

## DETECTION OF SALINE-FRESH WATER INTERFACE AT THE ABER COLLEGE FARM COASTAL AREA, NORTH WALES, U.K

Saeed Ahmed Soomro

*Department of Geology, University of Sindh, Jamshoro, Sindh, Pakistan*

### Abstract

The paper presents the results of a surface geophysical survey which was performed at Aber College Farm Area, N.Wales, U.K, using resistivity, electromagnetic soundings and chemical methods to detect the extent of the saline intrusion in the area.

A total of thirty four Vertical Electric Soundings (VES) and sixteen Electromagnetic (EM) soundings were measured in the study area. Several of these soundings were measured adjacent to borehole sites to aid in correlating the geophysical interpretations to chemically detected water quality data. By correlating the interpreted surface geophysical to water quality data from the boreholes, depth to a bulk resistivity of less than 35 ohm-m (or more than 250 ppm chloride concentration) and depth to a bulk resistivity of less than 7 ohm-m (or more than 500ppm chloride concentration) could be mapped in both the aquifers.

The permeability values of the sediments by pumping and other field and laboratory tests gave additional supporting data.

The study revealed that the combined electrical and chemical observations provide a dependable means for the detection and mapping of a saline intrusion and that the two aquifers in the area have been intruded. And the extent of saline intrusion is a function of permeability and the volume of fresh water available to prevent inland movement.

### Introduction

Because of the ever present danger of contaminating a potential aquifer with saline water in coastal areas by inappropriate groundwater exploitation, an important part of a hydrogeological investigation should be the detection of the saline-fresh water interface.

The application of vertical electric soundings and electromagnetic soundings is based on the fact that materials saturated with saline water represent much better conductors; than similar materials filled with fresh water. However, the accuracy of the electrical methods depend on the geological subsurface conditions, as the presence of other good conducting sediments, such as intercalated clay layers, can affect the correct interpretations of electrical data. Nevertheless, this disadvantage can often be overcome by increasing the number of the electrical soundings and constructing vertical sections of the area. From the manner in which the resistivity values vary over large areas, it is then possible to determine whether clay layers are present or not.

The goal of this study, a part of the Ph.D research programme carried out at the University of Wales, Bangor, U.K., was to relate vertical electric and electromagnetic soundings data to existing boreholes or to boreholes data drilled for this purpose. The chloride concentrations of the water samples collected from the boreholes, were determined and simultaneously correlated with the formation resistivities. Laboratory measurements of some sediment parameters from the site were made to examine the effect of permeability on saline intrusion.

**Previous Work:** Before moving to methods used for the detection of the saline-fresh water interface, it is worthwhile at this juncture to look at some previous work in this area, particularly geophysical and chemical methods.

Use of direct-current resistivity methods is not new to water resources investigations. As early as 1937, Swartz (1937) used this technique for locating fresh water lenses in salt water bodies on the Hawaiian Islands. Since then, much resistivity work on the detection of fresh-salt water interface has continuously been done in other parts of the world (Zohdy et al., 1974; and Gorhan, 1976).

The auxiliary point method (Ebert, 1943; Orellana & Mooney, (1966) for the approximate interpretation of resistivity soundings through curve matching was extensively used before the introduction of the iterative computing method. As the resistivity method is time consuming in that individual soundings may take from several hours to several days depending upon surface conditions and the required

depth, inductive EM electromagnetic techniques have been developed in the last 20 years or so. As inductive measurements require no contact with the surface, while in resistivity measurements current has to be introduced into the ground by means of electrodes, these techniques have certain advantages. Max-Min is the more traditional horizontal loop EM measuring system which measures in-phase and out-of-phase EM field responses. It is an effective system in obtaining the resistivity and thickness of the subsurface layers. Interpretation is done by computer software curve matching.

### Instrumentation & Techniques

**Resistivity Methods:** In the present study the techniques have been limited to one of the most commonly used Wenner electrode array, although the Wenner at some sites have made use of the Offset system (Barker, 1981).

The Offset Wenner system which has several advantages over both the schlumberger and conventional Wenner system developed at the University of Birmingham, was also used. By this system, it is possible to overcome the lateral resistivity variations, which are not detectable by other methods. It is also less time consuming. ABEM's battery operated resistivity meter, the Terrameter SAS 300, was used in measurements of all the Vertical Electric Soundings (VES) taken under different arrays.

The electromagnetic survey was carried out with the Max-Min I-8 (commonly known as Apex Max-Min) portable instrument. It permits the choice of eight octavely spaced operating frequencies i.e. 110, 220, 440, 880, 1760, 3520, 7040, and 14080HZ. To arrive at the much needed parameters, the most commonly used transmitter powered operating mode, MAX 1 (also known as the horizontal loop mode) is used; it is an effective mode in obtaining the resistivity and thickness of the subsurface layers.

**Interpretations:** The apparent resistivity/electrode separation curve obtained by vertical electric soundings is interpreted by the use of the computer software Bossix, and EM soundings by the use of EMIXMM programme both produced by the Interpex Ltd. These are in fact forward and inverse modelling programmes for interpreting soundings. Graphic displays obtained by EMIXMM are presented as in-phase and quadrature response versus induction number or as Argand diagrams (Eadie, 1979).

**Conductivity of Groundwater:** As conductivity is preferred rather its reciprocal resistivity, because the former increases with salt content, the conductivity of ground water samples is determined for all the water samples obtained from most of the VES sites. The conductivity of each groundwater samples so obtained is used to calculate Total Dissolved Solids (TDS).

The conductivity of groundwater samples is determined by a conductivity meter called Aqua-Lytic, which automatically gives water conductivity in mhos/cm at a reference temperature of 25°C. The accuracy of the instrument is checked out by calibrating at 25°C prepared standard solutions of 10, 100, and 1000 mg/l NaCl. A percentage error of  $\pm 2\%$  was arrived, which can be considered to be negligible.

**Determination of Chloride Ions In Groundwater by Chemical Methods:** Chloride in groundwater sample is most conveniently determined using atomic absorption spectroscopy (AAS). The first step is to quantitatively precipitate silver chloride by the addition of a known amount of silver nitrate. The amount of chloride in the original sample is then known by the determination of excess silver in the solution, when the precipitated silver chloride has been removed (Reichel, 1969; Truscott, 1970).

### Correlation of Formation Resistivity to Chloride Concentration

As measurement of fluid conductivity cannot resolve the type of dissolved solids. To derive more quantitative information about concentration of dissolved solids, an attempt has been made to correlate formation resistivities measured through direct resistivity methods to chloride concentration.

First, water samples from boreholes were collected and chemically analysed for chloride anions. The electrical conductivity for all the samples were determined and it ranged from 240 to about 10000  $\mu$  Mhos/cm at 25°C. Table 1 enlists all the details of the data obtained from the boreholes and with analysis carried thereon. The relation between chloride concentration and water conductivity on samples from boreholes was investigated. The data obtained from the site is summarized in Figure 1. Each dot represents one sample. The correlation coefficient is equal to 0.998.

