Geophysical Corner

MT Gauges Earth's Electric Fields

The Geophysical Corner is a regular column in the EXPLORER, produced cooperatively by the AAPG Geophysical Integration and SEG Interpretation committees, and edited by M. Ray Thomasson. This month's column is part one of a two-part series on magnetotelluries.

By KAREN RAE CHRISTOPHERSON

Magnetotelluries. That's a big word – longer than my last name! So, let's dispense with the big words for the rest of this article and use the abbreviation that most geophysicists know this technique by, that is, MT.

This first part of a two-article series will deal with the MT technique – what is it? Next month's article will explain the application of MT and show some case histories.

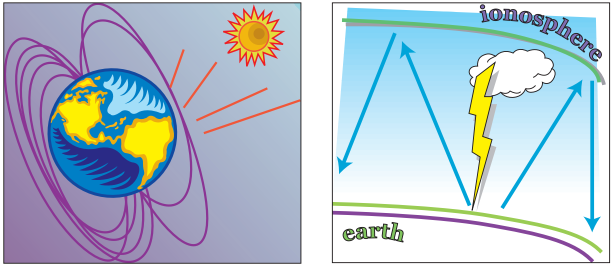
First, back to the big word. Where does it come from?

Dissected, it has two parts – "magneto" for magnetic and "telluric" for earth currents. This tells you something about MT. It is a geophysical method that measures magnetic and electric fields that are found in the earth.

Basically, MT is a geophysical method that measures naturally occurring, time-varying magnetic and electric fields. From these measurements we can derive resistivity estimates of the subsurface, from the very near surface to tens of thousands of feet.

What is the Source of the MT Signal?

The MT signal is caused by two things:



Figures 1-2: Interaction of solar particles with earth's magnetic field creates high-energy EM energy, which travel around the earth via thunderstorms.

Graphics, photos courtesy of Karen Rae Christopherson

Figure 3: This area is a typical candidate for MT application.

☐ In the lower frequencies (generally less than 1 Hertz, or 1 cycle per second), the source of the signal is interaction of the solar wind with the earth's magnetic field. As solar storms emit streams of ions, this energy disturbs the earth's magnetic field and causes low frequency energy to penetrate the earth's surface (Figure 1).

☐ The higher frequency signal (greater than 1 Hertz) is created by world-wide thunderstorms, usually near the equator. The energy created by these electrical storms travels around the earth (in a wave guide between the earth's surface and the ionosphere) with some of the energy penetrating into the earth (Figure 2).

Both of these sources of signal create time-varying electromagnetic waves.

Although these electric and magnetic fields are small, they are measurable. That's the good news. The bad news is that these signals vary in strength over hours, days, weeks and even over the sunspot cycle (which is about 11 years and creates an increase in the number of solar storms). So, geophysicists measuring MT have to measure for hours at each station in order to get enough signal to ensure high quality data.

This is especially true when measuring them at the lowest frequencies (about 0.001 Hertz, or 1 cycle per 1000 seconds). At these low frequencies, we need to record for 16 minutes to get one sample of data! That means we really need to record for several hours just to get a decent statistical average of good data.

What is MT used for?

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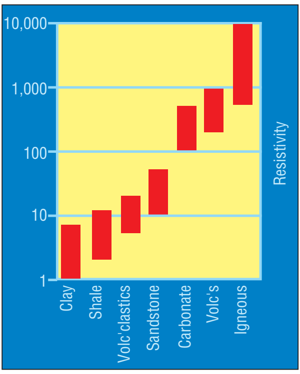

Figure 4: Resistivity values vary with lithology.

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The MT method itself has only been in existence since the 1960s. Practical systems came into use in the 1970s, with large improvements made in the 1980s. The last two or three years have seen the advent of smaller systems, taking advantage of GPS and faster computers, as well as 24 bit A to D conversion (more on that later).

