1961-1994: A third of a century of magnetotellurics

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In 1961 Prof. L. Cagniard began in-depth study of the application of the magnetotelluric method (MT) to geophysical prospecting. After his 1953 publication, based on an idea put into practice in 1950, he embarked on preliminary experiments to prove his theoretical findings. A small number of contributions from other countries appeared at the same period, but it is by now generally recognized that Cagniard went further than his contemporaries in comprehending the theoretical and practical implications of their findings which sometimes had been obtained by greatly simplifying the statement of the initial problem.

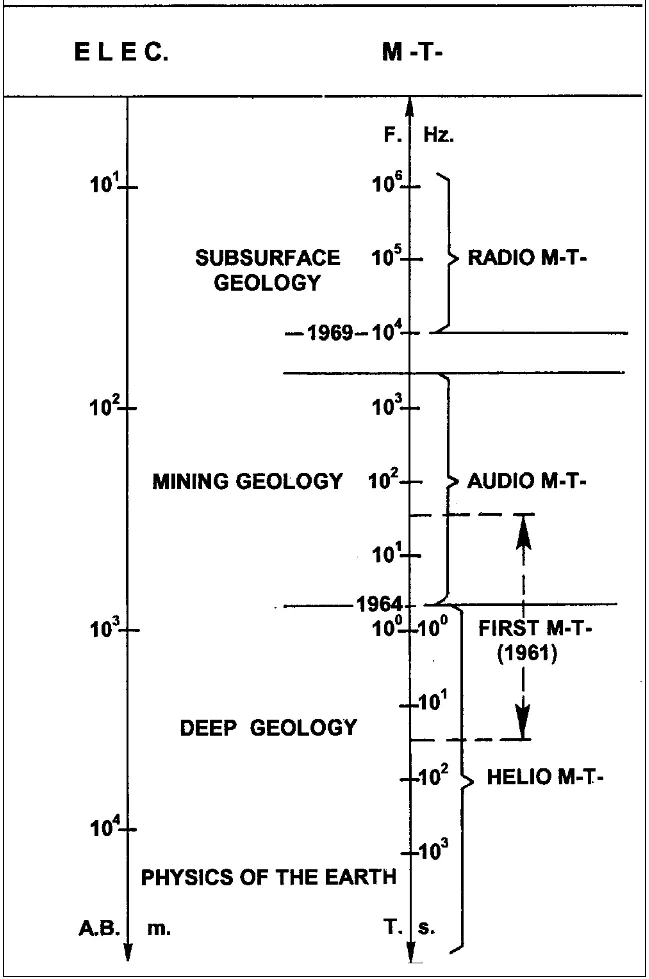
Some refused to accept Cagniard's proposed solution for the vast problem of natural planetary and external electromagnetism. It was some years before Madden and Nelson produced objective reasoning in support of Cagniard's aims, albeit at the cost of jostling somewhat the traditionally exhaustive and university-based lines of approach for this research, which invariably led nowhere in terms of better understanding of the subsurface.

MT of the first type. Cagniard's intention was to develop an alternative to the seismic method which was already dominating the search for oil. The examples that he cited in 1953 of the depth of penetration show clearly this preoccupation because the shortest period (1 s) associated with a realistic resistivity (10 Ωm) leads to a depth of the order of a kilometer. He was thus advocating a simple method similar in terms of presentation of results to electrical methods, but easier in its application in the field and reaching the same geological levels as seismic techniques.

A realistic approach to the geological problem led to study of a wider spectrum of frequencies and, because of this, the first commercially available instrument considered apt for recording MT phenomena was actually an electroencephalograph. The cranial electrodes were replaced by earthed probes and the magnetic variations were recorded by a magnetometer derived from flux meter instruments used in observatories for the measurement of rapid variations. The recordable frequency band was centered around 1 s, ranging from 30 Hz to about 30 s, which placed the resolution of the method on the order of 1 km, thus demonstrating the advantages to be gained by comparison with classical electrical methods.