On the basis of Figure 1, 500ppm chloride concentration correspond to a fluid conductivity of about 1900  $\mu$  Mhos/cm or a fluid resistivity of about 5 ohm-m and 250ppm chloride concentration correspond to a fluid conductivity of about 950

# Mhos/cm or a fluid resistivity of about 10 ohm-m. This is not far away from the information summarized by Kwader (1986), who has put 500ppm chloride concentration corresponding to a fluid resistivity value of 9 ohm-m. Here specially 500ppm chloride concentration has been selected because boreholes/wells that reach chloride concentration of 500ppm are considered to be significantly intruded with seawater (Goswami, 1968; Mills et al., 1988), and is taken as a basis for the fresh-salt water interface. In the present study on the other side 250ppm chloride concentration, which also correspond to a measured bulk resistivity value of 35 ohm-m (Table 1), is selected as the basis of a mixing zone (transition zone). This value is in more agreement to Mills and Ryder (1977); and Stewart et al., (1982) who have put the lower limit of the mixing zone between 200- 250ppm chloride concentration than Goswami (1968) who puts the lower limit at 300ppm chloride concentration.

To correlate formation resistivities to chloride concentration, the results of the interpretation of VES measurements are compared with the chloride concentration data of groundwater samples obtained from certain depths in the boreholes. And by carefully selecting resistivity sounding results of good quality, and representative of the regional hydrologic regime, some six data points were selected for the study area. These data points are shown in Figure 2. This figure is used for converting the aquifer resistivity into the chloride concentration of the groundwater at the location of measurement. On the basis of this figure, an aquifer resistivity of about 7 ohm-m is expected to correspond to a chloride concentration of 500ppm. This value is nearly in agreement with the work of Mills et al. (1988) and Hoekstra et al., (1990) who have shown it to correspond to a bulk resistivity of 8 ohm-m.

### Data Acquisition and Reduction

In the present study, the site of investigation, the College Farm area at Aber (Figure 3) is situated on the coast at the outfall point of the Aber river near Llainfairfechan in Gwynedd, North Wales, U.K. This is a part of the Ph.D thesis work carried out in years 1991-92 at this site. From the interpreted Quaternary stratigraphy of the A55 North Wales Coast Road at Llainfairfechan (Based on borehole logs collected for their construction, and the data obtained by sinking boreholes by manual percussion method in the study area), the lithological units in the area can be divided into two major groups: (a) the Holocene, which comprises of surface fill, sand & gravel, clays & silts & peat and (b) Pleistocene, which comprises of sand & gravel, Irish sea Till (Poorly sorted gravel-sand-mud

admixture) and Welsh Till. The geological and hydrogeological information reveals the presence of two aquifers in the study area separated by the impervious glacial till.

Average rainfall per year in years 1991 and 1992 was 1050mm. Using Cooper et al. (1964) equation, an approximate rate of flow of the fresh water to the coast is estimated to be 50 m<sup>3</sup>/day/m.

Thirty-four VES soundings were made at selected sites Figure 3 with the ABEM's Terrameter resistivity meter. Simple Wenner and Offset Wenner arrays were used upto the maximum electrode spacings ranging from 40m to 80m for the Simple Wenner array and 32 to 64m for the Offset Wenner array. Sixteen electromagnetic soundings were also made at the selected centres of the sites where previously VES soundings were made, using Max-Min 1-8 portable equipment.

Figure 4a shows an example of a comparison of field data to a mathematically fitted curve at site 10B. Lithologic information from an adjacent boreholes 10/2 was used to constrain the layer thickness in the VES interpretation. First the third layer consisting of sand & gravel (upper aquifer) was found to be conductive and 5.2m thick. The higher resistive layers either side of layer 3 means that ambiguity of interpretation due to equivalence would be a problem unless there was some external control. It was found convenient to divide this layer into two on the basis of results of water chemical tests and borehole log, providing a more complex seven layer model which was not resolved by the sounding curve. The inversion process then gave the best possible model along with the other close fitting models which are shown alongside the field curve (Figure 4a). Table 2 shows the comparison of the geological drill log, in borehole 10/2 and the interpreted results of the VES and EM soundings done near the borehole at site 10/B.

The complex model of seven layers thus obtained by using VES was then fed into the computer software EMIXMM programme for further inversion. Its equivalence programme was also started which finally gave a model in good agreement with the VES model having minimum percentage of fitting error (Figure 4b).

A geoelectric section Figure 5 A — A has been drawn after taking into account the ground surface leveling at the site. This is drawn perpendicular to the coast and across various sites of VES and EM soundings as well as borehole sites

10/1 and 10/2D in the area map (Figure 3). In the upper and lower aquifers a change in the salinity is easily detected through observation of change in the bulk resistivity of the aquifers. In the upper aquifer the mixing zone is separated from fresh water by the bulk resistivity range from 31 ohm-m (inland) to the 15 ohm-m (coast) with chlorides ranging from 250ppm to much higher values. In the lower aquifer, the mixing zone lie above and behind the saline water, with bulk resistivities range from 32 ohm-m to 8 ohm-m and chlorides between 250-500 ppm.

A second geoelectric section D-D' Figure 6, drawn perpendicular to the coast. The mixing zone in the main aquifer has bulk resistivities range from 8 ohm-m to 35 ohm-m with chlorides ranging from 250-500ppm. The saline water has bulk resistivities from 1 ohm-m to less than 18 ohm-m (up to 7 ohm-m) with chlorides more than 500ppm. Glacial Till acts as barrier and prevents the further saline intrusion. A third and final geoelectric section E-E' Figure 7, is also drawn perpendicular to the coast line.

The last stage of the detection of the saline-fresh water interface is the construction of the saline-fresh water interface contour maps in order to detect the extent to which saline water has intruded inland. All the geoelectric sections previously discussed have been used in the construction of these maps of the study area. The maps figures 8, 9 and 10 show the extent of contamination and saline zones.

**Permeability of the Sediments:** Using boreholes in the study area pumping tests were carried out to arrive at the permeability of the sediments. Besides, constant head test in the field and grain size and constant head permeameter tests in the laboratory were also used to calculate the permeability of the sediments. Table 3 summarizes permeability values measured or calculated by the different methods.

## Discussion

The contour maps Figures 8 and 9 show the extent of the contamination zones with salinity 250-500ppm chlorides in upper and lower aquifers. In the upper aquifer the contamination is restricted to a 100 metres wide coastal strip and has spread to a depth of 3 metres inland, whereas in the lower aquifer it has spread to about a 300 metres wide strip and to a depth of 50 metres inland.

**Table 1**  
Chemical Analysis of groundwater samples for Chloride ions

B.H. No.	Conduct. Mhos/cm at 25°C	Esti. fluid -m	Meas- ured aquifer resist	TDS (ppm)	Cl- concent- ration (ppm)
10/2D	240	42	157	154	58
10/2	290	34	110	185	70
10/1 T	500	20	54	320	131
10/1 TB	660	15	54	423	200
10/BT	900	12	40	578	244
10/1 B	1180	8.5	31	755	330
12	3200	3.2	6	2048	880
13	6600	1.5	3	4224	1820
14	5480	2	4	3507	1402
15	4922	2.1	4	3150	1450
16	9910	1	1	6342	2732

The saline water (Figure 10) with salinity of more than 500ppm chlorides has spread to a 100 metres wide coastal strip and a depth of 34 metres inland. Looking at the strip around the Aber river in Figures 8, 9 and 10, it is evident that the area surrounding the river is least affected either by contamination or extensive salinity as compared to other areas along the coastal area. This suggests that probably continuous fresh water infiltration from the Aber river prevented the saline intrusion in this section of the area. As there is heavy rainfall in the area, and most of the rain water infiltrates underground, with little or no withdrawal of groundwater, this has kept the gradient of fresh water towards the sea (refer rate of flow to the coast 50 m<sup>3</sup>/day/m) and in turn has restricted the saline water to a considerable depth.