At first, MT was used mostly for reconnaissance mapping of basins and geothermal prospects. In the 1980s, MT came into use for petroleum exploration, mainly in frontier areas. This is because MT is very portable (a station can be placed almost anywhere with access by horse, helicopter, snowmobile, etc.) and because MT works best where seismic has problems, i.e. areas of high-velocity cover such as volcanic provinces, overthrusts, carbonate cover or salt.

These days, MT can be used in frontier areas where seismic acquisition is difficult or prohibitive (due to cost or environmental factors) to map prospects (usually structural). The data are normally integrated with whatever other information is available (gravity, magnetics, geology, and borehole).

MT can be used in lieu of seismic in areas where seismic acquisition is not possible. MT can be applied in lead of seismic (to help determine the best placement of seismic lines). And MT can be acquired in conjunction with seismic, in order to have a “second” opinion of subsurface structure or stratigraphy.

What Can MT Tell Us About the Subsurface?

The main parameter that is derived from MT is resistivity. The main factor affecting resistivity is lithology – however, other parameters can come into play as well (such as pore fluid, pressure, and temperature).

Figure 4 shows how resistivity can vary with lithology.

Resistivity is given in ohm-meters. Note that the main contrasts are between the volcanic/igneous/carbonate groups versus the clastics under a higher resistivity material, but can be used to map sands versus shales – it all depends on the actual resistivity contrast between the units and the thickness of the units.

The deeper the unit is, the thicker it has to be in order to be mappable by MT.

MT data can be interpreted to give an estimate of resistivity variations with depth. This is normally displayed as a cross-section, where formations or units of differing resistivity are mapped in the subsurface.

Since MT needs a resistivity contrast to be present in order to map a boundary, and since these units need to be fairly thick to be mapped, the sections will not have the resolution of seismic sections.

How Are MT Data Acquired?

An MT crew will normally acquire between two and six stations at the same time. Each station is independent of the others. One MT station consists of a set-up as shown in Figure 5 (page 25). The stations can be anywhere from 1/4 mile to tens of miles apart, depending on the type of survey – is it reconnaissance or detail (prospect high-grade)?

At each MT station, five measurements (channels) are recorded. They are the magnetic field in two horizontal directions and in the vertical direction, and the electric field in two horizontal directions.

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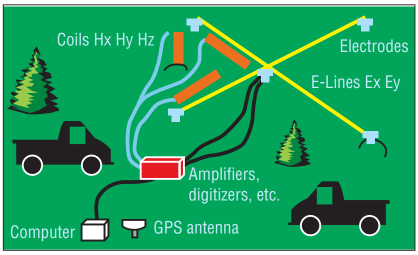

Figure 5: A typical MT station layout. The stations can be anywhere from a quarter-mile to tens of miles apart, depending on the type of survey.

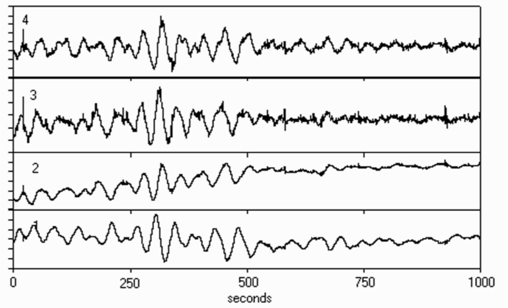

Figure 6: Actual MT time series recording. The amplitudes of electric and magnetic waves are measured as a function of time.

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The horizontal measurements are at 90-degree angles to each other (e.g. north and east) and as close to level as possible. The vertical electric field is not measured because it is assumed to be zero.

The directions are labeled as x, y and z, with z being the vertical direction. The electric field is abbreviated “E” and the magnetic field is abbreviated “H.” Hence, we measure Ex, Ey, Hx, Hy and Hz.

And, 10 to 30 channels are recorded at one time. More channels could be recorded, but this is usually limited by logistics.

The magnetic fields are measured with a type of magnetometer, basically an iron-cored coil with thousands of turns of wire. These coils are encased in waterproof containers, like PVC, and have a cable extending from one end. The coils are extremely sensitive to noise from wind, walking or trucks, and are buried in soil or under rocks to prevent movement.

