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Evolution of instrumentation and techniques in applied geophysics

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ABSTRACT Over the last hundred years geophysical exploration has become an established, powerful tool in the search for oil and minerals. An historical outline of the development of the instrumentation and the techniques of the four most important geophysical methods (gravity, magnetic, seismic and electrical) up to 1980 is given, starting from the earliest experiments in the 19th century and in the first decade of the 20th century. Particular attention is given to the first successful surveys; these have laid the foundations for a rapid growth. The development of instruments, from the torsion balance to gravity meters, from the Schmidt balance to atomic magnetometers, from mechanical seismographs to digital seismic apparatus is presented schematically, together with statements concerning the theoretical principles of the methods and the development of field data processing and interpretation.

1. Introduction

Knowledge of the historical evolution of a scientific and/or technical discipline, like the more general knowledge of the evolution of Mankind, is, in itself, quite fascinating. Such knowledge allows us to reconstruct the course of the human mind and, therefore, to understand the reasons for our actual behaviour and way of thinking and acting, but it is also an advantage because it avoids repeating errors and gives us a starting point for improvements. For instance, parameters that are no longer considered, because of the difficulties encountered making measurements and the long times needed, can again come to the fore because of the new techniques and new instruments available.

Such considerations have always prompted us to look into the various historical documents for the history of the evolution of the instrumentation and techniques used in Applied Geophysics, and in this we are helped by having, in our Department, texts and journals that go back as far as 1930, as well as instruments dating from the same years.

Many colleagues urged us to write the present article in the belief that such a presentation could be a useful source of information, especially for young researchers who have neither the possibility nor the time to deepen such a field in detail.

To thise aim, we describe the evolution of instrumentation and techniques for the period that starts with the origins of Applied Geophysics up to the 1980s. We are well aware that the young people of today can retrieve information related to the last 20-25 years quite easily. Our history refers mainly to four geophysical methods (seismics, electromagnetics, gravity, magnetics) omitting, for reasons of space, the less used methodologies (radioactive, thermal, etc.) and the geophysical borehole methods (the so-called logs).

We treat the evolution of the each method as a single entity; this is because, in effect, each method has evolved separately, even though there has been frequent interaction between methods, particularly between the gravity and magnetic methods.

The historical reconstruction is based on old texts - Alexanian (1932), Heiland (1940), Jakosky (1940), Nettleton (1940) and Fulcheris (1949) – and, above all, on a series of articles devoted to the history of Applied Geophysics published in Geophysics organ of the Society of Exploration Geophysicists (SEG), the oldest and greatest society among those devoted to Applied Geophysics. Among these, is an interesting and amusing article of Sheriff (1985), that traces the history of geophysical technology through the reproduction by a series of advertisements published in Geophysics, from 1936 to 1982. Indeed, a series of articles that treats the development of the single methods specifically was published in Geophysics N° 11, 1980: among these we quote Allen (1980) for the seismic method, Ward (1980) for the electric and electromagnetic methods, LaFehr (1980) for the gravity method and Reford (1980) for the magnetic method. Such articles include a wide bibliography on the evolution of Applied Geophysics and also on the main innovative technologies of the time.

We also consulted articles on pioneering surveys, published in Geophysics, early Geophysical Papers and Geophysical Case Histories I (Nettleton Ed. - 1949), always edited by SEG. Other information has been retrieved from Geophysical Prospecting, Geoexploration, Bollettino di Geofisica Teorica ed Applicata, Rivista Geomineraria, etc.).

2. Gravity methods

The roots of the gravity method go back to the 17th century, and can be traced to Galileo, who formulated the law of free fall and the motion of the pendulum, and Newton, who put forward the universal gravitational law. Richer in 1672 made the observation that the period of the pendulum depends on the measurement position, and Newton and Huygens correlated these variations with the non spherical form of the Earth.

It was these formulations that gave birth to dynamic geodesy, i.e. the jaw of science that tries to reconstruct the Earth's shape from gravitational field measurements. Indeed, at that time only pendulum measurements, which furnish the modulus of gravity acceleration, were possible.

In the 18th and19th centuries there was a notable improvement in the absolute and relative techniques of gravity measurements, and it was recognized that gravity is strongly influenced, by station elevation and masses between the topographic surface and the sea level. Indeed, the effects of elevation and masses are still taken into account as the two classical corrections of gravity data, and are respectively called Faye and Bouguer corrections.

It was in this period that an anomalous deficit and an excess of gravity were observed with respect to the mountains and seas. This led to the formulation, of the isostatic theories, by Pratt (1855) and by Air (1855), the first contribution of gravity to the knowledge of the inner Earth.

At the end of the 19th century, Von Sterneck constructed a pendulum that was relatively easy to handle and, in these same years (1888) the Hungarian, Baron Roland Eötvös began to realise a new gravity tool, the torsion balance. This consists of a beam carrying a mass at each end and suspended at the centre of gravity by a very fine torsion wire (Fig. 1). The instrument measures the differential gravitational effect on the two masses. The first torsion balance (curvature

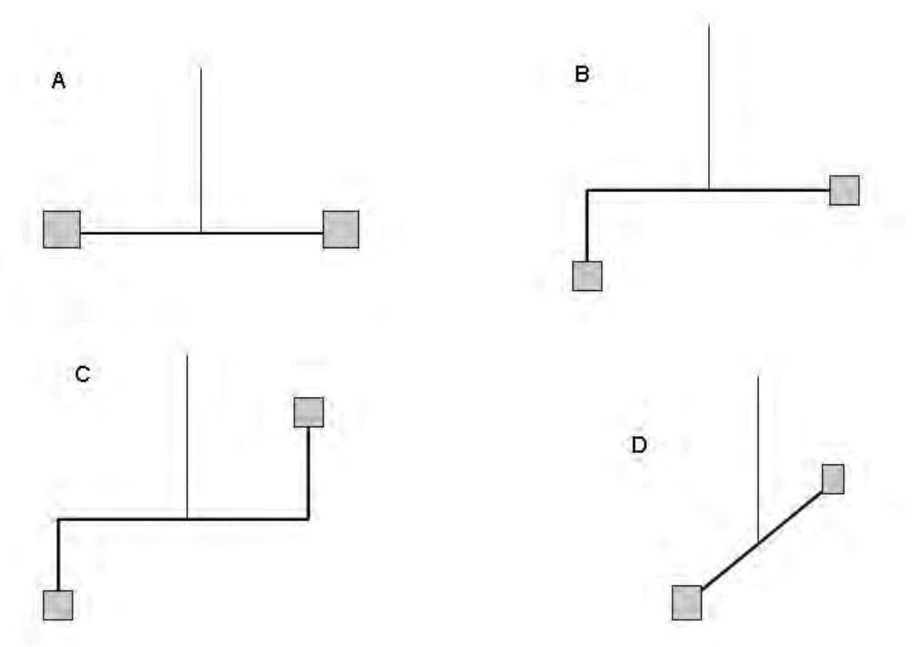

Fig. 1 - Schemes of Eötvös's torsion balances:
A - the first type of balance (curvature variometer) with the masses at the same level;
B - the second type of balance (curvature and horizontal variometer) with the two masses at different levels;
C - scheme of the balance with Z-shaped beam;
D - scheme of the balance with the tilt beam.

variometer) had the two masses at the same level (Fig. 1A) which allowed to calculate the so-called curvature i.e. the deviation of the equipotential surface from a spherical surface. When the equipotential surface has not a spherical shape, the small horizontal components of the gravity of the two masses create a couple of forces compensated by the wire torsion. The value of the wire torsion is obtained from the beam rotation. The differential curvature and the orientation of the minimum curvature are obtained by measuring the beam rotation with the instrument oriented in 3 different directions.

Soon after (1890), Eötvös devised a second type of torsion balance (Fig 1B), with the masses located at two different levels, that allowed the measurement not only of the curvature but also of the horizontal gradient of gravity. Thus, if this gradient exists, the equipotential surfaces are not parallel and, therefore, the gravity forces of the two masses (at different levels) are not parallel either and the horizontal components of the gravity vector create a couple that can be measured by the wire torsion. To calculate the two new values i.e., the components of the horizontal gradient, it was necessary to acquire two other measurements using different tool orientations. The tool was very sensitive (the unit of measurement was the Eötvös =10^{-9} s^{-2}), but even after the first improvements it still required 2-3 hours for each measurement.

Although Eötvös's interest was mainly geodetic, he showed that measurements with the torsion balance could furnish information on the structure of the Earth, similar to the information obtained using the pendulum. But perhaps it was Boeckh, the director of the Hungarian

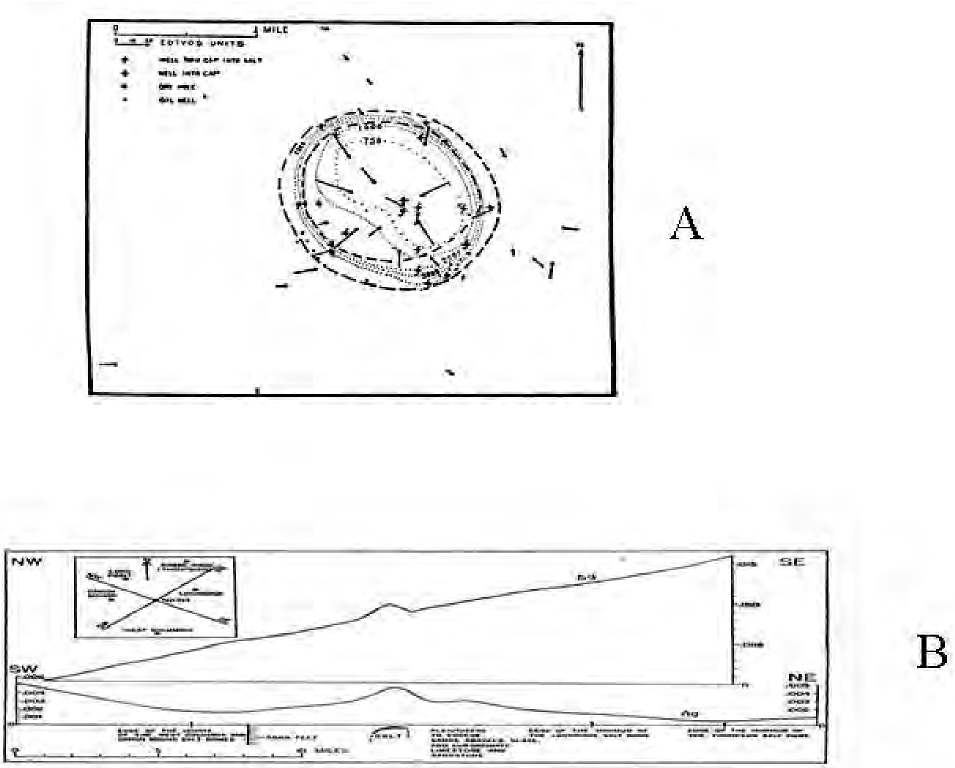

Fig. 2 - Results of the survey acquired with the torsion balance on the salt dome of Nash Texas, USA (after Barton, 1949):
A - horizontal gradient trend of gravity represented by arrows (the Eötvos scale to the left) and the geologic structure location carried out from the geophysical surveys (dashed lines) and subsequently from the boreholes (dotted lines);
B - diagrams of the trend gravity values in two normal directions, obtained from gradient integration acquired with the balance. Note the maxima corresponding to the salt dome.

Geological Service, who was the first to foresee the possible applications of the torsion balance in the search for oil. The first practical application, with measurements made at a hundred stations, was made at the Egbell oilfield in Czechoslovakia (1915-1916), and this was followed (1917) by an investigation into the salt dome of Hanigsen-Hanover by Schweydar and, in later years, by other surveys. However, the diffusion of the results achieved was delayed due to the ongoing war, and it was only in 1922 that two torsion balances were imported in the United States. In 1924, the first oil reservoir, detected with only geophysical methods, was discovered in Texas (at Nash, Brazonia County: Fig. 2). This discovery led to the rapid diffusion of the use of the torsion balance in the United States and throughout the world, and brought improvements, though slow ones, by the constructors, to an apparatus that has reduced the time needed for each station in the latest balances that used two Z shaped beams (Fig. 1C) or two tilt beams (Fig 1D and Fig. 3) to about two hours.

The torsion balance was highly influenced by nearby superficial masses, and therefore by the topography, so accurate corrections were needed to eliminate these effects. In 1924, Schweydar published topographic correction tables, which were completed with tables for rough

Fig. 3 - The Askania torsion balance with two-tilted beam, coupled to reduce measurement time. From the bottom: the support pedestal; the cylindrical apparatus that allows automatic rotation through a clockwork set-up for a series of prearranged orientations for measurements. At the top two opposing balances coupled with the central part where the transmission of bright rays occurs, the beam deviations are recorded onto a photographic plate. The height of the tool was 130 cm.

topographies in 1927. Along with the expansion of the torsion balance, and as a consequence of its good results, pendulum methods found widespread application in the search for oil, the apparatuses having been improved and adapted to field use and several pendulums being used contemporarily; the pendulums were built with low thermal expansion materials and with external commands.

In the United States, the first surveys began in 1925-26 with pendulums manufactured by the U.S. Coast and Geodetic Survey, and subsequently by the Gulf Oil Corporation. Also in Europe, after 1925, such surveys became more widespread, using Askania - Sterneck pendulums (Fig. 4). With similar pendulum apparatutuses, suspended in gimbals and installed in a submarine, F.A. Vening Meinesz (1934) performed the first deep water gravity survey off the Indonesian archipelago in the years 1926–1930, detecting strong negative isostatic anomalies in the oceanic trench (Fig. 5), as postulated by the then prevailing theory on geosynclinals. The same apparatus was used for a gravity survey in 1931 (Cassinis, 1934) in the Tyrrhenian and Ionian Seas (Fig. 6).

The application of pendulums was also facilitated by a series of studies developed for geodetic purposes: remember the introduction of the International Gravity Formula (Cassinis, 1930) and the tables for topographical correction of Hayford and Bowie (1912), completed in 1937 by Cassinis, Dore, and Ballarin tables of the Reale Commissione Geodetica Italiana.

