ELECTRICAL AND ELECTROMAGNETIC BOREHOLE MEASUREMENTS: A REVIEW

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Abstract. Electrical and electromagnetic geophysical techniques have reached a high level of technological sophistication since they were first used in boreholes less than one hundred years ago. Borehole logging – the detailed determination of rock and fluid properties adjacent to the borehole, and borehole geophysics – extending the range of geophysical investigation large distances away from the borehole, are essential for exploration, assessment and production of earth resources, as well as for fundamental studies of the earth. Borehole electrical and electromagnetic methods incorporate 17 decades of the electromagnetic spectrum, from 1000-s geomagnetic studies, through resistivity and permittivity measurements, to high-resolution resistivity imaging, NMR and optical spectroscopy.

Key words: Borehole, Logging, Resistivity, Electrical, Electromagnetic, Spontaneous Potential, Radar, Tomography, History

1. Introduction

The use of electrical and electromagnetic (EM) techniques for studying the earth dates back to eighteenth century measurements of the electrical conductivity of mineral samples and the earth, and the observation of fluctuating earth currents in long grounded wires. The methods were improved over the ensuing two hundred years, and by the early 1900s were being used in many countries for mineral exploration. The first underground measurements were made in mines in the late 1800s, but it was not until 1913 that electrodes were first lowered down boreholes.

In the intervening 82 years borehole techniques have risen to a high level of sophistication, and are now applied in fields as varied as mineral and petroleum exploration, geotechnical and environmental investigations and fundamental studies of stress and petrophysics in deep crustal boreholes. Present technology ranges from inexpensive resistivity probes used for shallow boreholes, to advanced at-the-bit resistivity tools used to guide 8-km long horizontal wells along narrow stratigraphic intervals to efficiently drain petroleum deposits.

This paper gives a brief overview of borehole electrical and EM borehole methods as applied in these diverse fields, and attempts to cover the broad range of applications and techniques in use today. By necessity the coverage will not be complete, but key references will be given to other review papers and bibliographies compiled in specific fields of study. The review focusses on English language literature, and does not attempt to cover papers published in other languages, although some key results are mentioned. Historical developments are drawn from

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Kelly (1950), Johnson (1962), Kunetz (1966), van Nostrand and Cook (1966), Segesman (1980), and Ward (1980).

1.1. THE FOUNDATIONS OF SURFACE ELECTRICAL AND ELECTROMAGNETIC METHODS

The earliest studies of electrical prospecting, according to Jakosky, (1940), can be traced back to 1720, when Stephen Gray and Granville Wheler tabulated the electrical conductivities of rocks, and 1746 when William Watson discovered independently that the ground is an electrical conductor.

It was later recognized that naturally occurring potentials exist in the vicinity of metalliferous ore deposits, and a number of workers attempted to exploit this new art of ore-finding. The first systematic studies of natural electrical potentials are usually credited to Robert W. Fox in England, who published a series of papers starting with Fox (1830) on the electrical potentials generated by sulphide deposits in Cornwall. The United States Geological Survey (USGS) carried out a major series of field studies in 1880 of the natural earth potentials in the Comstock gold lode in Nevada (Barus, 1882). Interestingly, Barus is often credited with developing the first non-polarising electrode, although non-polarizing electrodes were employed by Matteucci (see below) forty years earlier. In 1894 P. Bachmetjew in Germany identified a potential attributed to the movement of groundwater through subsurface sands. He based the explanation of these potentials on streaming potential or electrokinetic effects discovered by G. Quinke in 1859 and later studied by Helmholtz in 1879 (Rust, 1938). Further contributions at the USGS (Wells, 1913; Wells, 1914) developed the electrochemical basis of the passive self-potential phenomena.

Watson, in his 1746 work referred to above, also noted that the current passed through the ground between electrodes spaced 3 km apart varied in an erratic manner, different than if wire were used instead. The fluctuations were, of course, caused by telluric currents. Fox in the 1830s had also noted fluctuations in his earth currents measurements at Cornwall, which he attributed to opposing energies of currents in metalliferous deposits and interactions with earthquakes and volcanic activity. The first serious attempt to understand these fluctuations was by Charles Matteucci of the Greenwich Observatory, who in 1847 observed that earth currents in telegraph wires correlated with the aurora borealis (Matteucci, 1865). Further fundamental studies relating the earth's natural currents and magnetism followed in the early 20th century (van Bemmelen, 1908; Gish, 1923; Mauchly, 1918).

