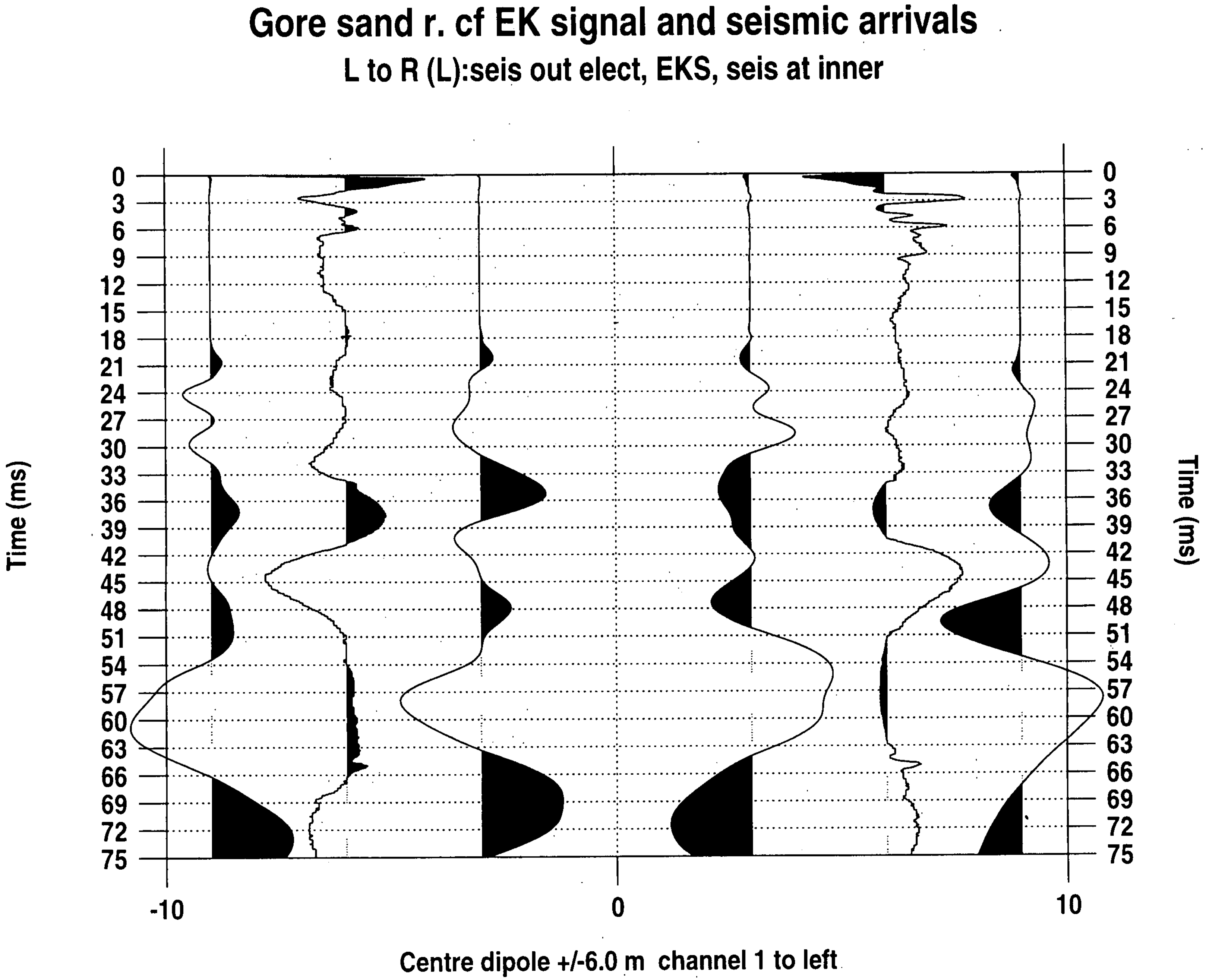


Figure 34 Gore river: comparison EK signal and seismic arrivals at electrodes (+/- 6.0m)