The physical and subsequent geological interpretation of the experimental curves showed clearly from the start the necessity of recording phenomena whose period was shorter than 1 s. Indeed, it is at about this period that the resistivity diagram yields information on kilometer-depth layers. Another experimental observation was that, unfortunately, it is about this frequency that the main sources of noise appear, in particular microseismics and wind effects on the instrument cables. The natural spectrum also showed a low level of activity in this range around 1 s which was isolated to obtain better amplification.

Table 1. Evolution of magnetotellurics from (1953) — from 1961 to 1994.



Other MT studies of the period were entirely founded on data acquired in the frequency range measured by observatories; i.e. with periods no shorter than 10-20 s. On applying simple two-terrain models to values of the order of 10 Ωm, it is easy to conclude that with periods of such length, penetration depths of several km would be attained, making detailed analysis of the sedimentary formations most often encountered impossible. Comparison with electrical sondage thus led to a development of the study of more rapid variations to enable analysis of upper geological levels (Table 1).

Extending the MT spectrum. From 1964, with the arrival at Garchy of A. Becker, efforts were made to extend the MT spectrum to higher frequencies by employing the earth-ionosphere cavity fundamental resonance in response to

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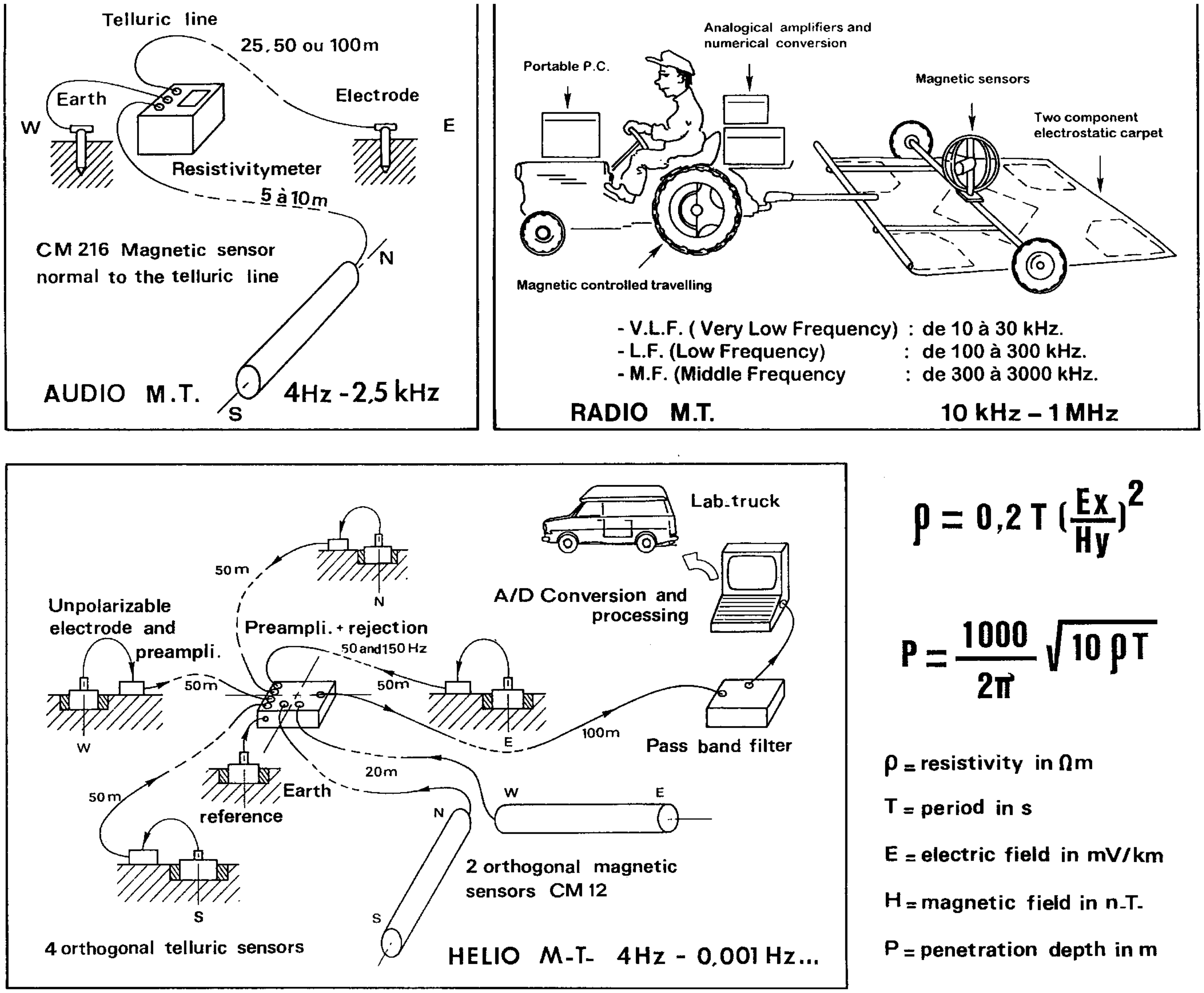
(Editor's note: The following is a summary of a full-length article by the same name which can be found in EdgeNET, TLE*'s online version. This version can be accessed via SEG's home page on the World Wide Web).*



