

Applications of magnetotellurics to petroleum exploration in Papua New Guinea: A model for frontier areas

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Magnetotelluric (MT) data have been acquired at more than 500 stations in the fold belt of Papua New Guinea since 1988. The MT stations were recorded for several clients and in various Petroleum Prospecting Licenses (PPLs). Most of the MT stations were acquired along dip profiles, trending across the Papuan fold belt. A total of 32 profiles were recorded across mapped surface structures and faults. The data were collected primarily on outcrops of (often heavily karstified) Darai limestone. The spacing between MT stations on the profiles varied from 400–2500 m.

MT shows promise as a technique which could provide answers to exploration questions in areas where interpretable seismic data are very difficult to acquire. In Papua New Guinea, several wells have been drilled on or near MT profiles. MT has been very successful in accurately predicting the depth to, and thickness of, Darai limestone in the subsurface.

Papua New Guinea is on the eastern half of New Guinea, the second largest island in the world. Papua New Guinea has over 600 languages, more than any country in the world. The island is transected by the Papuan fold belt which trends from southeast to northwest (Figure 1). Elevations range from sea level to more than 5000 m.

Much of Papua New Guinea is divided into PPLs which are

leased on varying terms. The leaseholders are primarily North American and Australian oil companies; however, interests from throughout the world are represented. Petroleum exploration commenced in the 1920s, initially fueled by numerous oil seeps and the presence of large structures. But it wasn't until the drilled discoveries of the mid-'80s that the area's true potential became known. Several wells drilled in the highlands by a consortium (including Chevron, BP, and BHP) have tested flow rates at more than 7000 b/d.

Geology. Interaction between the Australian and Pacific plates since Mesozoic time has created the complex Papuan fold belt, a series of northwest-southeast trending folds. Most of this area is covered by Darai limestone, an Eocene-to-Miocene massive limestone (Figure 2) that is up to 1000 m thick. The limestone is overlain in places by late Tertiary clastics and Pleistocene volcanics. Underlying the Darai limestones are very thick (up to 10 000 m) clastic deposits of Jurassic and Cretaceous age. The Toro formation, a late Jurassic/early Cretaceous quartz sandstone, is the drilled reservoir rock in most of the onshore discoveries.

Complex folding of the Papuan fold belt created the hydrocarbon traps. Thrusting is from northeast-to-southwest. Most of the faulting is thin-skinned, with repeats of Darai not uncommon in