In the late nineteenth century various patents were granted in Britain and the USA for prospecting methods using direct or alternating currents at low frequencies to measure differences in the earth's electrical properties associated with ore deposits. The earliest techniques measured the resistance of the ground between two electrodes (e.g., Fred H. Brown between 1883 and 1891) but were strongly affected by the region near the electrodes. Leo Daft in 1897, and Daft and Alfred

Williams in 1902 used alternating currents and mapped equipotentials with telephone receivers connected to two search electrodes placed on the ground. This technique suffered from inductive coupling between the transmitter and receiver wires (van Nostrand and Cook, 1966). The Daft-Williams method was also used in Sweden in 1906, with an alternating current of 10 to 40 mA and a voltage of 5,000 to 60,000 volts. An important advance in resistivity measurements was the development of a four-electrode resistivity array by Frank Wenner of the U.S. Bureau of Standards (Wenner, 1912, 1915). Wenner also described a normalization procedure to convert the measured data to "effective resistivity".

In France in 1912, Conrad Schlumberger improved the two-electrode resistance method by mapping equipotentials around a source electrode energized by d.c.. Schlumberger first plotted the electrical potentials at his family estate in Normandy, followed by another test at Sassy and a third in 1913 at Fierville-la-Campagne in the Calvados iron-ore basin (Allaud and Martin, 1977). Conrad tested the use of a short electrical dipole to attain greater precision, and identified anisotropy effects in the dipping strata. He also noted that switching transients were higher near buried steel pipes, and identified these effects as "polarization provoquée" (induced polarization), which he further developed in 1913. Independently, in the USA, (McCollum and Logan, 1913) studied "self corrosion" effects between metal pipes and the earth and polarization effects in soils.

Also in 1913, at Bor, Servia, Conrad Schlumberger found that if a transmitting electrode were implanted in an orebody, then the whole orebody was raised to the same potential and the orebody could be outlined by plotting equipotentials. This method, which Schlumberger called the "grounding method", later became known as mise-à-la-masse. In 1919 the younger brother Marcel joined Conrad Schlumberger to form a commercial venture to explore for metallic ores and conduct geophysical surveys, and from 1920 made use of the four-electrode technique and an apparent resistivity formulation. A summary of these early experiments is given by Schlumberger (1920) and Allaud, *et al.*, (1977).

Inductive electromagnetic (EM) methods were developed after galvanic methods were well established. In 1910-1911 the Germans Lowry and Leimbach experimented with EM at radio-frequency EM prospecting. In 1925 Harry W. Conklin received a patent for mining exploration with an high- frequency EM method (Conklin, 1917). Conklin used a surface transmitter coil 60 m in diameter and measured positions of equal intensity ("isogonal lines") using two receiver coils connected in opposition. Rapid development of EM for prospecting was made in Sweden from 1921 with the Sundberg EM method (Sunberg, *et al.*, 1923; Sundberg and Hedstrom, 1934), the forerunner of the highly successful horizontal-loop or slingram EM method.

1.2. THE EMERGENCE OF BOREHOLE LOGGING

Rust (1938) reports that in 1913 a borehole resistance log was made in Germany by Richard Ambronn, who placed one electrode at the surface and lowered the other through the drilling fluid down a borehole. The first quantitative borehole resistivity measurement is usually attributed to Marcel Schlumberger in 1921. Marcel determined in situ the resistivity of sediments in the Besseges coal basin to help interpret a surface equipotential survey by lowering electrodes to the bottom of a 750-m hole. The next borehole measurement was not made until 1927, in the Pechelbronn oil field in eastern France (Figure 1), by Henri Doll who had joined the Schlumberger brothers and directed their research at oil wells, where a much larger commercial market existed. From 1927 onwards rapid progress was made in borehole electrical techniques, based largely on experience with surface-based measurements.

The Schlumbergers called their borehole method "electrical coring" in analogy with the geologic coring (in 1933 the name of the technique changed to electrical logging). In 1927 the 3-electrode lateral array (one current electrode and two potential electrodes downhole) was developed, as was the concept of guard electrodes (called the current output sonde) to focus current into the formation and to reduce borehole effects. Also in 1927 the dip of the strata crossing the borehole was measured by detecting the distortion of equipotentials around the current electrode. In 1932 an inductive compass for dip measurements called the "electromagnetic inclinometer" was commercialized. Schlumberger obtained a French patent in 1928 on the use of the S.P. curve to locate permeable strata, after noting that field measurements of the naturally-occurring potential showed large excursions above and below oil sands. The effect was shown to be unrelated to electrode polarization, and was attributed to filtration of drilling mud into the formation (Schlumberger *et al.*, 1932). It was soon realised (Schlumberger *et al.*, 1933) that SP also had a large electrochemical component.