Both the torsion balance and the pendulums had numerous prospecting handicaps: the

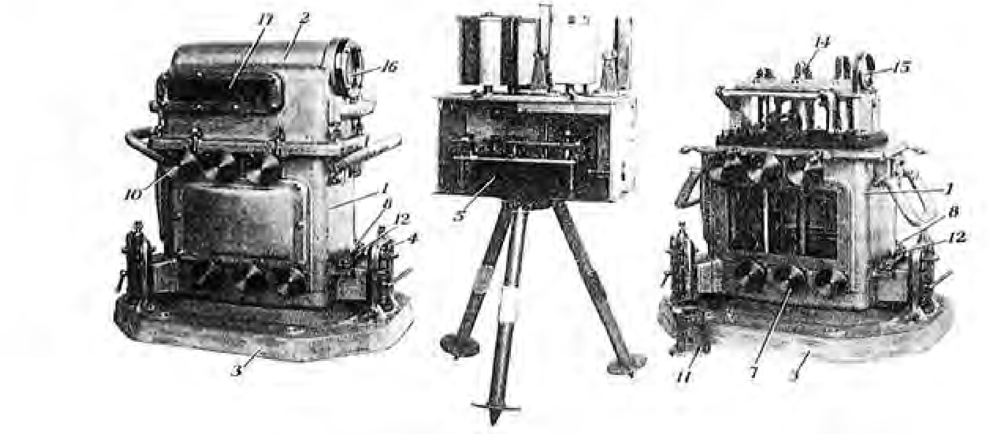

Fig. 4 - The Askania pendulum apparatus: In the middle of the figure, the photographic recording apparatus; to the left, the apparatus for field use, with its protection devices; to the right, open, showing the three pendulum compartments (after Heiland, 1940, pp.111).

observation required 2-3 hours for each station and skilled operators, the instruments were cumbersome to transport and set up in the field, the pendulum measurements had a poor accuracy (0.5-1 mGal).

The good results achieved with the gravity method led to continuous improvements in instrument quality, and finally resulted in a new type of tool: the gravimeter. The principle of the gravimeter, the measurement of the deformation of an elastic system subjected to a weight, had already been enunciated in the 19th century, but it was only in the 20th century that field instruments were realized. The first instrument (1916) was Ising's gravimeter, manufactured in Sweden and used a few times in Scandinavia, but gravimeters with a sensitivity similar to that of the pendulums appeared only at the beginning of the 1930s; the gravimeters most used were the Humble Truman (1930), Ho1weck-Lejay (1930), Mott-Smith (1938) and Graf-Askania (1938). By the end of the 1930s, gravimeters had reached a sensitivity of about 0.5-1 $\times 10^{-4}$ cm/s^2 in measuring gravity differences, and because of their manageability and measurement speed (several tens of stations per day), they very soon supplanted first the pendulums and then the torsion balance, though not completely in terms of measured parameters. In fact, whereas gravity measurements made on a horizontal surface enable the calculation of horizontal gradients, it is impossible to calculate differential curvature which, even now, can only be achieved using the torsion balance.

The Second World War interrupted the European production of gravimeters, but the American industry continued producing and improving them: they became even lighter (just a few kilograms in weight), more sensitive (1-2$\times 10^{-5}$ cm/s^2) and less sensitive to temperature variations. In addition to a few gravimeters already employed (such as the Gulf gravimeter), use was made of a series of metal gravimeters based on the La Coste seismograph principle (La Coste-Romberg, North American, Magnolia, etc.) and on quartz gravimeters (Worden, Atlas). Also remote control systems were set up (1941) to perform marine surveys to depths of about 100 m,

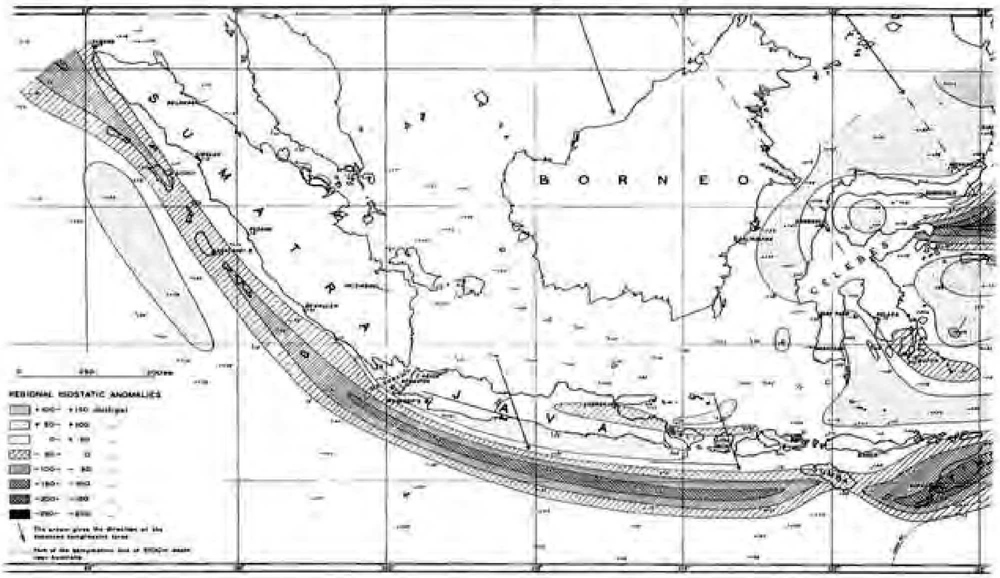

Fig. 5 - The isostatic anomalies map calculated from pendulum measurements of Vening Meinesz, taken in the seas surrounding the Indonesian archipelago. Note the strong negative anomalies in correspondence with the oceanic trench (after Heiskanen and Vening Meinesz, 1958).

the gravimeters being housed in appropriate containers and lodged on the sea floor. In the 1950s, the possibility of having relatively stable gravimeters with high sensitivity led to the realisation of gravity networks both national and worldwide (Morelli, 1946, 1959; Wollard and Rose, 1963): the first gravity map in Italy was set up with a station every 80 km^2.

In the 1960s, the first shipboard gravimeters with a sensitivity of 0.5-1x10^{-3} cm/s^2 began to be used in deep waters. Also in the 1960s, there was the introduction of the first borehole gravimeters, which were improved towards the end of the 1970s.

At the beginning of the 1970s the construction of a micro-gravimeter with a 2-3x10^{-6} cm/s^2 sensitivity allowed the extension of the gravity application to very detailed problems such as cavity detection, the control of elevation nets and the monitoring of mass displacement in the underground (geothermal fluids, magma masses, etc); in the same period the first attempts at gravity measurements from airplanes appeared.

Already at the beginning of the 20th century for the interpretation, the calculation of theoretical anomalies for bodies of simple form, useful for both the *a priori* evaluation of anomalies and for an indirect interpretation of the surveyed anomalies had begun: at the end of the 1920s, graphic methods and mechanical apparatuses were used to evaluate the gravity effects of 2D bodies. In 1948, Hubbert introduced the calculation of 2D structures with line integrals and in 1960 Talwani and Ewing introduced a rapid method for the calculation of three-dimensional anomalies.

In 1940, Nettletton introduced the concept of regional and local anomalies, and pointed out methods based on average and smoothing procedures to calculate regional anomalies. In 1949, Griffin introduced a fast, linear interpolation procedure using the average values of stations

Fig. 6 - Hayford isostatic anomalies in the south Tyrrhenian and Ionian seas determined from gravity measurements performed with Vening Meinesz apparatus mounted in the Italian submarine V. Pisani (after Cassinis, 1934).

located on the circumference centred at the station, and a least-squares surface fitting procedure was introduced by Agocs (1951). In the same year, Elkins indicated a method to calculate the second derivative from the Bouguer anomaly: such a method had the aim of enhancing anomalies due to the most superficial bodies; the method was improved by Rosenbach (1953) but after a period of application was practically abandoned. The separation of regional and residual anomalies again came to the fore (1954-1955) with the new opportunity offered by the availability of electronic computers: polynomial interpolation methods of various degree or orthogonal polynomial functions were introduced along with filters in both wave numbers (Dean, 1958) and distance domain (2D convolution).

The basic concepts on the significance of the data interpretation were set up in the 1930-1940s. In 1937, Tsuboi and Fuchida reported examples lacking biuniqueness in gravity anomaly

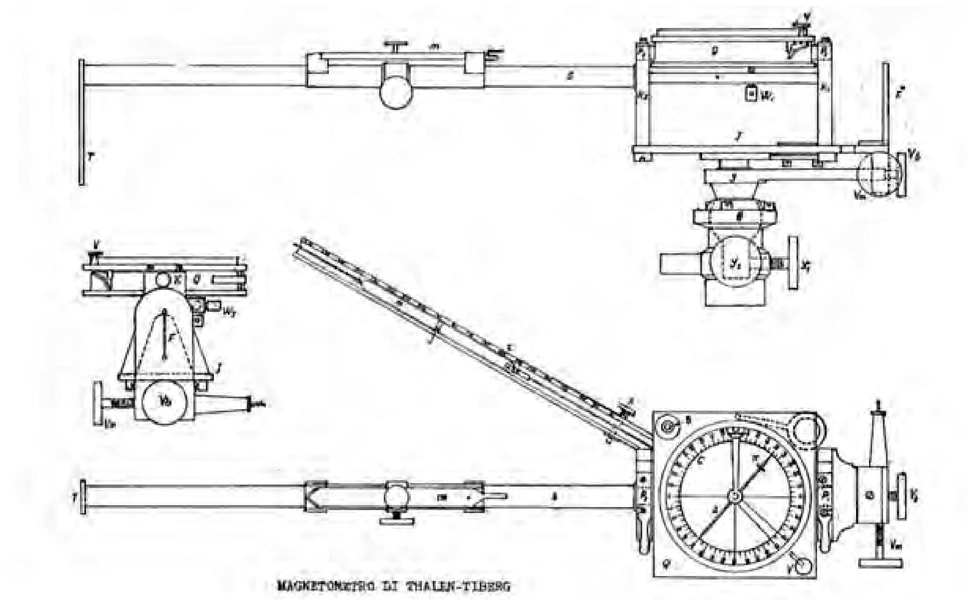

Fig. 7 - Thalen and Tiberg magnetometer scheme. The tool with the horizontal compass allowed the measurement of the declination and, with the aid of an auxiliary magnet situated on one of the two arms, the horizontal component of the Earth's magnetic field. Vertical rotation of the compass, allowed the measurement of the vertical component always through the auxiliary magnet (after Fulcheris, 1949).

interpretation, in the sense that the same gravity anomaly could correspond to more bodies in different forms and at different depths.

This idea was taken up by Nettletton (1940) who " reiterated that the achievement of a good fit between computed and observed effect is not criterion of the reality of the mass distribution from which the computation was made unless auxiliary control is adequate to remove the inherent ambiguity".

The concept was demonstrated by Skeels (1947) who took up Green's equivalent layer concept and demonstrated the dependence of the derivates on field gravity and magnetic fields.

The possibility of drawing up the total mass excess (or defect) was indicated by Hammer (1945), and in 1958, Bott and Smith drew up relationships to determine the maximum depth of anomalous bodies corresponding to a given anomaly. In 1949 Peter published the results of a series of fundamental studies developed for magnetic data, but also applicable to gravity data; the study, that started in 1929, was performed by a team of researchers at the Gulf Research and Development Company. Peter presented the concepts, and the computational methods, for calculations of the first order derivatives and of the upward and downward continuation of the gravitational and magnetic field.

The use of electronic computers, began in the 1950s, and introduced new interpretation possibilities: the computational rapidity of Fourier transforms allowed the interpretation of the data in the frequency domain. The use of videographs has allowed an interactive interpretation in which the operator guides the gravity model variations on the basis of geological and/or geophysical knowledge, so that the calculated theoretical anomalies fit the field data. In this context, since the 1960s, a series of computational programs for both 2D and 3D bodies have been developed, and over time they have become faster and faster, allowing, on the one hand, the extension of the use of interactive procedures, while on the other it makes procedures of automatic interpretation more acceptable, in terms of computing cost and through optimisation methods.

Interpretation through stripping, introduced by Hammer (1963), has also spread; this method eliminates the effects of the known superficial formation so as to have a simplified anomaly to use in the reconstruction of deeper structures.

The last basic concept, unfortunately not yet very welcome even in very known texts, is the concept of the Bouguer anomaly which, in the geodetic conception, is defined as the difference between “reduced” gravity and “normal” value, considered at zero level. As already pointed out by Grant and Elsaharty (1962) and reiterated by Naudy and Neuman (1965), in Applied Geophysics the Bouguer anomaly has to be considered at the gravity station level, and must be calculated as the difference between the measured gravity and the gravity effect of a model considering the Earth with an ellipsoidal shape (normal gravity plus Faye correction) and the masses above zero level (Bouguer and terrain correction).

3. Magnetic methods

Magnetic prospecting was the first geophysical method to be employed (Sweden, 1640). It was essentially based on the measurement of magnetic effects produced by geologic bodies such as magnetite ore, a mineral that can also be detected by a simple compass. Thus the dipping needle (Swedish mining compass) was the first tool employed for prospecting, and its use was superseded only in 1870 by Thalen and Tiberg’s magnetometer (Fig. 7) which measured also the horizontal and vertical components of the magnetic field with an accuracy of about 30-50 nT.

In 1879, Thalen published a report on the techniques he employed and on the results of a magnetic survey, entitling it “On the examination of iron times deposit by magnetic measurements”. This can be considered the first scientific paper on Geophysical Prospecting published, in the world. In the following year, magnetometers similar to his were used widely in the search for magnetic mineral ores.

In 1915, a German, Adolf Schmidt, built the balance that bears his name (Fig. 8). This balance consists, in very simple terms, of a magnetic needle lying, by means of a quartz prism, on two agate supports, the magnetic moment of the needle being balanced by the gravitational moment due to an eccentric barycentre. The tool allowed the relative measurment of the vertical component of the Earth’s magnetic field (Fig. 8A) with a precision of some nT, and measurement times of a few minutes. Not long after this, the needle that measured the horizontal component was also introduced (Fig. 8B). The tool, despite being delicate, remained for some decades the most widespread tool for magnetic prospecting because it was easy to handle, accurate and light in weight; it helped extend the use of magnetic surveying in the search for low magnetization hydrocarbons and minerals.