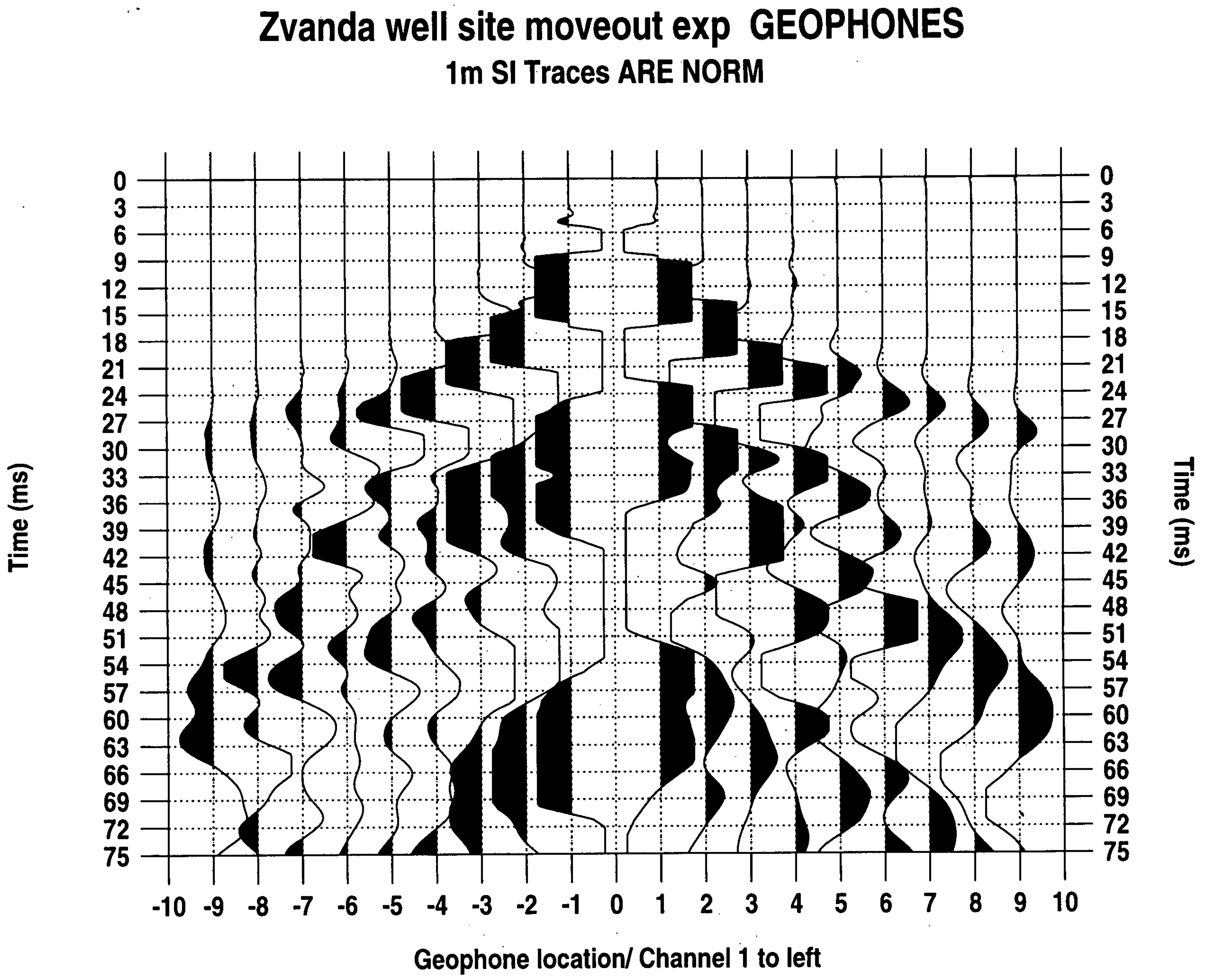


Figure 35 Geophone moveout experiment at Zvawanda well site

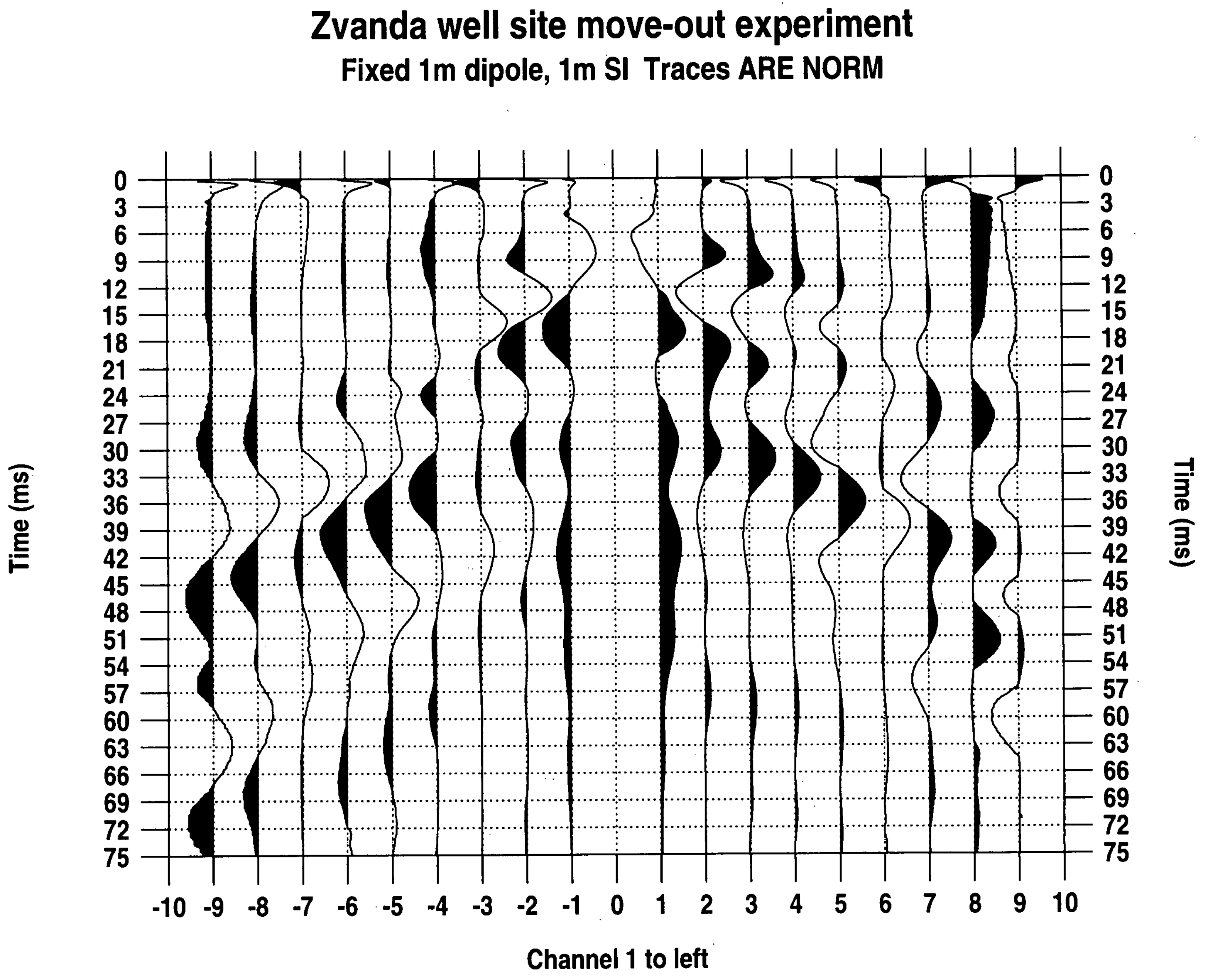


Figure 36 Dipole moveout