British Geological Survey

REGIONAL GEOPHYSICS RESEARCH GROUP

Report 85/4

REPORT ON GEOPHYSICAL STUDIES RELATING TO THE COASTAL AQUIFER OF THE MOMBASA DISTRICT, KENYA

R M Carruthers

NATURAL ENVIRONMENT RESEARCH COUNCIL

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R. M. Carruthers

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SUMMARY

Airborne electromagnetic coverage of the Coastal Plain within 110 km of Mombasa provides information on conductivity variations to depths of 50-100 m. Conductivity levels are generally high due to saline water occuring at shallow depth within the fossil reef by the coast, and to the presence of Jurassic shales which outcrop to the west. Zones of higher resistivity are found over the sandy facies of the Plio-Pleistocene reef complex and one of these coincides with the site of the Tiwi aquifer. However, resistivity sounding data indicate that the reduced INPUT amplitudes relate to their intermediate position between formations of high conductivity and not directly to the aquifer: the back-reef deposits comprise a mixture of sands and clays underlain at least in part by (?)Tertiary clays which have resistivities in the range 20-50 ohm.m.

The results of geophysical surveys by Austromineral to the south of Mombasa have been reinterpreted to show the ambiguity inherent to the data: their resistivity sections give more detail at depth than is justified by the quality of the data. Resistivity results provide an indication of the major lithological variations but quite different conditions can give identical resistivities and it is not possible to identify positively the freshwater producing zones. Seismic refraction methods also failed to resolve the back-reef sequence. A combination of induced polarization and resistivity methods might provide more information on clay content and water salinity but this approach has not been tested here.

Additional resistivity results in the less-developed region north of Mombasa supported the view that aquifer conditions deteriorate towards Malindi. Conductivity values are generally higher in response to saline water at shallow depth within less premeable, finer-grained sediments. Resistivity values of 30-40 ohm.m obtained over Baraumu deposits near Malindi were similar to those given by the 'claystone' south of Mombasa and by the material causing the INPUT low near Msambweni. Similar values could be obtained from a water-saturated sand/clay sequence but it seems likely that Tertiary deposits have been detected below the reef complex in much of the region.

Further geophysical investigations are not recommended at this stage for siting boreholes although reference should be made to the INPUT maps: borehole logging data would be useful for correlation with surface results and for defining the aquifer in more detail. Additional work should be considered if drilling results prove unsatisfactory due to salinity problems or to the occurrence of lateral variations in lithology.

CONTENTS

DIAGRAMS

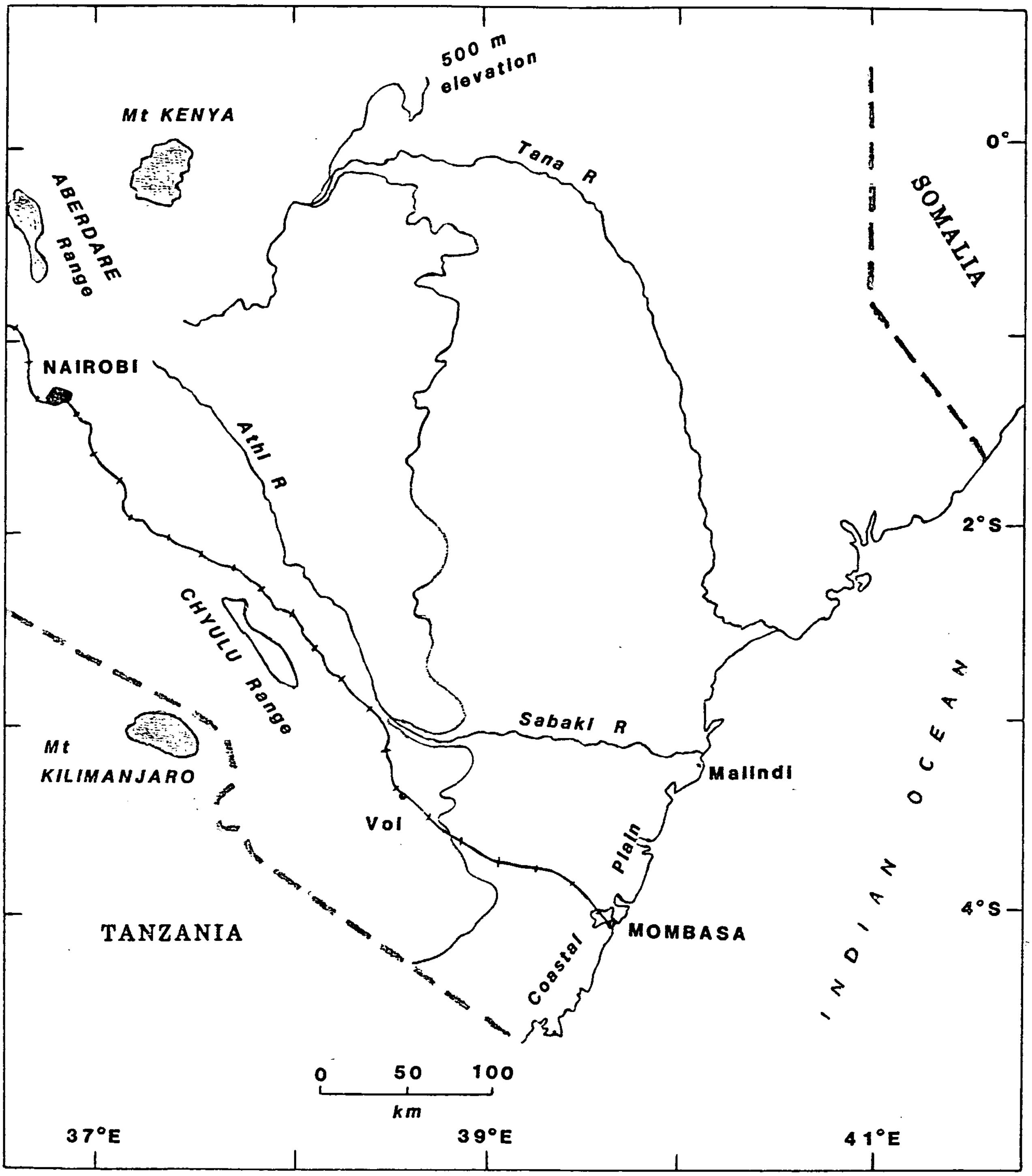

Fig 1. Regional location map

1. INTRODUCTION

The British Overseas Development Administration (ODA) supported a visit to Kenya during 1980 for an assessment of the potential for developing ground-water resources in the coastal region around Mombasa (see Fig 1). Following the recommendations which resulted from this appraisal (Buckley,1981) it was agreed with the Ministry of Water Development (MOWD) that a Technical Cooperation project should be set up to undertake a comprehensive hydrogeological study of the area from the border with Tanzania in the south to the Sabaki River north of Malindi, encompassing about 200km of coastline and extending inland to include parts of the Foot Plateau and Coastal Range. The emphasis initially was to be on establishing the resources available within the known Tiwi aquifer system to the south of Mombasa before looking at the Mombasa-Kilifi, and the least promising Kilifi-Malindi, districts in greater detail. This project effectively commenced in May 1984 after the UK hydrogeologist took up residence in Mombasa.

Geophysical surveys for groundwater exploration had already been carried out and it was felt that the significance of this work should be evaluated at an early stage of the project so that the results could be incorporated into the programme. Accordingly, the visit of a geophysicist was arranged for July-September 1984. Of the six weeks based in Mombasa, five were devoted to fieldwork, mostly in the less well-known areas to the north, with the remaining time being spent on assembling the existing information and on a preliminary data analysis. The interpretation and report writing were completed in the UK. Telford(1976) provides general background information on the theory of the geophysical methods and their use in the field.

2. GEOLOGY

The geological reports of Caswell(1953;1956) and Thompson(1956) provide detailed descriptions of the formations occurring near the coast. Buckley (1981) gives a comprehensive summary which includes results of the recent remapping undertaken by the Mines and Geology Department with UK assistance: new maps have yet to be published but provisional copies are available at a scale of 1:50,000. Some of the main features of the local geology are repeated here for completeness.

The regional strike of the strata tends to parallel the coast on a SSW-NNE trend and the dip is to the east with the older Karroo sediments outcropping on the higher ground inland. These Karroo rocks form part of an extensive sequence which includes both arenaceous and argillaceous components. They appear to have limited groundwater potential as wells typically show poor yields of a brackish water fit only for consumption by livestock. The best prospects are thought to lie in the upper units, especially the Mazeras Sandstone Formation, where increased secondary permeability due to structural disturbance may be combined with higher rainfall and recharge, and a reduced risk of contamination from older waters, as for example in the Shimba Hills, a part of the Coastal Range.

Jurassic sediments are predominantly shales with subordinate limestones of marine origin which were laid unconformably on the Mazeras Sandstone; faulted contacts are also seen. These shales make up much of the Foot Plateau, between a Mazeras escarpment and the Coastal Plain, and they can be regarded as forming an impermeable barrier dipping seawards beneath the more recent sediments. Limestone beds may provide a groundwater supply but they have limited outcrop width and there is little evidence of their potential.

The Cainozoic deposits of the coast comprise a sequence ranging from clays to sands and reef limestone as the nature of sedimentation varied in response to changes in sea-level, drainage patterns and the proximity of high ground inland. The oldest beds, Baratumu Formation of Tertiary age, tend to be clay-rich although conglomerates, sands and limestones are found together with the marls and hard clays. The subsequent Marafa Beds, as seen north of Malindi also consist mainly of fine grained sediments but their presumed lateral equivalents south of Mombasa are coarser in part. The similarity of these formations in a given area combined with the lateral changes in lithology make indentification and correlations uncertain. Borehold yeilds tend to be low and suitable only for supplementing local rural supplies.

The Magarini Formation has an outcrop which extends for most of the length of the project area, lying to the back of the Coastal Plain and lapping onto the Foot Plateau. The generally coarse-grained but poorly-sorted, derived material of the Lower Magarini suggests that deposition was associated with the erosion of a land surface rejuvenated by faulting. In contrast, the Upper Magarini is characterised by a well-sorted dune-sand which is typically reddened by iron oxide. The thickness of these Magarini beds exceeds 100 m in places but for the most part they seem to lie above the water-table; their fine-grained texture will in any case tend to restrict borehold yields.

The Pleistocene reef complex can be considered as two components, with a sandy back-reef facies lying inland of the reef limestone itself. This sandy facies may be an extension of the Lower Magarini. It consists of sands, both coarse and fine, with clays and limestone debris which were deposited in a lagoonal environment. The poorly-consolidated nature of this material gives it very good aquifer properties locally, as proved by boreholes into the Tiwi aquifer, although lateral variations associated with the location of inflow channels and the reworking of the sediments can be expected. Changes in sea-level influenced the development of the coral reef and a total thickness of more than 100 m occurs near Mombasa. Austromineral(1980) report some good well yields from the fossil reef but with a risk of sea-water contamination unless the output is controlled carefully. As the reef is relatively compact, its ability to transmit water can be attributed to solution cavities and facies variations. Normal faults seen as predating the pre Plio-Pleistocene rocks usually trend along the regional strike and downthrow to the coast; a subordinate set lie NW-SE with a downthrow to the northeast.

3. PREVIOUS GEOPHYSICAL SURVEYS

3.1 Gentle report

The first comprehensive study of the hydrogeology of the coastal district around Mombasa was produced in 1968 by Gentle who considered the 70 km long strip from Gazi in the south to Mtwapa Creek, 10 km north of Mombasa. In the course of this work he took resistivity soundings with a Wenner array for comparison with borehole data. The results indicated that resistivities decrease through both the sands and coral, from values of several hundreds of ohm.metres within the dry and unsaturated upper layers, to less then 10 ohm.m at depths of a few tens of metres. An intermediate interface could usually be related to the water table although the correlation was inconsistent. The underlying, conductive layer gave values approaching those obtained from a sounding by the shore, which suggests that saline water originating either from direct sea-water intrusion or from older, connate water, is present inland. Archie's empirical formula proposes that the porosity ϕ can be determined from the ratio of the saturated formation resistivity ρ_f to the resistivity of the fluid ρ_w when clay minerals and electronic are absent. In the case of sands this usually stated as:

$$\phi = 0.9 \ (\rho_w/\rho_f)^{1/2}$$

Taking ρ_f = 2 ohm.m from Gentle's data and ρ_w = 0.2 ohm.m for sea-water implies an effective porosity of 25-30% for the coastal sands: for limestone a slightly higher porosity would be deduced by omitting the 0.9 multiplying factor.

Gentle interpreted his results by matching the field data directly against a set of master curves to get resistivities and thicknesses for four layers. He attributed the second layer, which tended to die out towards the coast, to a zone of water seepage; resistivities for layer three were higher in coral, usually greater than 100 ohm.m, compared to sands because of the more rapid downward percolation of water and limited capillary action; the fourth layer represented a saturated zone with no differentiation of fresh and saline water though the water table was closer to the top of layer three in some cases. While pointing to the general agreement between the resistivity results and the hydrogeological picture, Gentle did not suggest that this line of investigation would provide a means of delineating the aquifer in detail.

3.2 INPUT Airborne EM survey

An airborne mineral-reconnaissance survey undertaken on behalf of the Mines and Geology Department in 1977 included use of the INPUT system. Following a successful test flight over the Tiwi aquifer this Canadian (CIDA) project was extended to a sixth area which encompassed the strip of coastline from Shirazi, about 60 km south of Mombasa, to the River Sabaki, 8 km north of Malindi, and extending for up to 12 km inland. The nominal flying height and line spacing were 120 m and 1 km respectively, with a flight direction of about N300 .

3.2.1 INPUT technique

INPUT is the tradename of an airborne electromagnetic (EM) system developed by Barringer(1962), the acronym representing induced pulse transients. By operating in the time-domain with discrete pulses of an energising field, the relatively weak secondary response originating from eddy currents induced within conducting bodies in the ground can be measured in the absence of the strong primary field. This helps to improve the signal to noise ratio and the depth of investigation relative to continuous wave systems.

Pulses of alternating polarity, with a length of about 1 ms and a repetition rate of 288 pulses/s, were transmitted from a loop on the aircraft; the secondary field was detected with a receiver coil towed 150 m behind and the signal was analysed over six channels centred at 0.3, 0.5, 0.7, 1.1, 1.5, 1.9 ms after pulse termination. Each analogue channel trace represents an integrated response for a time constant set to 3 s or 6 s: the resulting lag can be combined with the effect due to the separation between the receiver coil and the tracking camera used for position fixing. A reference signal from the primary field is used to offset the response from eddy currents in the airframe.

3.2.2 Data processing

The standard method for presenting survey results is to pick anomalies from the analogue records and to plot their position, together with any diagnostic information such as amplitude ratios, in plan. This brings out the spatial distribution of the anomalies and allows comparison with other maps. However, the results from the coastal survey indicated such a complex anomaly pattern set within a high background level of conductivity that it was decided a contour format would be more appropriate. In order produce this the data relating to channels two and five were digitised and various corrections were applied to obtain coherent data sets. Changes in ground clearance can have a significant effect on the measured signal amplitude and the adopted adjustment factor, derived empirically by comparing the results of flying at different heights above water, was exp(0.0225(h-120)) where h is the height above ground in metres. Before applying this correction, the altimeter data were interpolated to 30 points per fiducial and smoothed using a 33-point, running-average filter with a lag of 6 points; the corrected amplitudes were then smoothed with a 5-point running-average filter and contoured. A separate approach to eliminating false anomalies caused by variations in elevation was to contour the ratios of the amplitudes of channel 5 to channel 2 on the basis that the amplitudes should be affected proportionately. Where small values had been recorded on channel 5 they were set arbitrarily to zero to avoid any distortion due to uncertainty in the base level. As the secondary field decays more slowly in the presence of a better conductor, the ratio values may provide useful information on the lateral variations occurring within the area.