However it could not be used on a mobile support (car, aircraft, ship). In the 1930s a series of studies that led to the construction of the rotating spool magnetometer began, though scarcely accurate, and the formulation of a new magnetometer, the fluxgate magnetometer. In this

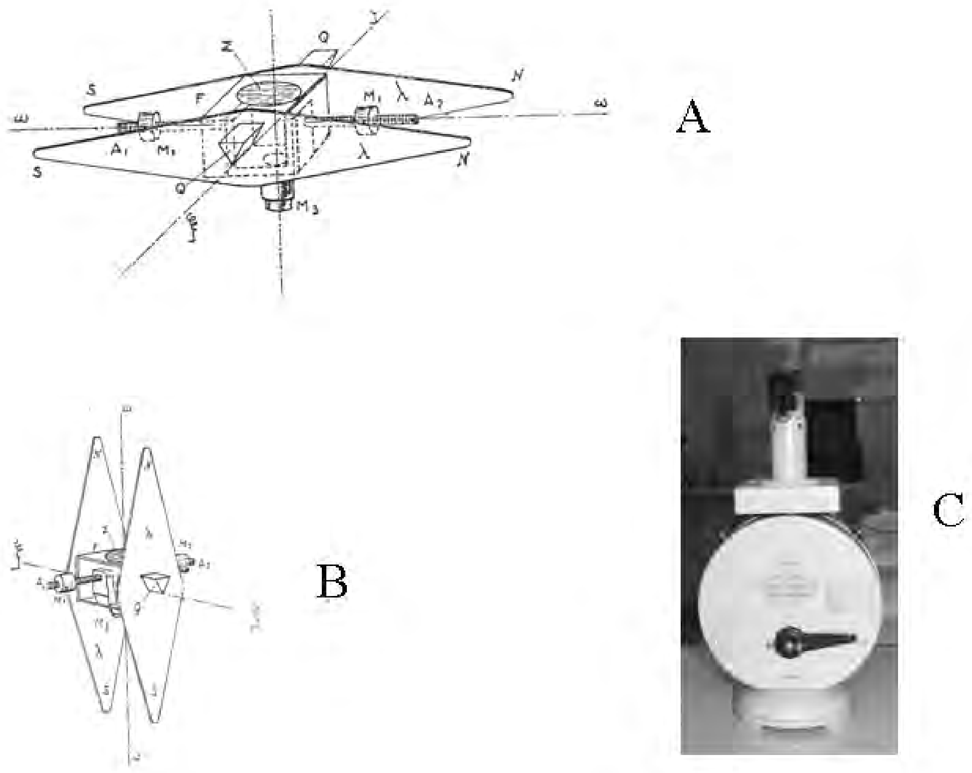

Fig. 8 - Schmidt balance: A) the needle for the measurement of the vertical component; B) the needle for the horizontal component measure; C) the external view of the tool (around 40 cm high) mounted on a tripod.

magnetometer the measurement is based on the effect of the Earth magnetic field on the current output of a secondary coil of a transformer magnetized beyond saturation by a sinusoidal primary field.

The advent of the Second World War accelerated studies in the United States of America because the fluxgate magnetometer was used in aircrafts to detect submarines. After the war this magnetometer was immediately put to use for geophysical prospecting (Vacquier, 1946; Wyckoff, 1948), thus opening the era of airborne magnetic prospecting; the initial precision of the tool, that measured the total magnetic field, was some nT.

Between 1955 and 1960, two new types of magnetometers for measuring the Earth’s total magnetic field progressively replaced the fluxgate magnetometer as the airborne magnetometer. One is the nuclear precession (or proton) magnetometer, realized when Packard and Varian (1954) observed the free precession of the magnetic moment of the hydrogen nucleus (proton) around the Earth’s magnetic field. At the beginning, it had a precision of some nT and then of 0.1 nT. The second magnetometer is based on measuring the Zeeman sublevel energy of some atoms (rubidium, caesium, helium) effected with techniques introduced by Dehmelt (1957); the principle of the phenomenon (optical pumping) was observed (1950) by the French Kastlers and Brossel of the Ecole Normal Supérieure. The tool, with a precision of about 0.01 nT, was developed almost contemporarily in France (Giret and Malnar, 1965) and in America (Herbert and Lamgan, 1965).

In the same period, there was the improvement of navigation systems that allowed good accuracy in positioning recovery: photographic systems and land doppler-radar systems, and land and sea radio and inertial systems.

The possibility of using the fluxgate magnetometer and nuclear magnetometers on airplanes, and with the use of digital recording systems, it took a short time before, the surveying of wide areas with high precision was made possible at low cost; such surveys have been made over whole nations, like Italy where, between 1975 and 1979, AGIP surveyed the whole national territory and the surrounding seas with profiles 5 and 10 kms apart for a total of 256,000 km.

The use of the nuclear magnetometers spread quickly, also for land surveys, supplanting new mechanical magnetometers that measured the magnetic field components [the torsion magnetometer of Haalck, (1956) and the "Pocket magnetometers" 1960, 1965]. The use of the land proton magnetometer especially spread rapidly, both for its low cost and for the possibility of recording, almost automatically, the data of stations and the measured values.

The good accuracy reached with the magnetometers also allowed their use as gradiometers, both on land [fluxgate: Aldred, (1964)] and in the airplane [optical pumping technique: Hood (1965); Slack *et al.*, (1967)].

Further progress has been due to the use of satellites, such as the Pogo used in the 1970s and the MAGSAT, launched in 1979, that furnished the magnetic field on a global scale at a height of 350 km.

The end of the 1920s saw the beginning of systematic studies on rock susceptibility in relation to the content of minerals (Slichkter, 1929; Stearn 1929), and in the same years Koenisberger highlighted the importance of remanent magnetization in rocks. Later studies (Néel, 1948 - 1955), led to the individualization of the different types of magnetization in minerals and rocks, with particular reference to the ferrimagnetic and antiferrimagnetic mineral groups, and to the recognition or confirmation of the mechanisms to which the permanent magnetization of rocks is due: thermal, (Thellier,1938; Koenisberger, 1938; Néel, 1949) depositional (Johnson *et al.*, 1948) and chemical (Koenisberger, 1938).

Rock magnetization with inverse polarity, compared to the actual magnetic field, was identified at the end of the 19thcentury and the hypothesis that this was due to an inversion of the magnetic field was proposed in the 1920s by Matuyama and Mercaton. The studies by Nagata *et al*. (1952) tested the possibility of an inversion of magnetic polarity during rock cooling, delaying the acceptance of the hypotheses of the Earth's magnetic field inversion in the past. The work of Cox *et al.* (1963) on samplings of reversed polarity rocks dated with potassium-argon methods not only proved the possibility of such inversions of the field, but also led to the reconstruction of a temporal scale of the inversions.

Wine and Matthews immediately applied the Cox *et al.* (1963) time scale of magnetic polarity in a survey on magnetic anomalies around the mid-Atlantic ridge, thus confirming the "sea-floor spreading", and obtaining a measurement of the rate of the ocean opening.

The evolution of magnetic data interpretation has, on the whole, developed in parallel with gravity data, the differences being due to the dipolar nature of magnetization. Haalck (1930) put into prominence the already known, Poisson relationship, as being the gravity and magnetic effects due to the same body; with this relationship magnetic potential could be calculated from

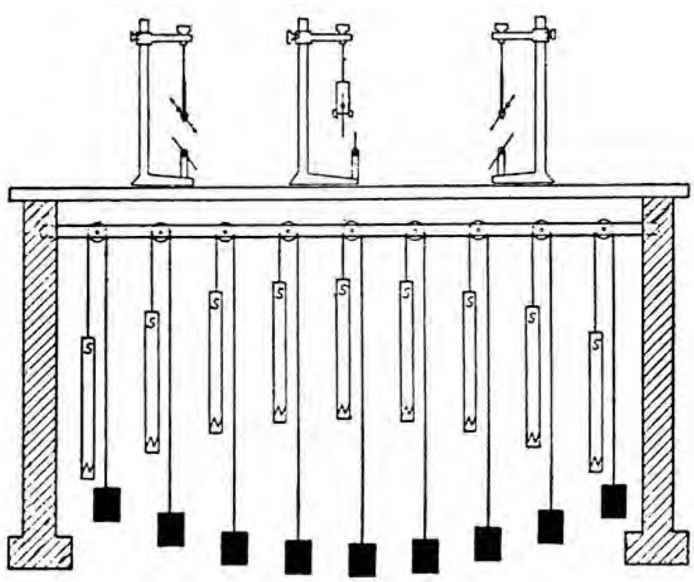

Fig. 9 – Schematic diagram of the apparatus for experimental interpretation of magnetic anomalies (Jenny, 1935).

the gravitational potential by means of derivation in the magnetization direction.

Based on this, theoretical anomalies were calculated for simple shaped bodies like spheres, ellipsoids, dikes, contact between two formations, etc..

This allowed the extension, from gravimetrics to magnetics and vice versa, of the properties and techniques that were to be defined, and that have already been illustrated in the previous paragraph: for instance, the upward and downward continuation were studied, as already said, by the Gulf Research and Development Company for magnetic data (Peter, 1949) and then extended to gravity.

Particular procedures were applied for the interpretation of the magnetic anomalies peculiar to the bipolar nature of the field. At the beginning there was the proposal of theoretical models (Nippold, 1930) in which the magnetic bodies were modelled with a couple of poles, and of reduced scale physical models (Hotchkiss, 1915; Keys, 1932, Jenny, 1935) in which the magnetic fields were measured experimentally (Fig. 9).

The introduction of the airborne magnetometers and the use of proton magnetometers on land led to an increase in the number of measurements which, in turn, brought the introduction of automatic and semiautomatic data processing and thus made the interpretation simpler and fast. The studies of Baranov (1957) must be remembered here; these led to the transformation of the values of the total field measured on a plain in the so-called ‘pseudo-gravimetric anomalies’ or ‘reduced to the pole’ values (anomalies that would be obtained if the bodies were at the pole with vertical magnetization). These techniques simplify the interpretation in that the maximum anomaly values lie above the anomalous body.

In the 1950s, a series of methods were introduced to determine the depth of the magnetic bedrock through the measurement of particular anomaly parameters (width, sharpness, etc.): since the first approach by Peter (1949), the method, still very popular, has undergone improvements introduced by Vacquier (1951), Bean (1966), Grant and Martin (1966), Naudiy

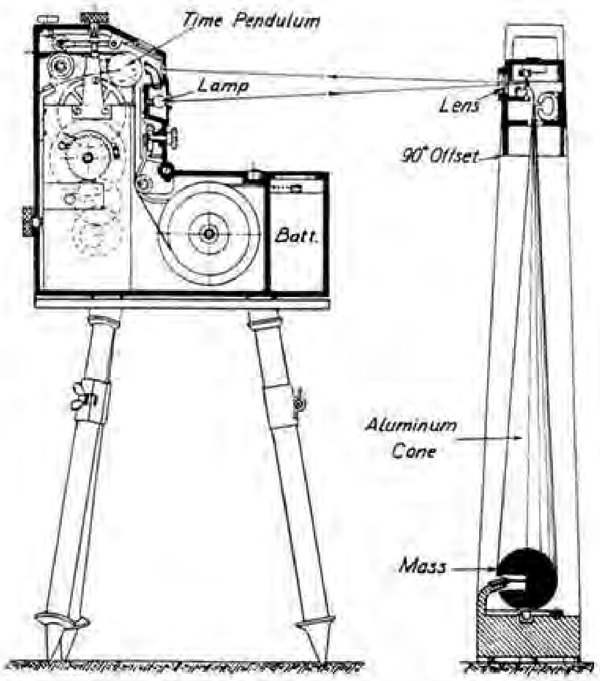

Fig. 10 - Mintrop's Seismograph. It was composed of two parts: on the right is the seismograph (s.s.) with the inertial mass at the bottom; it transmitted its differential movements through an aluminum cone to a small mirror. On the left is the camera that records a light beam produced by a lamp and reflected by the small seismograph mirror onto photographic paper. The tool was about 1 m high. (after Heiland, 1940).

(1971), Am (1972) etc..

At the beginning of the 1970s, automatic interpretation methods were introduced on both frequency domain (Dean, 1958; Bhattacharyya, 1966; Spector and Grant, 1970), and space domain, exploiting optimization methods for the adjustment of the theoretical anomalies to the experimental data (Bosum, 1968; Johnson, 1969).

4. Seismic methods

The basis of seismic prospecting can be found in the 19th century, in the studies that Stokes, Poisson, Rayleigh and Kelvin carried out on the theory of elastic waves propagation. The first field experiments of seismic wave velocity measurements were performed by Robert Mallet in 1851: his source was electrically-shot gunpowder and the seismoscope was a bowl of mercury, its surface reflecting a spot of light that was observed through a small telescope, the travel time was recorded by a hand operated chronograph. The velocities he found were 250 m/s for sand and 500 m/s for granite. In 1876, the U.S. American general H.L.Abbot (1878) used a dynamite explosion of about 20,000 kg as the source, and employed techniques like those above to measure travel times with source-receiver distances in the order of 8-20 km: a propagation velocity of up to 2400

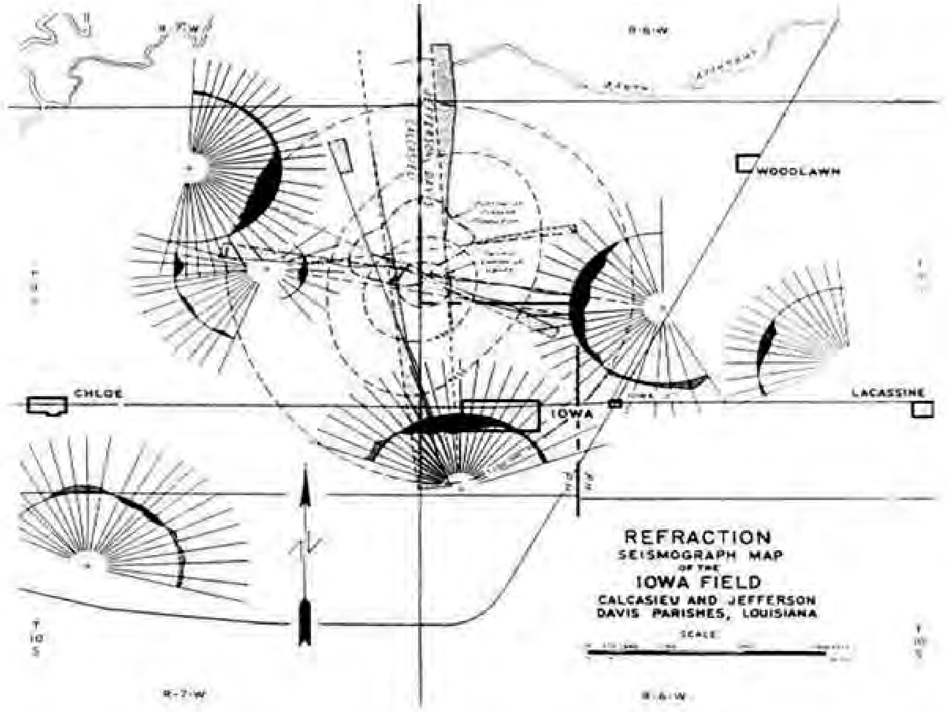

Fig. 11 - Fan shooting scheme performed on the Iowa field. In the directions of shot-geophone propagation the diagrams show the travel times "leads" (shorter times - in black) and delays (in grey) in comparison with the normal travel times in the formation without salt domes. Time leads point to the presence of a travel through a salt dome with higher wave speed. The intersection of the travels with time indicates the position of the dome (after Eby, 1943).

m/s was determined. Analogous experiments were carried out in 1886 by Milne and Gray and, in 1889, by Fougué and Lévy using photographic recording seismographs; in 1900, Hecker employed nine mechanical seismographs, these having become available after the construction of the first true seismographs like those of Milne and Wiechert. In 1901, Belar very clearly demonstrated the possibility of employing the seismic method to determine the elastic characteristics of rocks to resolve problems of engineering geology (excavation of a tunnel, etc.).