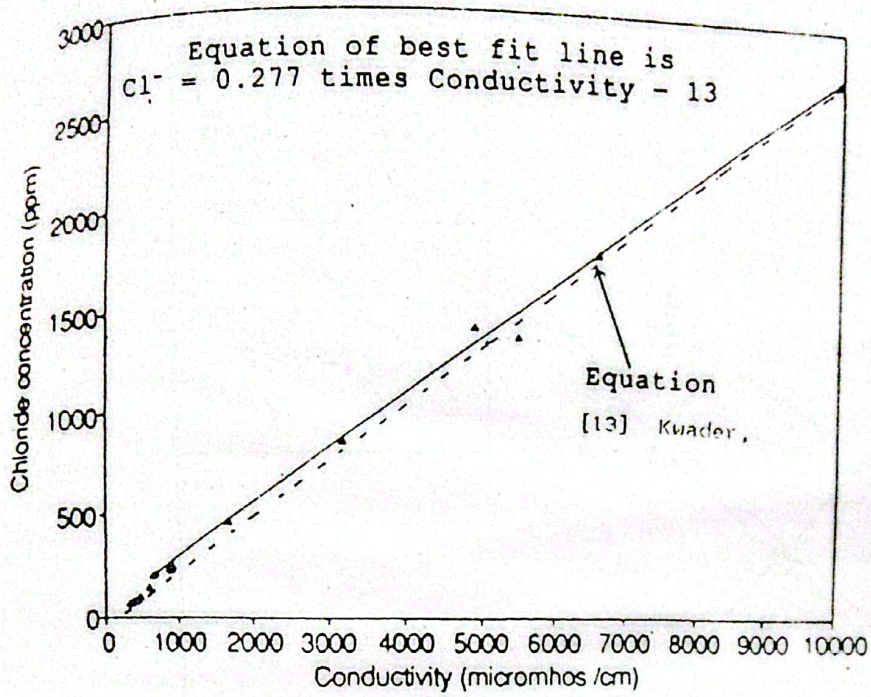


Fig. 1. Relation measured between Chloride concentration and fluid conductivity on water samples.

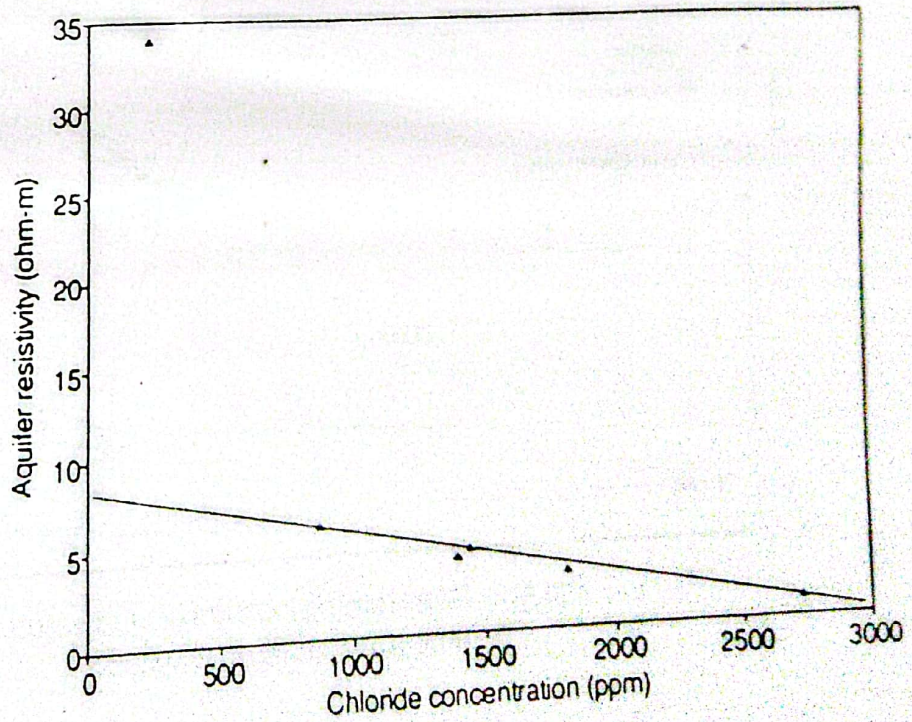


Fig.2 Relation between Chloride concentration and aquifer resistivity in selected borewells.