experiment at Zvawanda well site

TRIGER PROBLEM

LtoR: loose trigger/refixed trigger

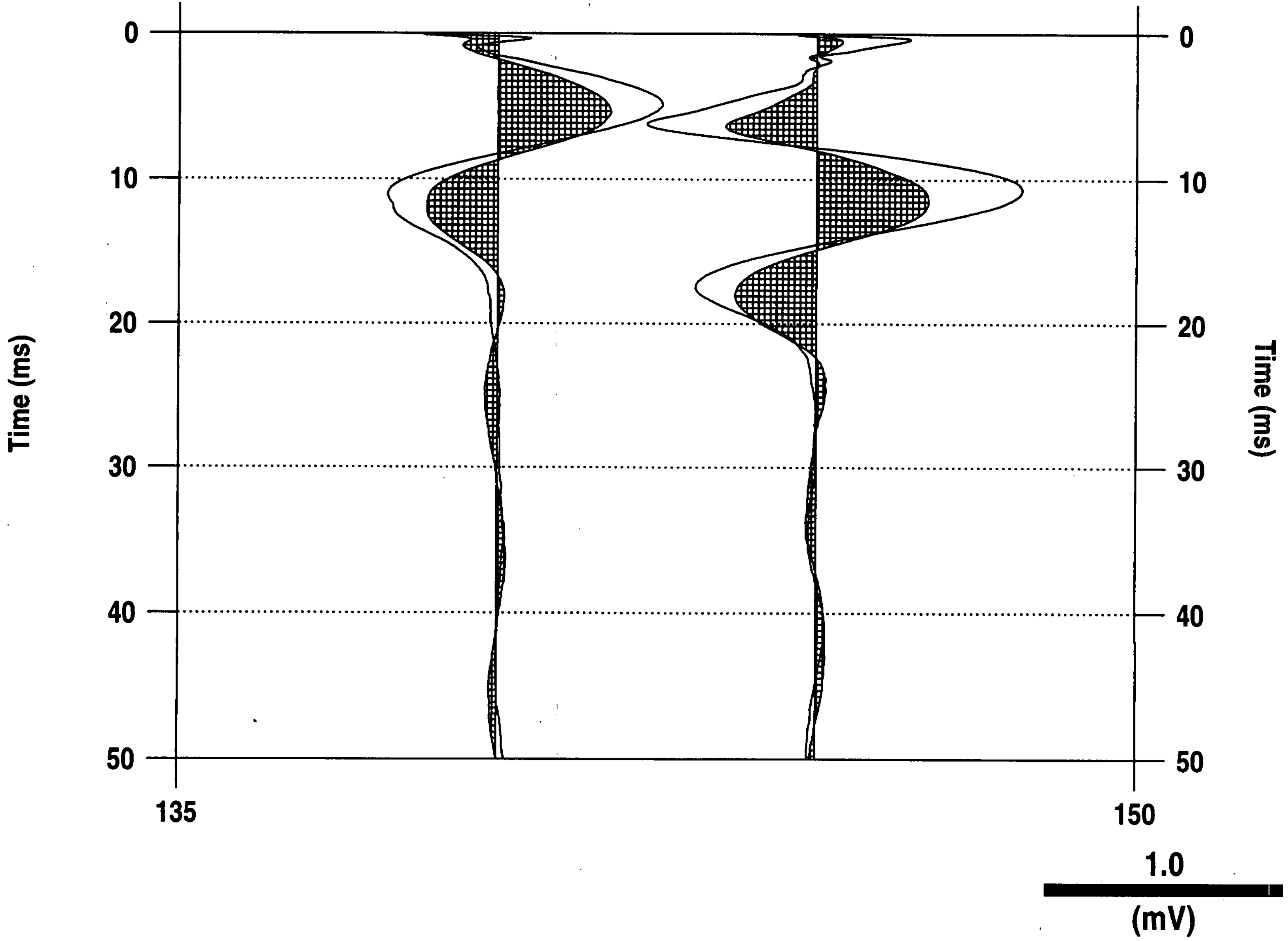


Figure 37 EK responses showing timing delay introduced by loose trigger