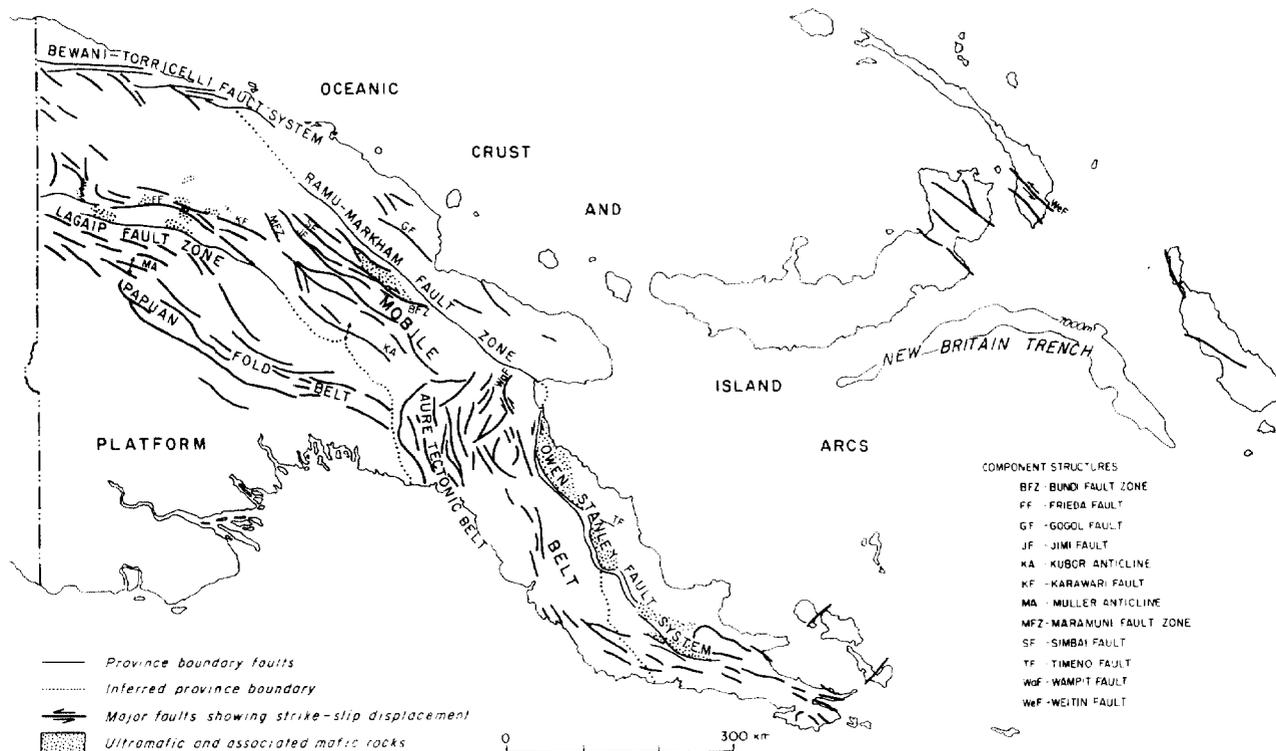


Figure 1. Tectonic map of Papua New Guinea.

the subsurface. There appear to be several detachment surfaces along which the thrusting has occurred. On the southwest side of the fold belt, the thrusting style changes to Foreland-style thrusts.

MT, definition and application. Magnetotellurics measures natural time-varying fluctuations in the earth's electric and magnetic fields. The resistivity of the subsurface is computed from the ratio of these field variations at 40 discrete frequencies, ranging from 500 Hz to .001 Hz (1000 s period). Frequencies are predetermined to be equally spaced (with seven frequencies per decade) on a logarithmic scale.

Data are converted in the field to apparent resistivity and phase. "Apparent resistivity" does not represent "true" resistivity, but is essentially a bulk average. The apparent resistivity is calculated at each frequency from the ratio of variations in mutually perpendicular horizontal electric and magnetic fields. Hence, two apparent resistivities are calculated at each frequency—one for the ratio between the electric field in the x direction and the magnetic field in the y direction (called the xy apparent resistivity) and one for the electric field in the y direction and the magnetic field in the x direction (called the yx apparent resistivity). The orientation of x and y does not matter as long as they are mutually perpendicular. Data are reoriented analytically by computer analysis so that the coordinates align with the primary strike direction.

An example of an apparent resistivity magnitude plot versus frequency (on a log-log scale) is shown in Figure 3. Frequency is plotted on the x-axis, increasing from right to left. The magnitude of apparent resistivity is plotted on the y-axis, decreasing from top to bottom. This plot shows high resistivity material (Darai) in the

near surface (high frequencies), low resistivity (clastics) in the middle frequencies, and high resistivity (basement) at greater depth (low frequencies).

The apparent resistivity versus frequency data are interpreted (transformed from frequency domain to depth domain) to produce a profile of true resistivity variation as a function of depth. High-frequency electromagnetic waves are attenuated in the near surface and low-frequency waves penetrate deep within the subsurface. Thus, MT provides subsurface resistivity information computed from the 40 frequencies for essentially 40 depth points spaced from within about 100 m of the surface down to about 20 km. The depth determination is dependent upon the frequency of measurement and the resistivity of the subsurface.

Magnetotellurics is most effective if recorded where high resistivity rocks are at or near the surface, because this allows for the deepest penetration of the MT signal. The electromagnetic signal is attenuated much faster in low resistivity rocks (shales, siltstones, sandstones) than in high resistivity rocks (limestones, flow volcanics, metamorphic and plutonic rocks). Therefore, in Papua New Guinea (PNG) the MT method is best applied in the fold belt, where the Darai limestone makes adequate seismic penetration difficult. MT holds less potential in the lowlands (where seismic quality is acceptable) because clastics at the surface rapidly attenuate the signal, reducing the penetration of the electromagnetic waves.

MT data are best interpreted when recorded at stations located along a dip profile, so that a two-dimensional assumption can be made. (A 2-D subsurface is defined as having resistivity variations in depth and in the dip direction only, with no variation along strike.) The data are interpreted using 2-D algorithms, which

Age		Papuan Basin Stratigraphy
Tertiary	Quaternary	Era Beds
	Pliocene	Ourubadi Beds
	Miocene	Pnyang Fm
	Oligocene	Darai Lmst
	Eocene	Mendi Gp
	Paleocene	
Mesozoic		Ieru Fm
	Cretaceous	
		Toro Ss
	Jurassic	Koi-lange Fm
Triassic	Basement	

Figure 2. Simplified stratigraphic chart, PNG highlands.