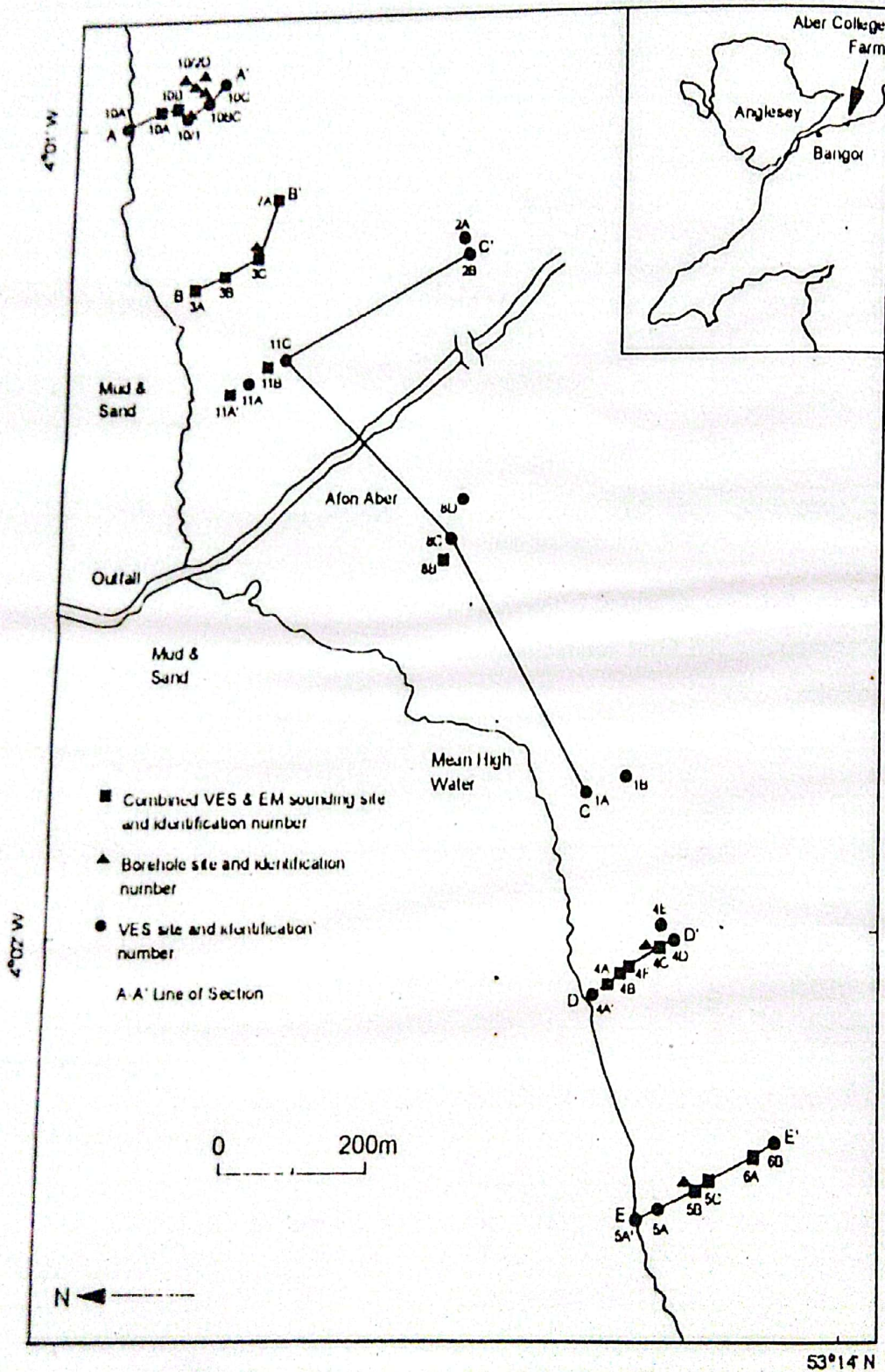
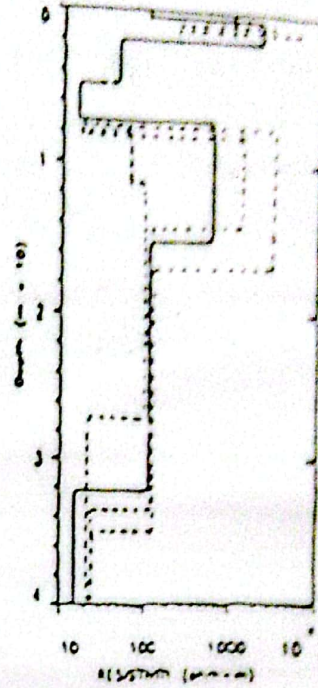
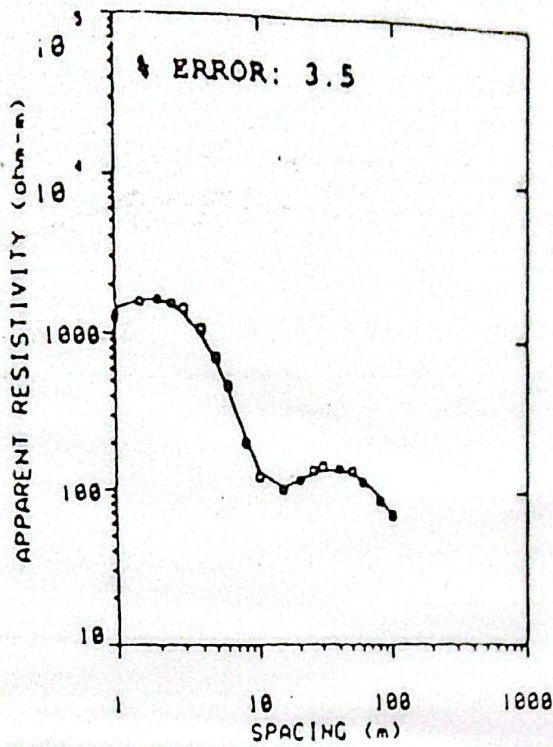
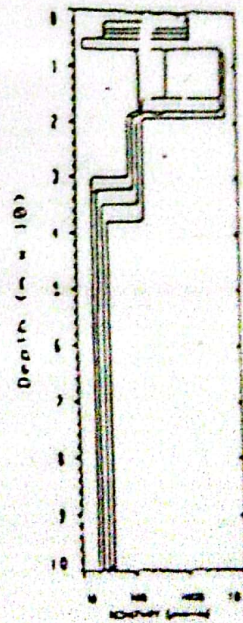
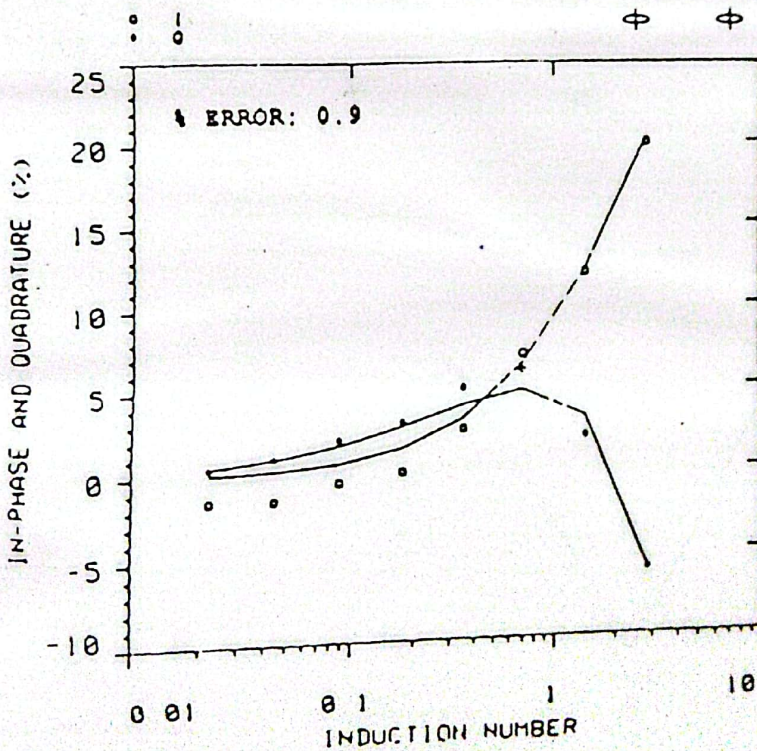


Fig 3. Map showing location of study area, Aber College Farm, Gwynedd



.a.



.b.

Fig. 4. Vertical electric sounding curve (a) and electromagnetic sounding curve (b) at site 10B based on field data points, alongside their equivalence curves.