In the meantime, also theoretical studies progressed. In 1899, Knott wrote about wave propagation through discontinuity surfaces, but it was Wiechert and Zoeppritz who, in 1907, introduced the general formulation for the problems of wave propagation in subsoil, reflection and refraction. In 1910, Wiechert elucidated the principles of seismic refraction and, in the same year, Prince Galitzin indicated the possibility of deducing, from hodographs (time-distance diagrams), the characteristics of the geological structure of the Earth's upper formations.

During the First World War, there was an attempt, but without great success, to locate enemy guns by observing the air waves generated by the gun's shot and the refracted waves produced in the ground by gun recoil.

Ludger Mintrop, who had been a student of Wiechert, acquired experience before and during

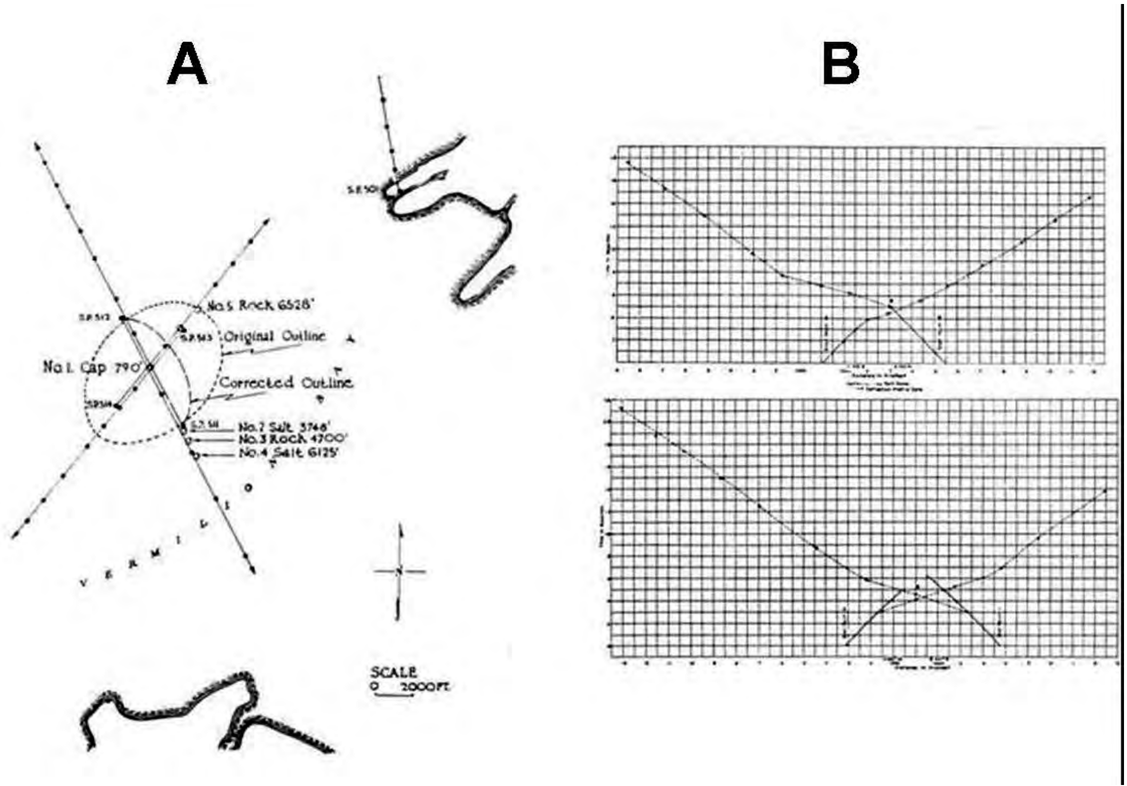

Fig. 12 - Seismic refraction profile details of the Vermilion Bay salt dome:
A - map showing the position of the two refraction profiles with partially conjugated shots;
B - time-distance diagrams of the profiles - note the diagram tracts with greater velocities related to the refraction travel at the top of the dome (after Rosaire and Lester, 1932).

the war and this led to his making an application, in 1919, for the first patent employing seismic refraction to explore the subsoil and, in 1921, to his founding the first seismic exploration company the Seismos GmbH.

After a first series of surveys in Germany, Holland, Austria and Sweden, Mintrop and his Company began operating in the United States in 1923 with the in-line refraction method; initially their results were not good but then, in 1924, they identified their first oil reservoir, “Orchard Dome”, in Texas. Seismos were using mechanical seismographs (Fig. 10), with recording on photographic film, surveying positions, and estimating shot times by air wave arrival.

This success was soon followed by others in 1925, showing the validity of the refraction method for oil investigations. Indeed, the introduction of the fan-shooting technique speeded up the method (Fig. 11). The good results that were achieved brought about the birth of an American prospecting company, the Geophysical Research Corporation, and led to various oil companies putting proper seismic crews into the field. Equipment improved, and variable reluctance and electromagnetic geophones, resistance-coupled amplifiers and galvanometers for photographic recording came into use; radio connections were employed for the shot time, and the air wave to

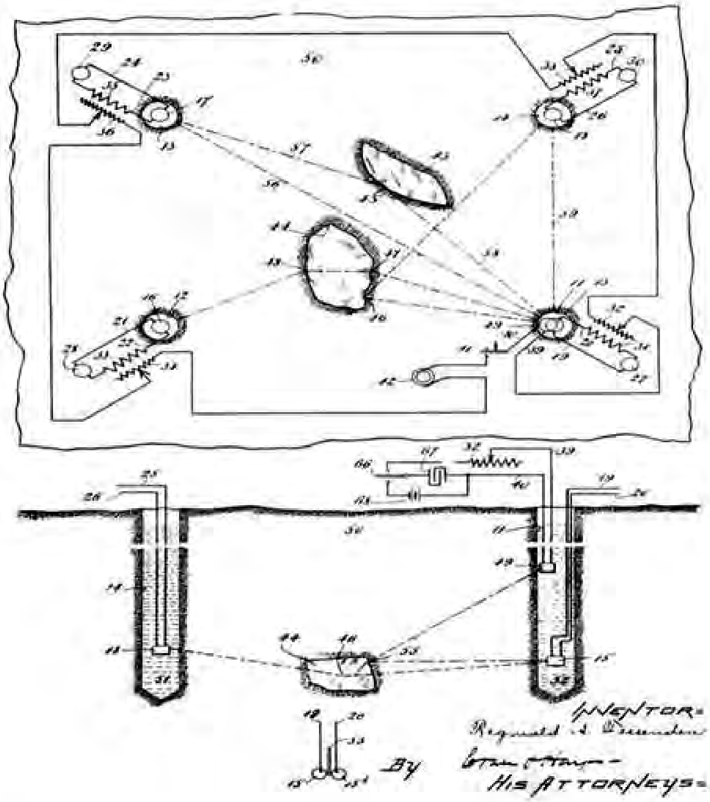

Fig. 13 – Equipment scheme of the Fessenden's patent. The equipments, foreseen to produce shot and receiver waves, were of the electromechanical type (eco-sound) and therefore inadequate for seismic reflection on land (after Allen, 1980).

determine the shot – geophone distances. Such techniques were used to explore wide areas of the Gulf coast, from Texas to Louisiana. Refraction profiles were also used to detail salt dome features (Fig. 12) and to detect high-velocity layers; furthermore the interpretation technique became more refined.

These same years saw the beginning of the first seismic reflection experiments: in 1914 R. Fessenden built and used the first echo-sounder, both in the air to locate icebergs and in the sea for bathymetric studies and to locate enemy submarines. In 1917, he took out a patent for the application of the method to be used in searching for minerals (Fig. 13). At the beginning of the 1920s, different geophysical groups made various attempts to apply the method, but without great results.

Further studies were made and decisive improvements were brought about by the Geophysical Research Corporation under the direction of J.C. Karcher: it was recognized that reflection required different equipment from that used in refraction. These equipments used reluctance geophones, vacuum tube amplifiers, a hand cranked 35 mm movie camera, oscillograph and a light-slit timing line system driven by a tuning fork; multichannel devices were introduced with which four to six complete recording channels could be used together instead of single complete recording units used in refraction surveys, band-pass filters from 40 to 90 Hz, controlled by the

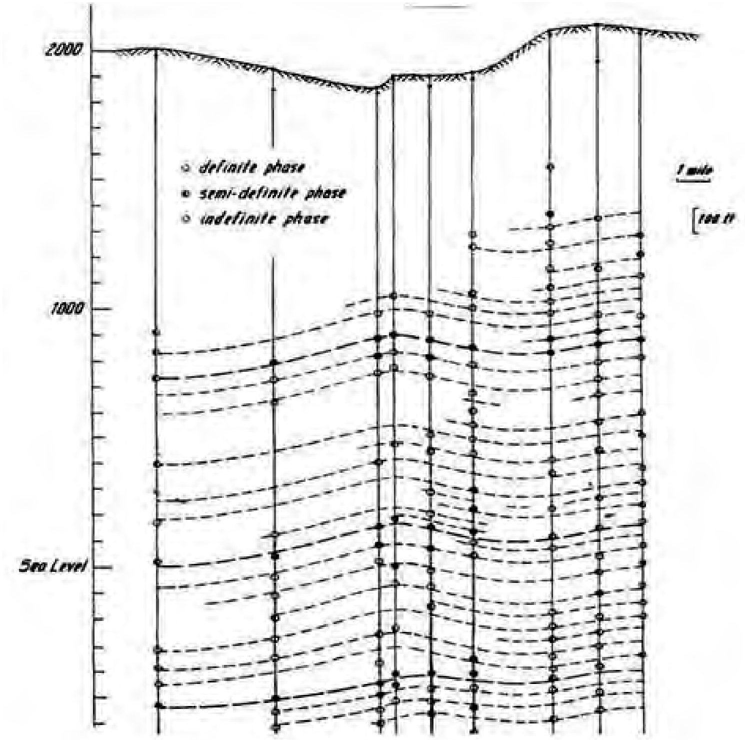

Fig. 14 - Seismic section with correlation technique. In the section the vertical lines indicate the positions of seismic spreads located at irregular distances, and the circles represent the reflecting horizons in depth with their characteristics. The reconstruction of the geological structure was performed correlating the horizons with analogous characteristics (after Heiland, 1940).

central frequencies of geophones and galvanometers, were introduced. In the field, the procedure was to place 4 – 6 detectors in line with the shot, the distance between the detectors being in the order of 60 meters with the nearest one about 300 meters from the shot. It was at this time that the importance of the weathering layer began to be understood. After a series of experiments carried out from 1926 to 1928, reflection prospecting led to the discovery, in 1930, of three productive structures in Oklahoma. Thus began the prodigious development and diffusion of the method that still exists today.

At the beginning, the method applied for interpretation was one of correlation (Fig. 14): in the seismic section, below the position of the geophone lay-out the arrival times of the reflected waves (or the relative depths) were reproduced and the various arrivals were correlated on the basis of the reflection character. Immediately after 1929, the measurement of the dip of reflecting horizons from the difference in seismic wave arrival times to the outermost geophones began (dip shooting: Fig.15). Therefore correlations were made also on this basis.

In the 1930s, the equipment underwent a series of innovations. The number of channels climbed to 12, and in some experiments to 40, multiple geophones per trace began to be used (1933) and electromagnetic geophones were built with electric damping. Amplifiers became more stable and were improved, having self-contained filters with switch selection for the cut-off, and amplitude was regulated with time-programmed amplification (1932) and later by automatic controlled gain (1938). Seismic field parties began to assume an organization that would remain much the same over the years, namely a recording truck (Fig. 16), one or more drilling crews, a

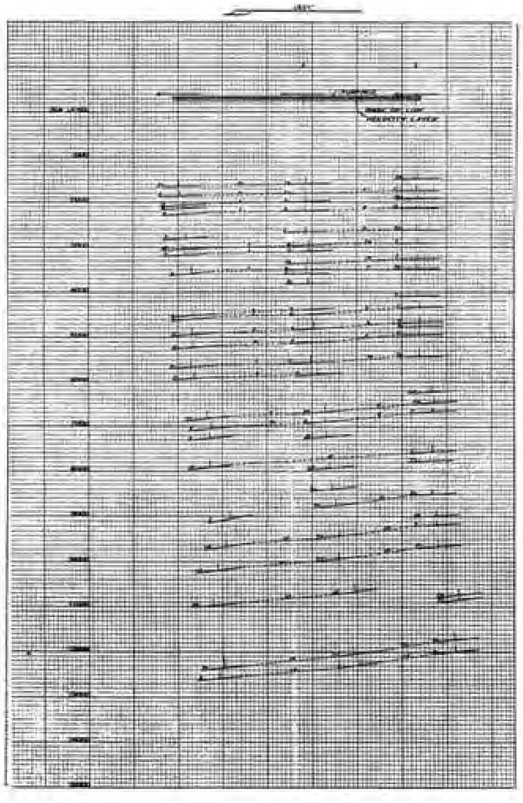

Fig. 15 - Seismic section with dip shooting technique. In this section, the indications of the layer slopes are reported. Therefore the correlations are performed considering also such a new characteristic (after Jakosky, 1940).

shooting unit, a surveyor team, a permit man , etc..

To assist the reader's immediate perception of the progress achieved in seismic reflection over the first 15 years, examples of recordings made in 1926, 1930, 1934 and 1940 are shown in Fig. 17. These highlight the evolution of reflection techniques.

In the 1940s, through to the beginning of the 1950s, the equipment, mainly of 24 channels, did not change substantially, but it did continue to improve with improvements in the electronics field, becoming more sophisticated and more sensitive with a low noise level. Electrical mixing of adjacent traces (mixing) was experimented.