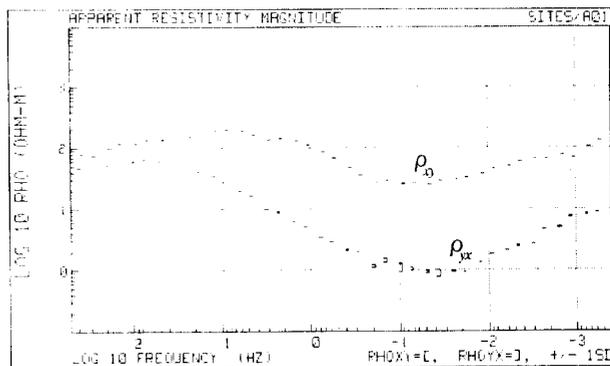


Figure 3. Sample MT apparent resistivity plot.

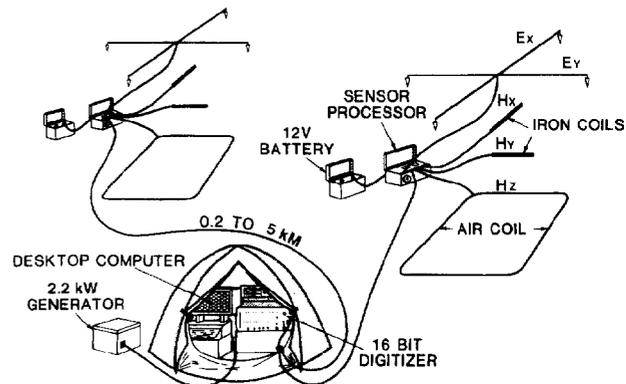
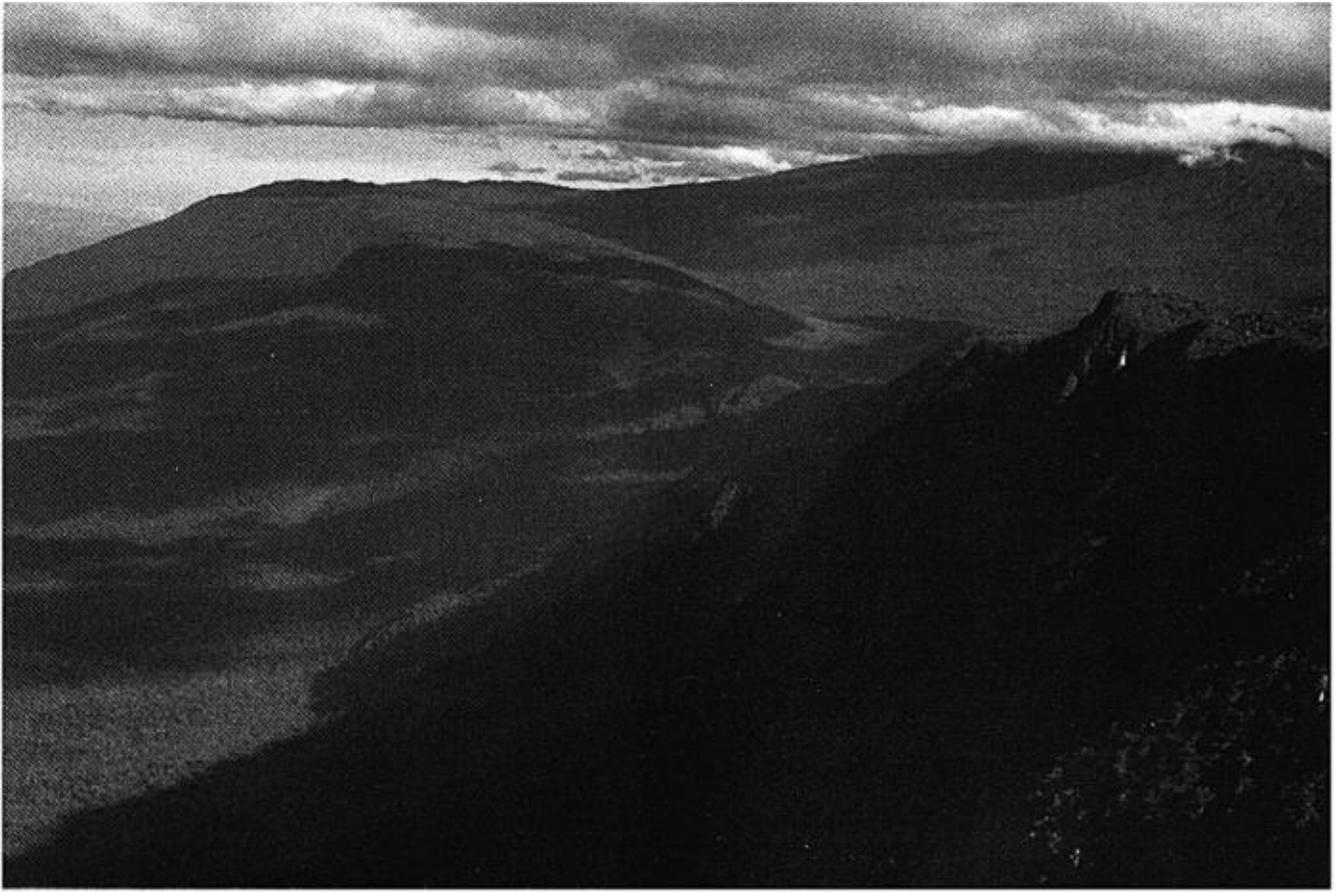