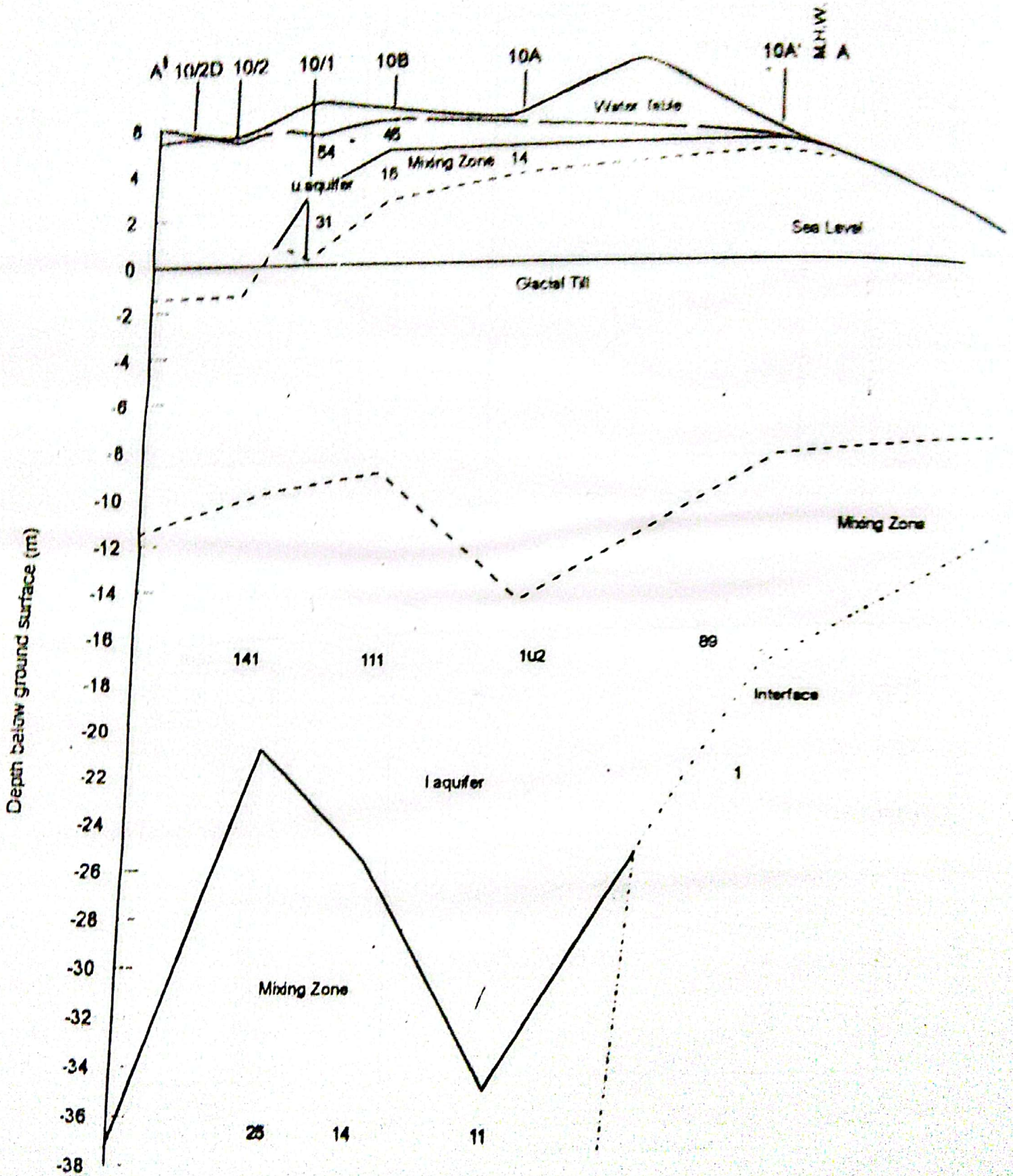


Fig. 5. Saline and fresh water interface along line A-A'.  
Scale: Hor: 1:1000, Vert: 1:200.

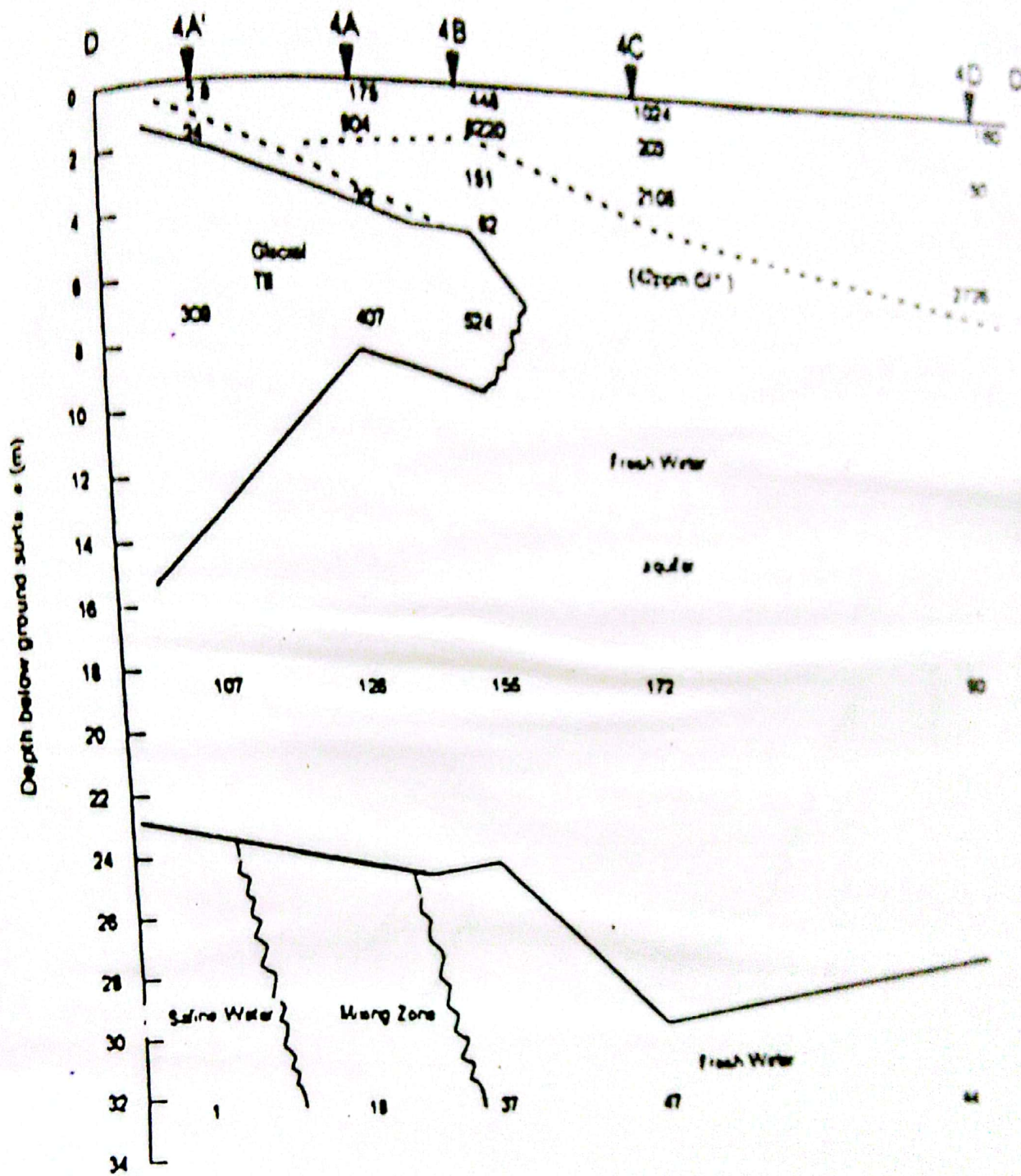


Fig. 6. Geoelectric section D-D' derived from vertical electric and electromagnetic soundings.  
Resistivities in ohm-m.  
Scale. Hor. 1:750, Vert. 1:200.