The maps were contoured automatically and this influences their presentation in two ways. First, there is an emphasis on making correlations orthogonal to the flight direction which has the effect of suppressing anomaly trends lying oblique to it and which also gives a rectilinear appearance to some of the contouring. Second, the extrapolation of anomaly gradients between flight lines occasionally results in features such as highs or lows for which there is no real evidence. Both of these problems are exacerbated when the line spacing is increased and where the size of the anomalies is relatively small. The possibility of errors in the applied corrections adds to the uncertainty in the contouring but as the altimeter records were not available it is difficult to assess how large these might be.

3.2.3 Data interpretation

Quantitative interpretation of INPUT anomalies is possible to a limited extent by computation or scale-modelling: Palacky and West(1973) give some examples including the response of a homogeneous half-space which is probably of most relevance to the coastal aquifer. The more usual, qualitative approach relies on categorizing anomaly types and identifying suitable targets for ground follow-up. The contractor's interpretation report (Hetu, 1978) on this survey outlined anomalies thought to relate to bodies of fresh water using a 1, 2, or 3 priority rating. The assessment was based mainly upon the coincidence of an area of reduced conductivity in the sandy back-reef facies with the known Tiwi aquifer. The steep amplitude gradient on its eastern flank was attributed to the fresh-water/salt-water interface while a second gradient identified further inland was ascribed to the boundary between the back-reef and Upper

Magarini formations: both contacts were traced over most of the survey area.

Especial significance was attached to the fresh-water/salt-water interface on the basis that it represents the seaward limit to resource investigations, and that the largest accumulations of fresh water should occur close to it. Most of the priority 1 targets were the larger conductivity lows in this situation with an expression in all three types of contour map. Second priority targets included smaller resistive zones close to the interface, as well as other anomalies further inland and some which were not clearly expressed in each data set. Of the 34 target zones, 10 were put as first priority and 20 as second priority, with more specific reservations qualifying the remainder at third priority. These priorities were to be reviewed in the light of any follow-up work as some of the targets had similar characteristics. Other targets were representative of a group of anomalies so that the prospective area would be increased if favourable results were obtained. The report also makes the point that the INPUT data probably contain information which would assist geological mapping of specific rock units and fracture zones if ground control confirmed the apparent correlation. Ground follow-up was not a part of the INPUT survey contract and so the report was limited to making recommendation for further work based on their assessment of the airborne data alone.

3.3 Austromineral survey

A groundwater assessment of the coastal region immediately to the south of Mombasa (see Fig 2) was carried out by Austromineral(1980) as part of a technical cooperation programme agreed between the governments of Austria and Kenya. The project area covered some 400 km and included the Tiwi district. The main geophysical input to this study was undertaken in 1978 with the collection of resistivity sounding data at intervals of 400-500 m along nine traverse lines covering a total length of about 42 km. A Schlumberger array was adopted for most of this work but the Wenner electrode configuration was necessary to provide sufficient signal for measurements at the larger current electrode spacings of up to 1000 m in length. A seismic refraction survey was restricted to a single traverse of 3.5 km length when it became clear that consistent refracting interfaces were being detected within or at the base of the back-reef, Kilindini sands formation.

Investigations were concentrated in the area of outcrop of the Kilindini Formation as this had been identified as having the best aquifer potential, given the impermeable nature of the Jurassic rocks and the likelihood of sea-water contamination if additional heavy demands were to be met by taking supplies from the fossil reef by the coast. The objectives of the survey were to define the overall geometry of the aquifer system within the back-reef sands, to indicate the presence of facies variations within them and to provide information on water quality with reference to sea-water intrusion and possible interaction with connate water.

3.3.1 Resistivity survey results

Resistivity soundings by 5 existing wells taken together with 12 more from Gentle's survey allowed a correlation to be made between interpreted bulk resistivities and water conductivities for coral limestone and for the back-reef sands. From this limited base it was deduced that the conductivity of the pore fluids was more important than variations in porosity or clay content in determining the bulk resistivity. It was also apparent that resistivity values for clays (20–40 ohm.m) and the Jurassic shales (2–10 ohm.m) might equally originate in sands saturated with brackish or salt water respectively, or in coral limestone with saline water. Taking 9–10 ohm.m as the minimum resistivity of potable water implies that layer resistivities should be >70 ohm.m to represent an aquifer in clean sands.

Traverse locations were related to targets identified by the interpretation of the INPUT survey though in fact only two of the lines crossed the central part of an anomaly. The soundings were interpreted by standard curve matching of observed, apparent resistivity values against a set of theoretical 3-layer curves, combined with a 'maxima–minima' technique. The latter method approximates to the measurement of differential resistances whereby another quantity, the so-called true resistivity ρ_T relating to a layer element at depth, is derived. The assumption here is that current flow is along the layering in a horizontally stratified sequence so that resistances can be combined in parallal. Then:

$$\rho_T = \frac{a_2 - a_1}{a_2/\rho_2 - a_1/\rho_1}$$

where ρ_1 and ρ_2 are the apparent resistivities measured at current electrode separations of $2a_1$ and $2a_2$ respectively; this value is taken to refer to a depth of $(a_1 + a_2)/2$. Maxima, minima and inflection points in the curve of ρ_T against depth are attributed to the presence of different layers within the sequence. In effect the ρ_T plot highlights small variations in the apparent resistivity curve which might otherwise be overlooked or disregarded, and the method can be useful for resolving thin beds in the upper parts of a sequence. however, there is a danger that 'noise' in the field data may be translated into additional layers in the interpretation.

Austromineral present the results of their interpretations as cross-sections with the layer resistivities correlated along each traverse. Typically, the sequence has been resolved into 5–10 layers to depths of 200 m and it is clear that the true resistivity curves have been used as the basis for much of this. The justification for illustrating such detail with only a very limited amount of direct borehole control or other geophysical data is open to question, particularly for the deeper part of the sections where the theoretical asssumptions are more obviously inadequete. Identification of a layer at depth tends to be heavily dependent upon individual data points which may be disturbed by such factors as superficial lateral variations, low signal strength, poor electrode contacts: the form of their apparent resistivity field curves and the magnitude of the discontinuities when potential electrode spacings were increased suggest that these effects are significant.

3.3.2 Report findings

The main conclusions reached with the help of the resistivity survey were:

(1) Jurassic shales show a low resistivity, usually <15 ohm.m, which can be attributed to connate water of low mobility: the boundary between the shales and the back-reef sands is clearly defined and there appears to be little transfer of saline water from the west, except perhaps in the uppermost layers;

(2) the depth to shales below the coastal plain is thought to be 200-250 m although high observed conductivities may be due to saline water within the sandy facies;

(3) layer resistivities of >50 ohm.m within the back-reef probably represent an aquifer with fresh-water saturated sands varying in thickness from 30 m to 100 m. There appears to be an association with morphology so that thicker sands lie on the line of valleys draining the inland hills towards the southeast. Some of these channels provide direct recharge to the sands as they dry up before reaching the coast, but in other cases effluent streams with a SW-NE trend must restrict groundwater storage;

(4) the coral limestones contain brackish/saline water with fresh water restricted to relatively small lenses in the upper layers. The eastern boundary of the main aquifer does not necessarily correspond with the edge of the fossil reef although in places an impermeable clay zone is developed here: where this is absent salt water can be expected at shallower depths inland;

(5) conditions in the back-reef deposits of the Diani catchment, south of Tiwi and the Mwachema creek, differed significantly. The higher conductivities measured here may reflect sea-water intrusion as a result of lower recharge rates into the aquifer and on a less continuous clay zone backing the fossil reef.

The two boreholes drilled for this project were sited near geophysical traverse lines towards the northwest margin of the zone indicating thick, freshwater saturated sands. Both holes showed a similar sequence: sands predominant to a depth of about 70 m (15-23 m below sea-level) followed by a sequence of dark, compact clay/mudstone to nearly 200 m depth./ The sands varied from fine-to coarse-grained, with beds several metres in thickness. Geophysical logging - resistivity, self potential and gamma ray - was used to help in defining the succession and in fixing the well design: gamma ray logs showed the best correlation with sample cuttings but no other records were available for correlating between boreholes. Cores obtained from the lower, clay unit were thought to indicate a formation of Plio-Pleistocene, rather than Jurassic, age but there was no positive evidence for this. Good-quality water was produced with a recommended sustainable yield of 5.5 l/s: this is to be compared with the 70 l/s taken from the Tiwi producing wells.

A comparison of the resistivity profiles and drilling results shows broad agreement between the two, with a resistivity interface at about 70 m depth separating an upper layer of over 70 ohm.m from a more conductive zone of <30 ohm.m. As the wells were not sited at a resistivity sounding a detailed correlation has little meaning, though it could be said that the presentation of the geophysical sections fails to highlight the major lithological division and the water table. The predicted depth to Jurassic shales was not reached. Further consideration is given to the interpretation of the Austromineral data in section 4 of this report.

3.4 Resistivity surveys near Msambweni

An INPUT survey target located by the coast at Msambweni, 50 km south of Mombasa, was covered by resistivity soundings in 1979 as part of a research project (Mwangi,1979). This marked conductivity low is unusual for being situated very close to the coastline over an area mapped as coral limestone: elsewhere, lows of this amplitude invariably lie inland of the main reef outcrop. Schlumberger soundings were taken at intervals of 200-300 m along 12 traverse lines with maximum current electrode separations of 1000 m or occasionally 2000 m, and the results were interpreted by the interactive procedure of matching the field data against theoretical curves generated by computer for specific input models.

The form of an apparent resistivity map for current electrode separations of 300 m showed good qualitative agreement with the INPUT data, particularly with the channel 2 contours. Interpretation of the resistivity soundings identified five distinct layers. Unsaturated sands and coral gave resistivities of 90 ohm.m from the surface to depths of 10-20 m, consistent with ground elevations above sea level. The second, most extensive zone had resistivities of 20-35 ohm.m extending to depths of over 300 m, below which there were indications of a conductive layer of about 5 ohm.m. Two other, more localised layers occurred at the top of, or within, this second zone: one, more conductive at 2-20 ohm.m, can probably be attributed to sea-water intrusion and brackish groundwater; the other, more resistive at 30-80 ohm.m, appears as a relatively narrow channel to a depth of about 75 m, broadening further inland.

In the absence of borehole control only the superficial layers have a know relation to lithology. Mwangi and Swain(in press) suggest that the second zone and the upper part of the conductive layer are coral, possibly underlain by Plio-Pleistocene sands, within which the water quality is likely to be poor; the more resistive zone, especially the supposed buried channel, represents a favourable groundwater target recharged from the northwest. One difficulty in interpreting this anomaly is to account for its uniqueness , given the extent of the outcrop of coral limestone along the coast. Elsewhere, the fossil reef is characterized as a 2-20 ohm.m layer at relatively shallow depth, suggesting the effects of sea-water intrusion, and so at Msambweni the coral would have to be significantly less porous or protected in some other way from the ingress of sea-water. It seems unlikely that fresh water could be flowing seawards here in sufficient quantity to account for such a thick, electrically homogeneous layer. An alternative explanation would be that the coral is thinner here. Austromineral make the point that clays may isolate the fossil reef from the Kilindini sands, and the steep anomaly gradients interpreted as the 'saline interface' from the INPUT survey imply either a barrier or a rapid change in depth to saline water close to the mapped geological contact. The resistivity of the second zone would also be consistent with clay formations, or older Tertiary beds, of the type proved in the Austromineral boreholes.

4. GEOPHYSICAL SURVEY RESULTS

4.1 Equipment and field procedure

Two items of geophysical equipment, a Geonics EM34-3 and ABEM SAS300 resistivity set with booster, were brought over from UK for use on the project. The EM34-3 is a moving source, two-loop electromagnetic instrument which has been designed for conductivity mapping. The strength of the secondary magnetic field at the receiver relative to the primary, transmitted signal is calibrated to give a direct readout of the apparent conductivity of the ground within an operating range of 1-100 mS/m i.e. resistivities of 1000-1 ohm.m. The depth of investigation is controlled mainly by the coil orientation and by the coil separation, which is set to 10 m, 20 m or 40 m by monitoring the primary field strength. The coils, about 60 cm in diameter, are normally set to be co-planar, either horizontally or vertically: the former gives a greater depth of investigation but the readings are more sensitive to noise due to lateral variations in the ground and to misalignment of the coils. Some confusion in terminology may arise because the coils can be considered as magnetic dipoles aligned along their axes: thus, horizontal coils are equivalent to vertical dipoles and vice versa. The concept of dipoles is intrinsic to the mathematical treatment of the technique and it is sometimes carried over to descriptions of fieldwork. However, as it is the coils that are seen in practice they are referred to in this report. An indication of the relative depth of investigation can be obtained by considering the contribution to the signal that arises from current flow at different depths in homogeneous ground. For horizontal coils the response is a maximum from depths of about 0.4s, where s is the coil spacing, and 70% of the signal originates within 1.5s of the surface: for vertical coils the greatest response is from the uppermost layers and 70% of the signal comes from a depth of within 0.75s of the surface.

A comparison of results from the three coil separations at both orientations provides an indication of the changes in conductivity with depth, but the data are insufficient for resolving the different layers quantitatively except in the simplest cases. Where other information, from boreholes or resistivity soundings, is available an equivalent set of EM34-3 values can be calculated for a complex conductivity model for comparison with the observed values. However, the equipment is best suited to mapping lateral variations in conductivity. It was tested here to see how effective it might be for detecting the saline interface and for providing a rapid assessment of drilling sites.

The SAS300 Terrameter measures the potential difference resulting from current pulses of alternating polarity and it has the facility of stacking up to 64 sets of data in order to enhance the signal relative to background noise. Maximim currents of 500 mA or more typically 200 mA can be transmitted in favourable circumstances when the booster unit is connected. A digital readout displays the apparent resistance of the ground directly. Some difficulties were experienced during the survey in reducing contact resistances at the electrodes in dry sands and light soils. These limited the current levels to 50 mA or less and made the potential measurement less reliable even when a Wenner array was used. Most of the data were collected with an expanding Schlumberger array configuration to give 'sounding' curves with ten points per logarithmic decade from current electrode separations of 2 m out to 200-500 m and potential dipoles of 0.5-50 m.

Interpretation of the resistivity soundings (see Appendix) was based around a microcomputer programme for generating a theoretical curve for a horizontally-layered model, using the linear filter technique proposed by Ghosh(1971). The field data were stored and processed by the same programme. Modelling of the field data is attended by the usual problems of equivalence and suppression as indicated by the Austromineral report, but resistivity surveys still offer the possibility of providing useful information relating directly to the occurrence of the aquifer. One of the objectives in this survey was to see if any criteria could be established for producing meaningful interpretations of the resistivity data on a regional basis in conjunction with the INPUT survey maps.