In 1937, the Western Geophysical Co. (Salvatori, 1937) introduced a continuous profile (single coverage), that allowed a surer correlation than the single shot techniques with isolated detector spreads employed until then. At the end of the 1930s, the interpretation took into account continuous velocity variation with depth, hence curved rays. The calculation of nomograms and graphics allowed, for a given law of velocity with depth, the determination of the position of the reflecting surface with respect to its dip and to the shot point position. These determinations were based on times read directly from the seismogram in correspondence with the reflections. For each recognizable reflection the read times were the time related to the geophone nearest the shot and the delay time between the most distant geophones. Through the support of particular, simple devices the reflection was drawn on a seismic section with appropriate length segments positioned with respect to the shot point (Fig. 18). In this way, an in-depth seismic migrated

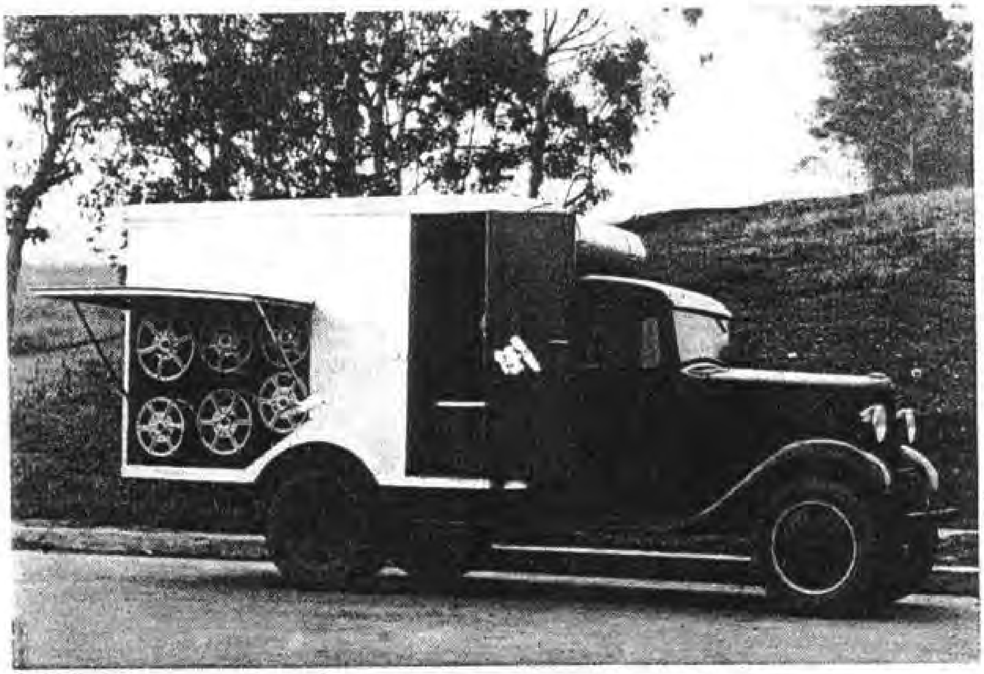

Fig. 16 - Recording truck of the 1930s for 10-channel equipment (after Rieber, 1936b).

section was reconstructed geometrically (Fig. 19).

The velocity law was chosen on the basis of velocity measurements performed with geophones located in drilled wells or from the reflection recordings (Green, 1938). In this period it was already common usage to make corrections for weathering and elevation.

At the end of the 1940s, a typical reflection group consisted of one or more field crews each with 7-8 vehicles and, between technicians and workers, around 20-40 people. There was also a processing team equipped to detect reflected events on seismograms, to read arrival times, to calculate the location of the events themselves, and so on up to the compilation of the sections and the final maps.

In the 1930s and 40s in the USA, the refraction seismic technique was still employed as a subsidiary to the reflection seismic technique. Seismic refraction interpretation was improved with the hypothesis of plane parallel or dipping layers, velocity varying with depth (from the 1920-30s) and with curved layer techniques: included among these is the technique of delay times introduced by Gardner in 1939. Instead, in Europe, under the influence of Mintrop, the refraction method continued to be used as the main seismic prospecting method. Indeed, until the end of the 1930s, the seismic reflection method was almost totally ignored, but then some American seismic equipment began to come into use. One of these pieces of equipment was imported into Italy by AGIP at the beginning of the Second World War, and was used in Val Padana where some promising structures were located. At the end of the war, one of these structures was drilled and

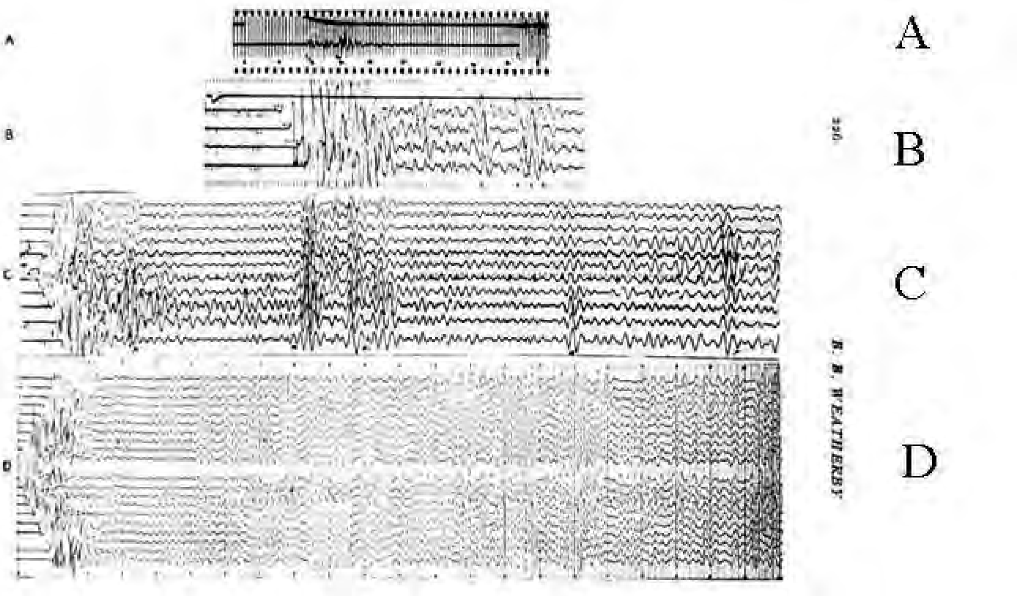

Fig. 17 - Seismic reflection records for the years from 1926 to 1940 (after Weatherby, 1940):
A - record of a first experiment surveyed on the Nash dome in 1921 with a single geophone. The upper trace is the time break;
B - 1930 record from the Seminal Plateau. 4-channel equipment;
C- 1934, 10-channel registration with automatic gain control;
D - record performed in Texas in 1940 with a 20-channel equipment.

the positive results convinced the AGIP manager Mattei to avoid the dismantling of AGIP, thus beginning the development of the said company.

In the USA, a seismic transmission technique, with surface shots and receivers in wells, was used for detailing salt dome boundaries (McCollum and LaRue, 1931; Gardner, 1949). Already from the very beginning seismic methods found applications also in marshy zones and very shallow waters (Rosaire and Lester, 1932). Subsequently, in the 1940s, such applications were performed also in deeper waters (100-200 m), the geophones being dragged along the sea bottom or suspended by a cable strung between boats. Thus multiple reflection and the explosive bubble phenomena were studied.

Up until the beginning of the 1950s, all the recordings were performed on paper or photographic film thus no processing of the recorded data could be done. An advancement on this had been proposed by Rieber (1936) who had set up a system for recording seismic traces on film as a sound track, very similar to what was being used in talking pictures. The film, similar to a present-day variable density record, could be reread, and allowed filtering in the direction of wave travel and frequency.

In 1953, the introduction of the new type of recording on magnetic tape started to revolutionize seismic reflection methods. Such recordings had the great advantage of being easily reproducible, therefore allowing the processing of the recordings in later phases. The first improvement was wide band pass recording in the field, and then the filtering of the record with appropriate filters. Immediately after, cross-correlation techniques and preset delay filters were

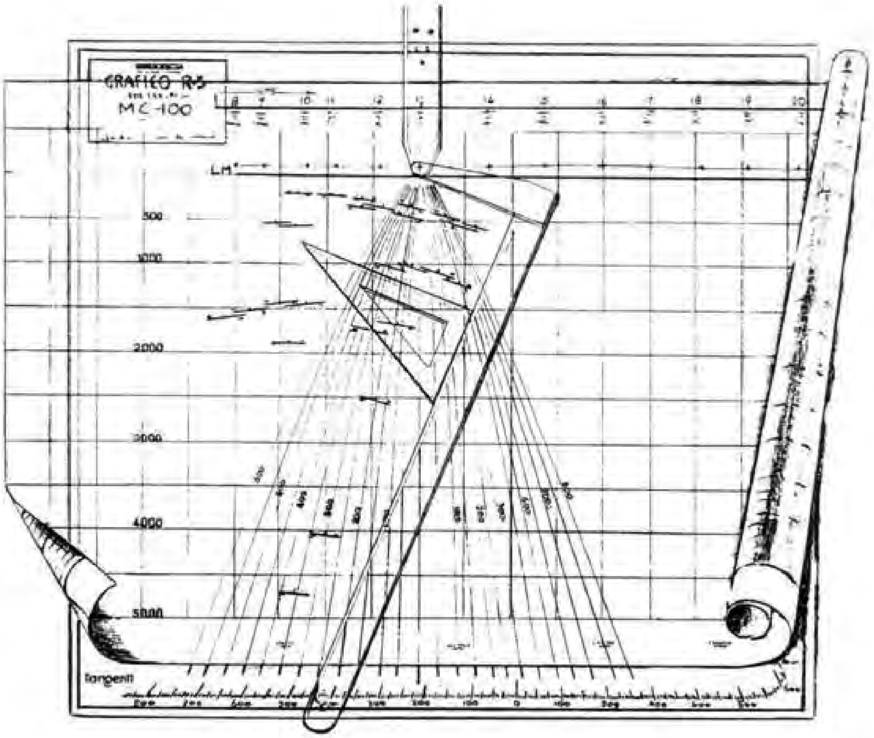

Fig. 18 - Device for seismic section construction: 1940s to 1950s (after Ranucci and Monti, 1963).

applied to the traces, through mechanical systems, to perform the weathering and elevation corrections (static corrections), constant for each trace, and to correct each trace for the hyperbolic geometry of the reflected event (dynamic corrections - NMO), even time varying (Fig. 19). Another advantage for the use of magnetic recorders was the possibility of stacking more seismic records: in the field this permitted the use of a repetitive source with low energy (weight drop) or low-power continuous wave energy source (vibrators) instead of the explosive. Vibrators (Fig. 20) were quoted for the first time by Dunlap and Jonson (1958). The possibility of stacking traces led to the introduction of the multiple coverage technique, of fundamental importance to improve the signal to noise ratio (Maine, 1956, 1962). Reproducible, processed traces also revolutionized data representation: film sections, in which the seismic sections were represented by the same traces brought below the recording point, were introduced. The seismic section, became an objective, reproducible document beginning from field recordings rather than the result of personal interpretation. At the same, time representation techniques were improved with the introduction of variable density and variable area sections. As a result of variable density sections on transparent paper, sophisticated optical techniques, such as the laser diffractometry, were introduced (Fig. 21); this allowed the application of mono and two-dimensional filters (Jackson, 1965; Dobrin *et al.*, 1965), correlations, etc.. Then, to study seismic phenomena (1960), synthetic seismograms were introduced.

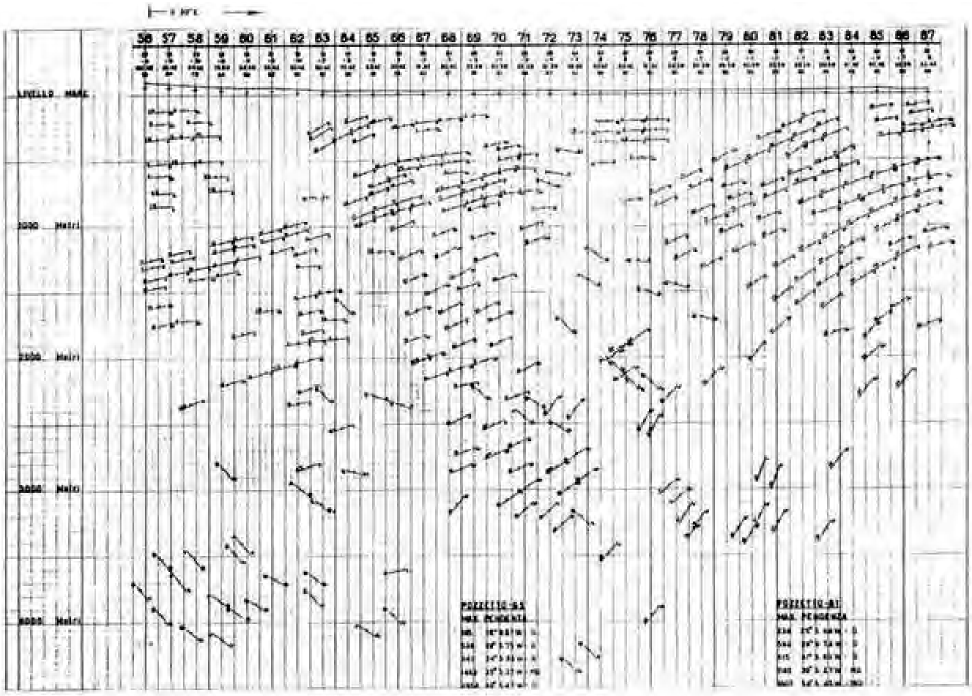

Fig. 19 - Seismic section drawn with the methods of Fig. 17. The reflecting surfaces are shown in their actual position and slope in depth through segments of length, in scale, equal to half the geophone spread (after Ranucci and Monti, 1963).

The second great revolution in data acquisition and processing began with the introduction of digital techniques. In 1952, some oil and geophysical companies agreed to support a research program of the Massachusetts Institute of Technology (MIT) on the application of digital techniques to seismic reflection data processing. This led to the formation of the MIT Geophysical Analysis Group (GAG) with the participation of others like F.A. Robinson, S.M. Simpson and S. Treitel. From 1953 to 1957 the group compiled a series of 11 reports where the applicability of the statistic analysis of time series and the digital processing techniques to the seismic data was shown, with particular reference to filtering, to improvement in the signal to noise ratio, to waveform recovery (predictive deconvolution), etc.. A synthesis of the main GAG results, together with an index of the reports and vast bibliography can be found in Geophysics, 32, 1967, pages 415 to 525.