Figure 4. Typical two-station MT field layout.



Karius Ridge, Southern Highlands near the BP Hides gas discovery well. The ridge is created by faulting. Elevation change is 3000 ft from top to bottom.

provide an estimate of subsurface resistivity variations in a vertical sense and also a lateral sense along the profile.

Acquisition. MT data are acquired simultaneously at 2–5 stations, or at one station with a reference station. (At the present time, the number of stations recorded simultaneously is limited by the maximum number of channels on the recording systems.) Each MT station is “referenced” to another station (called remote referencing) in order to remove any incoherent signals between the two stations and provide a method of easily removing noise from the signal.

At each MT station, five components of the earth’s electromagnetic field are measured (Figure 4). Magnetic field variations are measured in two perpendicular directions (x and y) by iron-cored coils and in the vertical direction (z) by an air loop (a loop of wire laid on the ground horizontally to measure the magnetic flux passing through it). Horizontal electric field variations are measured in two perpendicular directions (x and y) by dipoles whose length varies from 50–200 m. They are coupled to the ground by porous pot electrodes. These dipoles measure the fluctuations in voltage drop between the electrodes at each end. The vertical electric field is so small that it is considered negligible and is not measured.

Signal variations of the five components are amplified at the station location. Amplifiers are powered by 12-volt batteries. The signals are communicated to a digitizer and computer via hardwire or radio telemetry. This recording equipment can be housed in either a tent or a utility truck at a distance of several hundred meters to several kilometers. Power for the recording equipment is supplied by a portable generator. In PNG, most recording is done using a hard-wire link to a tent, as the dense jungle interferes with radio telemetry transmission. However, hard-wire telemetry cables (comm-lines) have proved especially inviting to pigs, who seem to savor chewing and eating through the insulation. Cables have also been cut and used as belts in several villages. This necessitates posting sentries along the cables to keep pigs and others away (and to help reduce noise during recording).

MT data are recorded for 12–24 hours at each location, and processed in real time. Since the source of the MT signal is affected by solar activity and interference of solar wind with the earth’s magnetic field, the quality and strength of the signal fluctuate on a diurnal and annual basis. Thus recording is continued in the field until a sufficient number of high-quality data stacks have been obtained. This is usually accomplished in 12–24 hours. The determination of when to complete recording is usually done by a bird-dog (representing the client) or, on agreement, by one of the contractor’s geophysicists.

The spacing of MT stations ranges from a few hundred meters to more than 2 km, and depends on the desired subsurface resolution. For example, if one is trying to locate an anticline with a width of 1 km, the MT stations must be spaced several hundred meters apart so that they can properly map the structure.

Interpretation. Although MT does not have the resolution of seismic, it can typically map up to seven bulk layers in the subsurface. The layers must have a mappable resistivity contrast with their adjoining layers (normally a resistivity contrast of 10:1 or more). The limit on the number of layers is based on interpretation algorithms and the fundamental behavior and response of the MT field. MT can easily distinguish resistivity differences between near-surface alluvial clastics and volcanics, the Darai and other limestone formations, Jurassic/Cretaceous and younger clastics, and electrical basement (defined as the deepest high resistivity layer which MT data can determine, which is not necessarily true geologic basement).