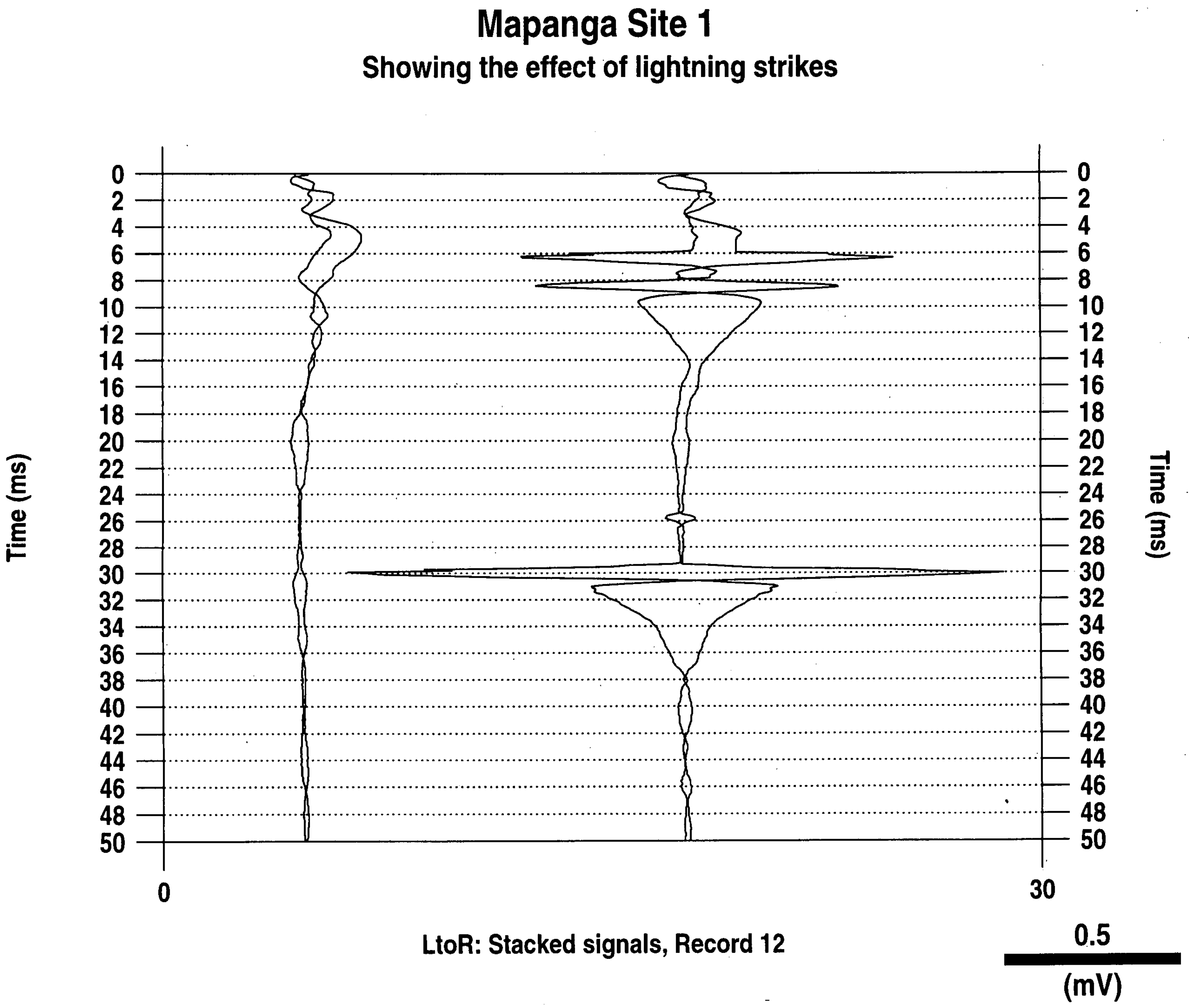


Figure 38 EK responses showing the effect of lightning strikes

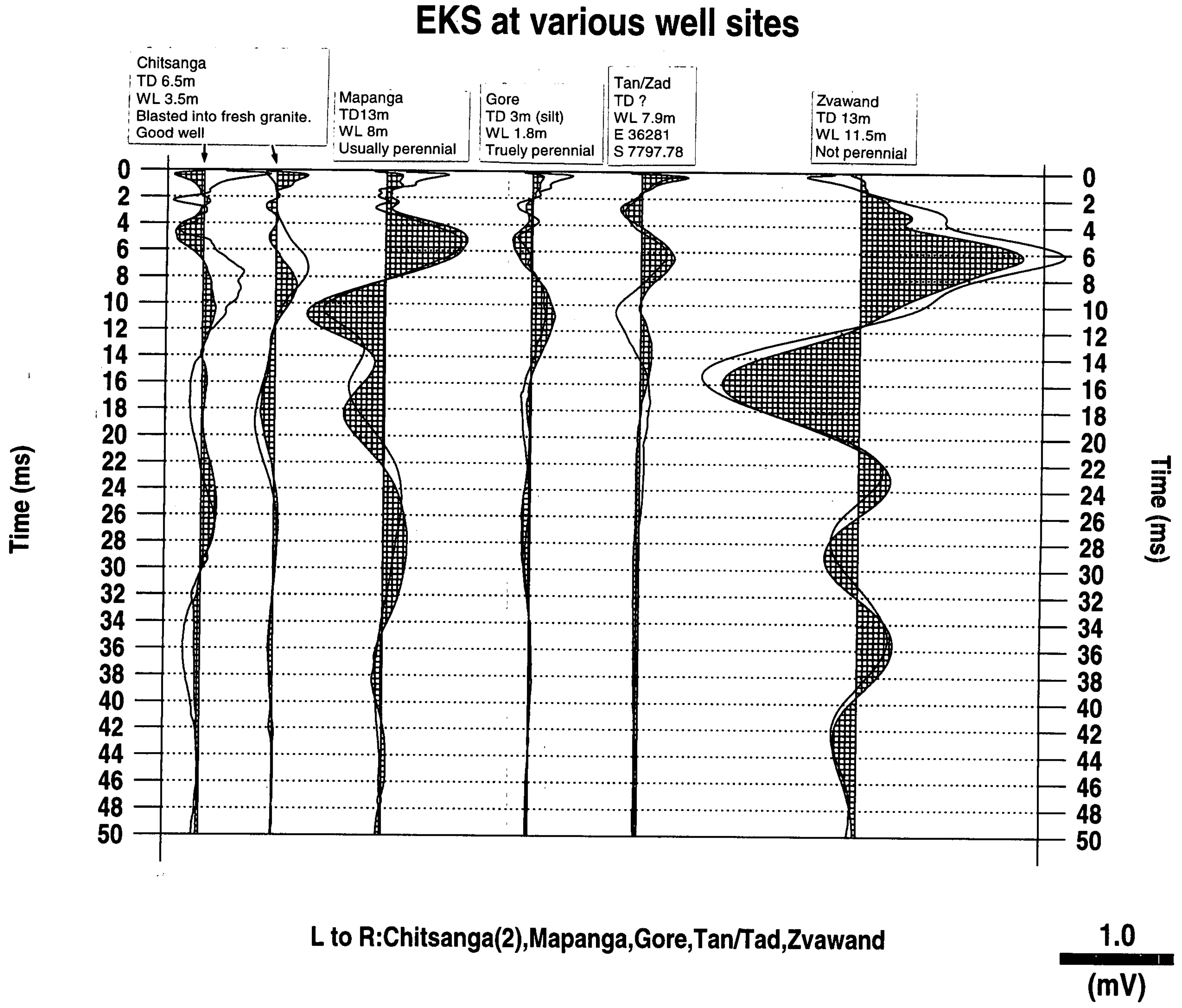