$$\rho = 0{,}2\,T\left(\frac{E_x}{H_y}\right)^2$$

$$P = \frac{1000}{2\pi}\sqrt{10\,\rho T}$$

ρ = resistivity in Ωm

T = period in s

E = electric field in mV/km

H = magnetic field in n.T.

P = penetration depth in m

Figure 1.

atmospheric storms (called the Schuman resonance at approximately 8 Hz) and its numerous harmonics up to 2000 Hz. In fact, international attempts were made in this field and work was directed towards the design of fast-working autonomous MT equipment which could complement the existing low-frequency apparatus.

The lack of information for the first few hundred meters encountered with the low-frequency MT was also encountered with this audio MT. For this case too, it became apparent that information on the uppermost levels would be necessary to correctly interpret structures at depths normally attained by audio MT (10s-100s of meters).

It was while attempting to develop MT towards still higher frequencies that the final version of this method evolved. Finding that from about 2 kHz upward the natural signal was devoid of regular phenomena before reaching VLF frequencies (10-30 kHz), we decided to inject a current to fill this gap by creating what we termed artificial MT (MTA). The first trials were published under this name. In simultaneously testing direct injection of current and the use of a loop on the surface, we became aware that in the latter case, for fairly high frequencies (100 kHz), considerable losses were incurred through capacity with the earth. From this observation it became apparent that the effect might be used for the measurement of high-frequency ground potentials by creating a capacity-type rather than a conductivity-type contact. We built a capacity-based probe, verified that it produced the same measurements as classical electrodes, and founded a new variant of MT on it which was at first used in civil engineering and pedology.

MT of the second type. Somewhat later, when the problem of measurement of magnetic variations was thought to be satisfactorily solved, it was again briefly brought into question when SQUIDs were becoming operational. I decided, with G. Petiau, to look again at the question of measurement of electric potentials using unpolarizable electrodes. A detailed study of the problem, taking into account the specific needs with regard to MT measurements (whose duration may run from a few hours to several days, and the need for rapid installation in the field), resulted in the design of new Pb-PbCl$_2$ electrodes. The Brest Workshop decided in 1994 to submit these to a comparative test at Garchy for one year (1995-1996), on the suggestion of K. Vozoff, in order to be able to discuss the results in Japan in 1996.