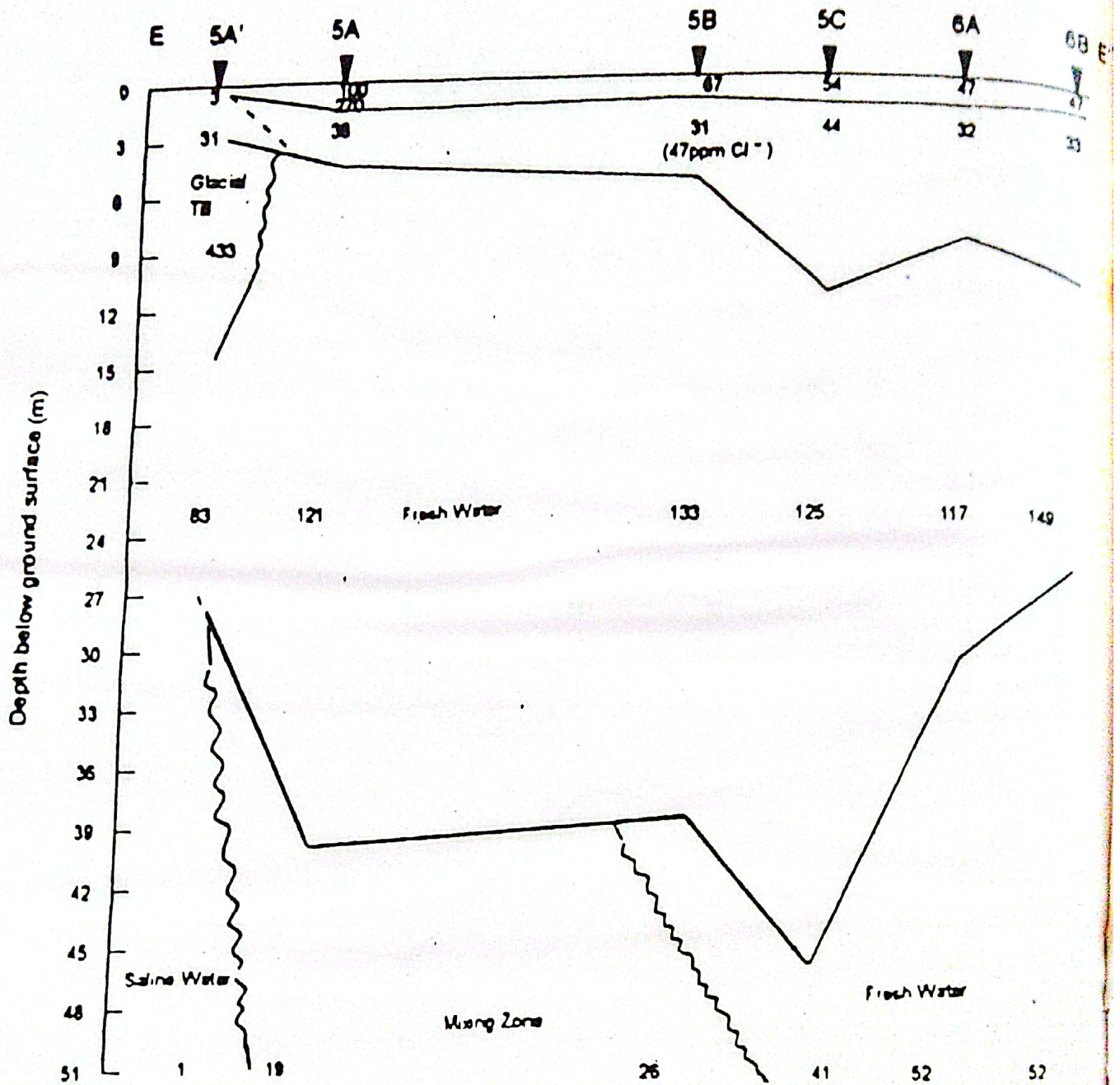


Fig. 7. Goelectric section E-E' derived from vertical electric and electromagnetic soundings.  
 Resistivities in ohm-m.  
 Scale: Hor: 1:1000, Vert: 1:300.