MT data can be interpreted both qualitatively and quantitatively. Many of the computed MT parameters can be interpreted, by inspection, to provide information on locations of faults, predominant geologic strike, generalized subsurface stratigraphy, etc. MT data can be quantitatively interpreted using one of several numerical codes available from academia or private enterprise. These algorithms are based on either a 1-D, 2-D, or 3-D subsurface. Some assume a flat earth surface and some can incorporate



Karstified limestone ridges, Southern Highlands. Each ridge is created by a thrust fault exposed at the surface.

topography, the latter being important when interpreting MT in PNG as severe terrain (steep slopes, karsts) can distort the data.

The final product of the modeling is a colored cross section of resistivity variation with depth that can be interpreted and readily compared with geologic and/or other geophysical sections.

Exploration and MT. Because of limited access, thick jungle cover, rugged terrain, and varying weather conditions, exploration in PNG is very difficult. To date, most of the wells have been drilled on surface structures or based on geologic mapping, aerial radar and satellite imagery, gravity, magnetics, and seismic refraction and reflection profiles. Seismic has been successful in the lowlands, where clastics crop out and logistics are easier. However, in areas of karstified limestone outcrop in the Papuan fold belt, seismic exploration has been expensive and disappointing or of very poor quality. The poor seismic quality results from high velocity of the limestone coupled with a highly karstified surface. Thus, other geophysical exploration techniques have been employed.

Since 1988, several companies have conducted MT surveys to determine the applicability of the method to exploration in the fold belt. Although inhospitable to seismics, the fold belt of PNG is an ideal MT exploration area. Because the Darai limestone lies at or near the surface and is very resistive (normally 200–400 ohm-m), the MT signal can penetrate easily into the underlying clastics (a combination of sandstones, siltstones, and mudstones) which have an average bulk-resistivity between 2.5–7.5 ohm-m. This provides a resistivity contrast at the Darai/clastic interface of as much as 100:1.

Other factors contributing to the application of MT in PNG are: most of the fold structures are elongated and hence highly two-dimensional, aiding to reliability in interpretation if the data are recorded along dip profiles; MT is highly portable (1–5 stations can be recorded simultaneously per day).

An MT survey in PNG usually requires 3–4 hours per day of helicopter time (in a Hughes 500 or similarly structured craft) to

transport the crew to and from the field area and to move the stations. All of the equipment can be moved in sling nets and 3–5 sling loads normally are required to move the stations. Equipment includes the computer, digitizer, generator, electronic repair and monitoring gear (including an oscilloscope), several kilometers of comm-line, iron-cored coils, electrodes, dipole wire, air loops, batteries, shovels, water jugs, tent, radios, and personal gear. An MT crew usually consists of four contractor personnel (mostly geophysicists or geologists), a bird-dog (if desired by the client), 3–5 boss-boys, and a varying number of local labor hires (depending on the number of stations being recorded simultaneously and work conditions).

An MT station can generally be recorded within a few hundred meters of any land surface on which a helipad can be built. No single piece of MT gear weighs more than 50 kg; thus all of the equipment can be carried to the station location from the helipad or sling drop. This may necessitate cutting and bridging. However, the rugged terrain that is a major problem in PNG seismic operations does not unduly hinder MT acquisition.

A normal recording day starts at first light (approximately 0630 hours) with a determination of data quality (recorded during the previous night), usually by the geophysicist who remained on-site and monitored operations. If the recording is satisfactory, the rest of the crew is flown in, stations are picked up and moved to the next locations. Preparations for recording at the new stations (installation of recording gear, tent and computer set up, field checking of all comm-lines for good signal transmission) and recording of test data are usually accomplished by mid-afternoon. If there are no problems, recording is started and most crew personnel go back to camp via helicopter. The only crew members who remain on site are the monitoring geophysicist and a few boss-boys. The cycle repeats each day until the survey is completed.

The recording cycle can be interrupted by poor weather, poor data quality, equipment failure, helicopter down time, and other logistical problems. If all goes well, satisfactory MT data at a particular site (the stations being recorded simultaneously from one recording tent) can be acquired in one day. However, this acquisi-