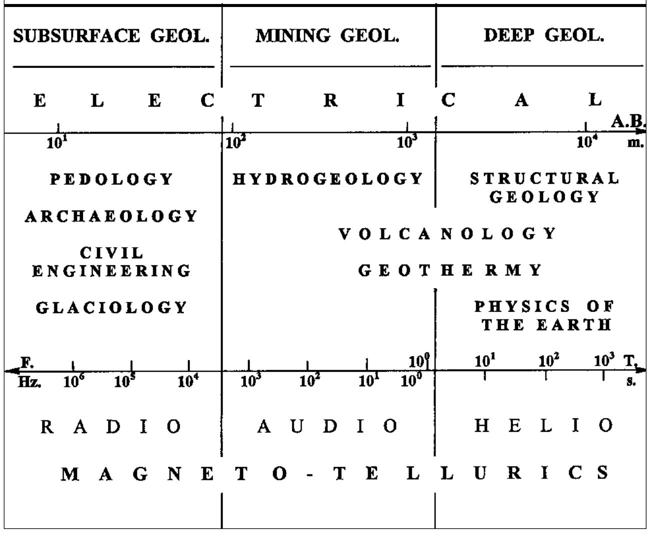
The end of the 1970s thus saw the availability of three variants of MT. Audio and low-frequency MT were developed during the energy crisis. Indeed the search for geothermal potentials in low and in high enthalpy became general at this period. "Artificial" MT underwent a strong development in civil engineering and then in pedology in France only. At this time a problem of nomenclature arose. MTA could no longer be used because it became confused with audio MT which had been coined in the U.S. Our term "rapid MT" was no longer appropriate for the middle spectrum and the study of lower frequencies was ill-described by "slow MT." My proposition was to name the highest frequency variant "radio M-T" bearing in mind the type of source used, and to use audio MT for the middle frequency range. It seemed that to be coherent with the two other terms a reference to solar sources was required and that the Greek "helio" would be appropriate for euphonious reasons. If in each case the characteristic prefix is retained whole, an harmonious denomination is obtained (Figure 1).

Radio MT. The most detailed applications of this variant are in archaeology, where the outlines of anomalous structures are sought amidst a conducting or resisting setting.

Another application is agricultural drainage, in particular finding old drains because experience shows that it is highly desirable to take into account the siting of an old drainage system when installing a new one.

Audio MT. One of the most recent applications of audio MT is searching for water in the volcanic surroundings of the French Massif Central. This was in a basaltic plateau where the geology consisted of a basaltic and doleritic volcanic cover overlying a thick mudflow; a lahar some hundred meters thick, overlying Miocene sands and Oligocene clays; and a gneiss bedrock. The operation was aimed at discovering the location of a Miocene valley corresponding to a river now flowing east-to-west but which could at the time have been flowing south-to-north. It was hoped to find the rare water of this plateau in the sandy horizons of this ancient valley. The audio MT was carried out in good conditions since the plateau presented very little relief and the experimental curves indicated clearly the presence of a conducting formation between two terrains of higher resistivity, one being the bedrock and the other at least the upper part of the volcanic formations, the lahar and the sandy levels being attributable, according to their composition and the presence of water, either to the higher resistivity formation or the conducting one.

Table 2.



Helio MT. The most interesting applications of this version was done in the Rhine valley as a contribution to the telluric "chanelling current" controversy. This experimental campaign was also carried out in favorable conditions since the MT results could be checked by several means. The local geology is well known. Numerous wells and salt mines give a good knowledge of the sedimentary fill of this tectonic corridor so that geologists were able to furnish a fairly clear picture of the structure and nature of the terrain. Certain geophysical studies had already profited from the exceptional advantages of this region which had become to some extent a calibration model. We were able to verify that the interpretative results corresponded with known structure and with the quantitative data concerning the sedimentary formations.

Encouraged by this result, we could look forward to MT contributing to the resolution of geological problems concerning, for example, the risk of natural catastrophes. In volcanology the latest example is the case of the village of Nyos in Cameroon where the events of l986 caused the deaths of about 2000 people. Two lakes, Nyos and Monoum, gave off deadly emissions of CO_2 at intervals of several years; one hypothesis concerning the origin of these emissions made reference to a volcanic eruption. The helio and audio MT work sought to identify the possible magma chamber at medium or slight depth, a few km at

Table 3.

Version	Main sources	Freq. Range	Penetr. Depth	Magn. Sensor	Tell. Sensor	Acquis.Time
RADIO M-T	Broadcast. systems	1MHz - 10KHz	1 - 50 m.	45 cm Ø loop	Capacitive or an electrostatic carpet (1-5 m.)	Instantaneous
AUDIO M-T	Atmospher. storms	2,5KHz - 1Hz	30 - 1000 m.	Flux feedback rod 1,15 m. long	Metallic or unpolarizable (15 - 100 m.)	30 mn.
HELIO M-T	Solar activity	1Hz - Diurnal	> 500 m.	Flux feedback rod 1,5 to 2 m. long or SQUID	Unpolarizable (100 - 1000 m.)	½ day to semi-permanent

the most, which could have produced a sublacustrine eruption. The sondages show few directional differences after rotation of the measurement axes. The most important effect is the topography which can be more or less roughly corrected by observations in the field as the maps lack precision. The final result shows a formation of higher conductivity at a depth of 6-10 km and with (at most) a thickness of 1 km; this could very well represent the magma chamber being sought.