Figure 39 EK responses at various existing well sites

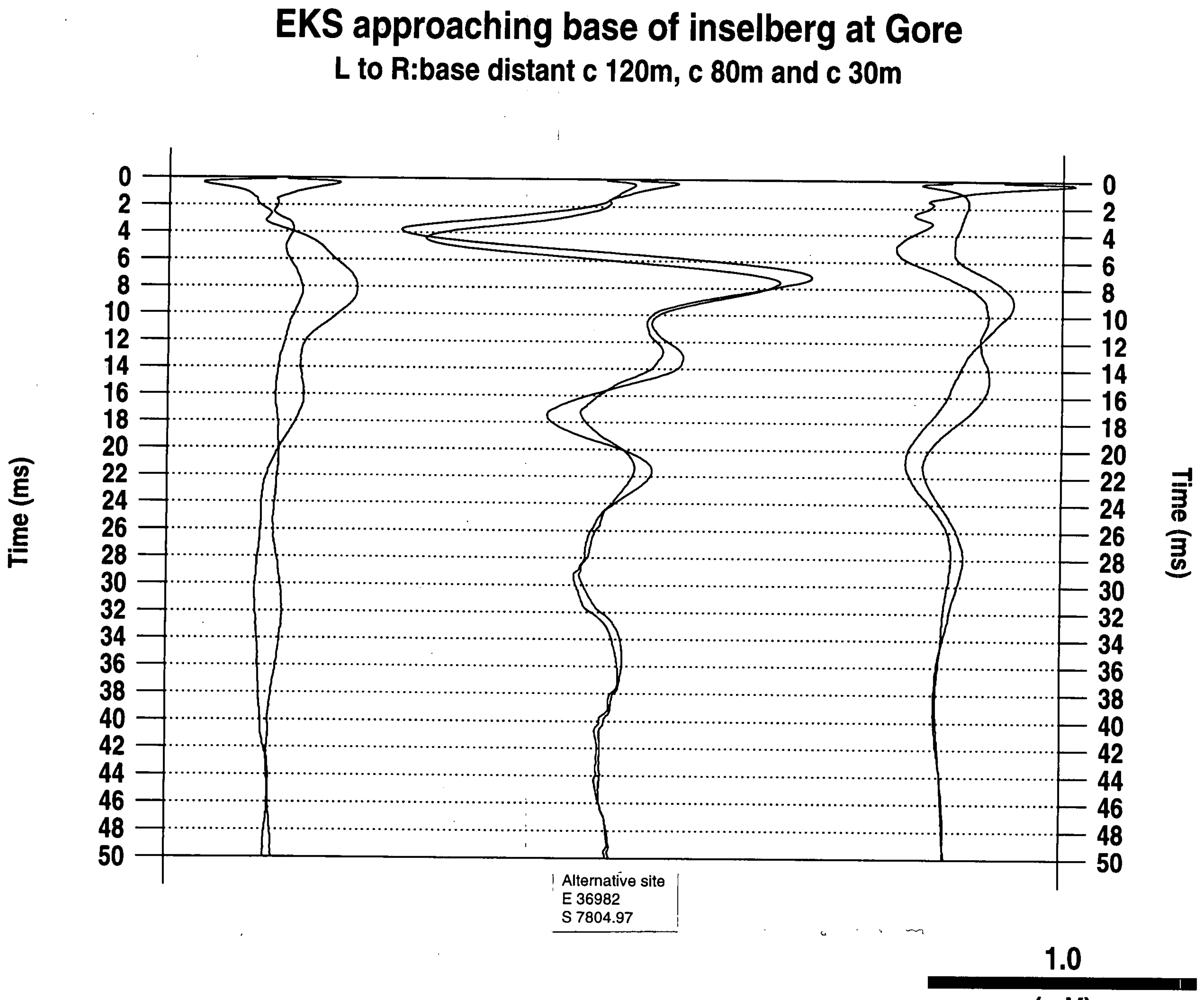


Figure 40 EK responses at sites approaching the base of an inselberg (Gore)