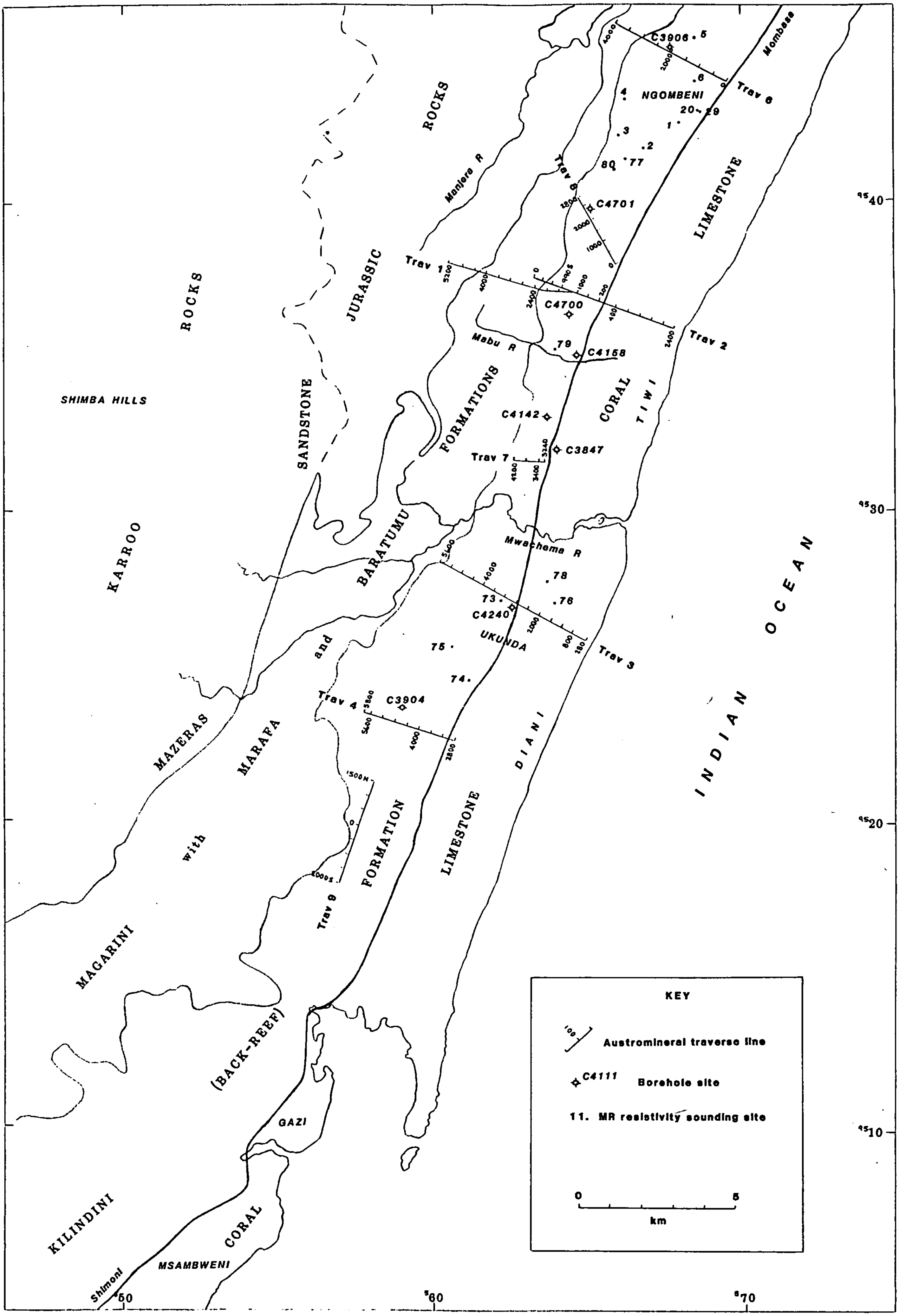

Fig 2. South coast area location map with geology

4.2 Results from south of Mombasa

The area south of Mombasa (see Fig 2) has the highest priority for groundwater development as there are proven reserves close to the main concentration of population and tourist hotels. Two possibilities for meeting increasing demand are the developing of local groundwater resources, and the laying of a second pipeline from Mzima Springs at the southern end of the Chyulu Hills. Austromineral recommended the construction of a well gallery of 9 boreholes into the Kilinidini Formation. The projected total yield of about 50 l/s is relatively low in comparison with the quantities of water produced by some single holes in the district but they argue that this type of supply would be less susceptible to a deterioration in water quality and more reliable in the long term. Before the potential for groundwater supply can be assessed fully more information is needed on such matters as the extent and thickness of the aquifer, the distribution of saline water and the available recharge.

4.2.1 INPUT survey and EM34-3 data

Buckley(1981) reproduced the channel 5 INPUT data for the South Coast area and pointed out that while the correlation of the anomaly pattern with lithology was good, the association with groundwater occurrence and quality was unclear. In particular, the significance of the interpreted saline interface with its implication of a near-vertical boundary is uncertain. It is reasonable to assume that the high amplitudes recorded over the reef limestones are a response to saline water at shallow depth as the resistivity of the limestone itself is intrinsically high and clays are not commonly reported within it: anomalies set within this conductive background probably reflect changes in flight elevation as well as the presence of solution channels, large-scale differences in porosity or facies variations. The existence of an overlying layer of fresh water, which is certainly present locally, would not be apparent in these circumstances.

The steep anomaly gradient marking the landward margin of the reef indicates that the influence of saline water diminishes rapidly as a result of either a porosity/permeability barrier to the further intrusion of sea-water, or a greater head of fresh water. The gradient is not uniform and it is more obviously discontinuous in the channel 2 data for which the resolution is higher. Steeper gradients tend to occur in the southern part of the area but the Tiwi section is well-defined and shows a resistive 'bulge' towards the coast which might be related to fresh water discharging through the reef. North of Tiwi, within about 10 km of Likoni, the gradients are noticeably diffuse, suggesting that the depth to the saline interface increases more slowly here. The amplitude ratio contour maps also show a similar pattern: in general, higher values attributable to a more conductive formation occur on the seaward side of a steep gradient near the reef/back-reef contact, supporting the view that there is a distinct lateral change in conductivity rather than an increase in depth to the same interface; near Likoni values remain high.

The amplitude anomaly gradient interpreted as a lithological contact between back-reef and Magarini sands diverges somewhat from the mapped geological boundaty in the south, but north of a line through the Mwachema creek there is closer agreement. In the north, amplitudes are higher over the Magarini beds than over the reef limestone while the ratio values are

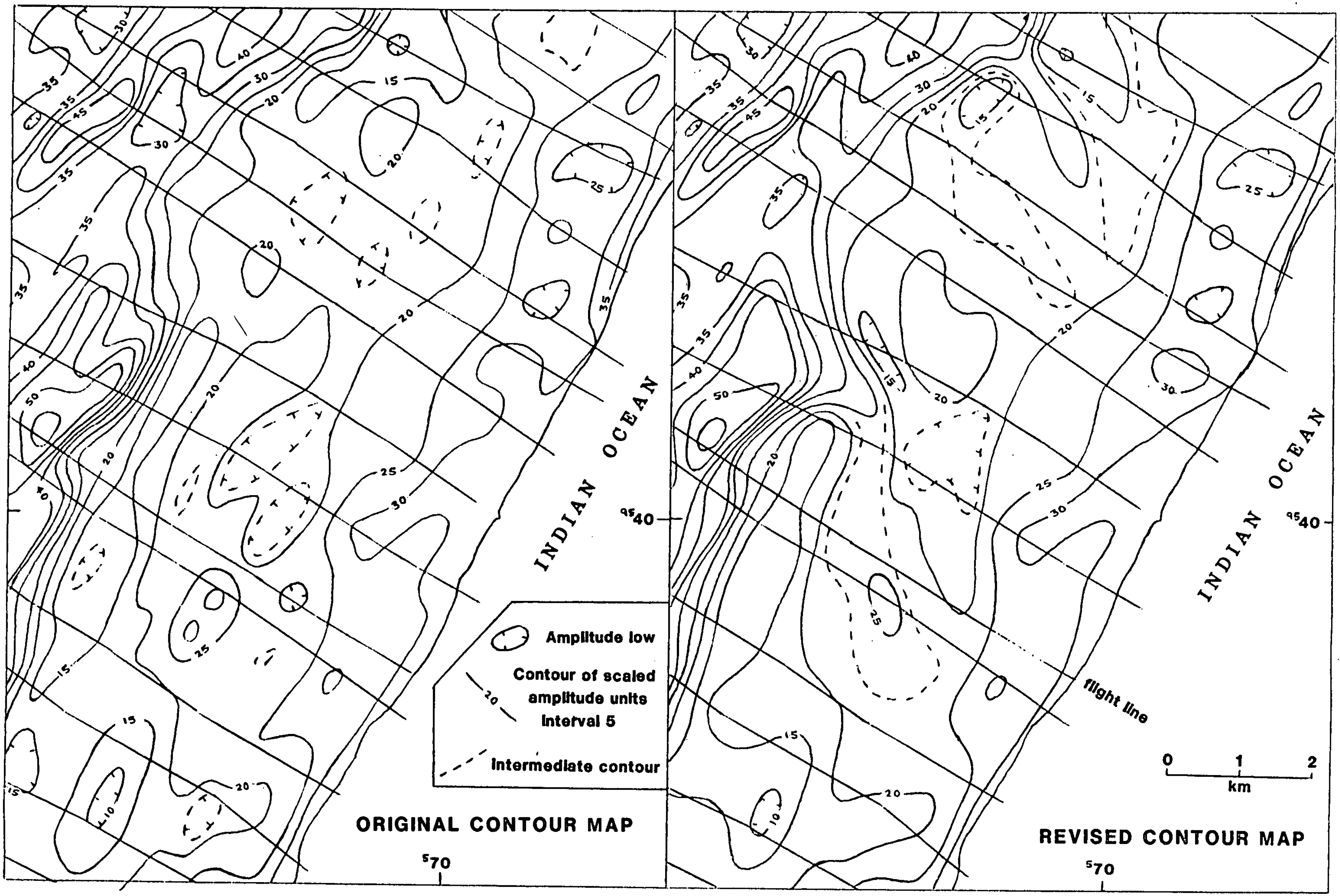

Fig 3. INPUT survey channel 2 amplitude data from south of Mombasa

similar to those for the back-reef sands. Further west again, over the Jurassic shales, amplitude ratios show only a slight increase. This pattern implies that the depth to conductive Jurassic shales controls the background amplitude levels observed over both the Magarini and Kilindini beds, with the steeper gradients near the contact representing a step - possibly fault-controlled or a result of erosion along an earlier coastline - in the profile. Variations in facies or pore fluids would account for the superimposed anomalies. The bulk conductivity of the shales seems to be somewhat less than that of the fossil reef with its saline intrusion. South of the Mwachema creek, ratio values tend to be slightly lower over the Pleistocene sands and there is more evidence of a gradient near their western margin: this may result from thicker Tertiary sediments.

EM34-3 data were collected over a part of the area during the period May-July 1984 (Adams, personal communication). Readings were taken at intervals of 0.5-1 km beside the main roads and tracks to give an indication of the type of information that could be obtained. Values range from 2 mS/m to >300 mS/m and the variations with different coil spacing brought out the main characteristics of the upper part of the sequence. For higher observed values the non-linearity of the meter response becomes significant, more especially with the horizontal coil configuration for which the response inverts and falls rapidly to negative values when true conductivities exceed about 200 mS/m,: a correction can be made assumming uniform ground, but with the strong contrasts found here this will only be approximate. By the coast, dry coral gave values of <10 mS/m at 10 m coil spacing, increasing to >300 mS/m, with some negative values, for the horizontal coil configuration at 40 m spacing when saline water occurred at shallow depth. Further inland, the conductivity contrasts were less extreme witn 10 m coil readings typically 20-30 mS/m, increasing with depth. Lateral variations were correlated by contouring the data although they are too sparse to define other than major trends. More fragmentary patterns are seen at 10 m and 20 m coil spacings; at 40 m spacing a definite alignment parallel to the coast emerges with minimum values in the central section to the west of the contact between reef limestone and the back-reef sands, coinciding with the main INPUT anomaly lows. The increase in conductivities towards the Magarini deposits is attributed to a greater clay content in the upper layers. Detailed traverses showed that a distinctive increase can occur over distances of 100 m, inside the western margin of the Kilindini Formation. It is not clear whether this represents a facies variation in the back-reef deposit or an error in the geological mapping as in some localities the conductive zone could be correlated with the occurrence of the Marafa Formation: the extent of these features may be significant in limiting the size of the aquifer but more detailed surveys would be needed to define their geometry.

One area of interest was about 3 km SW of Ngombeni, near the track junction at 100 m grid reference (5664 95415), where the EM34-3 results were at variance with the INPUT maps in showing high conductivities over an INPUT anomaly low. Although there was a possibility of interference from overhead cables and a water pipeline the EM34-3 values are almost certainly genuine. The discrepency may be due to ambiguity in contouring the INPUT data and the irregular spacing of the flight lines in this area gives added scope for changing anomaly trends using the same data set. Figure 3 shows a comparison between the original contouring and an alternative which accords better with the ground survey results. The revised version brings out N to NNW trends for which the INPUT maps provide some evidence elsewhere in the South Coast area.

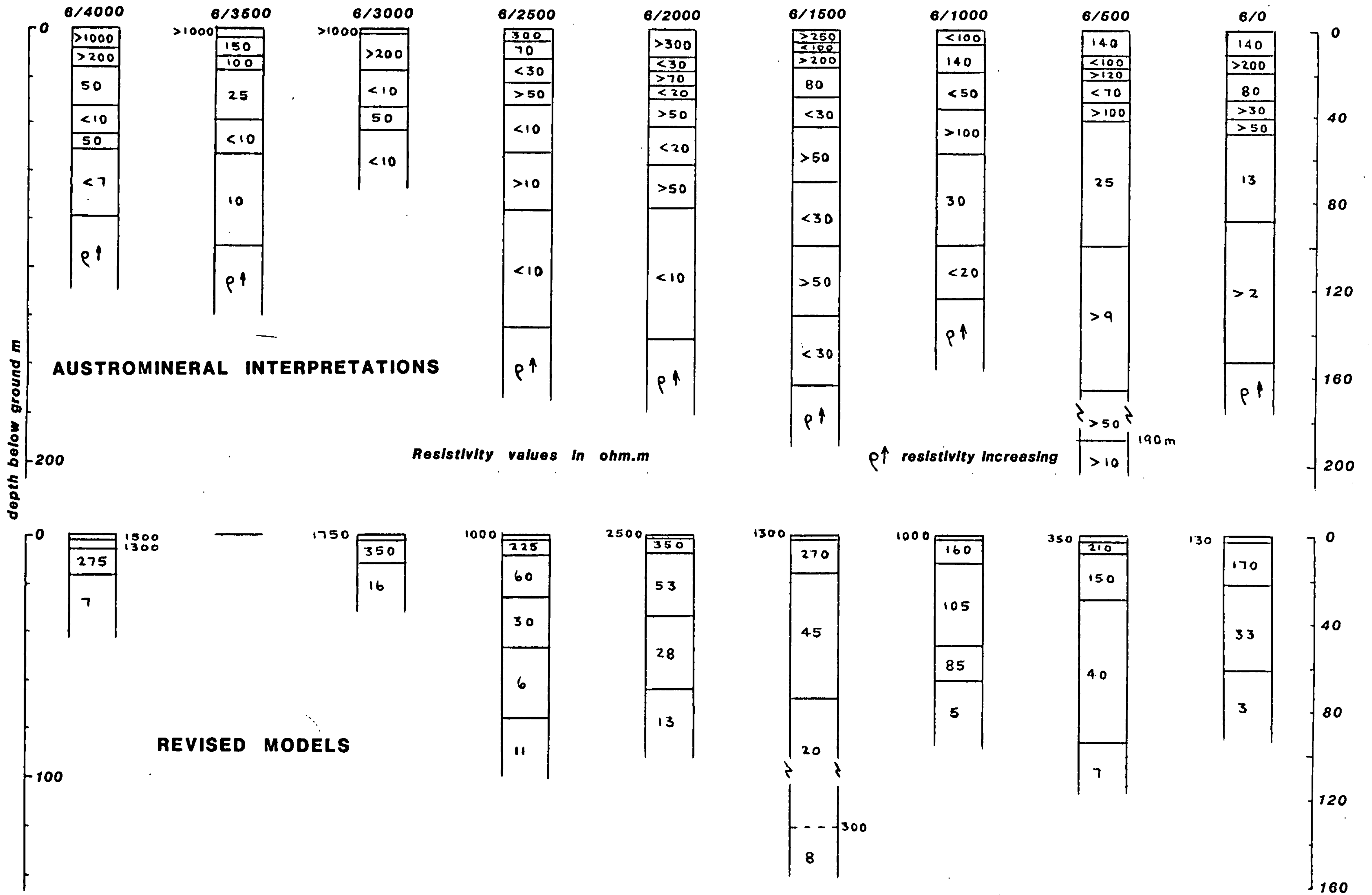

Fig 4. Austromineral and revised resistivity interpretations for Traverse 6

4.2.2. Resistivity data

Expanding Schlumberger array resistivity results were obtained from 15 sites, most of which were concentrated in two localities, Ngombeni and Ukunda (see Fig 2), where it was expected that boreholes would be drilled as part of the project. The Ngombeni area was recommended for drilling by Austromineral to test the northern extent of the aquifer, while at Ukunda there is a possibility of drilling near a deep production well which was abandoned due to high salinity. An existing borehole, C3906, on the northwest margin of INPUT anomaly target A6-12 by Ngombeni, went from unsaturated sands into (?)Baratumu Formation clays of low specific capacity at a depth of 27.5 m but the interpretation by Austromineral of their resistivity traverse number 6 which passed near this site suggests that conditions might be more favourable towards the coast. Figure 4 shows a reinterpretation of the resistivity data for this report which makes no use of the maximum-minimum method (see 3.3.1 above) and presents a simpler form of section. It should be emphasized that while the revised version represents the field data more closely the models remain poorly constrained. Upper layer resistivities are high, >100 ohm.m throughout the traverse, indicating a cover of dry sands with the possibility of coral at 6/0: this zone thins towards the back of the Kilindini Formation at 6/2000 and 6/2500 but thickens again over the Magarini sands. The resistive sequence appears thickest at about 60 m near 6/1000 and the lower half of this should be water-saturated given the values of 100 ohm.m. It is surprising that the water table is not expressed more clearly here as its influence appears to have been picked up at 6/0 and 6/500 by the increase in conductivity at 20-30 m depth. Resistivities of 15-30 ohm.m are taken to represent clays by reference to C3906 so that saturated sands would not be expected west of 6/1500. At 6/1500 itself the apparent thickness of the 20 ohm.m layer is probably exaggerated by lateral variations distorting the field data but the zone of 45 ohm.m is potentially water bearing at depth. Underlying resistivity values of <10 ohm.m suggest saline water in the eastern half of the traverse, while to the west Jurassic shales may also be a factor.