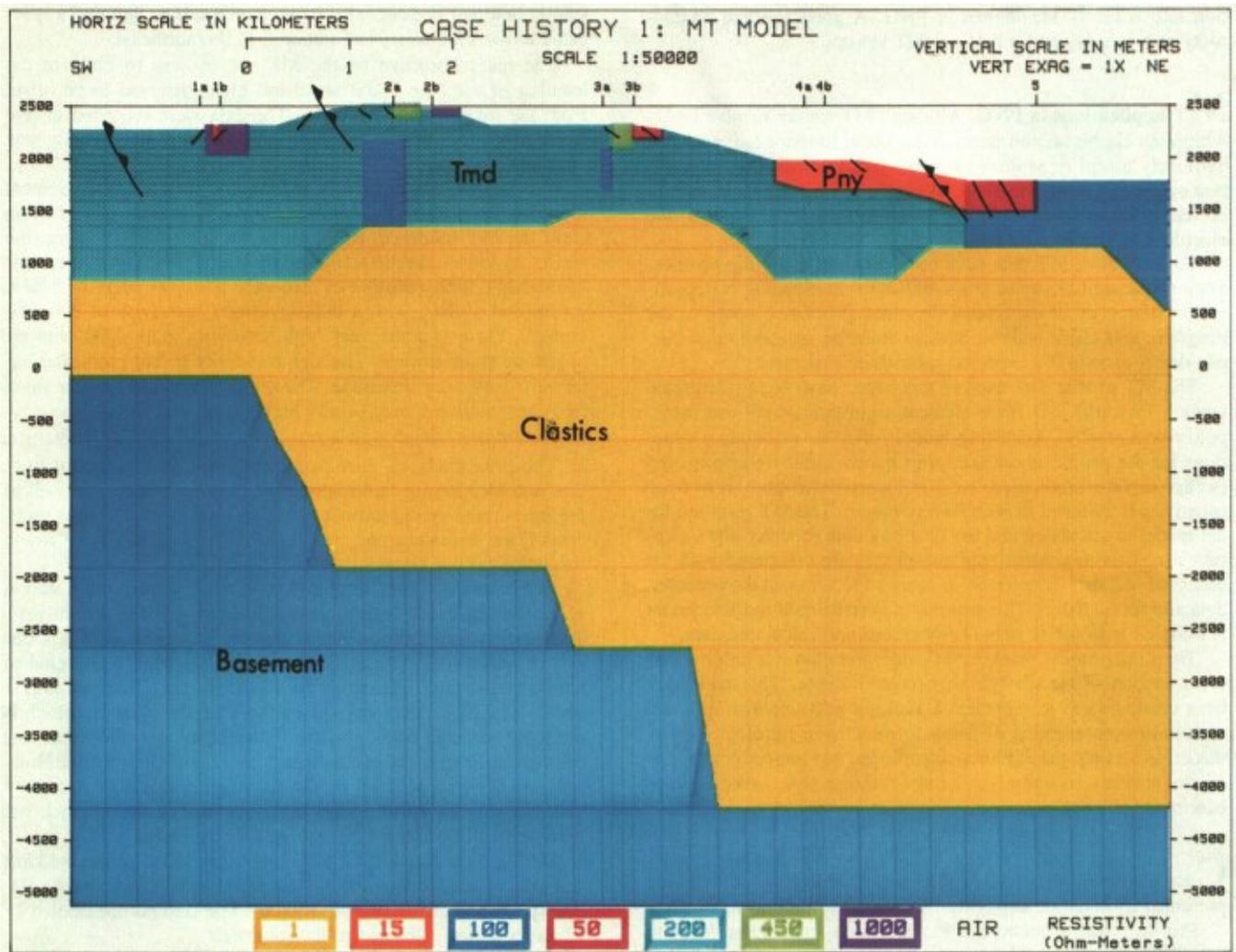


Figure 5. Final MT model, case history 1.