In geothermal prospecting, our latest operation was in northern Portugal. Heavy audio MT coverage and two extensive helio MT profiles (perpendicular to the main tectonic axis associated with electrical dipole-dipole measurements) allowed the hydrothermal system to be analyzed with good detail.

Conclusion. MT has fulfilled many of Cagniard's expectations as a new and truly competitive alternative to seismology. Today it occupies a significant place among accepted geophysical techniques even if it is, at present, practiced more in university contexts than in industry.

In fact, such a method does not develop in a static research context, but forms a part of a group of allied methods which have all progressed together at a time when MT was finding a foothold in geophysical research. In seeking to place it alongside other methods one cannot avoid comparing it with seismology on the one hand and with electrical methods on the other.

With seismology, setting aside the initial idea of proposing an alternative solution to one which was already coming to dominate the others in the 1950s, at any rate in the search for oil, theoretical analogies have been discussed on the question of the problems of wave reflection and refraction. The development of electronic computers has transformed the relationships of these methods and their applicability, but it remains obvious that seismology benefits from much greater investment for the interpretation of complex structures.

One may compare, in a very schematic way, the evolution of seismology and MT in observing that seismology carries with ease the investigation right to the center of the earth whereas MT presents certain difficulties. On the other hand near the surface, MT in its radio version has met with greater success than its rival. At intermediary levels, in mining and oil, the quality of results depends greatly on the resources allocated to each method, both having initially been concerned with structures at greater depths and subsequently returned, by degrees, to the surface.

To the best of my knowledge it has never been shown that the study of the propagation of vibrations is *de facto* a better means of studying the earth's structure than the study of electromagnetic waves although in strict terms mention should not be made of propagation in MT as this would be to trespass into the domain of radar. And we again find in this evaluation the similarities which were pointed out at the start on the question of medical instrumentation (electroencephalograph). In this domain, does the use of ultrasonic echoes give better results than M.R. Imaging or the Scannner? The answer to this would not seem to be simple, for the methods do not give the same performance in all contexts and with all types of human tissue or, indeed, all types of geological terrain. They are complementary, therefore, and this is the attitude to adopt if precedence is to be given to the result and not to the defense of one method or another.

Table 2 illustrates the relationship between MT and the electrical method in the context of an investigation, with a few indications as to logistical means to be employed (quadripole dimensions, MT variant method etc...). This time our observations are reversed with respect to those we have just made in reference to seismology. It is in the uppermost region (<1 m) that the electrical method is least challenged by MT. Concerning the interpretation, it is today just as easy to calculate a direct electrical sondage as it is in MT whereas in the 1960s the latter method offered the fastest results. In fact these two methods are very close both in the physical parameter that they measure, in the presentation of experimental results, and in the philosophy of direct or reverse interpretation. But this table very quickly establishes the superiority of MT as soon as the depth exceeds a few hundred meters

In completing this mostly French retrospective, it is comforting to observe that MT now occupies a place not to be denied in the cortege of geophysical methods. Its availability in three variant forms (Table 3) demonstrates its influence in geosciences from the subsurface down to depths of a few hundred km. In this, if not elsewhere, it should be considered on a par with seismology.

André Dupis received an MSc (1960) and a Diplome d'Etudes Supérievres in geology (1961) from the University of Paris.He then started geophysical research with Prof. L. Cagniard at the Garday Centre de Recherches Géophysiques (CRG) to develop a technique and equipment to apply MT theory. Dupis continues his MT research in deep geology, geothermal, mining, and civil engineering applications at CRG and is also attached with the Laboratoire de Géophysique d'Orléans (directed by J. Zlotnicki) UMR6530, at the Centre National de la Recherche Scientifique. He is a member of the Société Geólógique de France, EAGE, IUGG, and SEG.

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