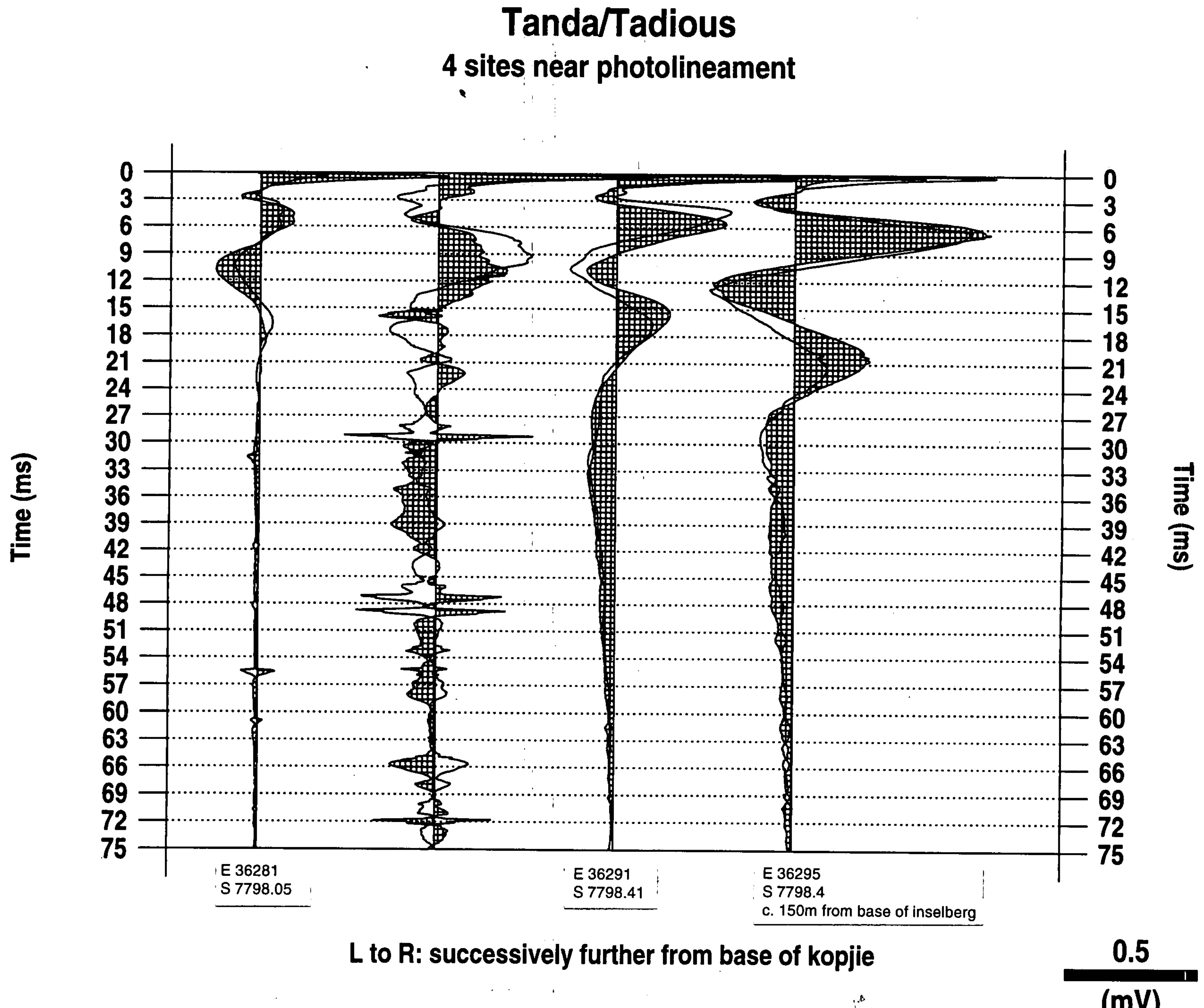


Figure 41 EK responses in the vicinity of a photolineament

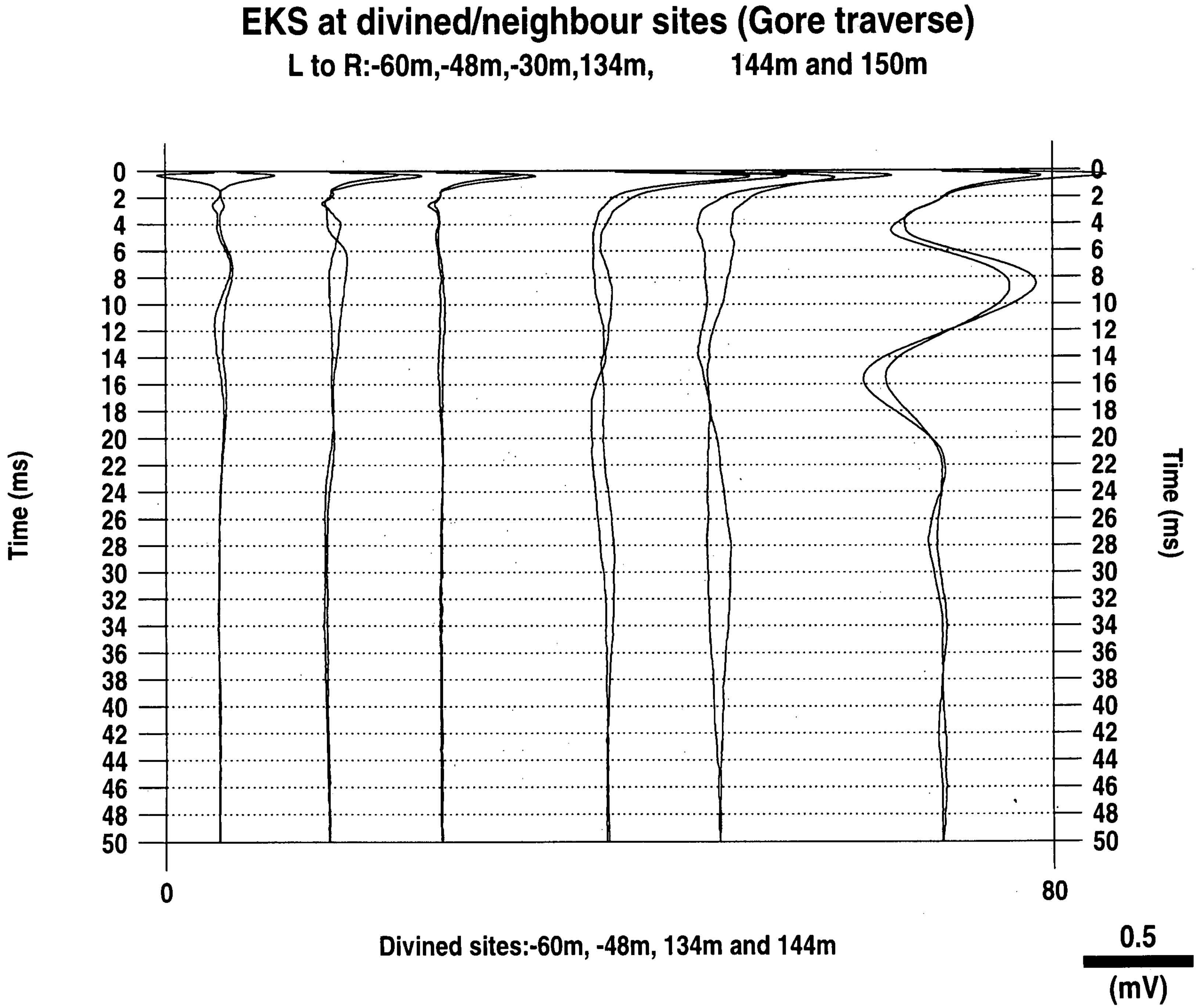


Figure 42 EK responses at divined and neighbouring sites (Gore Traverse)