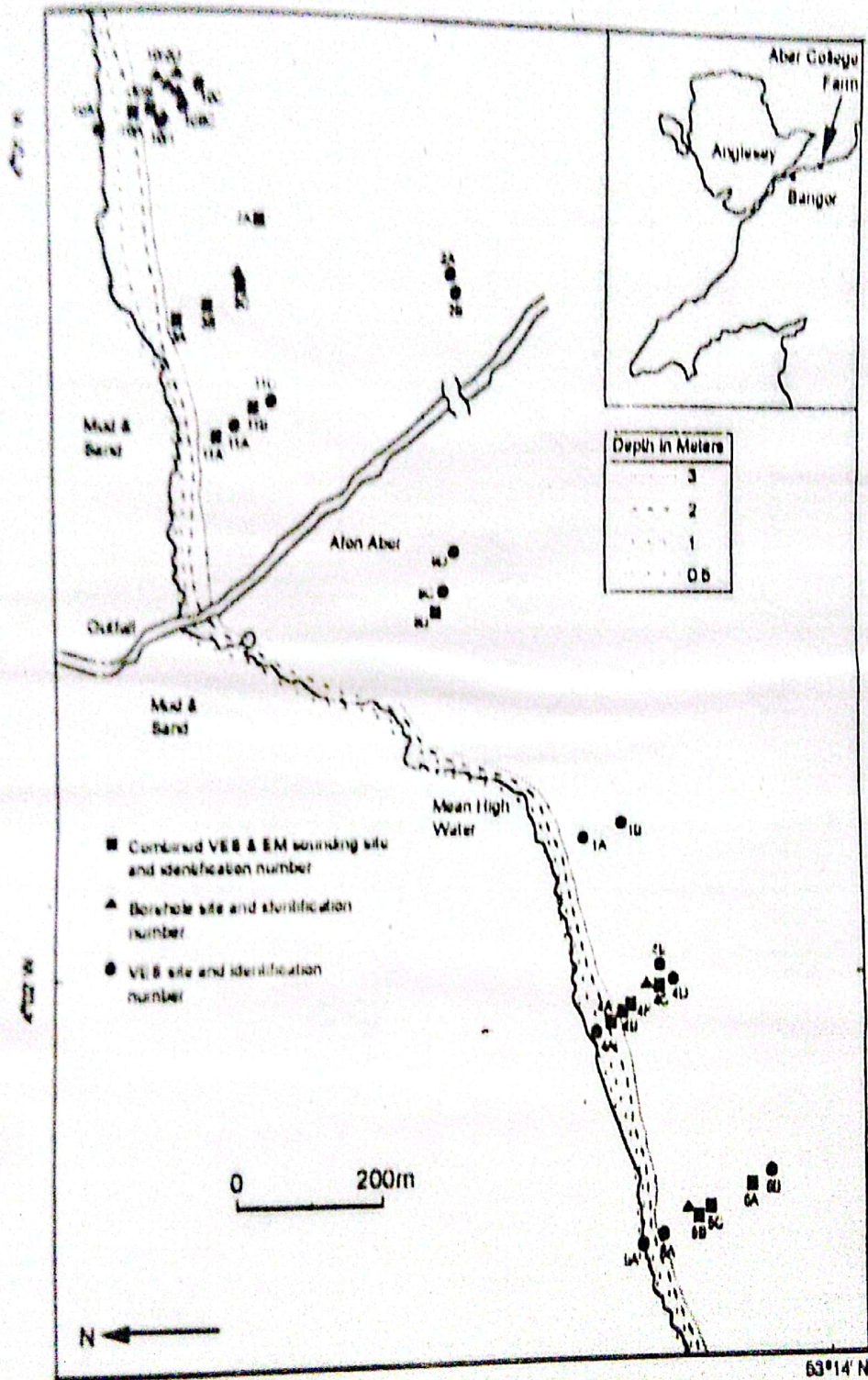


Fig 8. Depth to a bulk resistivity of less than 35 ohm-meters (or more than 250ppm chloride concentration) Upper aquifer, Aber College Farm.

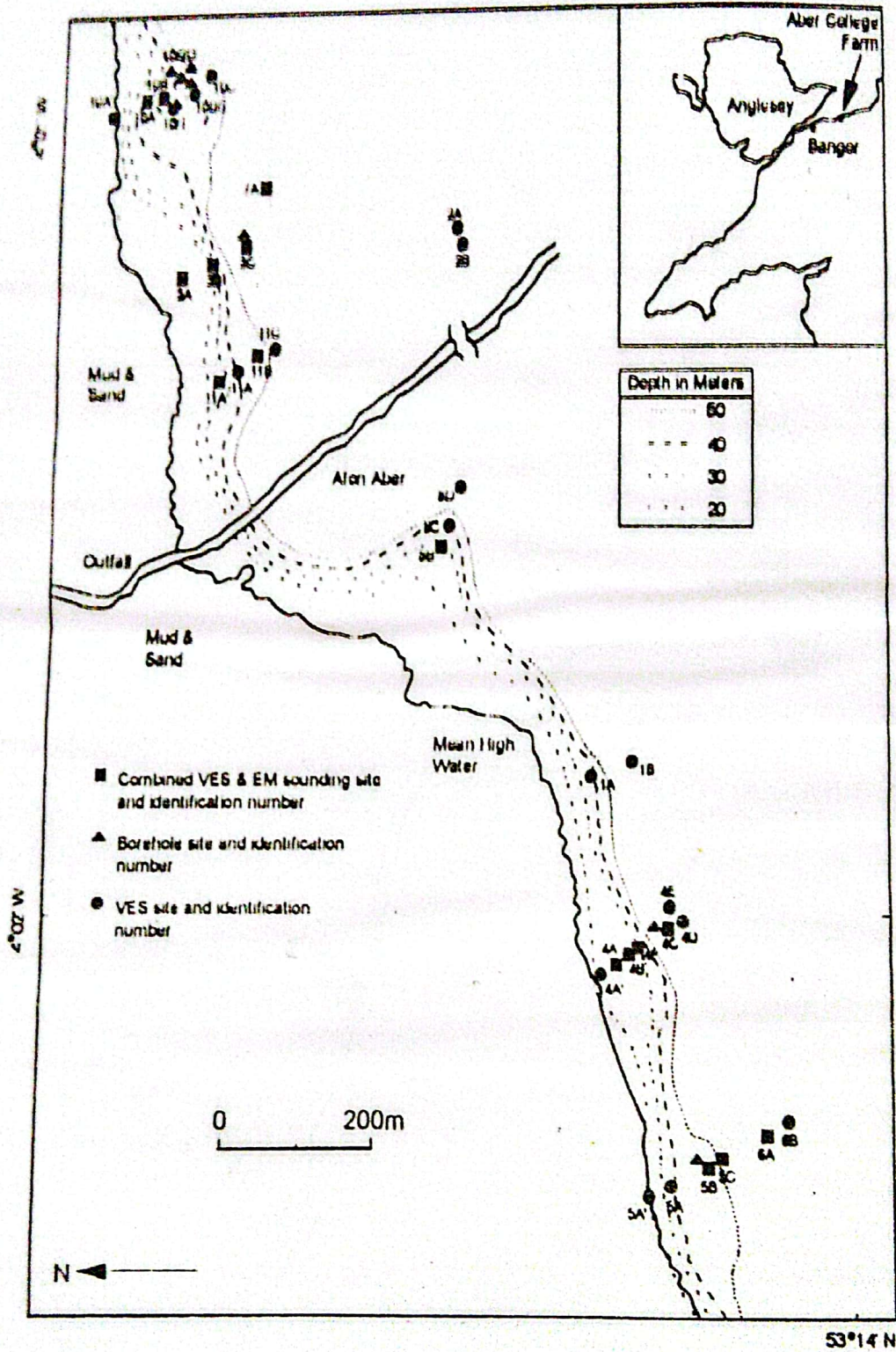


Fig 9. Depth to a bulk resistivity of less than 35 ohm-meters (or more than 250ppm chloride concentration) Aber College Farm.