The first applications were made in 1961 and in 1963 the first digital equipment came on market. Within 4-5 years all the seismic teams, also those with magnetic tape recordings, adopted digital equipment. This also completely transformed the composition of the in-field seismic crews, that became only a peripheral acquisition tool, while processing centers equipped with big computers were created. The digital techniques not only facilitated the application, and with mathematical rigor, of the already used analogical techniques, it also opened up new horizons in seismic processing. Progress was immediate, being regulated by the development of theoretical studies, by equipment improvement and by the potentiality of the computers. Predictive

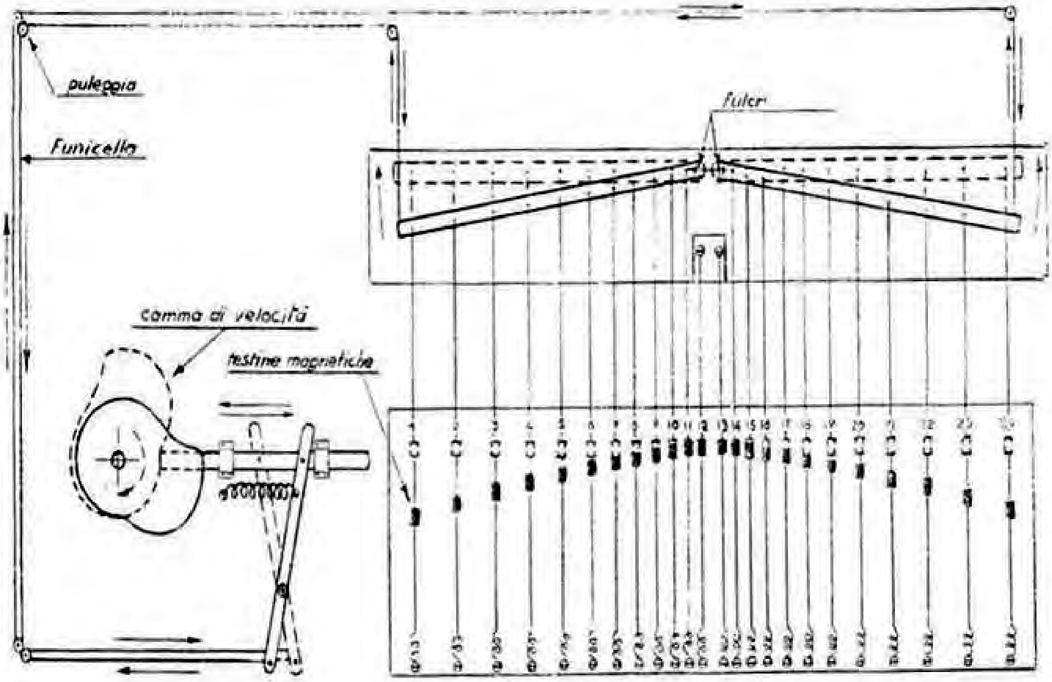

Fig. 20 - Equipment for dynamic corrections. The system was based on the mechanical movement of the magnetic heads during the running of the magnetic tape. The movement of the heads was regulated by a cam whose profile was drawn on the basis of the law of variation of speed with depth for the investigated zone (after Ranucci and Monti, 1963).

deconvolution techniques were applied immediately, and multiple coverage and velocity analysis techniques became routine. The seismic section, obtained with the usual procedures of representation of that time, set the recorded events under the recording position even if they came from dip or lateral structures. The complexity of the seismic section in non horizontal formations had already been put in evidence by Rieber in 1936, and was put into a more complete form by Hagedoorn (1954) to whom we owe the definition of the term ‘migration’. Graphic procedures for tilted structure reconstruction had already been introduced as early as the 1930s, but for the 1970 sections they were far too rough and totally inapplicable. In 1970s, digital migration techniques were introduced for the reconstruction of the seismic sections of complex geological structures, and this also eliminated noise like diffractions that ‘collapsed’ in their actual positions. Claerbout (1971, 1972) developed a finite difference algorithm for migration based on the scalar wave equation: by computing two wave fields, one from the source and one from the measurement point; the reflectors were defined as their intersection. Loewenthal (1976) introduced the ‘exploding reflector model’ concept in which only one-way travel time was considered: the measured data were treated as the boundary condition, the geological model as an initial condition and the wave equation as the connecting link. From here numerous other improvements were born: migration in the frequency dominion for constant velocity (Bolondi *et al.*, 1978; Stolt, 1978) and the employment of the Kirchoff integral (Schneider, 1978). Then the

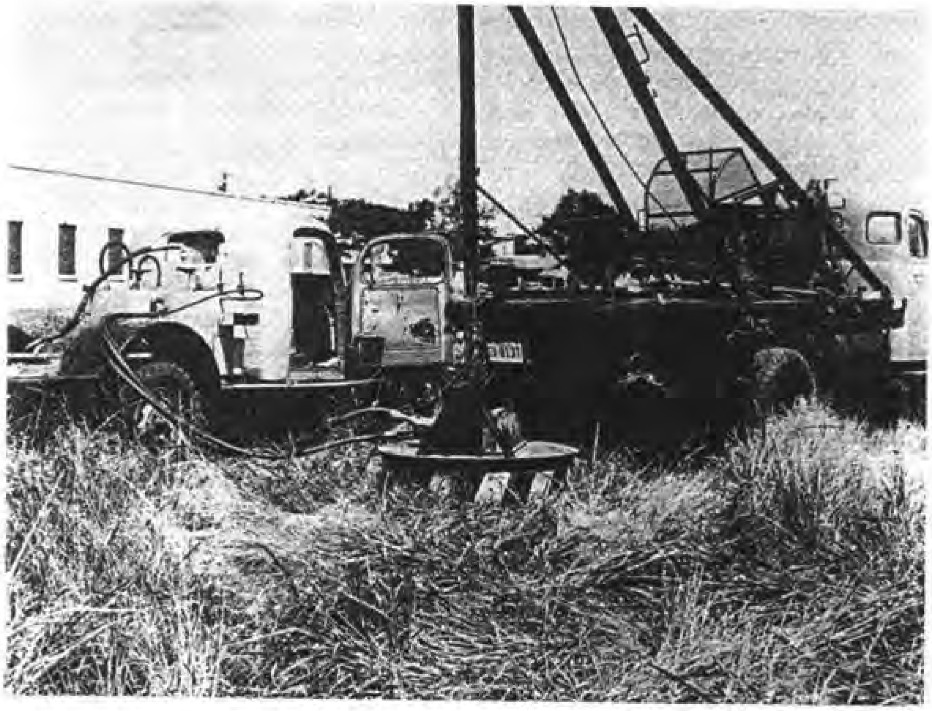

Fig. 21 - First example of vibrator with pump truck and transport truck (after Dunlap and Johnson, 1958).

Dip Moveout process was introduced to transform the prestack data set so that each common mid-point gather of traces contained an event from the same depth point of tilted structures (Deregowski and Rocca, 1981).

Meanwhile progress in electronics and computers led to an increase in the number of channels in field recording equipment: the 24 channels usually used until 1968 with a 1200% multiple coverage, rose, in a few years, to 96-240 channels with a peak of even 1000 channels (1975) and coverage up to 5000% (Fig. 22). Such an increase was due to the progress made in the equipment, some of which was remote-controlled by radio or cable. The first introduced was the binary gain with overall dynamics of 160-180 dB and then, in 1970, a gain with "instantaneous floating point". The number of channels favored the acceptance of three-dimensional techniques (3D) which started around 1973, and that gained greater importance and diffusion with the three-dimensional reconstruction of oil structures (in the 1980s). Processing techniques, in first place migration, and the techniques of representation were adapted for 3D surveys and brought about the use of the most powerful computers in existence.

The high level reached by the recording systems led, at the beginning of the 1970s, to processing techniques that preserved the amplitude ratio of the various waves. The "true amplitude sections" gave prominence to the so-called "bright spot" that helped to identify gas reservoirs. The true amplitude processing allowed also the introduction of trace inversion and a series of techniques to underline the characteristics of the single reflected event, important for the stratigraphic interpretation of seismic section. To be remembered among these is the "complex

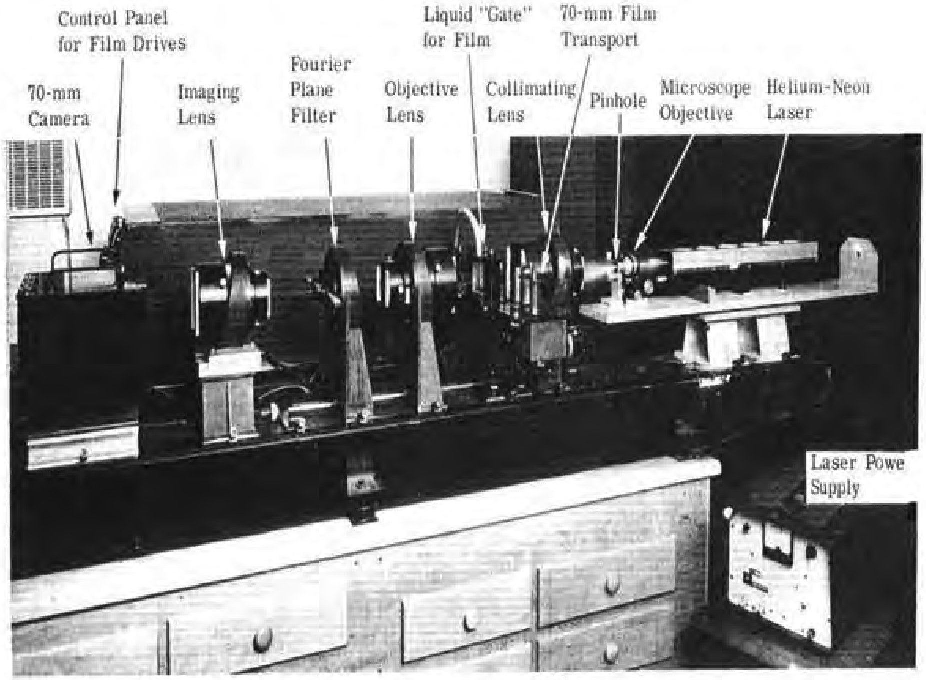

Fig. 22 - Optical equipment for F-K two-dimensional filtering of seismic sections. A monochromatic light beam (laser) is sent onto the seismic variable density section, working as a diffractometer to obtain two-dimensional spectra (F.K.); with appropriate masks it cancels the part of the spectra to be eliminated, and with an imaging lens the filtered section is obtained (after Jackson, 1965).

seismic wave analysis” technique with the introduction of the use of attributes (Taner *et al.*, 1979). At the beginning of the 1980s the great development of seismic modeling began, that was important for both an understanding of the propagation phenomena and data interpretation (inversion).

The 1960s were also characterized by innovations and improvements in the techniques of data acquisition: the explosive, used less and less, was replaced on land with vibrators and in the sea by numerous repetitive sources of various nature (mixture of explosive gases, air gun, vapor shock, sparker, etc.). The applications of marine seismic reflection also multiplied thanks to the introduction of hydrophones mounted on floating cables: so suitably equipped boats, and then ships, that clearly improved the data output began to be constructed.

In the same years, another innovation “on land” was the use of S waves both as conversion waves (Ricker and Lynn, 1950) and as SH waves (White *et al.*, 1956). Different types of sources for SH were tested in the 1960s and ‘70s: in Russia sources with particular patterns of explosive charges were experimented (Puzirev *et al.*, 1966), in France (Layotte, 1988) the Institut Français du Petrol employed great masses that gave hits along the horizontal at opposite ends of a plate coupled to the ground surface (Fig. 23), and in the USA horizontal vibrators were built (Cherry and Waters, 1966).

In Russia, the method of the vertical seismic profile (VSP) was set up initially by Gal’perin (1957, 1961); it found wide applications especially after the 1970s. The method uses geophones

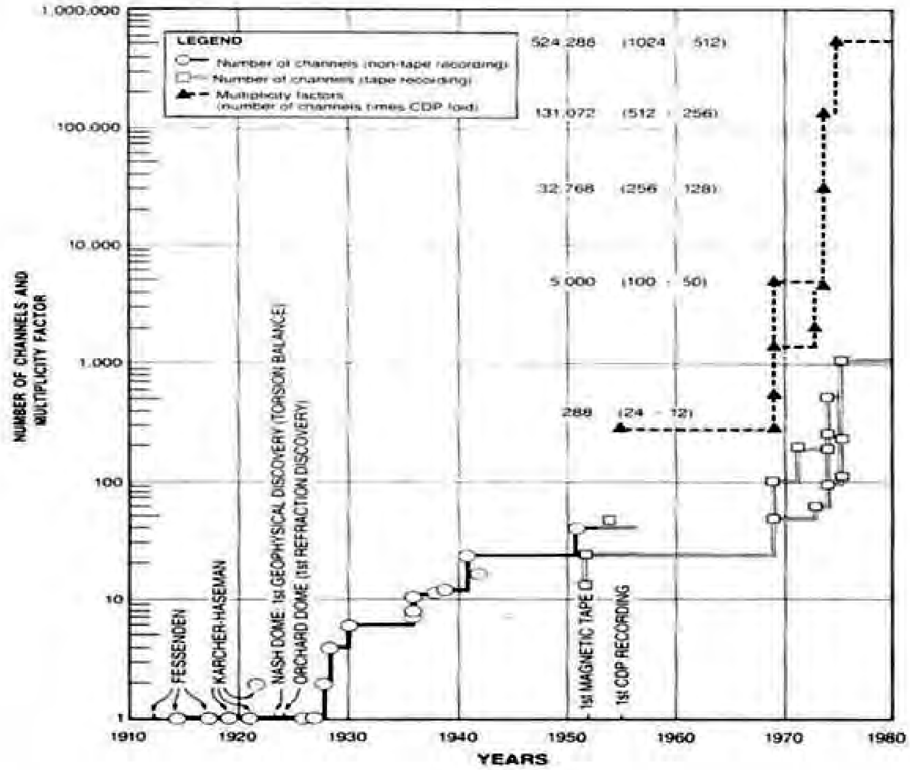

Fig. 23 - Channel number and coverage used in reflection seismics from 1920 to 1980. Note the strong increase in both values after the initial development of digital equipment (after Allen, 1980).

in a hole and sources on the Earth's surface and takes into consideration both the direct and the reflected waves, thus it has made a substantial contribution to the understanding of the propagation phenomena.

In the same years, the first proposal of tomographic inversion techniques applied to cross-hole seismic surveys was presented (Bois *et al.*, 1971).

The study of factors regulating the propagation of elastic waves in rocks is relatively recent. Gassman (1951) made theoretical studies of the wave propagation in a packing of sphere both saturated and dry; Wyllie *et al.* (1956) determined the effect of porosity and pressure on velocity experimentally, and set out the relationship that still today goes under the name of Wyllie's law. In the 1960s, the effects of rock fractures on velocity were studied theoretically and experimentally: particularly interesting are the works of Walsh (1965-1968) and Kuster and Toksoz (1974) who also examined attenuation, a phenomenon that had come under particular study by the beginning of the 1980s. It should be noted that, for many years, the only on-site attenuation measurements were those carried out by Mc Donald *et al.* (1958) in Pierre Shale, Colorado.

