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Stratigraphic Interpretation of Magnetotelluric Data in Central Saudi Arabia

Ian C.F. Stewart, Thomas C. Connally
Saudi Aramco
and Jeffrey H. Copley
Zephyr Geophysical Services, USA

ABSTRACT

The pre-Khuff interval of the Paleozoic sediments in central Arabia is poorly defined by conventional seismic techniques, although this layer has significant potential for hydrocarbon exploration. Model studies indicated that magnetotelluric methods could outline the regional changes expected in the pre-Khuff in the area, which are largely dependent on the topography of the Precambrian basement. The Hercynian orogenic event created an extensive block-faulted terrane of half-grabens and horsts. The Hercynian structural relief was infilled in the Permo-Carboniferous and faulting reactivated in Triassic and later time, but the relationship between pre-Khuff and post-Khuff structure was impossible to understand using seismic data alone. In this survey of almost 500 magnetotelluric (MT) stations, essential control on the shallower section was provided by seismic interpretations, in addition to well log data for depths and resistivities. The MT method was very successful in confirming the presence of significant pre-Khuff section over some basement structures, as well as defining areas where the section is thin or absent which may be suitable for further exploration for stratigraphic traps.

INTRODUCTION

The magnetotelluric (MT) method has been used for more than twenty years to delineate the electrical resistivity structure of sediments in the search for hydrocarbons. The technique has been outlined by Vozoff (1972) and Orange (1989) and will not be described further here. Magnetotelluric methods are now becoming more commonly employed by many companies around the world as part of integrated exploration efforts. This is particularly the case in areas where access is difficult or where unusual or complicated structure occurs which can not be imaged using conventional exploration techniques. Typically this may be where seismic methods are very expensive or difficult to use, or where the data is of poor quality.

In the present example, the MT technique has been used in an area in central Saudi Arabia where the shallower geological structure is relatively simple, and is well defined by high-quality seismic data. However, the deeper sediments, immediately above the economic basement, are poorly resolved in the seismic data, and MT has been used to outline the variations in these horizons, which are potentially of economic interest. Unlike many MT surveys which involve interpretations of complex regional structure, in this case the method was used in an area which had previously been intensively explored, and where the objectives of the MT work were quite limited. The area in which the MT survey was undertaken is shown in Figure 1, which also indicates the main oil fields as well as two areas and a profile for which the MT results are described in this paper.

Seismic techniques can resolve the sedimentary structure down to the base of the Permian Khuff carbonate formation, which typically is at a depth of the order of 2,000 to 4,000 meters (m) in the area of interest. It is known that an appreciable thickness of pre-Khuff clastics can occur between the economic basement and the base of the Khuff over large areas. These pre-Khuff Paleozoic formations have considerable potential for hydrocarbon exploration in central Arabia (McGillivray and Husseini, 1992). However, multiples tend to obscure all primary events below the base of the Khuff, and it is usually not possible with even the best seismic data to map this zone reliably or to determine from the seismic data whether basement or clastics underlie the pre-Khuff unconformity. Magnetic depth estimates can not be used