Traverse 8 is of interest in that there is good evidence of water-saturated sands only in the vicinity of 8/1500 and 8/2000 (see Fig 5) coinciding with a conductivity low bounded by steep gradients on the channel 2 INPUT data. To the northwest, clay would be expected at shallow depth. To the southeast the situation is less clear with a thick zone of 20-30 ohm.m differentiated from the clay layer of <20 ohm.m: there may be more brackish water in the sands here or perhaps an intercalated sequence of sands and clays which is not resolved i.e. is suppressed by the resistivity interpretation. The ambiguity in attributing resistivity values is such that the reverse situation could apply, with clays overlying sand containing more brackish, or saline water. Borehole C4701 sited beside Traverse 8 defines a clear break in lithology at about 70 m depth. This relates heavy clay to the layer of <20 ohm.m while C3906 indicates values of about 30 ohm.m for at least the upper part of the clay sequence. It also appears that C4701 was drilled close to the westward margin of the thick Kilindini sand deposits, though C4700 which was situated more centrally by Traverse 1 gave similar results.

Traverse 1+2 provides a section from Jurassic shales in the west, which crosses Magarini and Kilindini deposits, to the fossil reef by the coast. The dry coral limestone is characterized by high resistivities, followed by a rapid decrease originating from an interface at about the depth to sea-level: with such a large contrast the response of a thin layer of fresh water overlying the sea-water intrusion will be heavily suppressed in the

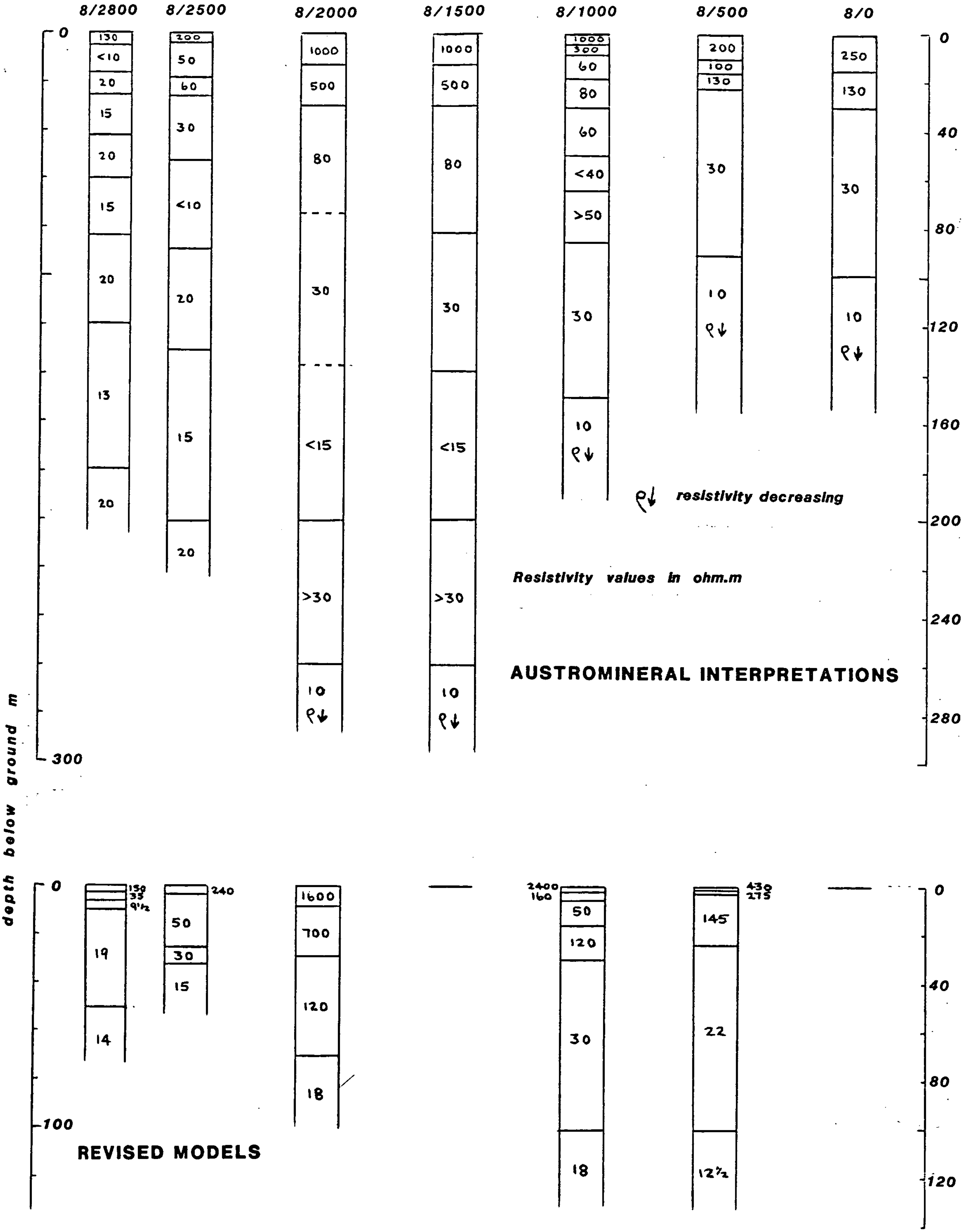

Fig 5. Austromineral and revised resistivity interpretations for Traverse 8

resistivity data, and the prospects of identifying it are poor. A change in the sequence is apparent westwards from 2/200 (see Fig 6) close to the margin of the reef, where layers of intermediate resistivity are resolved giving a significant increase in the depth to the conductive base. Upper layer resistivities from the Kilindini sands are generally lower than for the limestone and there is evidence of lateral variations in the back-reef facies with a higher clay content to the west. Freshwater saturated sands would be expected from 2/0 to at least 1/1625 as indicated by resistivities of >60 ohm.m to depths of 50-120 m. The water level is probably near 40 m depth but the indications of it from the resistivity interpretations are not consistent and suggest interference from facies variations. Another distinctive lateral discontinuity occurs west of 1/1625 where the Kilindini sands appear to terminate abruptly over a distance of less than 50 m, giving way to a channel of highly conductive material. This zone correlates closely with a conductivity high in the EM34-3 and INPUT data which can be linked to the narrow belt of the older, Marafa Formation shown on the revised geological map. Near-surface resistivities increase again over Magarini Formation sands but within 20 m of the surface the low values suggest that Marafa Formation or Jurassic shales are present. The mapped contact with the Jurassic near 1/4400 sees a reduction in the resistivity of the overlying layers which persists to the end of the traverse. Borehole C4700 mwas drilled some 800 m south of 1/1300, but while the results are not directly comparable there is approximate agreement between the resistivity interface at about 80 m and the logged change in lithology at 70 m depth. The range of equivalence inherent to these multi-layer models, combined with likely errors in the field data, are such that the depth to the base of the resistive layer could be varied by several tens of metres: the interpretations shown are biassed towards fitting the available information and they woild not necessarily have been derived a priori. The values given for 1/1000 give a better apparent fit to the field data but the resistivity of the fourth layer should almost certainly be increased to allow for a reduction in its thickness. The resistivity for the underlying claystone here appears to be about 30 ohm.m with a deeper interface indicating increasing conductivity. This is consistent with Traverse 6 and suggests that at 8/2000, the only relevant data point available for reinterpretation on this line, the deepest layers have not been fully resolved. In fact, conductivities probably increase steadily with depth through the clays rather than at discrete interfaces, and they may become indistinguishable from values in the Jurassic shales.

The additional soundings obtained near Ngombeni were located between traverses 6 and 8. None of the results gave clear evidence of a significant aquifer in this area though the proposed borehole site, close to the margin of the fossil reef, was the most promising. Near-surface resistivities were high, indicating dry soils and sand to depths of at least 2 m, with the exception of MR3 which showed a clay-rich sequence throughout. At MR5, MR6 and by the borehole site (MR20, MR21, MR29) resistivities >80 ohm.m persisted to depths of 20-30 m; elsewhere, conductivities increased into a clay zone within which sandier layers can be expected at MRl, MR4 and possibly MR77 and MR80. Only at the borehole site were resistivities >40 ohm.m interpreted below sea-level i.e. the expected maximum depth to fresh water, though most of the soundings were consistent with an interface occuring near this level. This implies that the evidence of C3906 is applicable to much of the area. At MR77 and MR80 rsistivities of 25 ohm.m and 35 ohm.m respectively, could extend to depths of 60 m and 70 m; by analogy with C4701 these values are taken to indicate hard clays but sand with brackish water might be present. Results from MR20,MR21 and MR29 at ground elevations of about 30 m were disturbed by overhead cables at the more distant electrode spacings and so the depths of 50-60 m to the base of the more resistive zone, while correlating with

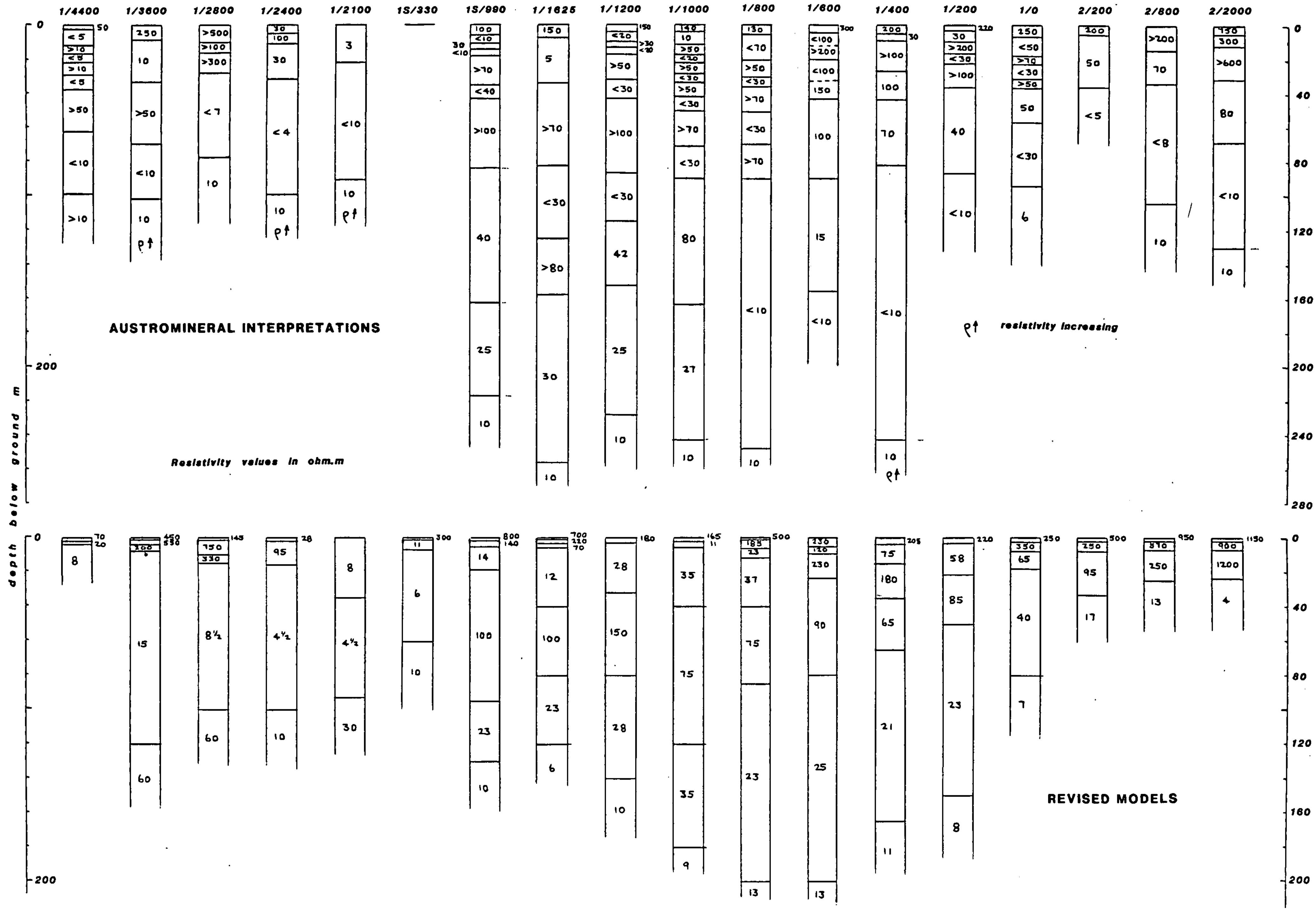

Fig 6. Austromineral and revised resistivity interpretations for Traverse 1 - 2

6/1000, are less reliable than they might be. The high conductivities observed at MR3 ressemble the data from near 1/2000 and a similar explanation would be expected although the Marafa Formation is mapped as being several hundred metres further west. Austromineral suggested that it represents saline water of low mobility derived from the Jurassic shales but the possibility is considered less likely as it fails to account for the limited extent of the zone.

The high-yielding C4158 or Tiwi 3 production well site at Kidzumu, 2 km south of C4701, shows a thick sequence of sands and marls which may have been channelled along a WNW-ESE drainage line now occupied by the Mabu river. Two Austromineral soundings here have a similar form to those over the aquifer on Traverse 1 but their interpretation indicates a resistive layer of 160 ohm.m with a thickness of less than 15 m extending only to near sea-level. The soundings differ slightly at wider electrode spacings so that while one implies the presence of a thick underlying zone of 30 ohm.m the other is consistent with values falling to 15 ohm.m. There is nothing in the resistivity data to suggest that the clay formation below C4701 is not present here at C4158. A conductivity log of C4158 (Buckley,1981) showed a steady increase down the hole in the range 0.7-0.8 mS/cm, an equivalent resistivity of 12.5-14 ohm.m, so that the combination of water-saturated sands, possibly with some clays, and the marls could account for the shape of the sounding curves. It is not clear from the geological description of the hole whether the entire sequence forms part of the back-reef facies or whether earlier Plio-Pleistocene or Miocene deposits are in fact present. An additional sounding, MR79, sited 1 km further west differed from the others with a more resistive superficial layer to 3.5 m depth above a 30 ohm.m clay zone to about 45 m, and a more resistive underlying layer interpreted at 60 ohm.m to 100 m depth. This site would therefore seem to be at least as promising as Tiwi 3 if a reduced capacity for direct recharge through the upper clays is discounted: by analogy with C4700, the increased resistivity at depth may reflect a combination of harder claystone and thin sands with fresher water. At Tiwi 2, C4142 tends to confirm the existence of a thick zone at a resistivity of about 30 ohm.m relating to a mixed ssequence of corals, sands and clays. Given that the resistivity of the water in this hole was measured as 22 ohm.m, clean, saturated sands should have a resistivity >150 ohm.m and so it appears that the producing zones are relatively thin and unresolved, or contaminated with clay. The interpretation of C3847, a lower-yielding hole nearby at the margin of the reef, shows high resistivities through coral and sands to a depth of 40 m, that is to below sea-level: the resistivity of the underlying layer is poorly defined but a zone at 30 ohm.m could extend beyond 100 m before encountering values typical of saline water.