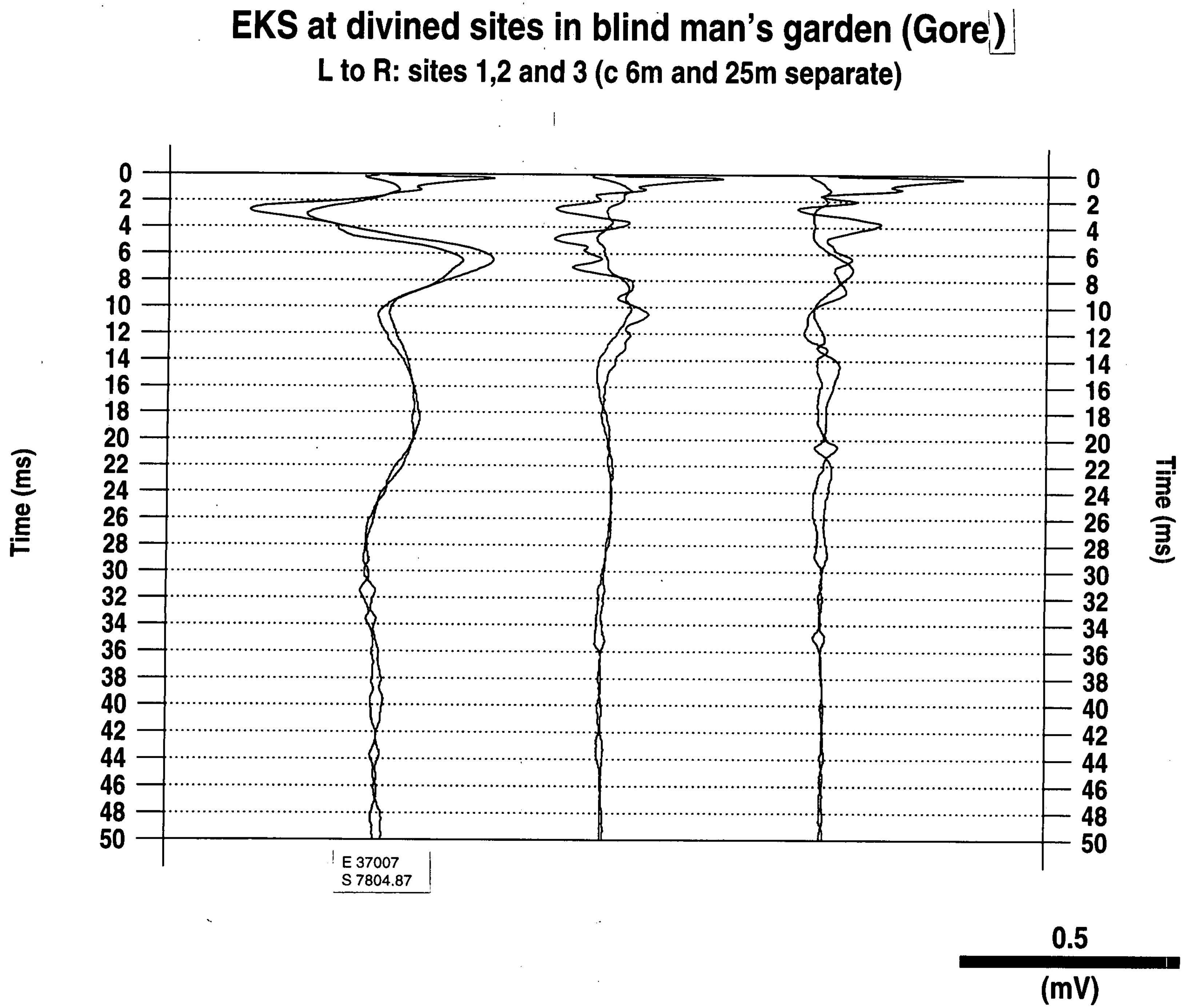


Figure 43 EK responses at divined sites in Gore (blind man's garden)

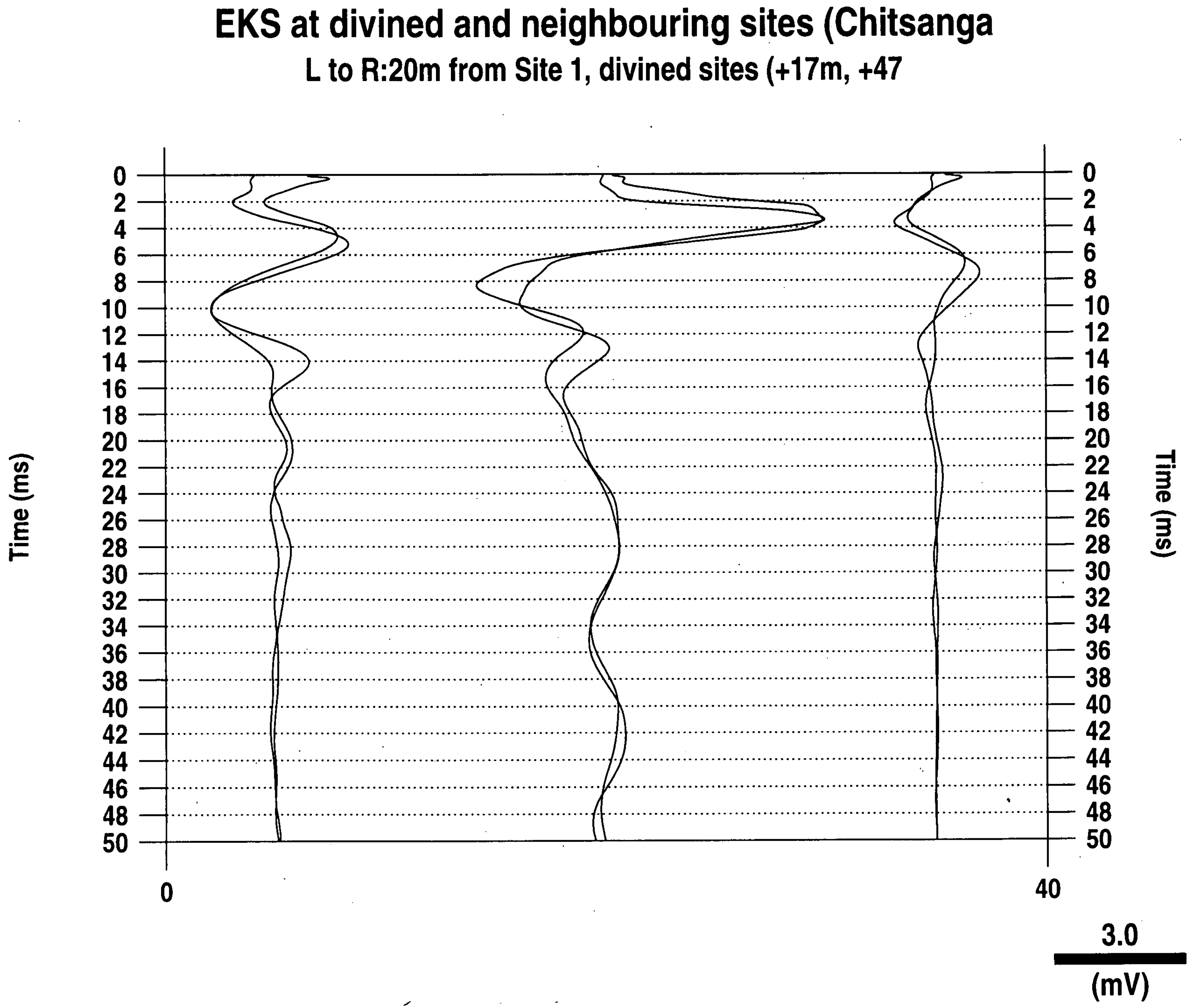


Figure 44 EK responses at divined and neighbouring sites (Chitsanga)