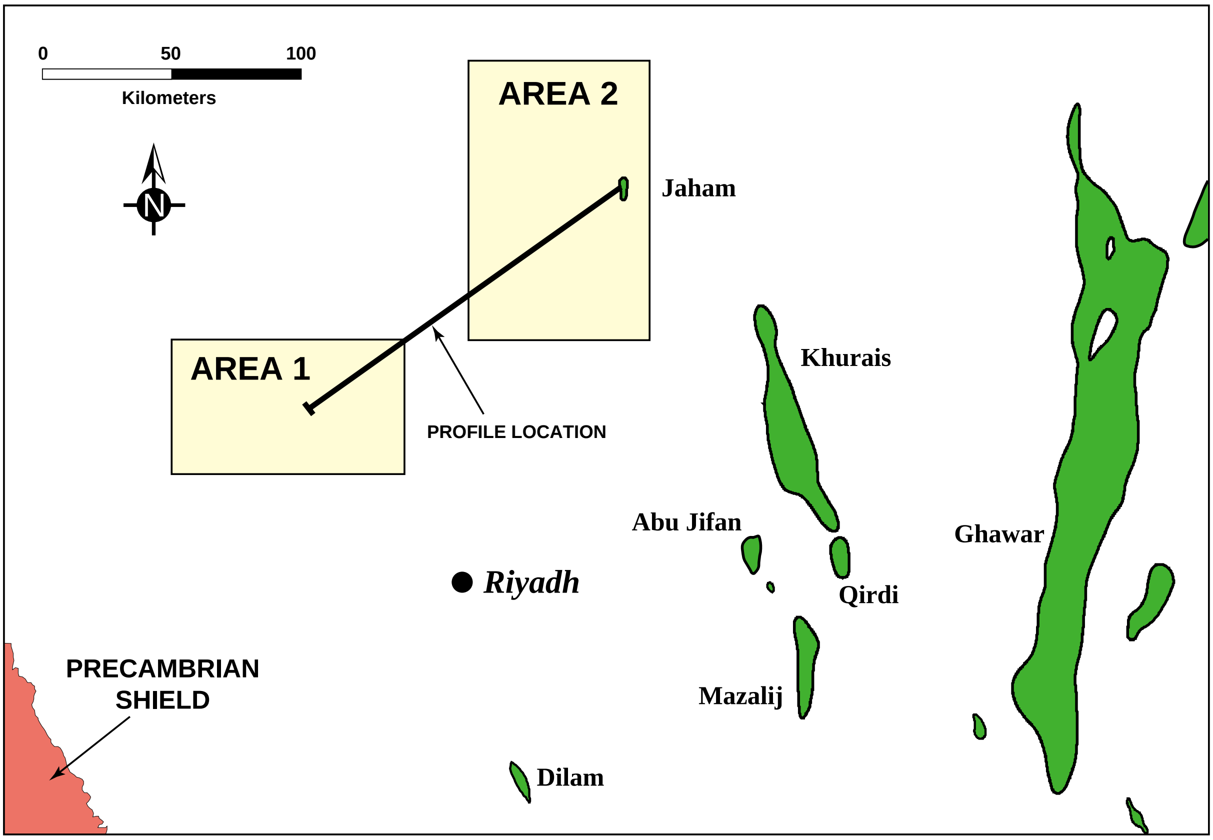

Figure 1: Location map for the magnetotelluric (MT) survey in Central Saudi Arabia, showing the areas and profile given in Figures 6 through 9, as well as some of the main oil fields.

alone to resolve this problem, since the essentially non-magnetic metasediments of the economic basement have no usable signature, apart from isolated igneous intrusions. The primary objectives of the present project were to demonstrate the feasibility and sensitivity of MT methods in detecting the presence or absence of the pre-Khuff clastic section, as well as to map the isopach of this interval over previously defined target areas. Favorable locations could then be subjected to more rigorous seismic exploration or re-processing of existing data.

The pre-Khuff section of interest here has several units which form the reservoir over some producing structures and may also contain high-quality source rocks. The definition of the thickness of the pre-Khuff sediments is important, since the higher blocks which form existing structures may have undergone sufficient erosion such that there is no section (potential reservoir) present, and the basement structure indicated by the isopach of the pre-Khuff could be a factor in predicting its internal stratigraphy. The exploration risks in drilling large structures are somewhat reduced if even a qualitative estimate of the reservoir zone can be made. In addition, the ability to use MT data for mapping the thickness of the pre-Khuff offers the possibility of locating large-scale untested stratigraphic traps as sites for further exploration. Several wells located at the crests of basement structures penetrated economic basement below the pre-Khuff unconformity. MT data were also acquired at these locations for calibration purposes.

FEASIBILITY STUDY

Resistivity logs from deep wells show that where present the pre-Khuff section has a generally lower resistivity than the sections immediately above and below it. The average resistivity of the clastic section is about 5 ohm-meter (Ω-m), with lower values (1 to 2 Ω-m) in the Qusaiba shale and higher values (10 to 15 Ω-m) in the basal siltstones. In order to determine the feasibility of employing MT methods to study the pre-Khuff in central Arabia, synthetic MT response curves corresponding to various resistivity models typical of the region were inverted to yield layered sections. Generally it is necessary to employ at least 8 layers in the inversion in order to obtain a realistic approximation to the original model. A simplified resistivity section based on 8 layers using well-log data is shown in Figure 2, where the crust

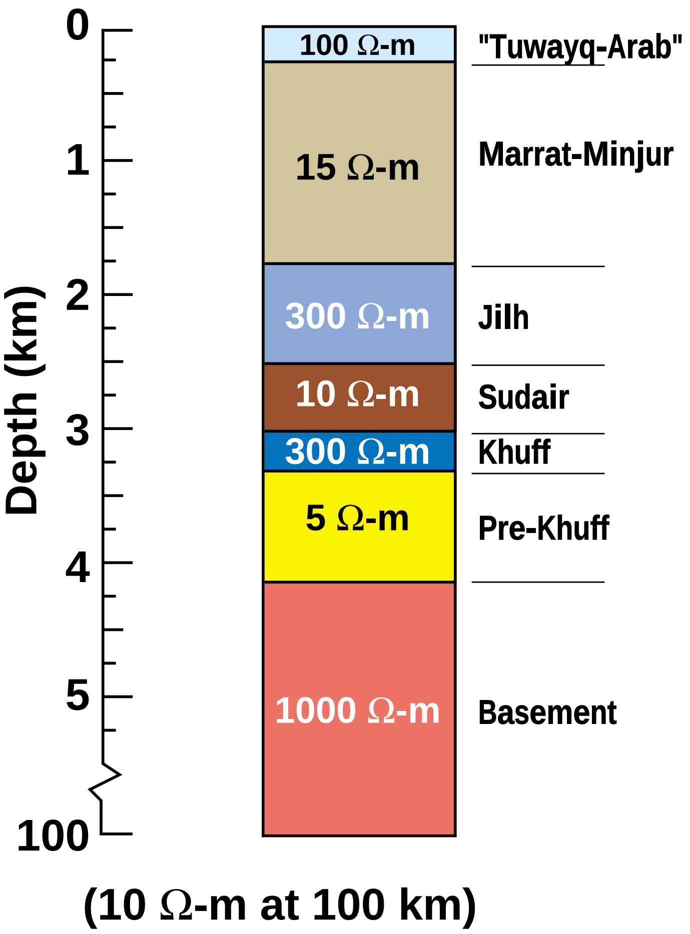

Figure 2: Simplified resistivity section with eight layers which was used to model the MT response expected in the survey area. The deepest layer is the half-space (10 Ω-m) below 100 km depth.

is fixed at 100 kilometers (km) thick, with an electrical basement resistivity of 1,000 Ω-m and 10 Ω-m below that. Note that it is beyond the scope of this paper to give a detailed discussion of the post-Khuff section, since we are only concerned with the overall effect on the MT response of the shallower electrical structure. The effects of varying the thickness of the low resistivity pre-Khuff layer on the MT response (apparent resistivity versus frequency) are shown in Figure 3. These indicate that, depending on the assumed resistivity, it should be possible to discriminate variations of perhaps 100 to 200 m in the thickness of the pre-Khuff, which may reach several thousand meters in some areas.