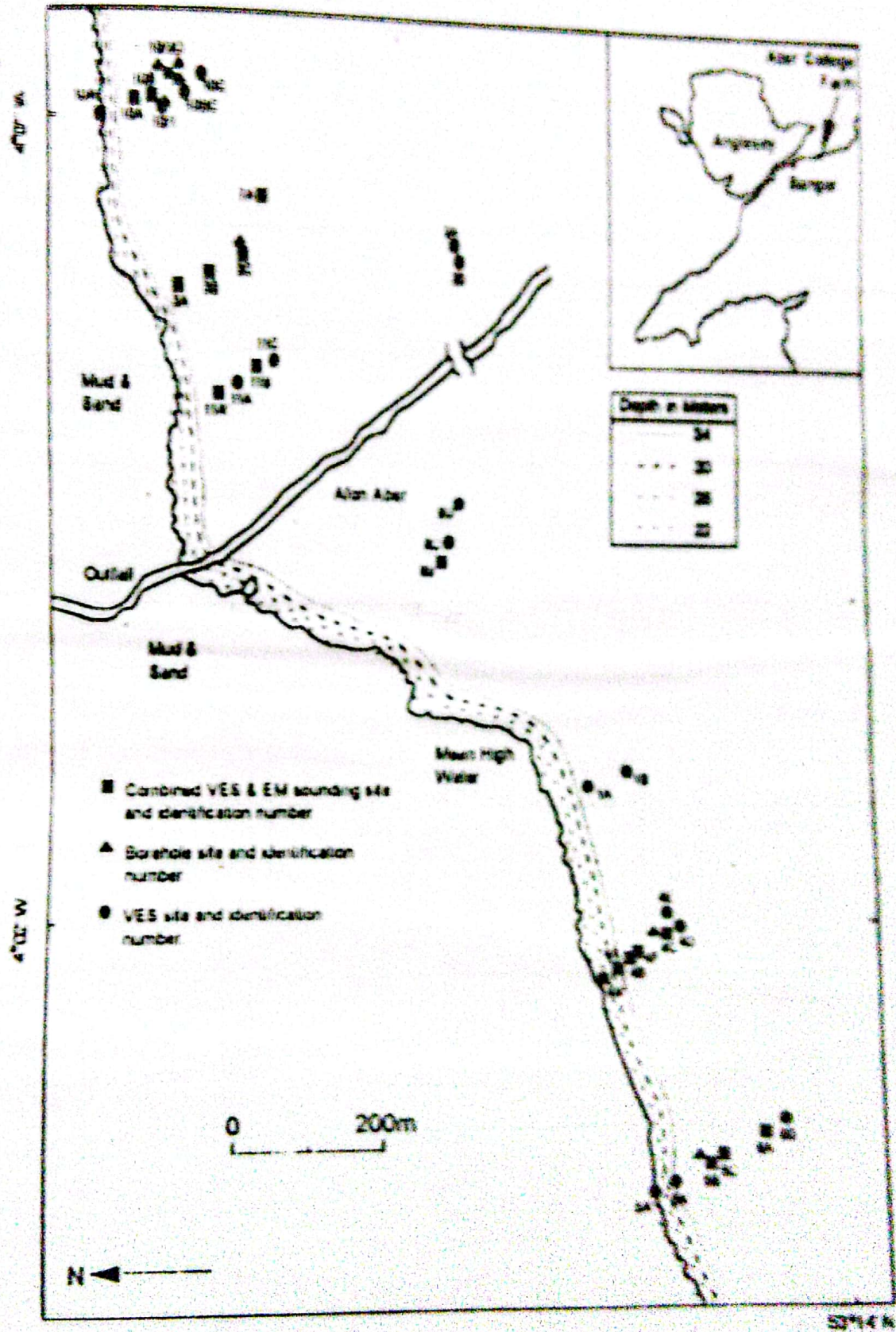


Fig 10. Depth to a bulk resistivity of less than 7 ohm-meters (or more than 500ppm chloride concentration) Aber College Farm

Table 2

Vertical electric and electromagnetic soundings data 10B with geologic log near borehole 10/2, Aber college farm.

Layer Number	VES Sounding Resistivity in ohm.m	VES Sounding Thickness in (m)	EM Sounding Resistivity in ohm.m	EM Sounding Thickness in (m)	Geological Drill Log
1	100	0.5	101	0.5	Silty and clayey soil with fine sand & gravel (1m depth).
2	2090	1.5	1593	1.5	Coarse sand and gravel (1.9 m - depth).
3	45	2.8	40	2.8	Thin lenses of peat & clay. Sandy silt with gravel saturated with water (4.6m - depth).
4	15	2.4	15	2.4	Sandy silt with gravel saturated with contaminated water (depth 7m). E.o.h.
5	614	8	550	10	Boulders, gravel, sand & mud admixture (correlated data)
6	111	17	126	15.5	Gravel & sand saturated with water (correlated data)
7	15	-	20	-	Gravel & sand saturated with contaminated water (correlated data)

Table 3

Method	Permeability (m/s)
1. Pumping test	$7.4 \times 10^{-4}$
2. Constant head (Field test)	$7.6 \times 10^{-4}$
3. Constant head (Lab. test)	$1.7 \times 10^{-3}$
4. Grain size (Hazen's formula)	$2.7 \times 10^{-3}$
5. Grain size (Kozeny-Carman)	$7.7 \times 10^{-4}$
6. By using electrical formation factor	$1.6 \times 10^{-3}$

The moderate values of measured permeability and transmissivity is another important reason for minimizing the rate of landward advance of the intruding saline water, as Howard (1987) has shown.

### Conclusions

Electrical resistivity depth probing (VES), electromagnetic soundings (EM) and chemical tests on groundwater samples obtained from boreholes indicate the existence of a saline-fresh water interface and a zone of mixing in the study area.

The extent of saline intrusion is a function of permeability and the volume of fresh water (either from rainfall or river flow or both) available to prevent inland movement; it is also a function of the availability of any natural barriers such as glacial till and bed rock.

### References

- Barker, R.D. (1981). The Offset system of electrical resistivity sound and its use with a multicore cable. *Geophysical Prospecting.*, v.29, p.128-143.
- Cooper, H.H.Jr., Kohout, F.A., Henry, H.R. and Glover, R.E. (1964). Seawater in coastal aquifers. U.S. Geological Survey Water Supply Paper 1613-C., P.C12-C32.
- Eadie, T. (1976). Stratified earth interpretation using standard horizontal loop EM data. *Research in Applied Geophysics*, No.9, University of Toronto, Toronto, Ontario, Canada.
- Ebert, A. (1943). Grundlagen Zur Auswertung Geoelektrischer Tiefenmessungen en. *Beitr. Angew. Geophys.* 10: 1-17.
- Gorhan, H.L. (1976). The determination of the saline-fresh water interface by resistivity soundings. *Bull of the Assn. of England Geol.*, 13, p. 163-175.

- Goswami, A.B. (1968). A study of salt water encroachment in the coastal aquifer at Digha, Midnapore district, West Bengal, India. *Bull. Int. Assoc. Sol. Hydrol.*, 13(3), p.77-87.
- Hoekstra, P., and Blohm, M.W. (1990). Case histories of domain electromagnetic soundings in environmental geophysics. *Geotechnical and Environmental Geophysics.*, v.II., 1-16.
- Howard, K.W.F. (1987). Beneficial aspects of seawater intrusion. *Ground Water*, v.25., no.4., p.398-406.
- Kwader, T. (1986). The use of geophysical logs for determining formation water quality. *Ground Water.*, v.24., p.11-15.
- Mills, L.R. and Ryder, P.D. (1977). Salt water intrusion in the Floridan aquifer, coastal Citrus and Hernando Counties, Florida, 1975. *US geological Survey Water Resources Investigations.*, P. 77-100.
- Mills, T., Hoekstra, P., Blohm, M.W. and Evans, L. (1988). Time domain electromagnetic soundings for mapping seawater intrusion in Monterey county CA. *Ground Water.*, 26, p. 771-782.
- Orellana, E. and Mooney, H.M. (1966). *Master Tables and Curves for vertical electric soundings over layer structures.* Interolencia, Madrid, p.34.
- Relchel, W. (1969). *Analytical Chemistry.*, Acs. L., 41(13), p.1886-1969.
- Soomro, S.A. (1993). *Detection of Saline Intrusions in Coastal and Estuarine Sediments.* Unpubl. Ph.D thesis.. University of North Wales, Bangor, U.K.
- Stewart, M., Lizanec, T. and Layton, M. (1982). *Application of DC resistivity surveys to regional hydrogeologic investigations, Collier county, Florida.* South Florida Press, West Palm Beach.
- Swartz, J.H. (1937). Resistivity studies of some salt water boundaries in the Hawaiian Islands. *Trans Amer. Geophysical Union.*, v.18., p.387-393.
- Truscott, E.D. (1970). *Ibid.*, 42(13), p.16557.
- Zohdy, A.A.R., Eaton, G.P. and Maybey, D.R. (1974). *Application of surface geophysics to groundwater investigations.* U.S. Geological Survey., p.116.