The results near Ukunda confirm the difficulty in reaching a reliable interpretation without borehole control. Ukunda lies within the Diani catchment and Austromineral make the point that conductivity levels in the back-reef deposits here are significantly higher than in the Tiwi catchment (see 3.3.2 above). In view of this it is perhaps surprising that INPUT amplitudes over the Pleistocene sands are only slightly higher in channel 2 and reach lower values in channel 5, while gradients over the sands/reef contact are still clearly defined. There appears to be an effect of scale or sensitivity in that the resistive units of interest as groundwater targets provide a relatively small contribution to the INPUT signal. A further implication is that the conductivity lows picked out from the INPUT maps, particularly on channel 5, are not specifically defining bodies of fresh water.

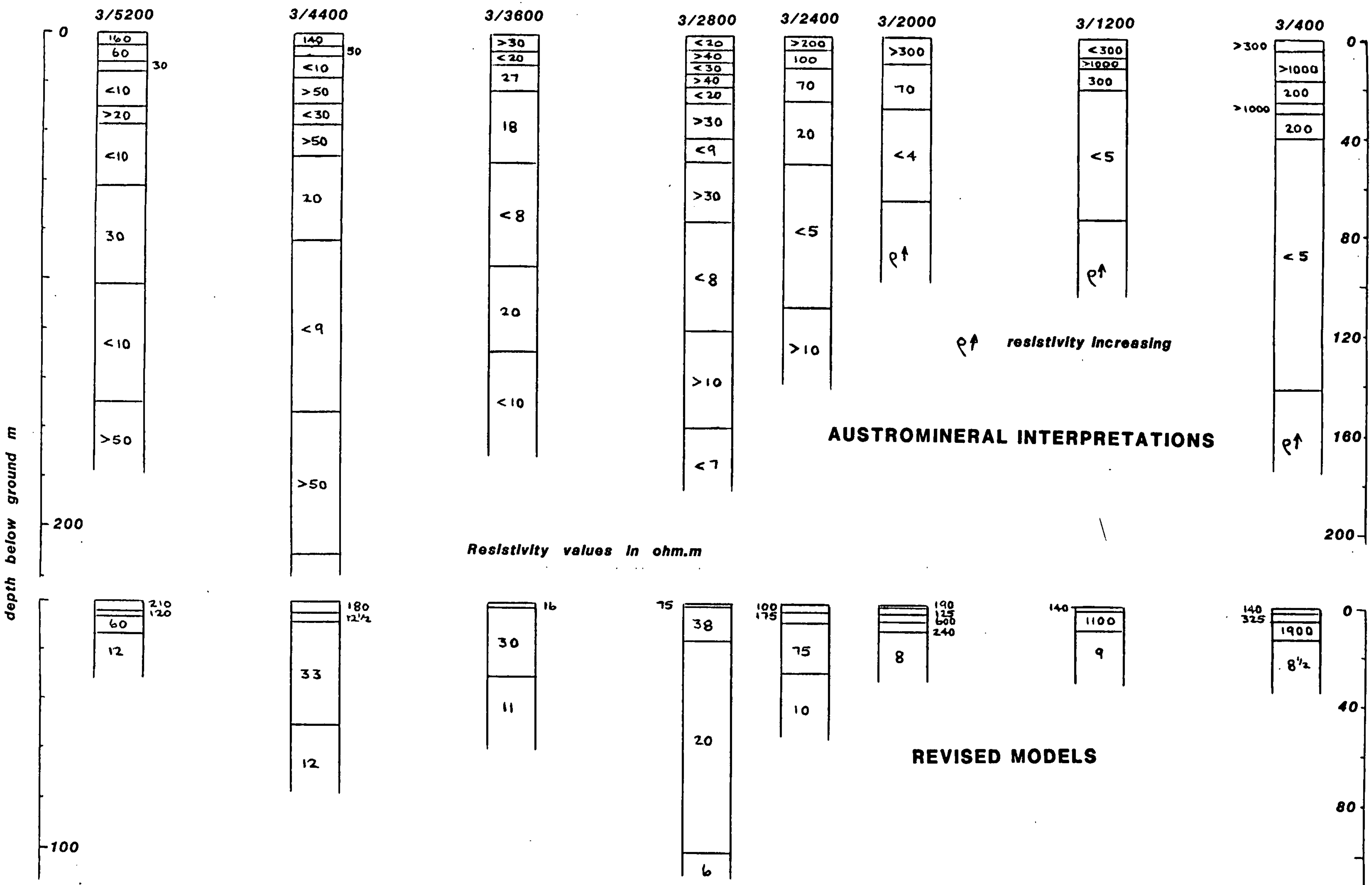

Fig 7. Austromineral and revised resistivity interpretations for Traverse 3

The INPUT anomaly pattern between the Mwachema creek and Ukunda is quite complex with a series of three lows separated by conductive channels extended in a SW-NE direction. One of the deepest boreholes along this section of the coastal plain, C4240, was situated at the southwestern end of this feature at the margin of the fossil reef: it proved a sequence of coral on sands with subordinate clay but, on pumping, water salinity increased to unacceptable levels - giving resistivities of <3 ohm.m - and the well was abandoned. The resistivity interpretation suggest that values reach no more than 35 ohm.m within coral lying above the rest water level: this would be unusually low and implies that the sounding was sited on the back-reef facies behind the borehole. Resistivities of 20 ohm.m extend no deeper than 45 m before a drop to <9 ohm.m within a sand/clay zone which almost certainly contains poor quality, or saline, water. Traverse 3 passed near the borehole and it shows (see Fig 7) the transition in upper layer resistivities from high values within the dry coral and sand near the coast to 40 ohm.m in a clay-rich zone which corresponds with an INPUT anomaly high in the channel 2 data; further inland resistivities increase again on Upper Magerini sands. Resistivities fell to <15 ohm.m within depths of 30 m over most of the traverse and gave no indication that freshwater-saturated sands might be present, except perhaps close to the water table. Additional soundings at MR73, MR76 and MR78 confirmed this pattern, with MR78 the most favourable in showing an 85 ohm.m layer extending to 40 m depth. The conductive base to MR76 and MR78 was <4 ohm.m, clearly indicating sea-water intrusion: the higher values given by Traverse 3 may be inaccurate because of a lack of instrumental sensitivity, an unreliability which probably extends to readings at furthest electrode separations on many of the Austromineral soundings. MR74 and MR75 were located southwest of Ukunda in the less conductive area shown by the INPUT survey. MR74, within target A6-6, picked up a resistive zone of sands to 18 m depth and a layer of 20 ohm.m to over 100 m: at MR75 the superficial layers of 5 m were conductive and underlain by an apparently uniform layer of 17 ohm.m. By analogy with C3904, about 2 km further southwest, these resistivities of 15-20 ohm.m are attributed to clays.

4.2.3 Conclusions from the South Coast area

(1) The main features of the INPUT survey maps derive from zones with resistivities of less than about 15 ohm.m. The unusually high background amplitude levels recorded throughout the area are attributable to sea-water intrusion at shallow depth within the coral limestone by the coast, and to conductive Jurassic shales which crop out inland and dip at a shallow angle beneath the Plio-Pleistocene deposits.

(2) A conductivity boundary is indicated near the mapped contact between coral limestone and the back-reef deposits. As dry coral usually gives slightly higher resistivities than the back-reef sands, groundwater salinity and/or bulk porosity must be higher for the coral in the underlying saturated zone. A correlation would be expected between the reduction in INPUT amplitudes and an increase in groundwater elevations: this can be checked when data from the recently established monthly well round become available. The effects appear too extensive to be caused by a permeability barrier of clays restricted to the contact zone itself.

(3) The INPUT amplitude gradient near the western margin of the back-reef deposits is less well defined but it can be related to the occurrence of Jurassic shales at shallower depths. Jurassic rocks do not crop out south of a line through the Mwachema creek but the overlying Baratumu and Marafa (or Lower Margarini) deposits also appear to include

highly conductive clays.

(4) INPUT amplitude lows occur where the conductive units lie at greater depth below thick layers of intermediate/high resistivity. They include the effects of dry Upper Magarini, and saturated Kilidini, sands and also of the impermeable claystones and clay/sand sequences with poor quality water: for all of these the bulk resistivities exceed about 20 ohm.m. The small, secondary anomalies which may be associated with aquifer conditions (or noise in the data) are best defined by the channel 2 data.

(5) EM34-3 equipment is useful for locating the lateral variations in conductivity on the ground as a check on the contouring of the INPUT data. Its sensitivity to variations in a vertical plane is inadequate for fixing the depth to saline water within the coral: equivalent depths for a two-layer model, which may be useful as a qualitative guide, could not be obtained because, perhaps, of current channelling or instrumental problems.

(6) Any interpretation of resistivity sounding data from this environment will be subject to ambiguity as the sequence is not sufficiently simple - quite different deposits can give similar resistivities. Detailed correlations presented by Austromineral in their traverse sections should be viewed critically: the alternative interpretations given in this report show the types of variation that might be expected. Interpretations should be revised as necessary when more drilling information becomes available.

(7) Where the aquifers themselves are relatively thin e.g. in an alternating clay/sand sequence or as a freshwater lens on saline water in coral limestone, they will be very difficult to detect without additional constraints on the interpretation. More information is needed from borehole logging on the aquifers: their effective thickness, clay content and fluid conductivity etc.

(8) Results near the Ngombeni borehole site suggest the presence of perhaps 30 m of potentially water-saturated sands but their lateral extent may be limited. While they seem to extend northwards to cross Austromineral Traverse 6, higher conductivities to the southwest are thought to indicate that clays (or poor quality water in sands) predominate below about sea level. The site is close to the coral reef outcrop but there are no indications of saline water at shallow depths nearby.

(9) The Ukunda site has no favourable geophysical characteristics. Two INPUT anomaly lows are centred about 2 km to the north and northeast but the contour pattern shows some evidence that there are intervening structural features with a north to northwest trend. The site is backed by higher ground capped with conductive clays and a channel of high conductivity leading from it to the northeast between the conductivity lows may represent more clays or saline water intruding from the Mwachema creek. Resistivity soundings show intermediate/low resistivity values: drilling beyond the clays found in C4240 at 88.5 - 101 m would not be recommended as saline water almost certainly occurs below this level, if not before.

4.3 Results from Mombasa - Kilifi district

Buckley(1981) discussed the evidence from the Vipingo estate area within which additional resistivity soundings were obtained. Similarities with the Tiwi area were apparent in both hydrogeology and geology though such high-yielding wells did not exist and there seemed to be more problem with

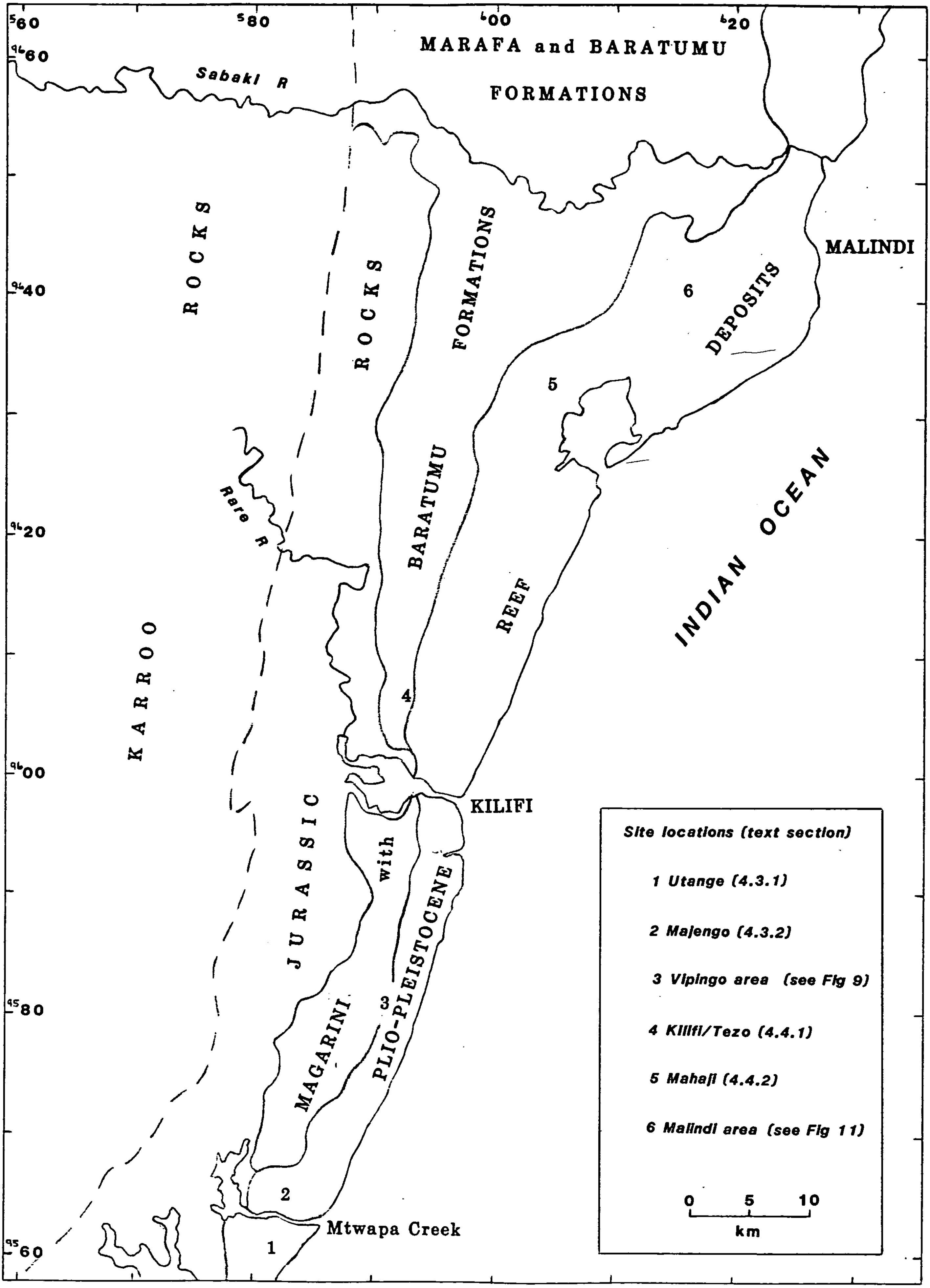

Fig 8. North coast area location map with geology

poor-quality water. Baratumu Formation is shown as having a quite extensive outcrop on the revised maps and the occurrence of blue clays in some of the boreholes near the coast suggests that it underlies the back-reef deposits both here and south of Mombasa.

Sites for the geophysical work (see Fig 8) were chosen on the basis of following up favourable indications from the INPUT survey, but the lack of up-to-date air photographs and maps made navigation difficult away from the main roads. In view of this and the limited time available, the most accessible and easily identifiable localities were used: the cut lines of the sisal estate proved of great assistance in this respect.

4.3.1 Utange, anomaly A6-13

The INPUT target A6-13 has a width of 2 km between a steep amplitude gradient to the west over the contact of back-reef facies against Jurassic shales, and a gentler gradient to the east against reef limestone. The northern end of the anomaly is closed by a high recorded over Mtwapa Creek. Amplitude ratios remain high, as might be expected given the proximity of the shales, though the reasons for maximum values being within the target area and for a displacement of the minimum axis further east are not clear. The target was rated at priority 2 because of interference on the recorded signal. Surface elevations are at 10-25 m above sea-level.