The preliminary model studies suggested that interpretations of high-quality MT data, utilizing constraints provided by seismic data, could provide a reliable estimate of the thickness of the pre-Khuff. The ability to use independent (seismic) data to constrain the thickness and depth of the major resistivity units in the shallower section down to the Khuff region is critical to deriving good solutions. The primary objective was to determine where the pre-Khuff section was present; the thickness and spatial variation were secondary goals.

DATA ACQUISITION

The acquisition system employed for the field work used standard real-time remote reference recording techniques, with 3 simultaneous 5-channel MT sites. Typical site spacing was about 5 km, and up to 12 km when radio telemetry was employed. Site locations were initially planned on a regional basis and later modified based on the in-field interpretation and discussions with exploration staff. Most of the data were obtained along profiles so as to outline regional variations in the pre-Khuff structure, but in some localized regions the site layout was more two-dimensional in order to map areas which had been identified from previous seismic and gravity work.

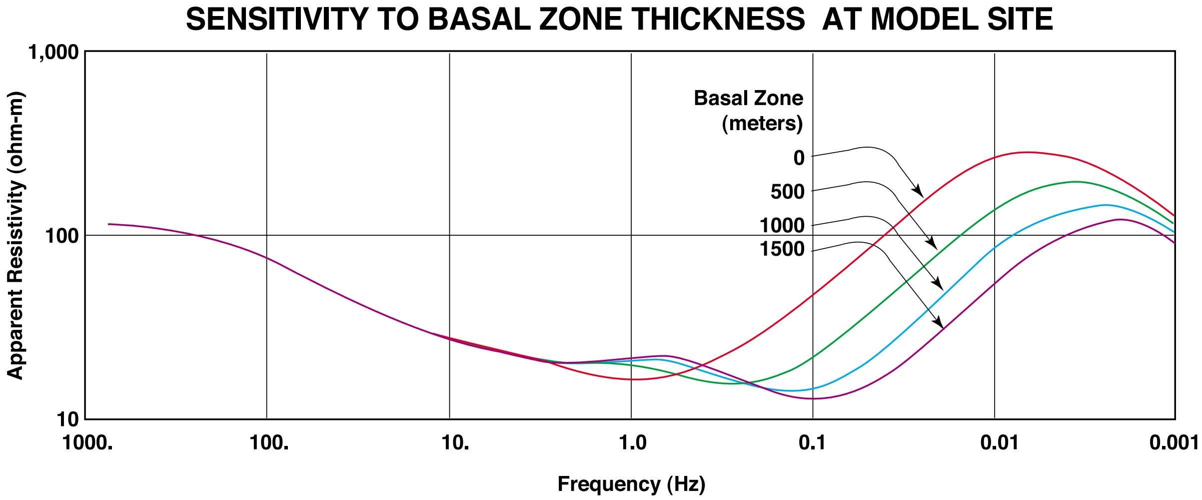

Figure 3: The effect on MT response (apparent resistivity against frequency) of varying the pre-Khuff thickness (fixed at 5 Ω-m) for the model shown in Figure 2.

Magnetic field signal levels fluctuated dramatically during the 7.5 months of acquisition, and this was generally the primary factor in determining the length of recording, which was typically 16 to 18 hours per setup. Although the topography was fairly flat, access to sites and general field conditions were relatively straightforward for only about one third of the sites, with varying degrees of difficulty for the remainder. Many sites were located in proximity to wells, pipelines and producing facilities, with a variety of noise sources from power lines, pumps and cathodic protection. During periods of low signal level or abnormal noise the recording times for some sites were extended to 2 days. Diligent field work and attention to detail by the field crew was the primary reason for the consistent acquisition of an optimum MT data set. Most of the data are of excellent quality, and fewer than 10 percent of the nearly 500 sites could be classed as less than good.

Editing of the data and much of the initial interpretation was carried out in the field, so that problems with the data could be rectified in a timely fashion. Further editing of the data elsewhere generally did not result in significant changes in the interpretation. Preliminary studies and analysis of the field data were undertaken using Geotools™ (Geotools Corporation) software on a Unix-based workstation.

INTERPRETATION

In the region being studied, the basement structure is dominated by a horst and graben style of faulting, in response to the regional tectonic pattern imprinted during the Hercynian orogeny and subsequently reactivated on several occasions. Vertical displacements in excess of 1,000 m can occur on some faults, and the motion may have varied in direction and rate with time. Typically the economic basement consists of metasediments which may be up to several kilometers in thickness, and contains localized late-Precambrian crystalline intrusions. Available well logs indicate that all the basement units tend to have a relatively high resistivity, ranging from about 50 to 500 Ω-m. Lower resistivities due to weathering can occur towards the top of the basement which may affect estimates of the pre-Khuff sedimentary thickness.

During the initial feasibility study it was determined that accurate estimation of the pre-Khuff thickness would require depth and thickness of the shallower post-Khuff section to be constrained by independent (seismic) data and that a many layer inversion model would be required, typically 10 to 14 layers at most sites. Two-dimensional model studies also indicated that in most cases one of the MT components should be a very close approximation of the one-dimensional solution, although the response in certain cases can be distorted by the compound effects of shallow, abrupt resistivity changes. Statics corrections were applied where appropriate. For the interpretation, in addition to seismic data, control was provided by well information, including formation depths and resistivity logs. Automatic inversion of the data (using a Marquardt algorithm) usually did not produce stable results, and it was found to be most satisfactory to adjust the shallower layers manually to obtain a good fit to the data before inverting for the pre-Khuff layer.