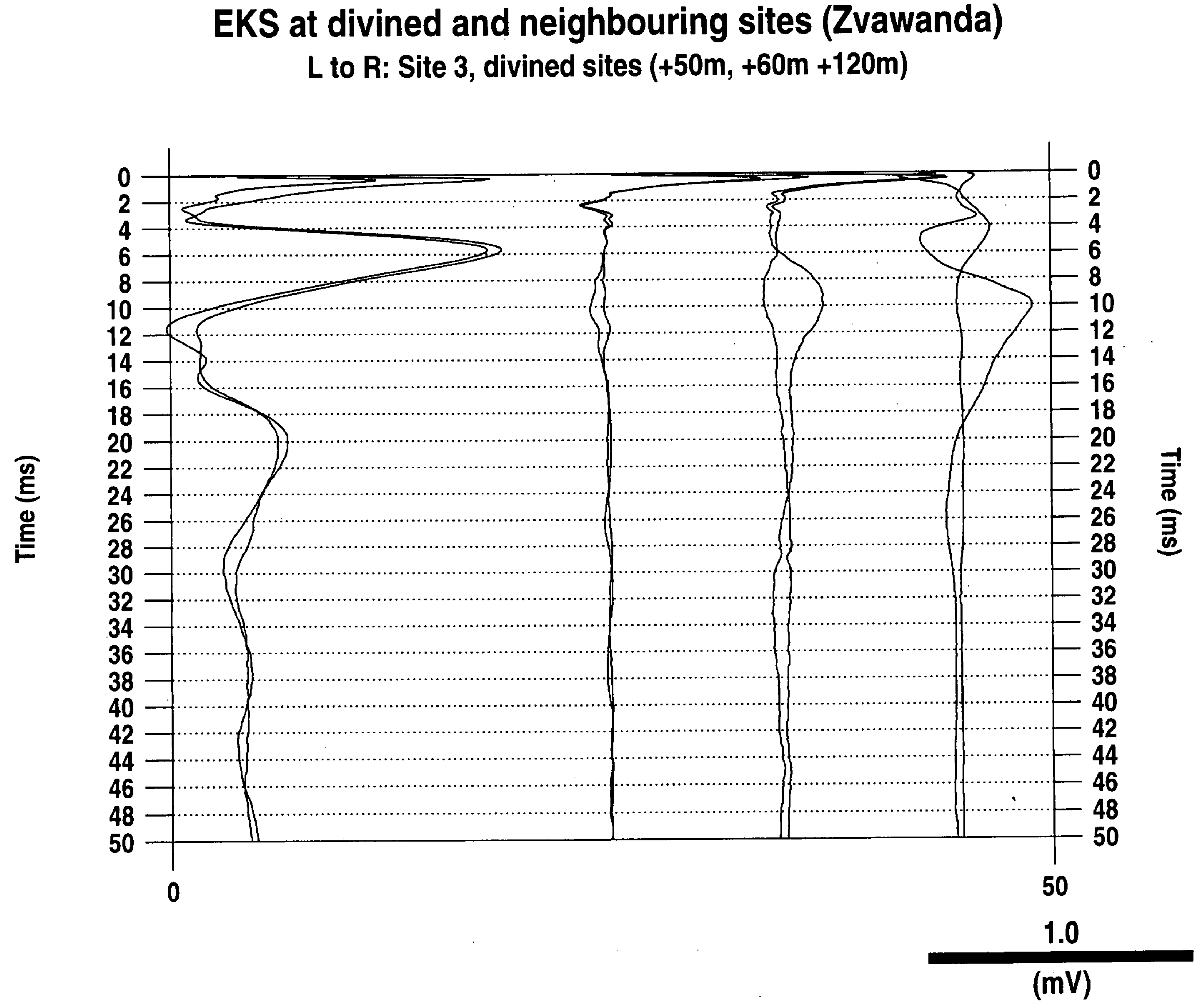


Figure 45 EK responses at divined and neighbouring sites (Zvawanda)

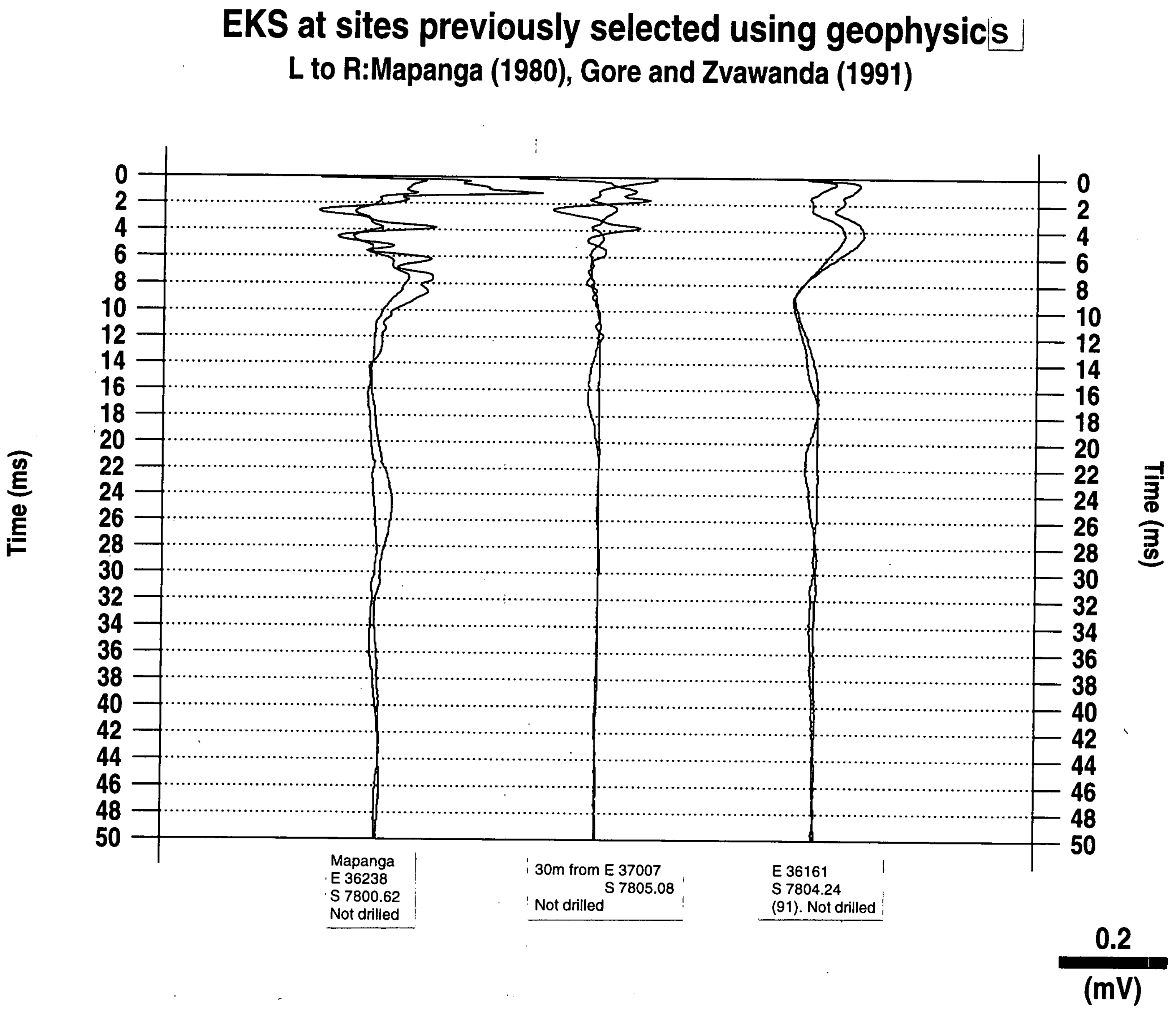


Figure 46 EK responses at sites previously selected using other geophysical techniques