Another field, where the refraction method is still applied, is related to civil engineering and applied geological problems. Moore (1952) reported the pioneer applications in this sector, and

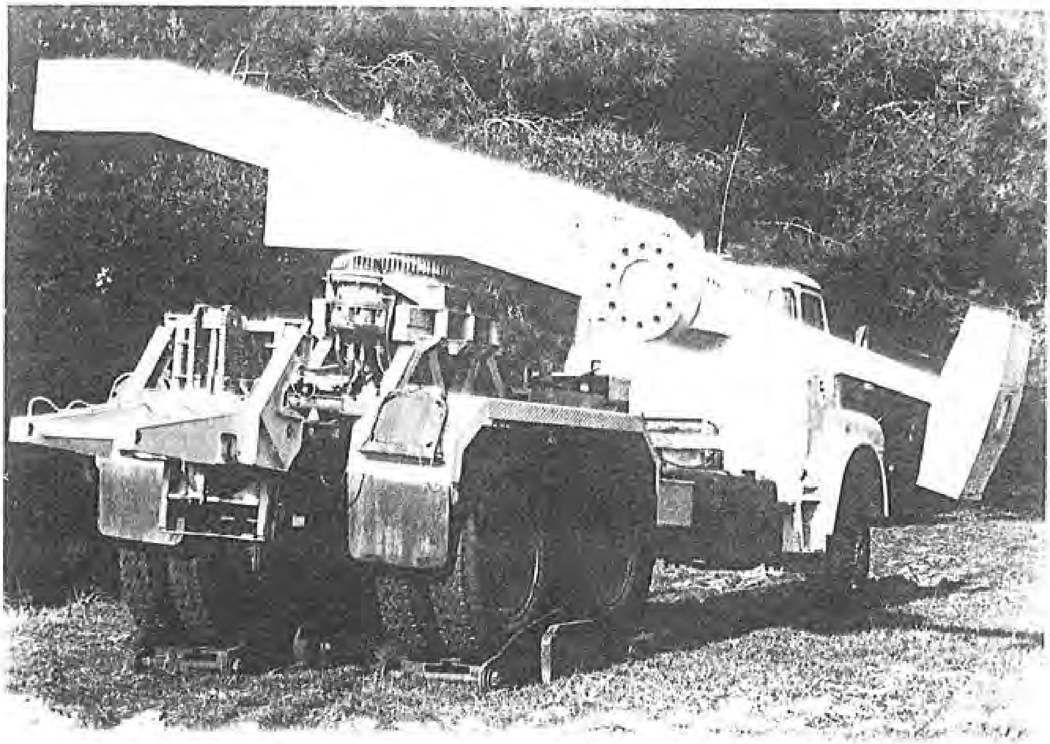

Fig. 24 - Marthor, a dropping weight SH wave source developed by the Institut Français du Pétrole (after Layotte, 1987).

referred to seismic refraction survey operations used in road construction since 1934 by the Bureau of Public Road-USA: the equipment consists of 3 simple microphonic carbon-button type detectors connected without electronic amplification to galvanometers, and in a conventional 35 mm film recording camera. At the beginning of the 1950s, small and portable instruments with 6-12 channels that facilitated field operations appeared on the market. It was not long before the recording was done on Polaroid film, and later, in the 1970s, on electro-sensitive paper that avoided having to develop the recorded film in the country. In the 1950s, there was a spreading of a series of single channel devices for the measurement of first arrival times (Fig. 24) through cathode-ray tubes and/or automatically from indicator lights (Stam, 1962).

The increasing applications of seismic refraction to determine weathering corrections and to resolve problems of engineering geology also led to progress in the interpretation after the flat layer interpretation methods developed in the 1930s and 40s. In the 1950s and at the beginning of the 1960s, various interpretation methods were proposed, the greater part of them being adapted to deal with problems of shallow depth. To be remembered are the plus-minus method of Hagedoorn (1959), the method of Hawkins (1961), those derived by the delay time method of Gardner (Barthelmes, 1946; Wyrobek, 1956; Bernabini, 1965; Layat; 1967) and finally the generalized reciprocal method of Palmer (1980). Starting from the end of the 1950s, the refraction seismic method began to be widely applied to the study of landslides, road routes, dams, foundations, etc. (Cassinis, 1959). It was also applied, for instance, at depths in the order of a meter, like in the determination of fractured zones around tunnels. The in hole methods were also applied starting from the early 1960s, and always for problems of rock characterization: cross-hole, down-hole, up-hole, sonic-log (Swain, 1962; Bernabini and Borelli, 1974).

In the investigations of shallow depth on land, attempts were made, starting in the early 1980s, to apply the reflection method. At sea instead, beginning from the late 1950s, first analogic single-channel seismic reflection systems were set up (Officier, 1959), with electrical (sparker), electro-mechanical (boomer and uniboom) and piezoelectric (subbottom) sources. The continuous seismic reflection profiles performed with such single channel systems found wide applications.

Around 1950, applications of refraction and wide-angle reflection seismic methods to crustal studies, started in the USA, Japan and Russia, utilizing big shots and recordings with various single seismographs, synchronized and set along profiles hundreds of kilometers in length. The methodology, named DSS (deep seismic sounding), was later widely applied also in Italy with good results particularly in the 1970s. After several experiments, especially in Germany in the 1960s, in the United States the near-vertical seismic reflection method was applied in 1975 to crustal searches and the results were positive. Thus in the 1980s, its use was extended to England, France, Germany, Switzerland and, after 1986, also to Italy with national and international projects.

5. Electrical and electromagnetic methods

The first attempts at using electrical methods date back to R. Fox who, in 1830, observed that natural electrical currents in copper mines were associated with copper ore. In 1882, C. Barus confirmed the possibility of detecting ore bodies by measuring electric potential in the ground, and for such measurement introduced the use of non polarizable electrodes. The industrial use of self-potential method began with C. Schlumberger in 1913 in Boz (Serbia) and the discovery of non magnetic ore bodies in Sain-Bel, France (Schlumberger, 1920).

As early as 1883, Brown investigated the possibility of identifying conductive ore bodies by flowing electrical current through the ground by means of electrodes; Fisher (1893) and Williams and Daft (1897) followed in his footsteps. However, in 1912, in this field too, C. Schlumberger first set up the method, for both scientific and industrial use, of equipotential lines, which was further developed during and after the First World War.

The method of using two current electrodes and two for potential to measure ground resistivity was introduced by Wenner (1912, 1917) and C. Schlumberger (1920) almost simultaneously: the most used electrode arrangement bear the names of these two pioneers of electric methods still today. The concept of apparent resistivity was introduced in 1922 and since then resistive methods have developed greatly. Already in 1923, the Schlumberger brothers (Conrad and Marcel) performed the first large scale survey that led to the detection of Aricesti's dome in Rumania. In the instrumentation used in the 1920s and 30s, the current used was both direct, with measurement of potential performed with potentiometers (Fig. 25), and alternating, with direct resistance measurement by inductive compensation devices. Also periodically reversed direct currents (Gish and Rooney, 1925) were employed (Fig. 26).

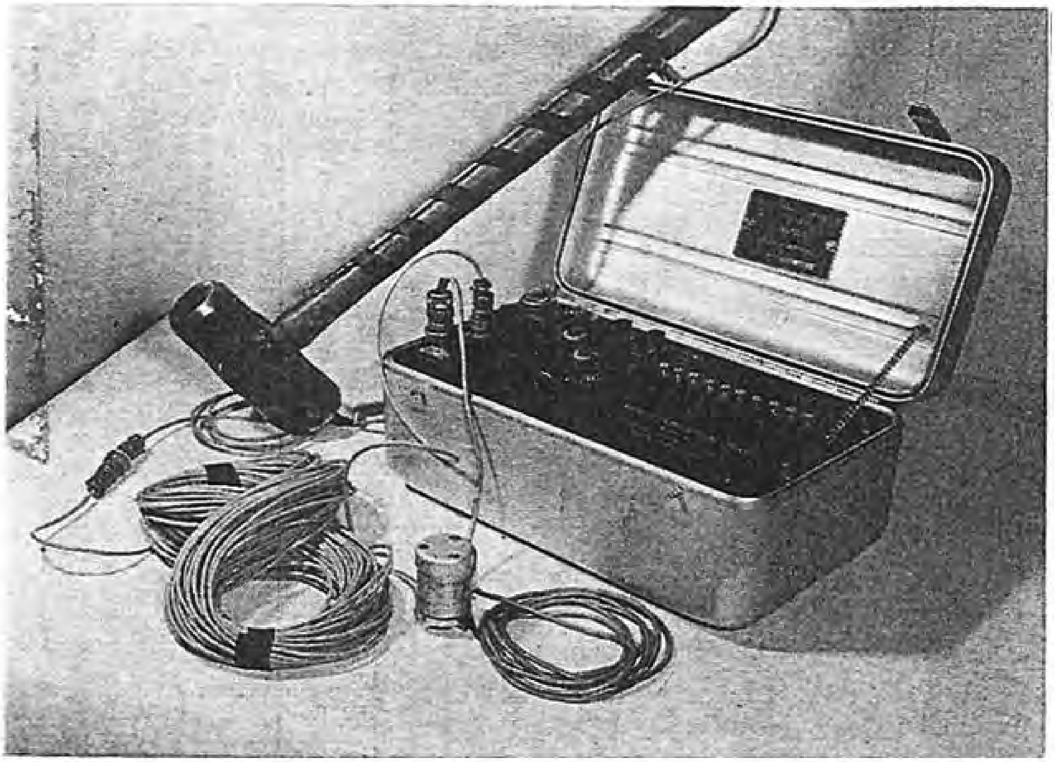

Fig. 25 - Model MD-1 single channel seismic equipment with geophone, hammer and connecting cable. Its use in the field provided fixed geophone position and hammer blows at increasing distances. The hammer hit activated the circuit of time measurement that stopped with first signal arrival from the geophone. Time was measured through a binary counting system and was read directly by indicator lights (after Stam, 1962).

In the 1920s, vertical electric sounding (VES) and resistivity profile methods were delineated, and studies for the calculation of theoretical anomalies began. After a first period in which the interpretations were made empirically (it was accepted that the depth of investigation was the same as the electrode distance), Hummel (1929) and Tagg (1930) drew theoretical curves for two and three horizontal layers and for the vertical contact with the electric images method. In the same years (1926), C. Schlumberger founded the Société de Prospection Electrique, which went on to produce some of the greatest geophysical companies, and gathered around himself a group of capable researchers: his brother Marcel, H.G.Doll, E.G. Leonardon, S. Stefanescu, R. Maillet, E.P. Poldini, etc..

In 1930, starting from the Laplace equation, Stefanescu and the two Schlumberger brothers drew up the general expression for potential due to a point source in horizontally stratified ground. Between 1932 and 1940, a series of fundamental studies appeared for the interpretation of SEVs: Maillet and Doll (1933) treated the problem of the anisotropic layer, Slichter (1933) and Langer (1933), and later Pekeris (1940), faced the problem of direct VES interpretation (from apparent resistivity directly to layer resistivity and thickness) and demonstrated the theoretical uniqueness of the solution; Roman (1931) introduced the use of bi-logarithm diagrams and direct comparison between theoretical and experimental curves. In 1947, Maillet discussed the general

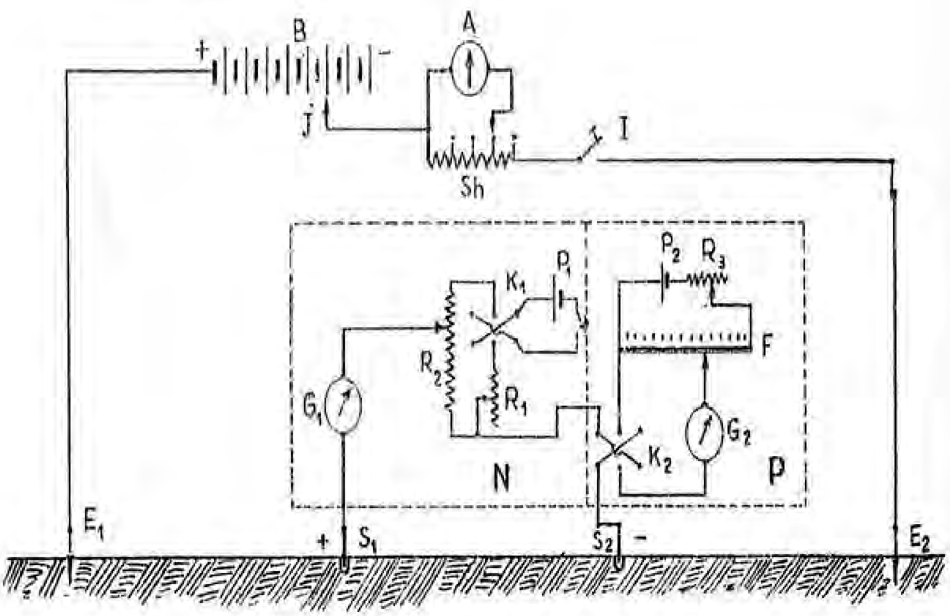

Fig. 26 - Potentiometer equipment for apparent resistivity measurements. At the top, the source circuit with the battery B and the ammeter A, provided with shunts for the change in scale. In the middle, the apparatus to measure potential formed by circuit N to preliminary zero setting of self-potential obtained by variable resistance R2, on the left the measurement circuit, activated after zeroing the self-potential, in which the potential produced by the input current is balanced by a counter potential produced by the battery P2 through the rheostat F (after Fulcheris, 1949).

equations for stratified layers and defined the conditions of practical equivalence among curves. Meanwhile the expressions for potential were drawn up for particular bodies: the sphere (Lipskaya, 1949), vertical layers (Hedström, 1932), and the dipping layer (Aldredge, 1937; Skalskaya, 1948).

The difficulty in calculating theoretical VES curves for more than two layers, led to the introduction of approximate methods that built multi-layer curves as an envelope of two-layer curves: at the beginning the curve for the first two layers was considered, then for each of the following layers a two-layer model was taken, the second layer being characterized by the resistivity of the considered layer and the first by thickness and resistivity drawn from charts or by formulae on the basis of the resistivity and thickness of the overlying layers (Lasfargues, 1956; Kunetz, 1966).

The advent of electronic calculators led to substantial changes in processing and interpretation techniques: in 1955 the Compagnie Génerale de Géophysique published the 480 VES resistivity charts for two and three layers already calculated for the Schlumberger arrangement in 1933-36 and immediately afterwards, the charts for the Wenner arrangement by Mooney and Wetzel (1956) appeared.

The1960s and 70s saw the development of direct interpretation studies, most of which used the integral function of Slichter (Koefoed, 1965). In 1971, Ghosh showed that the Stefanescu and Slichter integral could be resolved by a linear filter theory: this led to extreme simplification in the calculations and immediately to a generalized use of automatic interpretations with optimization methods that had already been introduced into this field (Vozoff, 1958; Meinardus, 1970).

Meanwhile numerical methods to calculate the potential for differently shaped bodies was developing continuously: Alfano (1959) used the integral equation method to model bodies with particular charge distributions on the discontinuity surfaces. For the 2D models, Madden (1972) introduced the transmission-line method, Jepsen (1969) the finite difference method and Coggon (1971) the finite difference method. For the calculation of the 3D models, it was necessary to wait until the end of the 1970s: Pridmore (1978) used the finite element method and Dey and Morrison (1979) the finite difference method to calculate apparent resistivity for the dipole-dipole array.

The refinement of measurement tools and the use of calculators led, in the 1960s, to a wider application of the dipole - dipole array for investigations at deep depths: in this field the continuous measurement system of Alfano (1974) and the transform introduced by Patella (1974) allowed dipole-dipole curves to be transformed into Schlumberger curves, thus simplifying the interpretation.

As already stated, the existence of a natural electrical field was carefully studied by the Schlumberger group. Besides the self-potential method, Schlumberger and Doll introduced, in 1936, the telluric method that exploited the low frequency (considered continuous) natural field induced in the ground by the Earth’s magnetic field. The method aimed at determining the thickness of a conductive sedimentary basin covering a dielectric basement. Assuming the current in the basement to be null, the current density should be inversely proportional to the thickness of the sedimentary cover (Fig. 27). To eliminate time variations, two horizontal components of the natural electrical field were recorded simultaneously at two different points, one was a base station kept at the same location and the other a variable station within the investigated area. The ratio between the analogous electrical field components furnishes the ratio of thickness. This method was applied widely in the 1940s and 50s, especially in Europe, but was then progressively abandoned.