The electric fields are measured with long “antennae,” or dipoles – usually wires about 300-500 feet long. The ends of the wires are connected to “pots” – sealed containers a few inches in diameter and about six inches high.

The pots have a porous ceramic base and are filled with an electrolyte solution (like silver/silver-chloride). These pots are buried a few inches in the ground and measure the voltage drop along the dipole length.

The wires are susceptible to wind noise, so they are usually placed directly on the ground.

The coils and electric-field dipoles are all connected to “sensor” boxes where filtering and amplification of the signals take place. Remember, these are very small signals we are measuring.

The data then are sent to a laptop computer where they are digitized and recorded on digital media. This is where the new 24-bit A to D systems come in. These new systems allow for a much larger amount of data (in amplitude) to be transferred from analog to digital (A to D) signal, meaning that we can get more information out of the data and have more to work with when processing.

The older systems were 16-bit A to D – now we can record 156 times more information than a few years ago.

The electric and magnetic fields are being measured as a function of time. An example of a time-series record is shown in Figure 6. Notice how the signals coincide with each other. The four channels are from top: Ex, Ey, Hx, Hy. Remembering basic physics, the electric field in the x direction (Ex) should correlate with the magnetic field in the y direction (Hy), and similarly Ey correlates with Hx. Hz (not shown) is recorded only to give us some information about the geologic strike. We will use Ex, Hy, Ey and Hx to tell us about subsurface resistivity.

The data are synchronized with GPS signals. This is important, because as we record two or more stations at one time these data are compared with each other for noise. This method, known as “remote referencing,” allows the data at one station to be compared to data at another station, recorded at exactly the same time, and compared for coherency.

Any non-coherent data are thrown out and considered as noise. This greatly improves data quality.

Recording at each station takes 6-18 hours, depending on signal strength and survey parameters.

Next month: What the data mean, and case histories.

(Editor's note: Christopherson has a BS in geology and an MS in geophysics. She has over 22 years experience using MT, working for the U.S. Geological Survey, BP (Sohio) and has been president of Chinook Geoconsulting in Evergreen, Colo., for the past 10 years. Her e-mail is chinookgeo@aol.com.)

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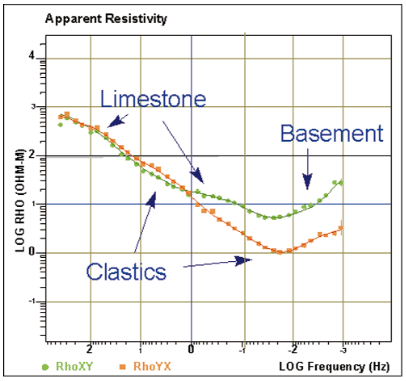

Figure 1 – An example of MT apparent resistivity curves (in ohm-meters) vs. frequency (in Hertz).

Graphics courtesy of Karen Rae Christopherson

MT Data Throws Curves to Viewers

The Geophysical Corner is a regular column in the EXPLORER, produced cooperatively by the AAPG Geophysical Integration and SEG Interpretation committees, and is edited by M. Ray Thomasson. This month's column is part two of a two-part series on magnetotellurics.

By KAREN RAE CHRISTOPHERSON

After Magnetotelluric (MT) data are acquired, they are run through several processing steps.

In part, noise is removed from the data. Examples of noise are thunderstorms, power lines, pipelines, and trains.

Part of the processing involves comparing the data at one station to another station that was recorded at exactly the same time (remote-referencing). Any non-coherent signal between the two stations is considered noise and discarded from the time series.

MT measures changes in the electric and magnetic fields with time. The data are transformed from the time-domain to the frequency domain. At each station, about 40 points in the subsurface are derived, as a measurement of apparent resistivity (and phase) vs. frequency.

The lower the frequency, the deeper the information.