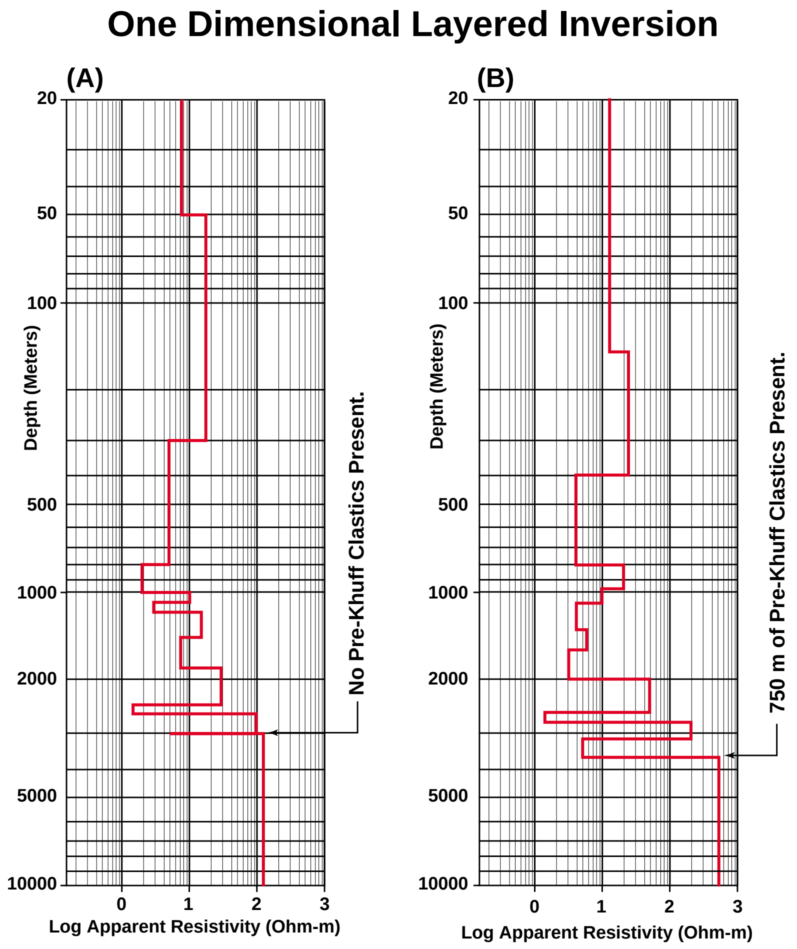

Figure 4: Resistivity models obtained by inversion of actual data, for an example where no pre-Khuff clastic layer is present (A), as well as for a site (B) where a 750 m thick layer of pre-Khuff clastics is inferred to exist (5 Ω-m immediately above electrical basement).

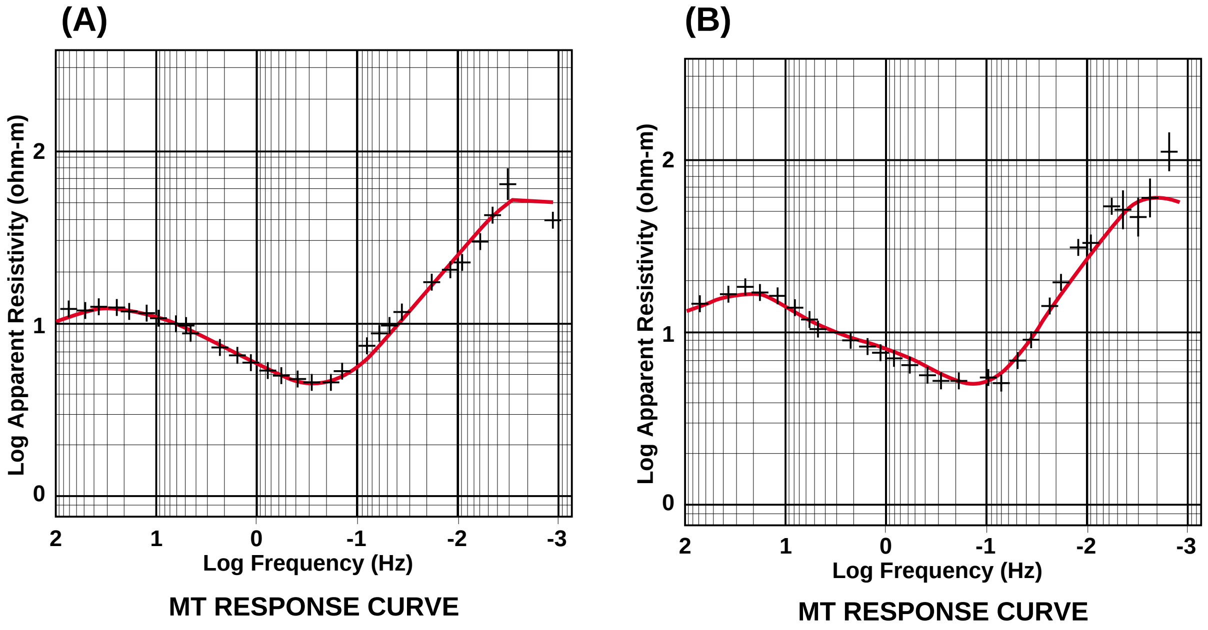

Figure 5: MT responses as observed (crosses) and calculated (solid curves) for the sites and resistivity models (A) and (B) shown in Figure 4.