Another field in which Schlumberger made the first observations was the induced polarization (IP). He observed (Schlumberger, 1920) the slowness in the decay of potential in the presence of particular bodies. Schlumberger’s group investigated some metallic minerals, but the method was almost abandoned except for some experiments in the USA and Russia in the 1930s and 40s. It was only at the end of the 1940s that reliable and systematic research, particularly by Newmont Exploration Ltd., led to the industrial use of the method.

Between 1948 and 1954, Seigel and Wait (see Wait, 1959) carried out a series of studies on the theoretical effects of bodies of different form and mineralization, and, in cooperation with Collett, they introduced the measurement method in frequency domain (1950). Subsequently, many organizations, especially Russian (Federal Institute for Scientific Research of Exploration Methods and Techniques in Leningrad under Komarov’s guidance) and American (Naval Ordinance Laboratory of Washington, MIT, New Mexico Institute of Mining and Technology), studied and applied the method, detecting also non metallic IP sources (Vacquier et al., 1957; Madden and Marshall, 1959).

With regard to interpretation, the strong affinity with direct current methods led to the extension of interpretation methodologies of direct current methods to IP methods and vice versa.

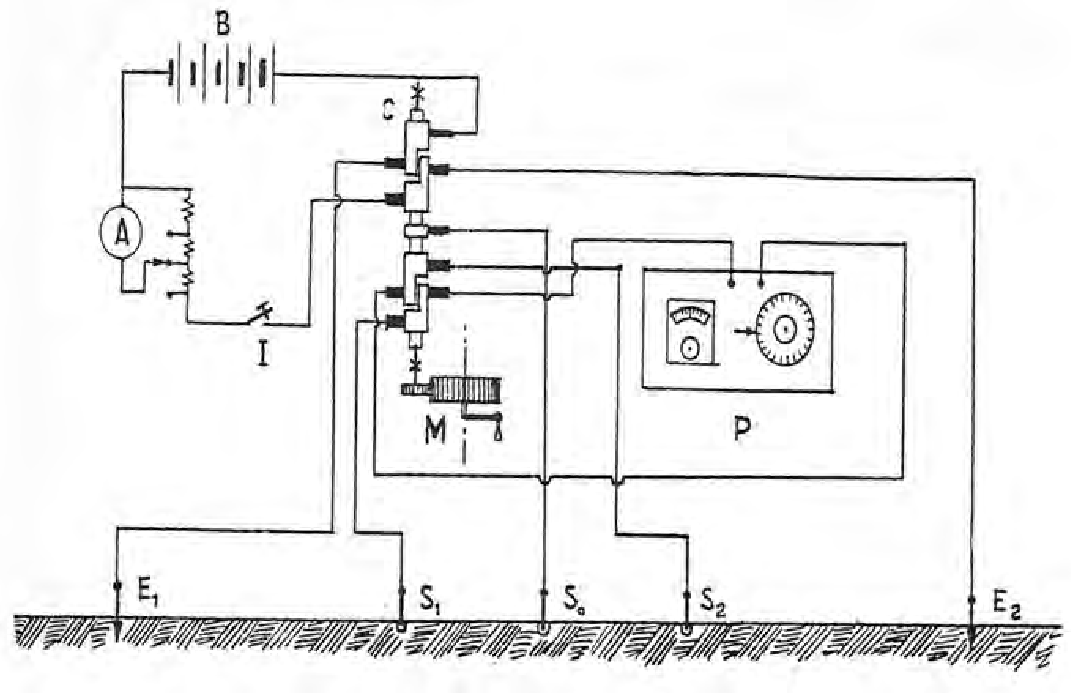

Fig. 27 - Gish and Rooney's apparatus. The current and the potential produced were contemporarily commuted by the rotating changer C, hand operated by the crank M (after Fulcheris, 1949).

Indeed, many of the methodologies proposed for numerical interpretation in 2D and 3D were projected for both resistivity measures and IP measures (Coggon, 1971; Madden, 1972).

Contemporarily with the first methods of direct electric current prospecting, alternating current methods were developed. Initially, an alternating current was employed in the method of equipotential lines with the advantage of performing simpler potential measurements. The first success was the discovery of ore deposits by Bergström (1913), and in 1924 the use of phase measures was also introduced. However, the method was later practically abandoned.

The most important development in the alternating current methods came from considering electromagnetic field effects produced by a coil or an electric dipole on conductive bodies. The first patent with an energizing coil was taken out by the German, K. Schilowsky, in 1913, but the basis of the method (source and receiver with coil) is found in the U.S. patent of H. Conklin in 1917. The method underwent wide development starting from the 1920s, especially on the part of a Swedish group led by Lundberg and Sundberg. Although there were operational groups of various nationalities (American, French, German, Australian and Canadian, as well as the Swedes), the first development of the method was essentially empirical, aimed only at the detection of conductive bodies with very scarce theoretical bases (skin effect and elliptic polarization of the field), even so, some important theoretical studies appeared in the same period (Peters and Bardeen, 1932; Slichter, 1932). Patents were taken out for a series of field methodologies that employed various sources (long cable, vertical and horizontal coils) and differently oriented receiving coils (Fig. 28). The theoretical models took into account only

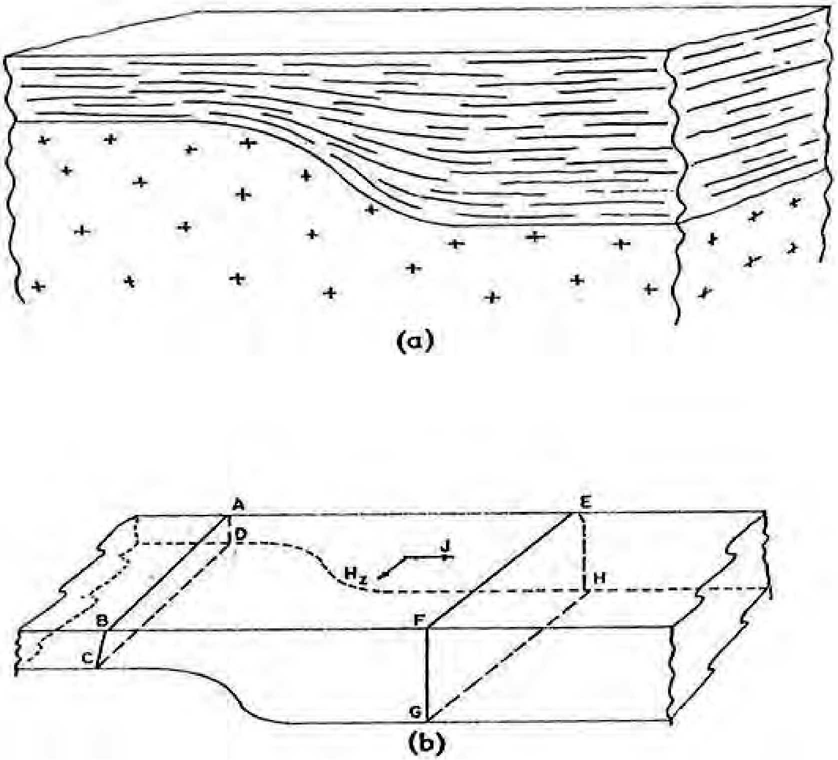

Fig. 28 - Telluric current method. At the top the scheme of a 2D sedimentary basin covering resistive bedrock; at the bottom the electric scheme. When the current flows in direction J, the variation in the section between ABCD and EFGH causes variation in current density, therefore the variation in the measured electric field on the topographic surface is inversely proportional to the variation in thickness. When the telluric current flows in the orthogonal direction there is no variation in current density: this indicates constant thickness in that direction (after Keller and Frischknecht, 1966).

simple primary field schemes produced mainly by coils, and qualitative evaluations of the primary field variation produced by underground conductive bodies, generally schematized with coils. Such evaluations were also made with small scale physical models. Even though they were very rough, the use of electromagnetic methods became widespread and led to the discovery of numerous conductive ore bodies.

An approach to the application of electromagnetic methods to study layered ground was the ELTRAN (electrical transient) method begun with the U.S. patent by Blau (1933). A current pulse was sent with an electric dipole, and the generated electromagnetic field was detected with another dipole located in line with the source dipole. The goal was to detect energy reflected by electrical discontinuities in the receiver transient. In some oil companies, the method aroused interest for about 10 years, with many field experiments, patents and papers but without any serious theoretical studies. Finally the claim that conductive sedimentary rock under normal conditions produces too low a frequency in the reflected signals for the resolution required in oil exploration came at the beginning of the 1950s. This disillusionment resulted in electrical

Fig. 29 - Geophysicists operating on the field with the amplitude electromagnetic method (after Heiland, 1940).

methods being used to a much lesser degree in oil exploration in the U.S. than in other countries.

Around 1950, the development of rigorous theoretical studies by various research groups, who started from the Maxwell equations, led to the refinement and debugging of the existing methods and the setting up of new methods, particularly of electromagnetic soundings that were able to investigate greater depths by greater transmitter-to-receiver distances and/or by lower frequencies. Between 1951 to 1963, numerous important papers on the response of uniform and stratified ground to e.m. fields produced by various sources (electric and magnetic dipoles, loops, line sources) from the American Wait, Wait and Campbell and Bhattacharyya [for a complete bibliography see Vanyan, (1967) and Kaufman and Keller, (1983)] appeared, following what had been set down by some researchers, among these the American Wolf (1946) and the Italian Belluigi (1946, 1950).

Contemporarily, and independently of the Americans, the Russians developed studies on electromagnetic methods starting from the early theoretical works of Fok and Bursian (1926), Bursian (1936) and from the first papers of Tikhonov (1946, 1950a). Indeed, the development that began in Russia after 1955 was superior to that of the Americans, and researchers from various organizations produced a huge number of papers (Tikhonov, Chetaev, Fedorov, Frantov, Gasanenko, Gilfand, Kozulin, Molokhnov, Shakhsurarov, Vanyan etc.). This development was also due to the wide application of electromagnetic surveys in the search for oil. In both America and Russia the first developments examined sources with harmonic currents that were simpler to treat with differential equations (frequency domain soundings). In Russia, beginning with Tikhonov (1946), they developed the transient methods (time domain soundings) that have the advantage of measuring induced field in the absence of a primary field, thus allowing an operation with both long and short transmitter-to-receiver distances. Among these, beginning from the mid 1960s through to the 1970s, short-offset time-domain electromagnetic soundings were the object of particular consideration, and there were numerous theoretical studies and applications for very deep measurements (Kaufman and Morozova, 1970; Rabinovich *et al.*, 1977; see also Kaufman and Keller, 1983).

Apart from fundamental theoretical studies dealing with electromagnetic fields, relatively few articles on measurement interpretation in the 1950s and 60s appeared. However, among these some theoretical charts were published for frequency domain soundings by Vanyan *et al.* (1964) for 4 layers and by Frischknecht (1967) for two layers.

Interpretation techniques became sharper both in Russia (State University of Moscow: Dmitriev, and the Institute of Geology and Geophysics in Novosibersk: Tabarovskiy) and in USA (University of Utah: Hohmann). Consideration was also given to 2D and 3D models, employing integral equation methods (Hohmann, 1975; Tabarovskiy, 1975), finite elements (Coggon, 1971) and finite differences, as well as physical models.

The same thing happened to natural source methods in the 1950s. The magnetotelluric method, an electromagnetic sounding method, was developed using the natural electromagnetic field; its launching and first improvements are credited to Cagniard (1953), though the principles of the method can be found in the work of Tikhonov (1950). This method has been applied throughout Russia and Europe and has undergone many improvements, among these its extension to two-dimensional cases with the introduction of anisotropy, and therefore of tensor impedance (Cantwell, 1960), and of three-dimensional methods for interpretation; also the equipment has been greatly improved.

The development of theoretical studies also led to marked improvements in the applications to metallic ore search and, since 1960, to the routine employment of traditional systems using multi- frequencies or transients on both land and in the air. Let us recall the response to an electromagnetic field of particular bodies like a sphere (Wait, 1951, 1960) and a cylinder (D'yakanov, 1960). Among the new field techniques of note are the AFMAG (Ward, 1959), that measures the inclination of the natural electromagnetic field of audio frequencies (100-1000 Hz), and the VLF (Paal, 1965), that measures the dip and bearing of the field produced by powerful radio stations transmitting a low frequency signal (15-20 kHz).

In this same period, after the first experiments carried out at the beginning of the 1950s (Pemberton, 1962), there was the expansion of some electromagnetic techniques used on land (in-phase and out-of-phase components, dip angles, transient response) to the use on the airplane and helicopter. Some particular techniques were also introduced like Dual-frequency phase shift, a method that employs a receiving coil located in a bird towed behind and below the aircraft (Patterson, 1961), and the Rotary Field method that uses a source transmitting a rotating e.m. field mounted on one airplane and a receiver with two coils mounted on a second airplane.

A last method (Georadar or GPR: ground propagating radar) is, instead, founded on the propagation and reflection of an impulsive high frequency electromagnetic wave (70-2000 MHz). This method was first employed in the determination of the thickness of glaciers (Evans, 1963), and subsequently, in the programs of the Apollo 17 lunar mission (Annan, 1973). Also at that time, Stewart and Unterberger (1976) reported its application to detect discontinuity in salt mines, as well as stratigraphic applications in salt mines and coal-bed investigations.

6. Final considerations

The brief and schematic outline of the history of applied geophysics methods has allowed us to show that progress, as with any other experimental discipline, was conditioned by instrument development and by technological developments. If the first pioneering applications of the early 20th century are excluded, the formulation of the main geophysics methods applied today and the first important successes as a tool for the exploration of the subsoil, date back to the second decade of the last century. The third decade and the first half of the 4th decade saw the formulation and enunciation of the basic principles of the various methods, like the theoretical ambiguity in interpreting the gravity and magnetic methods, the practical ambiguity in electrical data interpretation, and the construction of seismic reflection sections.

From 1955 to 1965, reproducible recording systems became a reality, first on analogical magnetic tape, then by digital technology. This marked the beginning of great development that led to fast and computer-aided elaboration, representation and interpretation; this was particularly so in the 1970s and was even more so in the following years through to today.

Today the actual possibility of elaborating, also automatically, enormous quantities of data, and of representing such data using three-dimensional technologies, a way that was once unthinkable, could lead one to forget the basic limits of currently used geophysical methods, limits that are intrinsic with the methods themselves. This paper provides the opportunity for today's researchers to take a look at the very roots of current geophysical exploration methods. This could be especially useful for the younger generation, as it highlights how this science has advanced step by step and hand in hand with the development of different technologies, and how advancement does not cease.

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