Some sample MT data are displayed in Figure 1, which shows apparent resistivity (in ohm-meters) vs. frequency (in Hertz). The data are plotted on a log-log curve, so "2" means 10^2 or 100, and 0 means 10° or 1.

Why are there two curves?

☐ One curve shows the apparent resistivity (rho) determined from the electric field in say, the north direction (Ex) and the magnetic field, in the east direction (Hy).

☐ The other curve plots the data for the other two orthogonal horizontal fields, Ey and Hx.

Hence, at every MT station we get two curves. These data are processed so that they align with approximate geologic dip and strike, regardless of the layout in the field.

The processing takes several hours per station.

Interpretation

The MT method assumes that the earth structure is two-dimensional, i.e. that there is a dip and strike. Therefore, most MT stations are acquired along profiles (2-D) or on a grid (3-D) from which profiles can be extracted.

Almost all MT interpretation is done in 2-D, usually dip lines. There are 3-D codes available, but they still require large amounts of computing power and are not normally practical for prospect level exploration problems.

The MT interpreter takes the processed data and interprets it to a representation of true resistivity versus depth. This can be done using forward or inverse modeling.

With forward modeling, the interpreter creates a cross-section, computes the MT response and compares it with the acquired data; for inverse modeling, the interpreter allows the computer to create a cross-section from the acquired data.

Both types of modeling result in cross-sections or maps of the subsurface where the resistivity of the subsurface is interpreted to represent certain geologic formations or units

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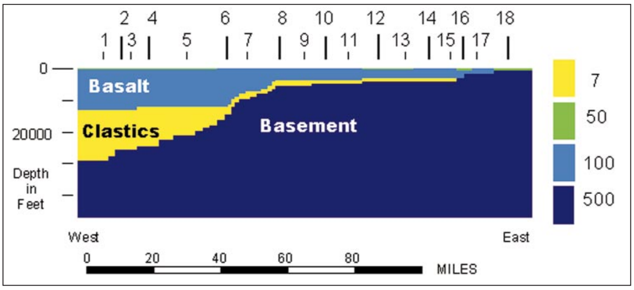

Figure 2 (above) – An MT resistivity section in the Columbia Plateau.

Figure 3 – An MT interpretation across an anticline in the fold belt in Papua New Guinea.

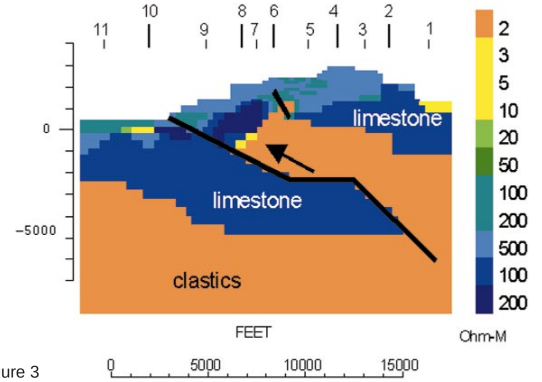

Figure 3

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(See figures 2 and 3).

MT interpretation is not easy, and a good interpreter must look at the data (not rely on inversion only) and *must* integrate geology.

There are two commercial MT workstations running on PCs. They allow the interpreter to process, review, edit, interpret, plot and map data. They also allow for the integration of other types of geophysical and geological data (e.g. structure, well logs, surface dips).

Often MT interpretation can be done rapidly in the field, allowing for changes or additions to field programs during acquisition.

Current Application of MT

There are hundreds of MT systems in use throughout the world for petroleum exploration, most being run by national oil companies (such as China, Japan and India) and a handful of contractors.

Since MT works best in areas of seismically high-velocity cover, many of these areas are frontier provinces.

In recent years, MT data for petroleum exploration have been acquired in Italy, northern Africa, China, Japan, the western United States, Colombia, Turkey, Greece, Albania, Jordan, Greenland, Pakistan, the Arabian peninsula, Papua New Guinea and the Gulf of Mexico (marine MT).