Resistivity sounding MR7, located east of the target on coral limestone, gave a typical curve indicating high resistivities within the upper layers before falling rapidly to about 2 ohm.m. The depth to saline water cannot be interpreted reliably but it appears to be at 17-27 m, the higher values being obtained by introducing an intermediate layer of about 150 ohm.m: thus it seems likely that a lens of fresh water does exist here. MR9, near the facies change, was almost certainly distorted by lateral variations at the wider electrode spacings. It showed lower values of 65 ohm.m, to 8 m depth and 32 ohm.m extending to (?)70 m over a layer of 2 ohm.m. MR8 within the target area showed a moderately conductive sequence but with underlying resistivities increased to near 10 ohm.m: a layer of 50-60 ohm.m between 5 m and 30-35 m depth is compatible with there being fresh water in a sand/clay unit above Jurassic, or Baratumu, deposits or more saline water. MR10 was sited 1 km further north in the central part of the target and close to a dug well with water at a depth of 19 m. The interpretation gave high resistivities in near-surface sands, a conductive zone from 5-10 m depth and a layer of 70 ohm.m to 27 m. The absence of a clear interface near the water table implies that resistivities are controlled by a small but significant clay content. The deepest layer was similar to that at MR8 and seems mainly responsible for the INPUT low relative to values over the coral limestone: no values were measured directly on the Jurassic shales to the west.

An EM34-3 traverse at 20 m coil spacing covering the 1.5 km between MR7 and MR8 via MR9 showed the main features: higher conductivity values over the coral limestone increasing into a topographic depression; a distinctive break in the profile at the change to back-reef facies; lower conductivities to the west. EM data near the resistivity soundings agreed qualitatively with the changes with depth but the observed conductivities were significantly lower than those predicted by the resistivity models.

4.3.2 Majengo, anomaly A6-14

This anomaly lies 5-10 km NNE along strike from A6-13, where the outcrop width of the back-reef formation has doubled. Amplitude ratio values are significantly lower but Hetu (1978) comments that the anomaly was poorly defined in the profile data. Narrow conductivity highs in channel 2 to the southwest might indicate clay bands or noise.

Only three resistivity soundings were taken in this area and these were near the eastern margin of the target because of difficulties in fixing positions. The inconsistency of the interpreted results may have arisen partly from distortions over the undulating ground as well as from genuine differences between the sites. MR11 and MR40 had a similar form to MR10 (see 4.3.1) with the resistivity of the underlying layer increased to 15-20 ohm.m from depths of 35-40 m at MR11, 55-65 m at MR40. The resistivity of the thick, intermediate layer at MR40 had to be reduced to 50 ohm.m while for MR12, where two resistive upper layers were defined to 6 m, the third layer of 30 ohm.m could not be resolved further. Two nearby boreholes, C3305 and C5668, proved a coral sand/clay mix continuing to depths of 40-45 m with yields of 1.5-2 l/s of fair-good quality water. The resistivity results show that clay-rich layers are present locally within 10 m of the surface but sandier layers would also be expected within the saturated zone. It was not possible to determine whether the variations in the channel 2 INPUT data had any significance in terms of the near-surface lithology: however, the low amplitudes recorded on channel 5 can be related to measured resistivities being relatively high at >15 ohm.m for depths of 100 m. MR22 was located near a recently drilled hole yielding about 15 l/s. This site was closer to the coast, east of the main Mombasa-Kilifi road, but still within back-reef deposits where channel 2 amplitudes were lower and amplitude ratios relatively high. Surface resistivities were very high at over 2000 ohm.m and though values decreased to 300 ohm.m within 3 m of the surface they remained as high as 70 ohm.m to 50 m: given the elevation of little over 20 m this is obviously a promising site. The resistivity of the underlying layer was poorly defined as the length of the array was restricted but it is probably about 5-10 ohm.m.

4.3.3 Vipingo, anomaly A6-15, A6-17

A6-15 is a priority 1 target positioned between a gradient in the amplitude ratio contours and the contour value from channel 5 interpreted as representing the saline interface. Further south these features were close together and accompanied by steeper gradients in the channel 5 data but over the Vipingo area they obviously diverge with the amplitude ratio change keeping more to the west. A6-17 lies at the western side of the back-reef deposits near the contact with Upper Magarini beds.

The locations and interpretations of a series of eight soundings covering the area of these anomalies and extending to near the coast is shown in Figs 9 and 10. The direct influence of saline water is clearly apparent from underlying resistivities of 2 ohm.m at relatively shallow depths as far west as MR17: at other sites, close to the decrease in amplitude ratios, the values are still less than 10 ohm.m but tending to increase. Resistivities in the upper layers are generally high throughout and the decrease in channel 2 amplitude as far as the main road corresponds to a gradual increase in the depth to saline water, without any marked discontinuity over the mapped edge of the reef outcrop. A possible explanation for this is that the reef continues further west beneath a cover of sand. At MR13 there are indications of the zone of intermediate resistivity, 50-80 ohm.m, shown by MR16 and MR17 within A6-15. Depths of 35-45 m to saline water are sufficient to accommodate a freshwater aquifer but there are obvious dangers of over-drilling into a transition zone or of subsequent upconing if pumping rates and water quality are not monitored

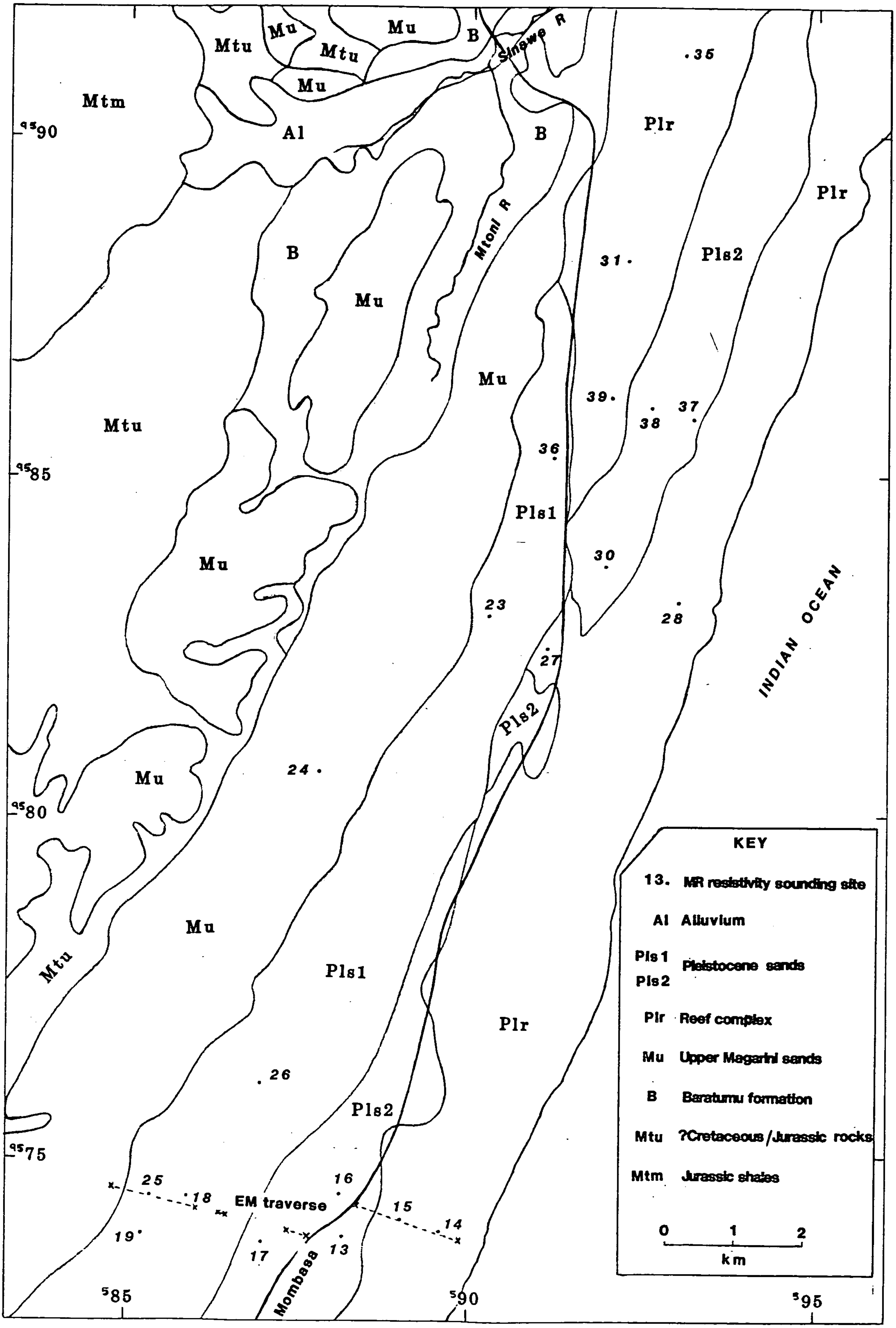

Fig 9. Vipingo area location map with geology

closely. It is clear that conditions here are not equivalent to those at Tiwi though the extent to which the differences in geophysical response originate within the facies of the back-reef as against the underlying formations has yet to be determined.

At MR18 the 25 ohm.m layer is probably a clay zone. A similar, but thicker and more conductive, layer was picked up by MR26 some 2 km further NNE along the margin of an amplitude high in the INPUT data. The topography follows a similar trend and the small-scale ridge/valley landform suggests some lithological control. Further west within A6-17 and close to the Upper Magarini beds, MR19 and MR25 show the very high near-surface resistivities typical of dry sand: with values of 70-100 ohm.m extending to depths of 60-100 m, sands would be expected below the water table, though for clean sands with a porosity of say 25%, these resistivites would indicate brackish water.

EM34-3 readings taken along a line which passed near the resistivity sounding points (see Figs 9 and 10) confirmed the main features of the conductivity patternshown by the INPUT and resistivity survey results. Corrected apparent conductivities of >100 mS/m were given with the 40 m coil spacing at the eastern end of the line, near MR14: these contrast with the values of about 10 mS/m for the 10 m spacing which indicate the resistive near-surface layers. The variations to the east of the main road are attributable to topography, with the tendency for elevations to increase to the west effectively increasing the depth to saline water. The consistency of the readings at 10 m coil spacing for both vertical and horizontal spacings was surprising as models show that they too should be sensitive to the depth of the conductive layer over the range expected. Values at all spacings are significantly lower than predicted from modelling the resistivity interpretations, and in view of the discrepancies observed elsewhere during the survey it may be that the instrument was incorrectly calibrated. Nevertheless, qualitative interpretation of the EM34-3 data is considered to be valid. Values from the 40 m spacing remain at a similar level on the west side of the main road up to MR18; beyond this there is a well-defined zone of lower conductivity centred around MR25. The section from MR18 to MR25 corresponds with the gradient to lower values in the INPUT amplitude ratio map though further west the ratios do not increase again where the conductivity of the upper layers returns to its previous level. This suggests there is a change in conductivity at depth near MR18 which might simply reflect the margin of the back-reef or perhaps the sub-crop of Baratumu Formation beneath the Plio-Pleistocene deposits. A series of point measurements was taken along a second line, 1.5 km further north, using the EM34-3 at intervals of about 500 m. This gave similar results to the first and confirmed that the low conductivity values occur several hundred metres east of the mapped boundary of the Upper Magarini Formation.

4.3.4 Vipingo/Shauri Mayo and anomaly A6-18, A6-19, A6-20

INPUT anomaly A6-18 lies over an 8 km length of higher ground formed of Upper Magarini Formation. Amplitude levels are especially low though ratio values remain high as might be expected for resistive sands overlying conductive clays/shales. MR24 was at an elevation of 120 m within this target and gave results similar to those of MR25 (see 4.3.3): high resistivities in the upper layers showing dry sand to 30 m; a zone of 150-200 ohm.m extending to about 75 m depth which has groundwater potential depending on the porosity of the Magarini sands and the contribution due to a small clay content, relative to brackish water; a poorly-defined underlying layer of 15 ohm.m which would be reasonable for Baratumu

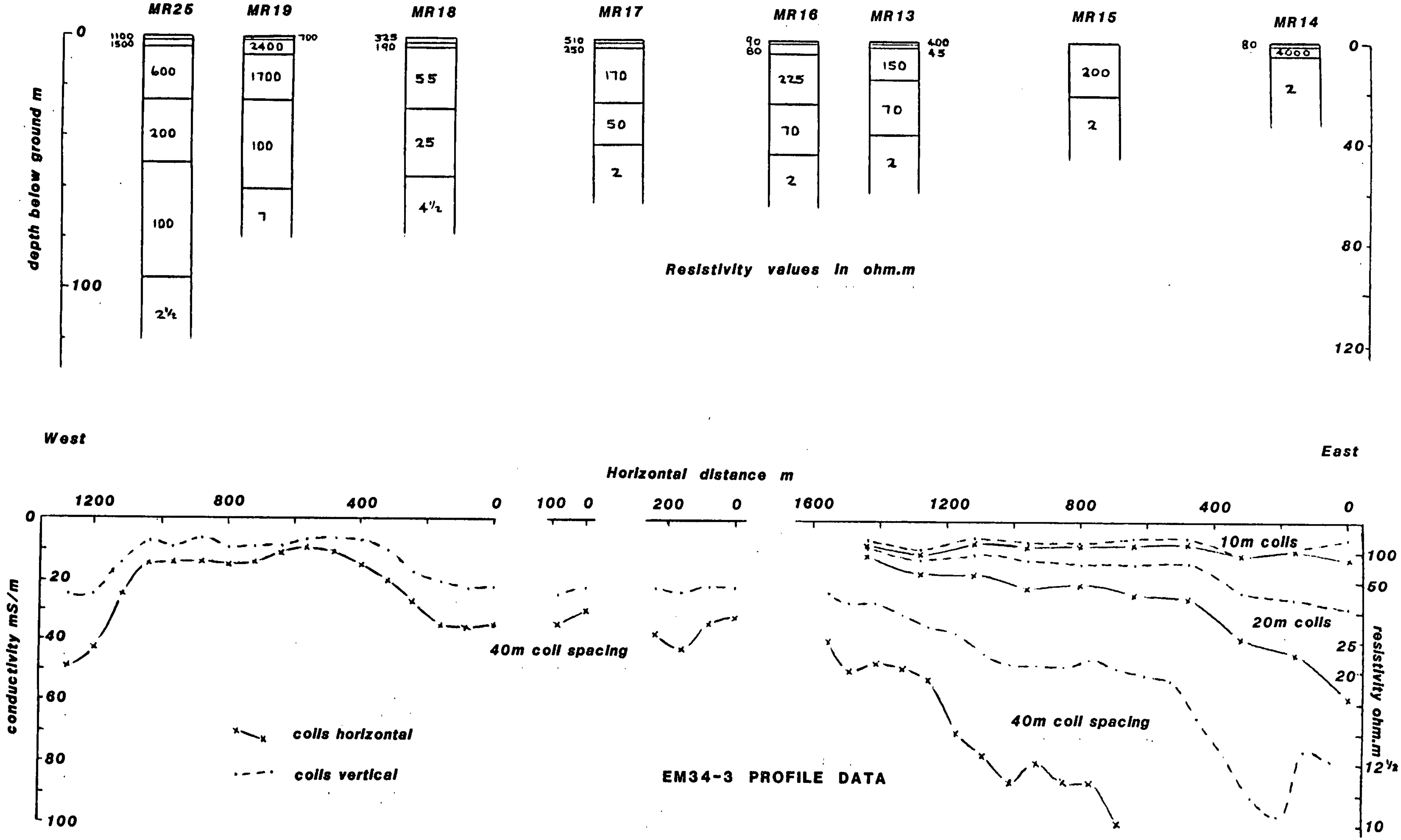

Fig 10. Resistivity interpretations and EM results from the Vipingo area

Formation on Jurassic shales.