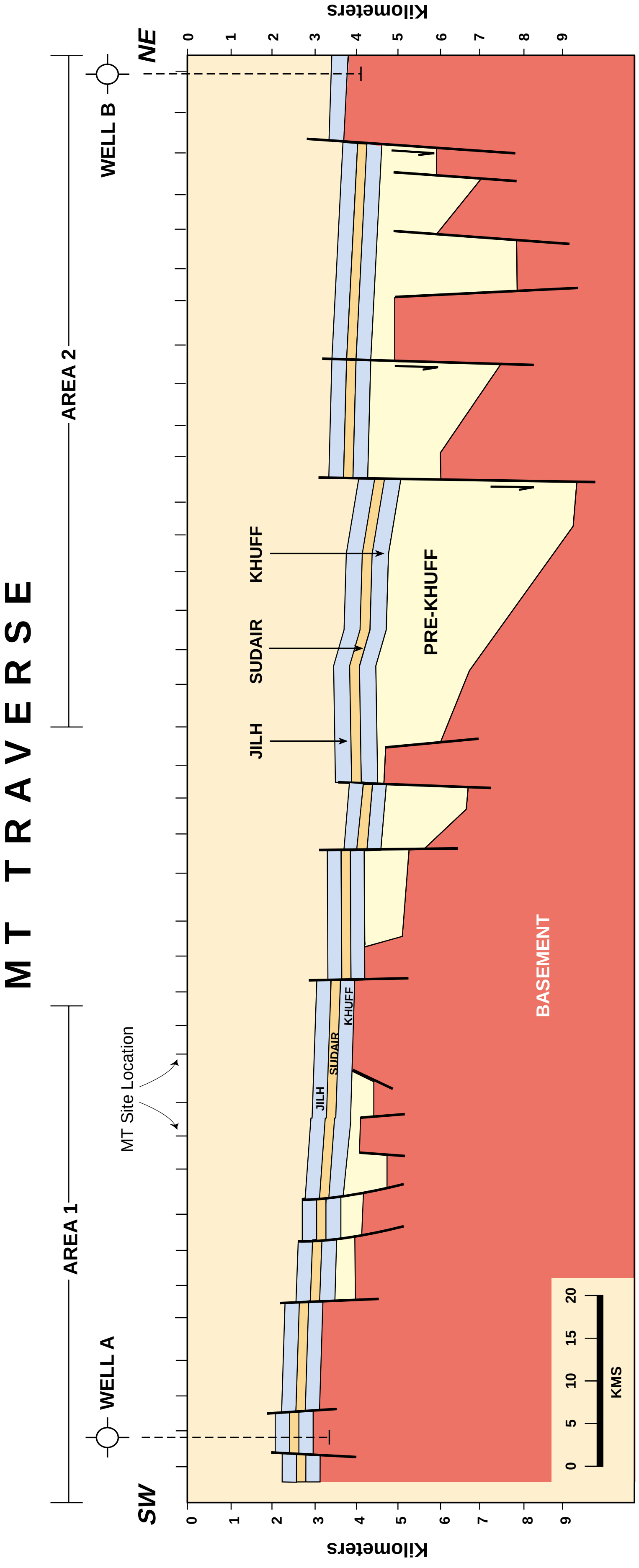

Figure 6: Interpreted cross-section from seismic and MT data. The total length is 160 km, and the MT sites and two well locations are also shown. The locations of Areas 1 and 2 given in Figures 7 and 8 are also indicated.

In Figure 4 the inverted models are given for two sites in the same area, at one of which the Khuff is directly over basement, whereas there is a significant pre-Khuff section (about 750 m) at the other. Their associated response curves at these locations are shown in Figure 5, which includes both the observed apparent resistivities and the curves corresponding to the models in Figure 4. It can be seen that the presence of the low resistivity pre-Khuff section has a marked effect on the apparent resistivity curve, and has moved the trough (low resistivity section) of the curve towards the low frequency (deeper) end of the plot. The phase response was also used for the analysis, but is not shown here.

There is some latitude in the interpretation of the pre-Khuff thickness, depending on the resistivity which is assumed to exist for this layer. Inversions were tested at a number of sites for varying pre-Khuff resistivities as part of the analysis of the sensitivity of the method. The interpreted pre-Khuff thickness will be approximately proportional to the assumed resistivity, and hence the resistivity should be constrained to near its correct value. Similar MT responses could usually be obtained by adjusting the resistivity of the pre-Khuff by a factor of about 2 from the mean value of 5 Ω-m, together with a corresponding alteration in the layer thickness. It was only possible to obtain a reasonable fit to the data with resistivities in the range of 2 to 10 Ω-m, although available log data suggest that the adopted resistivity of 5 Ω-m is a good average value for the purposes of most regional interpretation. Where the actual pre-Khuff thickness was known from other data (but not known to the interpreter), this resistivity yielded very satisfactory results.

A regional traverse about 160 km in length is presented in Figure 6, where the post-Khuff section is derived from seismic interpretations. The locations of the MT stations and two wells which penetrate basement are also indicated. The structure includes areas where the pre-Khuff sediments are thin or absent, as well as regions where this layer exceeds 3 km in thickness. A pre-Khuff section thinner than about 100 m at the depths shown in Figure 6 may not be resolved by our data, and hence would be classed as absent. This margin of error is obviously of some concern over localized structural highs, where the presence of even a thin pre-Khuff section has a bearing on the exploration potential of the area. If a number of MT stations in a region indicate that there is effectively no pre-Khuff section, as shown towards the western end of Figure 6, then the section may indeed be absent over much of the area. In this case, stratigraphic traps around the pinch out may form the most prospective type of structure. Where there is a significant pre-Khuff section, it is estimated that the thickness can probably be determined to within about 20 percent of the true value if the resistivity is reasonably accurate.