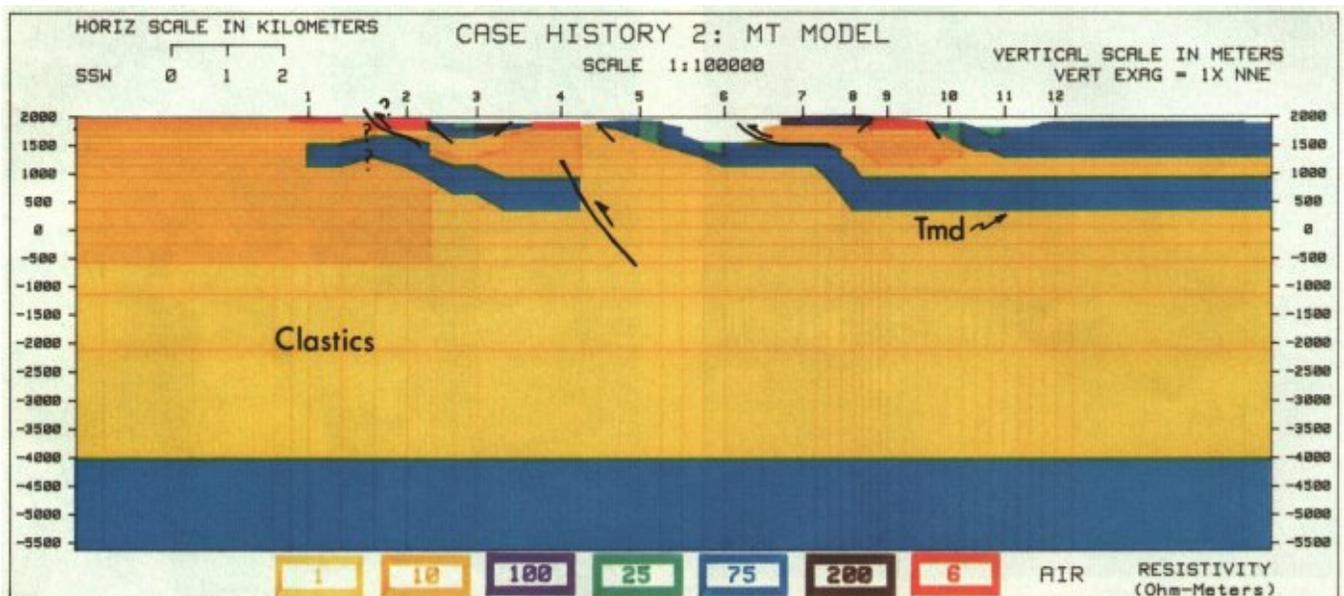


Figure 6. Final MT model, case history 2.

tion rate is rarely maintained in PNG. A good average productivity rate is a day and a half per MT set-up.

MT applications in PNG. Although MT cannot resolve layers within the clastic section beneath the Darai limestone, it has been extremely useful to exploration geologists by providing information on the structure at the base of the Darai limestone, indications of repeat Darai sections in the subsurface, and of depth to the electrical basement.

To date, most MT data have been acquired along dip profiles. Station spacing has varied from 400–3000 m. Spacing is dependent on frequency of expected subsurface structures, scope of the program, and client budget. Stations must be spaced so that they can detect or map the expected subsurface structures.

The MT profile data used in this paper have been interpreted using a forward, 2-D finite-element algorithm which can incorporate topography. A starting model (often a very simple structure) for the profile is created. Any known geologic information (wells, surface lithologies, etc.) is incorporated and an average resistivity is assigned to each finite element. The MT response for the model is calculated and the resulting data (both xy and yx apparent resistivities, amplitude and phase) are compared with the observed MT data. The model is changed to better fit the observed data and recalculated. This process is iterated until the interpreter is satisfied with the fit between observed and calculated data.

The final product from the MT interpretation is a color-coded cross section of resistivity variation with depth. The model has been created so as to represent a geologic section, with different resistivities representing different formations or lithologies. With this cross section, the exploration geologist can impose constraints on the structural section modeling, faulting style, and depth to basement.

Case histories. Two MT profiles acquired in PNG in 1988 are presented to illustrate key features of this exploration method.

Profile 1 was acquired in PPL-93 across a simple surface anticline. The profile was located northwest of Tari and consisted of nine stations (labeled 1a–5 in Figure 5) acquired along an 8 km line in the dip direction which trended from southwest to northeast across the anticline. The stations were recorded in pairs (with the exception of station 5) with about 300 m separating the two stations in each pair. The pairs were about 1500 m apart. Each



MT recording tent and helipad on ridge. The stations are placed off the ridge, about 200 ft lower than the tent to lessen topographic effects.

station in a pair is designated by an a or b suffix. Station 1a is located to the southwest, and station 5 to the northeast.

The main objective of the MT survey was to confirm the location of the base Darai structural high, believed to be offset from the surface anticline crest. The data were recorded in five days, an average of one day recording per pair. Data quality was excellent.

The data were interpreted using the 2-D forward finite-element modeling program mentioned previously. The final cross section from the MT modeling is shown in Figure 5. On the plot, the resistivity values are differentiated by colors. The Darai limestone is modeled with resistivities between 50–1000 ohm-m (blues, green, and violet), with a bulk (average) resistivity of 200–250 ohm-m. There is some very high resistivity (450–1000 ohm-m) limestone at the surface. The high resistivity perhaps indicates extremely dense, dry limestone. The section of 50 ohm-m limestone (red) near station 5 may signify highly fractured Darai. The clastic section is modeled with a resistivity of 3.5 ohm-m (yellow).