MR23 lay off the eastern margin of A6-18 and showed a more conductive sequence typical of the back-reef deposits in this area. The interpretation puts an interface at 50 m depth with resistivities of >50 ohm.m underlain by 4.5 ohm.m. At MR27, further east, and MR36 to the north near the edge of the fossil reef outcrop, the intermediate layer appears to be more conductive at 15-25 ohm.m but thicker, giving depths to clay/shale/saline water of 70-80 m: these results relate to MR26 and MR18 (see 4.3.3) which were at a similar elevation of 30-35 m along strike. Sites to the east of the main road show more definite evidence of saline water with underlying resistivities <3 ohm.m at depths decreasing towards the coast. MR30, MR35 and MR37 provided evidence of an additional interface at depths of 100-150 m below which resistivities increased to about 10 ohm.m: this probably reflects the base of the coral limestone. MR35 was between the targets A6-19 and A6-20 but it is representative of an area showing relatively low amplitudes and high ratio values. Amplitudes near MR37 were much higher though the resistivity interpretations indicate little difference between these sites. There is no explanation for this unless the presence of a low ridge affected the flying height: in any case the amplitude ratio contours are more consistent with the resistivity data. The evidence of saline water within 20 m of the surface at MR35 makes A6-19 seem unpromising. A6-20 is over Upper Magarini Formation at the edge of the back-reef deposits and near to Baratumu Formation outcrop: the prospects would be better here only if the Mtoni-Sinawe River is influent. MR34-3 readings showed that there is a large conductivity contrast between the Magarini sands and the Baratumu beds in this area so that any effect due to fresh water would probably be suppressed. Other EM34-3 readings between the Sinawe River and Kilifi Creek clearly differentiated between the back-reef and Baratumu deposits but even within the sands the conductivities increased rapidly at depth as confirmed by MR34. Deep boreholes to the north of MR34 proved a predominantly sandy sequence, to over 200 m, depth which would appear open to sea-water intrusion.

4.3.5 Conclusions from Mombasa-Kilifi district

(1) Amplitude ratio values from the INPUT data have a higher background level over the back-reef deposits in comparison with the area south of Mombasa. This implies the presence of additional conductive layers which might represent more brackish/saline water within the sands, or a reduction in thickness of the zone of intermediate resistivity (refer point 4 below).

(2) Low amplitudes in the channel 2 data around Vipingo are a result of consitently high resistivities denoting an absence of clay zones in the upper layers. The Upper Magarini sands are thick enough to depress values in the channel 5 data also.

(3) Variations in the resistivity sounding interpretations and EM34-3 data did not always correspond with amplitude contour data; a better correlation was found with the ratio maps.

(4) Resistivity values at depth are consistently <10 ohm.m and the thick zone at 20-30 ohm.m identified south of Mombasa does not appear.

(5) The resistivity data are consistent with there being at least a thin zone of fresh water within sands inland of the fossil reef. Interpretations bring out some large-scale features of the conductivity

variations but it is not clear to what extent unresolved, site specific factors are important in locating wells. The results need to be reassessed when more of the basic hydrogeological data are available and combined with properly constructed, logged boreholes.

4.4 Results from Kilifi-Malindi district

Groundwater supplies extracted from the Ganda wellfield some 6 km west of Malindi (see Fig 10) have been derived from gravels, probably deposited in an old channel of the Sabaki River, overlying Baratumu Formation. The hydrogeology of the area has been investigated by Bestow (1958). Apart from this particular exception the tendency towards finer-grained sediments and gypsum formation within the back-reef deposits suggests that the area southwards to Kilifi has limited potential for development. The INPUT survey data tends to support this view but a few promising anomalies were identified. It was felt that time could usefully be spent on resistivity soundings, both from the aspect of providing basic data and as a comparison with results from further south.

4.4.1 Kilifi-Tezo area, anomaly A6-21 to A6-24

MR32 and MR33 provide contrasting results within 1.5 km of the coastline to the east and west respectively of Kilifi. For MR32 values are high on all three INPUT maps and the resistivity interpretation puts saline water at a depth of 25 m below a resistive cover of the reef facies. MR33 was sited within target A6-21. This anomaly was assigned a priority 3 rating because of its poor expression in the profile data. The contour maps show it as lying at the southern end of a more resistive zone developed inland of the fossil reef, with a conductive embayment to the northeast. The outcrop width of the Plio-Pleistocene sediments increases north of Kilifi Creek and Hetu(1978) suggested from the INPUT anomaly pattern that the Jurassic shales are offset along a fault zone running through the creek. The resistivity sounding results confirm the presence of a deeper saline interface at 65 m, below a 60 m thick zone of intermediate resistivity and a cover of dry sands. The upper part of the central zone appeared to be more conductive, giving a range of 30-60 ohm.m throughout which suggests a clay/sand sequence.

The four sites MR65-68 were in the resistive zone north of MR33. At MR65 and MR66 within A6-24 the resistivity interpretations put conductive material, assumed to be clay-rich at 10-15 ohm.m, within 6 m and 30 m of the surface over a layer of 4-7 ohm.m; this confirms the unfavourable nature of the target as indicated by an old, deep borehole P58 at Tezo. MR67 and MR68 were sited further west in A6-22 on higher ground of Upper Magarini sands. High resistivities extended to 55 m and 80 m respectively, over a layer of 5-6 ohm.m, but given surface elevations of 85 m and 95 m it seems likely that any freshwater zone within sands will be thin. Borehole C1079 between these sites identifies the lowest interface as the contact with Jurassic shales which is associated with a low yield of saline water. The higher amplitude ratio values over this target can be taken as an indication of the shales beneath resistive sands. A similar response is not seen over the anomaly A6-24 where the ground is more uniformly coductive, though on its margin, where MR66 shows the resistive cover to be thickening, a steep gradient is developed with higher values to the east. EM34-3 data from near these sites were in better agreement with the resistivity sounding results than with the INPUT maps. A series of measurements from A6-23, by the Kilifi-Malindi road, to MR67 failed to pick out the main features shown in the channel 5 and ratio contour maps but it could be reconciled with the channel 2 data. The conductivity variations at depth, which are beyond the range of the EM34-3, probably relate to the limit of intrusion of sea-water through permeable reef deposits: the shallower conductive layers which determine the EM34-3 response contribute little to the INPUT signal.

4.4.2. Roka to Mahaji settlement, anomaly A6-26

The high near-surface conductivities shown by the INPUT and EM34-3 data to the east of the main road north of Kilifi indicate extensive sea-water invasion of the low-lying reef deposits, thouh even here it is possible to skim off limited quantities of fresh water. MR62 was sited on higher ground beside the main road some 6 km inland. Very high surface resistivities in the cover of dry sand overlie values of 1.5 ohm.m at 25 m depth, close to sea-level. The intermediate layer of 10 ohm.m below 6 m could be a silt/clay zone, an expression of partial saturation and brackish water, or a lateral increase in the thickness of dry sands.

The extent of the five resistivity soundings measured west of the Mahaji settlement was limited by the difficulty in getting satisfactory electrode contacts in the patially indurated, dry sands. However, at all the sites a conductive underlying layer of <6 ohm.m was detected. Evidence for an intermediate layer was poor because of uncertainties in the field data and the strong suppression effect. The depth to saline water is probably no more than 6 m at MR45, increasing to at least 14 m by MR50. The INPUT target A6-26 was close to a small valley but EM34-3 readings showed only a slight low across it. MR61 and MR46 gave similar results with the thickness of the resistive cover increased to 10-15 m and an intermediate layer of 40-70 ohm.m to about 35 m depth. MR49 was close to the boundary between back-reef and Upper Magarini sands. It showed the resistive cover reduced to a thickness of 8 m over the conductive layer of (?)Lower Magarini or Marafa formation.

4.4.3. Gede-Msabaha area, anomaly A6-27 to A6-31

The remaining sites investigated near Malindi (see Fig 11) fall within the area covered by Bestow(1958). Apart from the Ganda wellfield, which itself has suffered from dewatering, the prospects for groundwater development appear limited and aquifers of the Tiwi type are not to be expected: both low yields and high salinities are adverse factors. INPUT anomaly levels remain somewhat higher than those found further south and the gradient linked with the saline interface is more diffuse.

Sites MR41, MR42 and MR55 lie within A6-27 and give consistent results putting the depth to saline water at 30-35 m below ground elevations of about 15 m. Resistivities in the upper layers are several hundreds of ohm.m, decreasing to 65-70 ohm.m at MR41 and MR42, but possibly as low as 40 ohm.m at MR55. Given the expected water-table close to sea-level some freshwater-saturated sands should be present here. Further north near Msabaha, sites MR51 amd MR52 indicated less favourable conditions where INPUT amplitude ratios were noticeably higher. At MR51 no intermediate zone was detected between the resistive cover and saline water at 15 m: a deeper interface at 55-60 m brought in a layer of 10-15 ohm.m which might be older clays. MR52 was on the gradient in the ratio contours and a better fit to the data was obtained by including a 10-15 ohm.m layer from 15 m to about 33 m depth: here, this might be taken as representing brackish water rather than a clay-rich formation. Bestow comments that salinities in shallow wells decrease towards Msabaha with an increase in

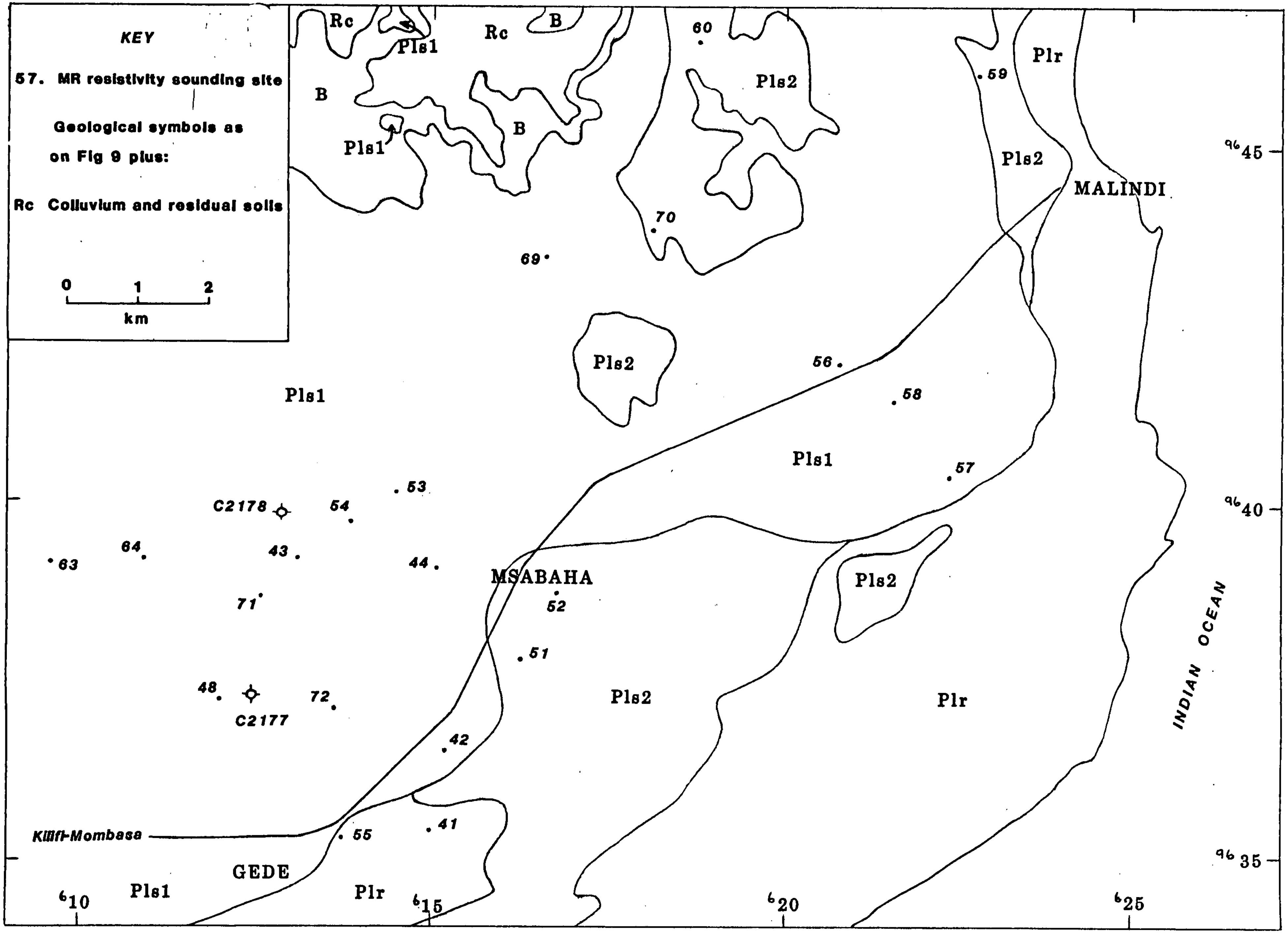

Fig 11. Malindi area location map with geology

porosity: this implies that the intermediate resistivities of MR41 and MR42 relate to more silty conditions.

A series of resistivity soundings were located west of Msabaha around A6-28 where low channel 5 ratio values were obtained. MR48 and MR72 lay to the south of the anomaly and they could be related directly to MR51 with depths to saline water of nearly 20 m: both sites also indicated that the deeper interface was underlain by slightly less conductive material. MR44 falls within the same group except that the conductivities remained high below 18 m. MR71, MR43, MR54 and MR53 were along the major axis of the INPUT target. MR71 showed resistive sands to 9 m underlain by a 40 m thick zone of 25 ohm.m: at MR43 this zone was apparently more than 100 m thick. Continuing northeast to MR54 two components of 50 ohm.m and 14 ohm.m were resolved extending to depths of 33 m and 75 m respectively, while at MR53 a 55 ohm.m layer was interpreted to 60 m depth. The resistivity of the deepest layer was 5-10 ohm.m. There is almost certainly a lithological change associated with this anomaly and the resistivities of 15-30 ohm.m imply clays, (?)Baratumu Formation, with perhaps an increasing sand content in the upper part towards the northeast. MR47 was beside a main track and the results appear to have been distorted by lateral variations. MR64 and MR63 sited further west confirm that a layer of 30-35 ohm.m extends in this direction with a thickness in excess of 100 m.

Access to targets A6-29 and A6-30 proved difficult but it was possible to locate MR57 in A6-30. The interpretation is similar to that for A6-28 with a layer of 15-20 ohm.m extending beneath sands from 15 m to 65-70 m depth above a layer of <2 ohm.m. Over A6-31, MR56 was of restricted length and the interface of 40 m separating layers of 30-35 ohm.m and 10 ohm.m is only approximate. MR58, which lay outside the anomaly to the east, indicated a zone of 40 ohm.m to 70 m depth but underlain by saline water at <2 ohm.m.

4.4.4 Ganda area, anomaly A6-32, A6-33

Near Malindi the narrowing of the outcrop of the fossil reef is reflected in the INPUT amplitude ratio contours by a broadening resistive zone which extends from the southwest (see 4.4.3) and pinches out the higher values at the coastline 2-3 km north of Malindi. The Ganda wellfield and its associated priority 2 target A6-33 are within this more resistive zone. MR70 was sited over the centre of the small anomaly. A layer of 33 ohm.m occurred within 2.5 m of the surface and extended to a depth of 40-45 m: beyond this the resistivities decreased to about 15 ohm.m to 60 m and then 6 ohm.m. The log for the nearby borehole 848 shows a light sand to 3 m, sands with some clay and coral to 39 m, coral to 44 m and then blue clay with limestone. Apart from the thinner resistivie cover at MR70 there is little to distinguish the results from those obtained to the southwest at MR53, MR54 etc but the boreholes C2177 and C2178 gave low yields and higher salinities. The aquifer may not be sufficiently extensive or resistive for it to be distinguishable from its finer grained lateral equivalents. However, MR69 did show a more conductive sequence with resistivity values >40 ohm.m to 6m depth, 15 ohm.m to 30-35 ohm.m and then 8 ohm.m. At MR60, 2 km north of Ganda, resistivities were >150 ohm.m to 5 m, 12 ohm.m to 35 m and then 9 ohm.m with some indication of a more conductive layer below about 125 m.

A6-32 was an unconvincing target associated with changes in flying height. MR59 confirmed this judgement with resistivities <5 ohm.m from a depth of 15 m indicative of saline water within coral limestone.

4.4.5 Conclusions from Kilifi-Malindi district

(1) The one known locality where a significant aquifer occurs was associated with reduced conductivity values detected from the INPUT survey. The anomaly was relatively minor and indistinguishable from others which occurred over less favourable ground. Similarly, while resistivity sounding results were more promising locally, they did not seem particularly encouraging in the regional content.