Two-dimensional coverage was obtained for part of the MT survey, and the MT stations and their interpreted pre-Khuff thickness for an area covering about 93 by 55 km are shown in Figure 7 (Area 1). The location of the western part of the traverse in Figure 6 is also given (cf. Figure 1). The interpreted layer thickness was hand contoured to include known and inferred fault information. In this map, the pre-Khuff wedges out, and the MT results suggest that there is considerable potential for stratigraphic plays around the basement high near the center of the area.

In contrast, a map of the pre-Khuff thickness from the MT data is shown in Figure 8 (Area 2) for an area 75 by 110 km towards the eastern end of the profile in Figure 6. The MT sites and interpreted faults are also included. The resulting contours are typical of those expected from horst and graben basement structure of a predominantly north-south orientation, with localized pre-Khuff thinning over the more elevated basement features.

For comparison with the mapped variations in pre-Khuff thickness in Figure 8 the residual gravity over the same region is shown in Figure 9. A simple two-dimensional boxcar averaging operator about 25 km across was used to smooth the Bouguer gravity field. This was then subtracted from the original gravity field to give a residual which enhances the shorter spatial wavelengths in the gravity and removes regional trends with wavelengths longer than about 100 km. It has been observed in central Arabia that many of the features in the residual gravity map are correlated with basement topography, and hence there is some correspondence with the variations shown in Figure 8. The trends in the gravity data therefore provide some assistance in mapping the MT results. An exception is the localized gravity maximum towards the south-western part of Figure 9, which magnetic data indicate is due to an intra-basement intrusion rather than basement topography.

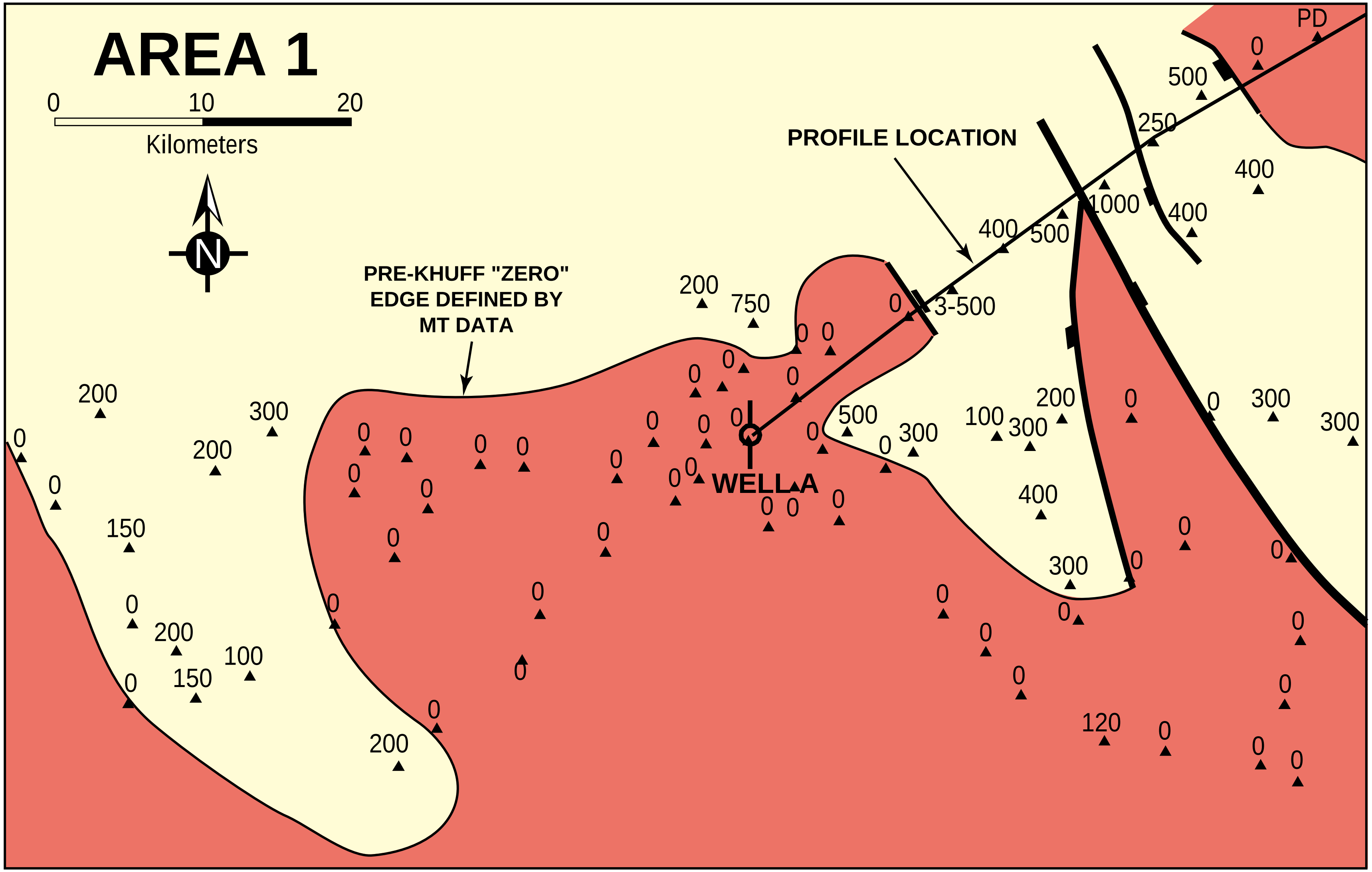

Figure 7: Area 1 around the western end of the profile in Figure 6, showing the pre-Khuff thickness in meters at each MT site, as well as the interpreted "zero" edge of this layer and some faults (heavy black lines). Sites with poor data are shown as "PD". The red colored area is interpreted to contain no pre-Khuff section.