Listed here are a few case histories involving the use of MT.

❏ Columbia Plateau, Washington state.

Thousands of MT stations were recorded in the Columbia Plateau during the 1980s in an effort to map the basin beneath the thick cover of flood basalts.

In places the basalt thickness exceeds 20,000 feet.

Shown in Figure 2 is a 2-D MT model cross-section, from west to east, extending from central Washington to near the Idaho border. Station locations are shown across the top of the section.

The section shows the Miocene flood basalts (light blue), the Oligocene/Eocene clastics (including volcanoclastics) in yellow, and basement (in dark blue). The section is vertically exaggerated about 5:1. The resistivity of these units (as modeled) is shown on the right scale.

The MT model shows the basalts

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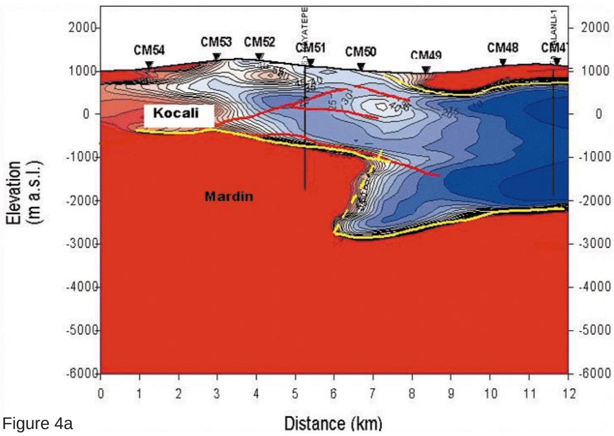

Figure 4a

Figures 4a and 4b show MT(above) and seismic sections (top right) from Turkey.

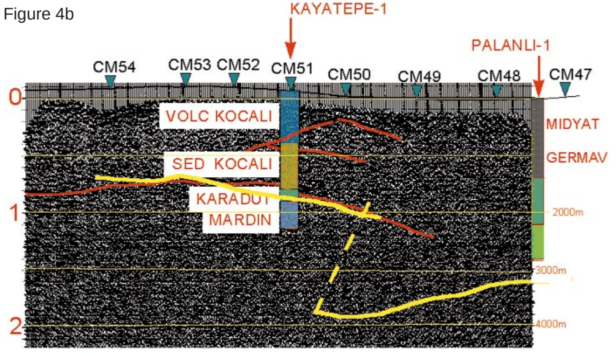
Figure 4b

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and clastics thinning dramatically from west to east, with the clastic section absent at the far east end. In this area, the basalts were probably deposited directly on basement rocks. Seismic data are almost impossible to acquire because of the thickness of the basalt cover.

Several wells were drilled on the Plateau that had good ties to the MT data.

❏ Papua New Guinea.

The Papuan Fold Belt extends lengthwise trending northwest along the island of New Guinea. Here, Tertiary carbonates have been thrust and folded into structures trapping large quantities of oil and gas.

Several large fields have been discovered here in the past decade.

The thickness of the carbonates in the fold belt is about 3,000 feet – and in places it doubles or triples in

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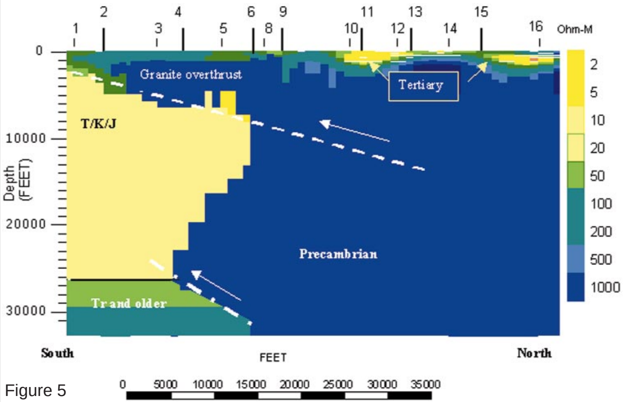

Figure 5

Figure 5 – An inversion of 15 MT stations acquired along a north-trending profile in southern Wyoming. Precambrian granites were thrust from north to south in this MT resistivity section.