The final model (Figure 5) incorporates approximate surface dips and locations of faults across the top of the profile as well as the interpreted geologic formations or rock types. “Tmd” indicates Darai limestone and “Pny” (orange) indicates the P’nyang formation (upper Darai siltstone).

The base-Darai structural high is located beneath the 3 station pair. The surface anticline crest is located at the 2 station pair. The clastic section increases dramatically in thickness to the northeast of station pairs 2 and 3. The model has been interpreted to have a thrust fault coming to the surface between station pairs 1 and 2. The high resistivity section beneath the clastics, which is normally referred to as electrical basement, may represent true geologic basement on the northeastern side of the profile. However, on the southwestern side of the profile, this high resistivity material may be either Darai limestone or basement which has been vertically offset by the complex thrust faulting.

Profile 2 consisted of 12 MT stations recorded across a 13 km line which trended from south-southwest to north-northeast. Station spacing varied from 750–1500 m. The stations are labeled 1–12, with station 1 located to the southwest.

The final model is shown as Figure 6. The objective was to



The author with some Hulis after a negotiated fee settlement.



Huli tribesman in traditional dress. The wig is made of hair woven with moss and other material.

map the structure of the Darai limestone and clastics in the subsurface. Along the profile, several thrust faults are mapped at the surface, including one between stations 2 and 3 and one between stations 6 and 7. Again color is used to differentiate between resistivity values. The clastics have resistivities of 1 (yellow), 6 (orange), and 10 (yellow) ohm-m. The Darai limestone is mapped by resistivities varying from 75–200 ohm-m (blue, violet, brown). The 25 ohm-m material (green) could be either resistive sandstone or weathered Darai.

As shown on Figure 6, the Darai is relatively thin (less than 50 m thick along most of the profile). The Darai is present in the subsurface between stations 2, 3, and 4, and many continue under station 1. A sheet of Darai limestone, which crops out at station 5, probably continues up and over station 4 to station 3. This same sheet exists in the subsurface between stations 6 and 7, and there is strong evidence in the MT data that it is also present in the subsurface beneath stations 9 through 12. This sheet of Darai appears to be flat-lying in the subsurface. However, it could have some relief on it that is unresolvable from the MT. It is difficult for MT to map buried resistive units within a very conductive section.

Stations 2 and 9 were located on outcropping Cretaceous clas-

tics, with station 9 located on the crest of an anticline. A very thin section of Darai limestone (about 200 m thick) is present at the surface at stations 7 and 8. This is probably a continuation of a sheet folded over station 9 and present at the surface at stations 10, 11, and 12.

The thrust fault mapped between stations 6 and 7 is apparent as the contact between 10 ohm-m and the overlying 100 ohm-m material. The thrust direction is from north-northeast to south-southwest. Between stations 2 and 3 the thrust fault is evidenced by the contact between the 6 ohm-m and overlying 75 ohm-m material.

Electrical basement is not well defined by the MT data. The MT modeling could only roughly estimate the basement level. Although it is doubtful that the basement is flat (as shown in Figure 6), there is probably little relief on it. Because basement lies below a fairly thick section (4000-plus m) of very conductive clastics (1 ohm-m), the MT has difficulty defining the basement level. Most of the MT signal is absorbed by the very conductive section by the time the basement level is reached.

Discussion and conclusions. MT can be utilized as an exploration tool in those areas of Papua New Guinea and other parts of the world where seismic is not viable. In PNG, MT acquisition to date has mapped the major structural features evident in the Darai limestone and underlying clastics along 32 profiles. In areas where the Darai limestone is at or near the surface and seismic exploration is difficult, MT can help provide answers to the exploration questions.

New designs in MT systems are presently underway to provide smaller, more portable equipment. Some of these systems will have more recording channels (20–40, compared to 16 at present) which will allow more stations to be acquired simultaneously. Lower system noise, higher sensitivity sensors, and faster computers may also provide for "cleaner" signal and lower the recording time from the present 12-hour minimum.

Future improvements in MT equipment and logistics, combined with a better understanding of the structural geology, should enhance the application of magnetotellurics to exploration for hydrocarbon-bearing structures in Papua New Guinea and other frontier areas.

Suggestions for further reading. A classic paper in this field is *The magnetotelluric method in the exploration of sedimentary basins* by Keeva Vozoff (GEOPHYSICS, 1972). A briefer description of the mathematical and physical theory is contained in *Applied Geophysics* by W.M. Telford, L.P. Geldart, R.E. Sheriff, and D.A. Keys (Cambridge University Press, 1976). **IE**

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