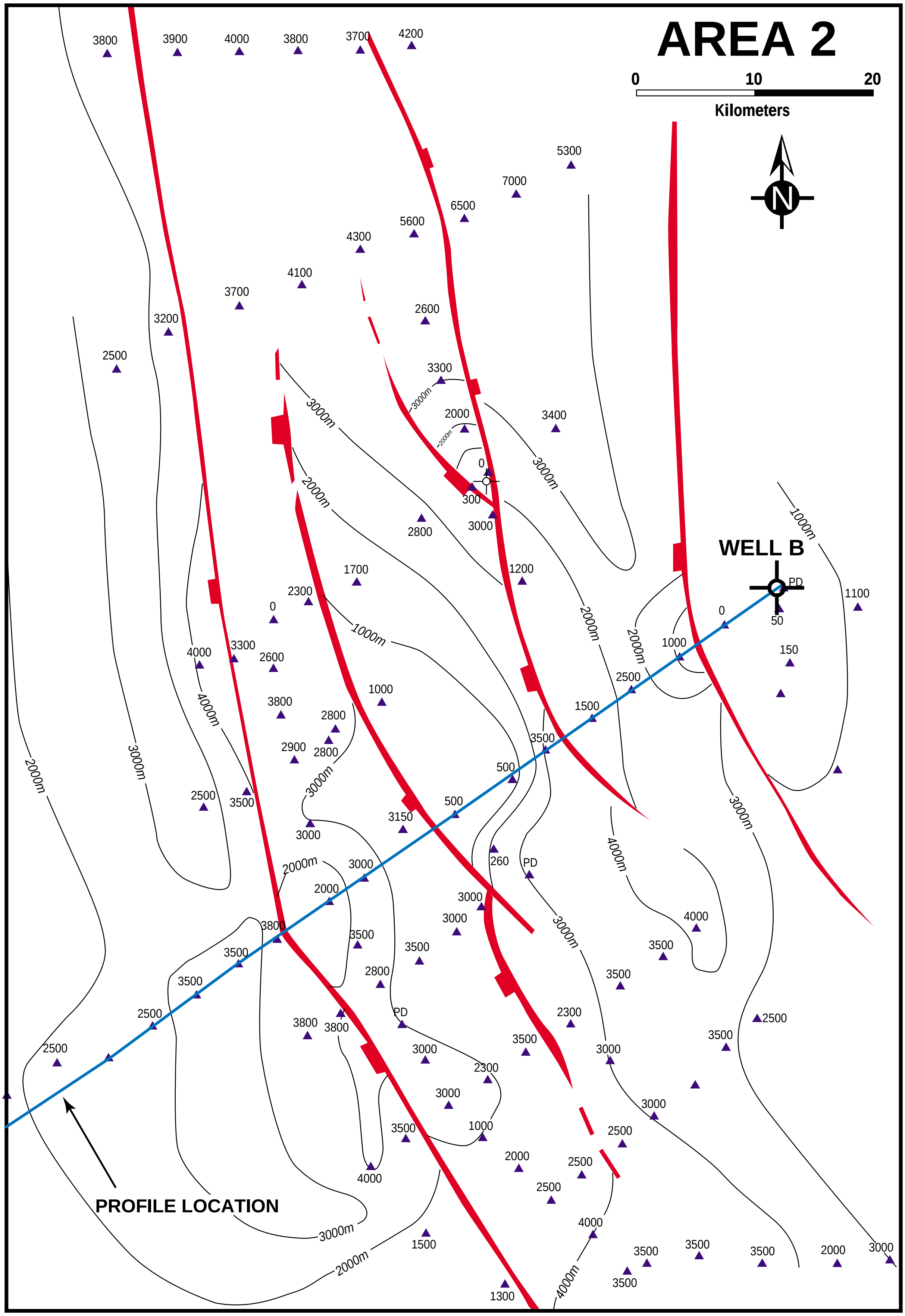

Figure 8: Area 2 around the eastern end of the profile in Figure 6, showing the pre-Khuff thickness in meters at each MT site, as well as the interpreted isopach in meters and some of the faults (heavy red lines).