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thickness due to thrusting. Seismic acquisition is expensive (more than $100K per mile for 2-D data) and the data are usually poor in quality.

MT data have been acquired over many structures to map the base of the surface carbonate unit and the thickness of subtrust carbonates (if present). The target reservoirs are Cretaceous sands, sealed by younger shale, and trapped in folds created by the thrusting.

Figure 3 (page 29) shows an MT model through an anticline in the fold belt. Only 11 MT stations were acquired, along a dip profile.

The MT data were interpreted and this resulting 2-D model shows the Tertiary Darai limestone (in blue) and the older clastics in orange.

The limestones are very resistive compared to the clastics (a contrast of almost 500:1). The primary thrust is shown, emplacing limestone and clastics in the hanging wall, with limestone also present in the footwall. The target is the folded clastics in the hanging wall.

There are also possible footwall plays.

MT interpretations on some structures in Papua New Guinea have estimated base limestone (pre-drill) to within 2 percent to 7 percent of drilled depth.

❏ Turkey

Much MT data have been acquired in Turkey owing to the outcrop of carbonates, volcanics, and other high-velocity rocks. Figure 4 (page 30) shows an interpreted MT profile and the corresponding seismic data. The red areas indicate more resistive units, and blues shows the more conductive units. The section is plotted with north on the left.

The Kocali (an ophiolitic melange) was thrust over clastics and carbonates. All are Mesozoic in age. The target is the Mardin carbonates. The seismic data are of poor quality. However, the principal reflectors were converted to depth and plotted on the MT section (red lines). The MT data show a more resistive section at depth corresponding to the Mardin. The results show good correlation to well data.

❏ Granite Overthrust, southern Wyoming.

Figure 5 (page 30) shows an inversion of 15 MT stations acquired along a north-trending profile in southern Wyoming. Precambrian granites were thrust from north to south.

The section is true scale, with no exaggeration.

The Precambrian granites are high in resistivity (500 + ohm - m). The subthrust Cretaceous/Jurassic rocks are 10-50 ohm-m.

A thin Tertiary section is present on the Precambrian at the surface. A possible secondary thrust fault is seen deeper in the section. Possible normal faults cut the thrust plate. The structure has not been drilled.

This survey was done to investigate the subtrust structure before acquiring seismic data.

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Global

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condensate, aggr. 111,000 mcfd & 2,036 bcpd.

New Zealand

Westech, Kahauroa 1, East Coast Fold, gas, 11,500 mcfd.

Westech, Awatere 1, East Coast Fold, gas, 3,100 mcfd.

Pakistan

OGDC, Tando Allah Yar 1, Indus, gas & condensate, aggr. 16,100 mcfd. & 380 bcpd.

OMV, Sawan 1, Indus, gas, 58,000 mcfd.

PPL, Hamza 1, Indus, gas, aggr. 6,920 mcfd.

OGDC, Jakhro 1, Indus, gas & condensate, 10,950 mcfd & 510 bcpd.

Union Texas, Dabhi North 1, Indus, oil, 2,640 bopd.

BHP, Zamzama 1, Indus, gas & condensate, aggr. 46,600 mcfd & 177 BCPD.

OGDC, Misan 1, Indus, oil & gas, 720 bopd, & 120 mcfd.

Premier, Zarghun South 1, Kirthar Axial Belt, gas, 24,9000 mcfd.

South Korea

Pedco, Gorae 5, Tsushima, gas & condensate, 75,000 mcfd & 1,546 bcpd.

Taiwan

CPC, Paishatun 8, Xinzhu Dpr., gas & condensate, 10,133 mcfd & 223 bcpd.

Thailand

Caim, Si That 2, Phu Phan Uplift, gas, 1,250 mcfd. ❏