(2) Resistivity sounding results confirm that high conductivity, 10 ohm.m, material underlies much of the district at relatively shallow depths. This probably reflects both sea water intrusion and, further inland, the retention of saline fluids within fine-grained sediments under conditions of low recharge. An area of lower conductivities was outlined within which resistivities at depth were 15-35 ohm.m, similar to values found south of Mombasa. These are attributed to Tertiary sediments of Baratumu type.

(3) The clean, dry sands found in this district gave very high electrode contact resistances. The low signal strengths which result from limited input current combined with the high conductivity of the underlying layers make it difficult to obtain good quality resistivity data. If surveys are required in this type of environment they should be undertaken during a rainy season: alternatively, signal strengths may be increased by using multiple electrodes; by adding salt water with detergent to reduce the resistance and surface tension effects around the electrodes; using a more powerful transmitter; using a Wenner, instead of a Schlumberger, array configuration. If such procedures are not followed misleading results may by obtained as demonstrated by some of the Austromineral data. Electromagnetic techniques are particularly useful in these circumstances as the induction of current below the resistive surface layer presents no problem.

(4) The resistivity values obtained over the Ganda aquifer were not distinctively high. The interpretation could be revised to resolve the intermediate zone into additional layers of lower and higher resistivity but there is no a priori justification for doing this; geophysical logging is needed to show whether the more complex model is a better representation in this particular case. The potential of other sites where similar resistivities were measured remains uncertain without extra hydrogeological and drilling data. The validity of the association of resistivity values with lithology suggested in point 2 above also need to be checked.

5. GENERAL CONCLUSIONS AND RECOMMENDATIONS

(1) The INPUT survey provides information on large scale conductivity variations which are related to lithology and it could be used to refine the geological mapping given suitable ground control. The smaller scale and secondary features of the contour maps have a variety of causes amongst which the occurrence of fresh groundwater is only one. Both the Tiwi and Ganda aquifers have an expression on the INPUT maps but similar anomalies elsewhere are associated with quite different conditions. The INPUT response is most sensitive to units with a high conductivity and there is little discrimination of the depth at which the anomalies originate. Despite these limitations the INPUT survey should be considered as part of the basic data set to be integrated with other hydrogeological information for the evaluation of borehole sites.

(2) Resistivity soundings can bring out particular aspects of the

local environment which relate to the groundwater but their effectiveness in the direct detection of the aquifers themselves is considered to be marginal. There is no evidence that high-yielding aquifers or variations in water quality can be mapped reliably. This is due in part to a lack of resolution inherent to the technique, and to the overlap in resistivity values between different units in the succession. However, at some sites favourable resistivity interpretations did correspond with more successful wells.

(3) Resistivity soundings may be useful for interpolating between boreholes where conditions differ due to changes in either lithology, permeability, groundwater salinity or formation thickness: if more than one factor is varying then ambiguity of cause will be a problem.

(4) Further correlation should be made between resistivity interpretations and any sites where reliably logged and tested boreholes are available. As a first step, resistivity surveys should be undertaken prior to drilling the project's boreholes. These may provide useful information on any lateral variations before final site selection and they could be used subsequently for correlation. It is important to establish how layer resistivities match against aquifer thickness, permeability, variations in water quality with depth and clay content (refer points 2 and 3 above).

(5) INPUT survey results suggest that the Pleistocene reef exerts a primary influence on the extent of sea-water intrusion. The effectiveness of the resistivity/conductivity techniques for mapping the depth to saline water cannot be judged without better borehole control: the reliability of depth interpretations and the ability to distinguish transition zones and overlying fresh water from resistivity data have yet to be proved in this environment. The vertical resolution of the EM34-3 equipment is inadequate in this respect but its efficiency in mapping lateral variations would justify its use if there is significant channelling of fresh or saline water through the coral limestone. IP (induced polarisation) methods can provide additional information on the occurrence of fresh water overlying zones of high salinity. Roy and Elliott (1980) show how IP data can be used qualitatively to complement resistivity soundings and refine the layer interpretation. Olorunfemi and Griffiths (1985) provide an example where IP values could be correlated directly with groundwater salinity though their techniques require laboratory sample measurements and relatively homogeneous aquifer conditions. If drilling results indicate that there is a need to define the extent of saline water in the coastal aquifer the application of IP techniques should be considered.

(6) The geophysical results from Msambweni need to be checked by drilling. Even if the shallow wells programme precludes the development of production boreholes the information would help in establishing the regional hydrogeological pattern, apart from providing lithological control. If the intermediate resistivity values do represent thick coral here an explanation is required for the change to higher conductivities further north: if the resistive channel is associated with an aquifer it would encourage the continued use of geophysics. There is an analogy between the resistivity values observed here and west of Malindi where Baratumu sediments occur: however, the INPUT anomaly is less clearly defined in the Malindi area.

(7) Use should be made of borehole logging techniques where possible. Natural gamma and neutron logs can be obtained through casing to provide information on variations in clay content and porosity. Resistivity and self potential logging is only practical in un-cased holes or opposite the

screened sections of non-metallic casing.

(8) The results of any geophysical surveys should be documented and archived in an easily retrievable form. It is particularly importnat that interpretations are reviewed in the light of drilling information so that a data base can be built up for relating resistivity values to lithology and groundwater conditions, and for demonstrating the circumstances in which the method is effective.

(9) The use of standard resistivity interpretation techniques is recommended; that is to match the observed apparent resistivity curve against values calculated for a horizontally layered model either in the form of published master curves or preferably as generated by a programmable calculator or microcomputer.

6. ACKNOWLEDGEMENTS

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APPENDIX: DIAGRAMMATIC REPRESENTATION OF RESISTIVITY INTERPRETATIONS

For each site there is a sounding number and a 100m grid reference which should be accurate to within 50m.

Layer resistivites are in ohm.metres; interface depths and layer thicknesses are in metres.

The interpretations shown are not unique: they represent the simplest models which are compatible with the available information and which give a good fit to the field data. The range of equivalent models is often quite large.

MR1
5680 95425

650
— 0.5
96 (3.5)
— 4
13 (4)
— 8
105 (20)
— 28
12 (17)
— 45
5

MR2
5668(5) 95417

2000
— 0.4
250 (2.6)
— 3
17 (16)
— 19
25 (11)
— 30
18

MR3
5660(5) 95421

175
— 0.3
16 (1.3)
— 1.6
4½ (21.4)
— 23
25 (10)
— 33
10

MR4
5662(5) 95433

1200
— 0.7
100 (2.3)
— 3
30 (11)
— 14
65 (20)
— 35
30

MR5
5685 95453

800
— .7
125 (2.3)
— 3
83 (32)
— 35
22

MR6
5685 95439

2300
— 0.8
750 (2.9)
— 3.7
195 (26.3)
— 30
60 (20)
— 50
10

MR7
5809(5) 95601

100
— 0.4
215 (2.1)
— 2.5
900 (8.5)
— 11
150 (16)
— 27
2

MR8
5798 95605

28
— .6
9 (1.6)
— 2.2
25 (3.3)
— 5.5
55 (22.5)
— 28
11

MR9
5803(5) 95606

——

600
——.8
65 (7.2)
——8
32 (62)
——70
2

MR10
5798 95614

——

750
——0.5
180 (1.5)
——2
95 (2.5)
——4.5
14 (5)
——9.5
70 (17.5)
——27
8

MR11
5819(5) 95672(5)

——

1100
——1
400 (1.7)
——2.7
20 (10.3)
——13
80 (22)
——35
18

MR12
5826 95674(5)

——

225
——.5
125 (5.5)
——6
29

MR13
5882 95738

——

400
——.3
45 (1.7)
——2
150 (13)
——15
70 (22)
——37
2

MR14
5896 95739

——

150
——.3
80 (1.2)
——1.5
4000 (3.2)
——4.7
2

MR15
5890 95740

——

195
——21
2

MR16
5881 95744(5)

——

92
——.7
80 (4.3)
——5
225 (20)
——25
70 (20)
——45
2

MR17
5870 95737(5)

——

510
——1
250 (2.3)
——3.3
170 (21.7)
——25
50 (17)
——42
2

MR18
5859 95744

——

325
——2
190 (2)
——4
55 (24)
——28
25 (27)
——55
4½

MR19
5852(5) 95739

——

700
——.4
2400 (6.6)
——7
1700 (18)
——25
100 (35)
——60
7

MR20
5686 95429

——

3000
——.8
250 (2.2)
——3
100 (27)
——30
75 (20)
——50
6

MR21
5686 95429
———
2900
——— .8
300 (2.2)
——— 3
105 (27)
——— 30
65 (25)
——— 55
14

MR22
5831 95653
———
750
——— .4
215 (4.1)
——— 4.5
350 (13.5)
——— 18
70 (7)
——— 25
8

MR23
5903 95829
———
110
——— 1.3
50 (7.7)
——— 9
125 (11)
——— 20
70 (20)
——— 40
50 (10)
———
4½

MR24
5878 95806
———
1900
——— 1.8
1050 (5.2)
——— 7
475 (23)
——— 30
165 (45)
——— 75
15

MR25
5854 95744
———
1070
——— .9
1500 (3.1)
——— 4
600 (21)
——— 25
200 (25)
——— 50
100 (45)
——— 95
2½

MR26
5870 95761
———
320
——— 4
50 (12)
——— 16
16 (64)
——— 80
4

MR27
5911 95824
———
92
——— .6
130 (4.4)
——— 5
70 (13)
——— 18
17 (54)
——— 72
3½

MR28
5930 95831
———
750
——— .5
1250 (5.3)
——— 5.8
2

MR29
5687 95429
———
1500
——— .5
250 (2.3)
——— 2.8
100 (17.2)
——— 20
85 (10)
——— 30
42 (20)
——— 50
6

MR30
5920 95836(5)
———
275
——— .5
475 (2)
——— 2.5
225 (10.5)
——— 18
15 (15)
——— 33
1½ (67)
——— 100
8

MR31
5923 95882
———
200
——— .5
110 (2.5)
——— 3
80 (9)
——— 12
150 (16)
——— 28
75 (12)
——— 40
2½

MR32
5961 96009
———
230
——— 1
160 (2.2)
——— 3.2
400 (11.8)
——— 15
76 (10)
——— 25
1½

MR33
5920 96020
———
1000
———1
500 (3.3)
———4.3
35 (8.7)
———13
55 (52)
———65
1½

MR34
5934 95963
———
200
———.3
120 (1)
———1.3
300 (1.7)
———3
30 (4)
———7
95 (20)
———27
2½

MR35
5931 95912
———
350
———1
380 (11.5)
———12.5
95 (6.5)
———19
2 (131)
———150
8

MR36
5912 9582(5)
———
165
———3.5
350 (7.5)
———11
150 (13)
———24
25 (56)
———80
4

MR37
5932 95859
———
300
———.4
1000 (8.1)
———8.5
125 (10)
———18.5
1½ (106.5)
———125
15

MR38
5926 958600
———
500
———1.5
720 (11.5)
———13
175 (17)
———30
2

MR39
5920(5) 95861
———
350
———.4
210 (5.6)
———6
130 (19)
———25
40 (5)
———30
2

MR40
5832 95861
———
80
———.4
200 (2.1)
———2.5
80 (4)
———6.5
6 (7)
———13.5
100 (6)
———19.5
50 (40.5)
———60
15

MR41
6150 96354
———
210
———.5
125 (4)
———4.5
200 (10.5)
———15
70 (15)
———30
2

MR42
6152 96365
———
210
———1.5
115 (4.5)
———6
65 (24)
———30
2

MR43
6131 96392
———
970
———4
250 (5.5)
———9.5
27 (110.5)
———120
2½

MR44
6151 96390(5)
———
525
———.6
3200 (3.9)
———4.5
22 (13.5)
———18
5½

MR45
6055 96331(5)
———
750
———.6
300 (3.4)
———4
250 (2)
———6
1½ (14)
———20
2½

MR46
6019 96332
———
5250
———1
3000 (1.5)
———2.5
1700 (7.5)
———10
65 (25)
———35
5

MR47
6112(5) 96389(5)
———
1600
———2.8
450 (3.2)
———6
10 (10)
———16
275 (14)
———30
5

MR48
6119(5) 96372
———
1250
———1.5
900 (4.5)
———6
55 (12)
———18
5 (42)
———60
8

MR49
5983 96331
———
7500
———.8
1100 (4.2)
———5
350 (2.5)
———7.5
6

MR50
6042 96336(5)
———
9000
———.6
2750 (1.4)
———2
1000 (5)
———7
45 (7)
———14
5

MR51
6163 96378
———
1400
———8.8
175 (6.2)
———15
2 (42)
———57
13

MR52
6168 96387
———
600
———.8
1300 (5)
———5.8
400 (3.2)
———9
100 (6)
———15
12 (18)
———33
4

MR53
6145 96401
———
1150
———6.5
30 (9.5)
———16
100 (24)
———40
9

MR54
6139 96397
———
3500
———6
2000 (2.5)
———8.5
250 (4.5)
———13
50 (20)
———33
14 (42)
———75
7

MR55
6137(5) 96353
———
300
———.6
135 (5.4)
———6
400 (16.5)
———22.5
40 (12.5)
———35
2

MR56
6208 96419
———
90
———.5
65 (0.5)
———1
85 (6.5)
———7.5
33 (32.5)
———40
10

MR57
6223 96404

———

175

———.8

135 (2.7)

———3.5

225 (11.5)

———15

17 (55)

———70

1¾

MR58
6215 96414

———

400

———.6

200 (1.4)

———2

125 (20)

———22

40 (48)

———70

1½

MR59
6227(5) 96460(5)

———

150

———.3

62 (13.7)

———14

4½

MR60
6188 96465

———

250

———.7

170 (4)

———4.7

12 (30.3)

———35

9 (100)

———135

1½

MR61
6025(5) 96332

———

8500

———1.1

2400 (8.4)

———9.5

250 (5.5)

———15

45 (20)

———35

3

MR62
6000 96230

———

2600

———.6

1100 (1.9)

———2.5

150 (3.5)

———6

10 (19)

———25

1½

MR63
6096 96391

———

2700

———.8

1200 (8.7)

———9.5

30 (115.5)

———125

5

MR64
6109 96392

———

3200

———1.5

1000 (5)

———6.5

35

MR65
5938(5) 96081(5)

———

1000

———.7

300 (2)

———2.7

50 (2.8)

———5.5

11 (26.5)

———32

6½

MR66
5949 96101

———

200

———1

150 (1.2)

———2.2

55 (25.8)

———28

13 (32)

———60

4

MR67
5907 96054(5)

———

3250

———2.5

1500 (5.5)

———8

250 (47)

———55

5

MR68
5907 96079

———

2250

———2

1600 (3.7)

———5.7

700 (0.5)

———6.2

30 (2.8)

———9

80 (71)

———80

6

MR69
6166 96434

———

220

———.5

100 (1.7)

———2.2

40 (3.5)

———5.7

15 (27.3)

———33

8

MR70
6181 96438

———

190

———2.4

33 (39.6)

———42

14 (18)

———60

6

MR71
6125(5) 96396(5)

———

1900

———2.7

750 (5.8)

———8.5

25 (41.5)

———50

9

MR72
6136 96371

———

1000

———.4

420 (10.6)

———11

100 (9)

———20

2 (70)

———90

9

MR73
5622 95272

———

30

———.3

7½ (6)

———6.3

38 (4.2)

———10.5

9½

MR74
5611(5) 95246

———

175

———2

125 (15.5)

———17.5

21 (102.5)

———120

12

MR75
5606 95257

———

40

———.7

12 (4.3)

———5

17

MR76
5639(5) 95271

———

350

———1

135 (12)

———13

22 (5)

———18

3

MR77
5662(5) 95413(5)

———

480

———.6

140 (1.6)

———2.2

12 (7.8)

———10

38 (8)

———18

22 (42)

———60

8

MR78
5637 95278

———

200

———.4

120 (1.3)

———1.7

150 (8.3)

———10

80 (23)

———33

45 (17)

———50

2

MR79
5639(5) 95352

———

800

———.4

170 (2.9)

———3.3

28 (39.7)

———43

60 (57)

———100

12

MR80
5659 95410

———

900

———.2

290 (1.1)

———1.3

1100 (2.2)

———3.5

80 (3)

———6.5

16 (3.5)

———10

35 (60)

———70

10