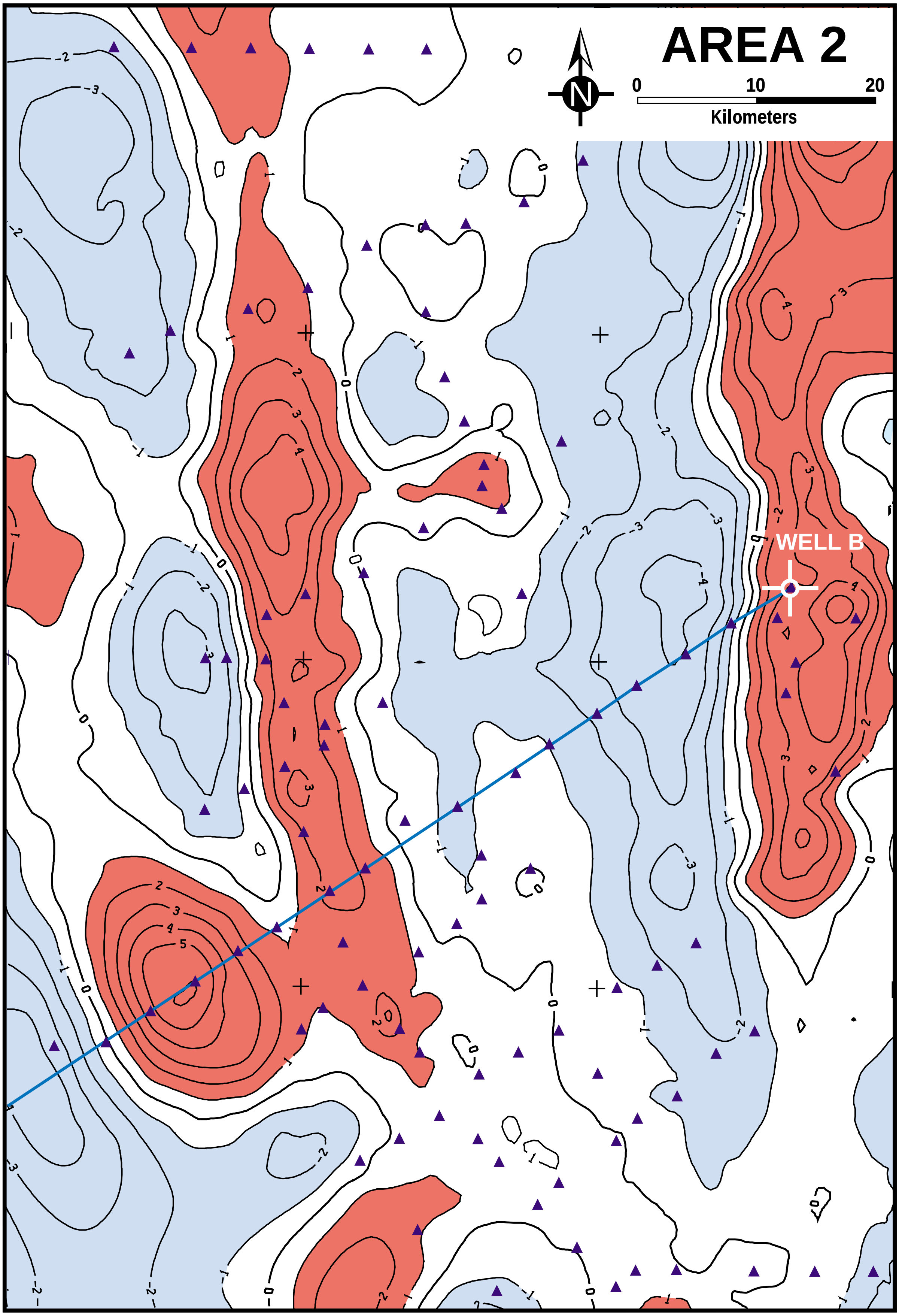

Figure 9: Gravity residual map for the area in Figure 8, showing similarities with the pre-Khuff isopach variations interpreted from MT data. Gravity contours are in milligals, and values greater than 1 milligal are shaded in red, while those lower than -1 milligal are shaded in blue.

CONCLUSION

Magnetotelluric methods were successfully employed in outlining the main variations in the thickness of the pre-Khuff sedimentary section in central Saudi Arabia, where this layer is poorly defined by seismic techniques. The interpretation was constrained by well data and seismic depth estimates for the shallower horizons, which were critical in obtaining reliable results for the pre-Khuff. In addition to changes in the pre-Khuff associated with basement block faulting, areas where this layer is apparently absent could also be identified. The locations where the pre-Khuff pinches out may be suitable for further exploration for stratigraphic traps. The results of the survey are consistent with a mostly extensional tectonic model for the Hercynian orogeny, with substantial erosion on the horsts and locally large amounts of section preserved in the grabens. While the tectonic history of the region is undoubtedly more complex than this, the MT data alone does not permit a more detailed discussion of the structure to be undertaken here. Overall, MT methods have proved to be a cost-effective way of mapping in broad detail the deeper horizons, and hence in providing some guidance for future hydrocarbon exploration in the region.

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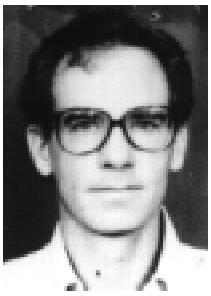
ABOUT THE AUTHORS

Ian C.F. Stewart *is with the Research and Development division in the Geophysical Department of Saudi Aramco. Prior to 1982, he was an Associate Professor in the Department of Earth Sciences, Memorial University of Newfoundland. Ian is a member of the SEG, AGU, SSA and several other professional societies and has a number of publications on regional structure using seismic and potential field methods. He received his PhD from the University of Adelaide.*

Thomas C. Connally *is a Geologist with Saudi Aramco. Tom worked for CONOCO International from 1977 to 1982, AMOCO International from 1982 to 1986 and later for Esmeralda Energy before joining Saudi Aramco in 1988. He received his BA and MA degrees from the University of Texas at Austin in 1970 and 1981, respectively. Tom is a member of the AAPG, SPWLA and the Dhahran Geological Society. His areas of interest include field geology and carbonate and clastic-modern depositional systems.*



Jeffrey H. Copley *completed a MSc at the Colorado School of Mines in 1978 and worked as an Exploration Geophysicist for CONOCO and Champlin over the next 6 years. As a consultant for the last 11 years specializing in magneto telluric (MT) methods, Jeffrey has been the primary MT geophysicist on exploration projects throughout North America and in many countries around the world. During this time he has been one of the several active participants in the improvement and development of MT field systems and interpretive methods. His current position is Consulting Geophysicist for Zephyr Geophysical Services, Denver, Colorado, USA.*

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