Further developments in borehole logging, extensively used in petroleum exploration and lesser in mining and geotechechnical areas, are described in a later section. We will use the term "logging" for techniques where source and receiver are lowered down the same borehole, usually in a self-contained housing known as a sonde. The fundamental purpose of logging is to characterize the geological formation in the immediate vicinity of the borehole, often as a substitute for core or fluid samples. Electrical and EM logging techniques range from self-potential, through galvanic and inductive resistivity methods, to high-resolution borehole imaging techniques, to high-frequency dielectric and nuclear magnetic resonance methods.

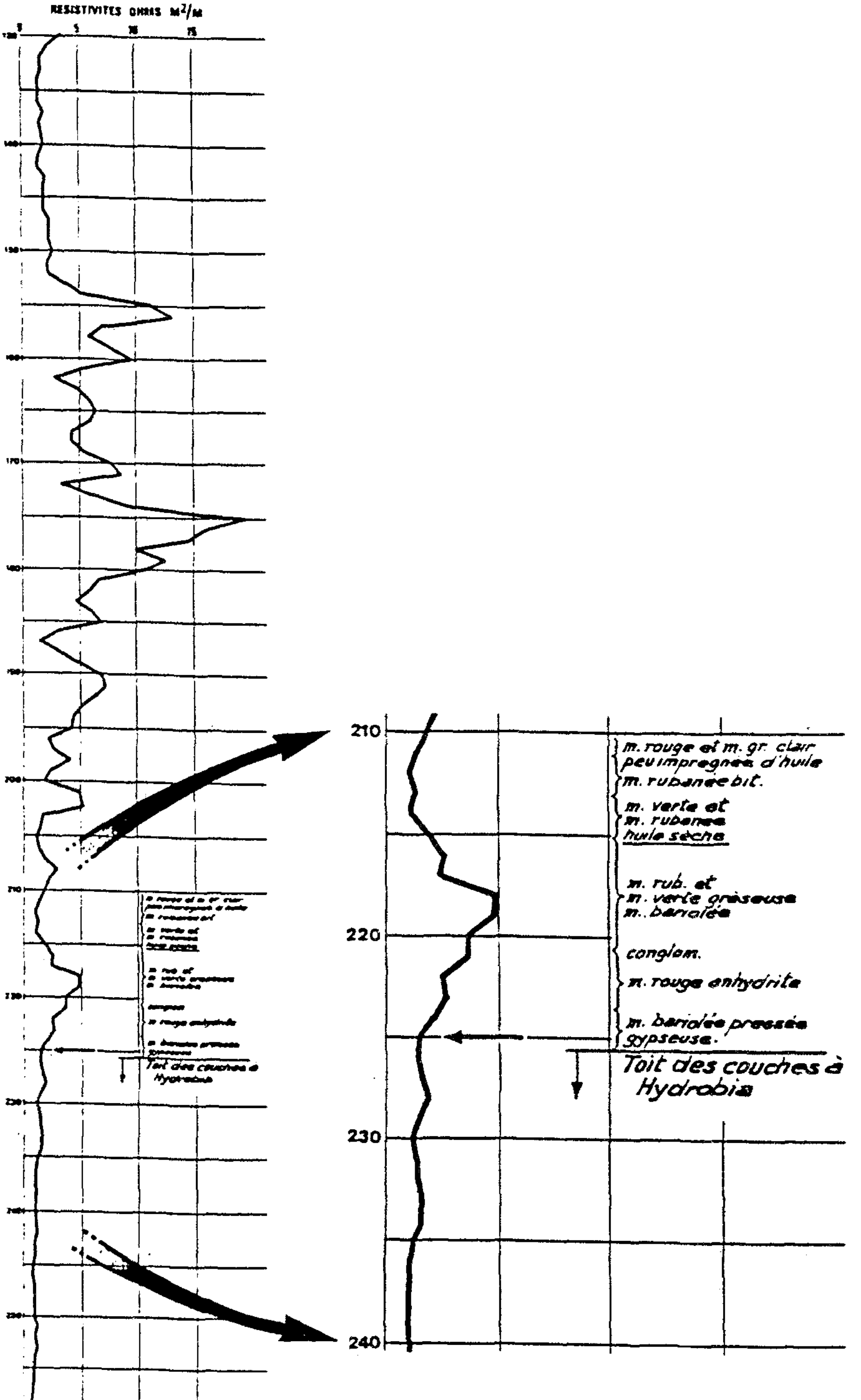

Figure 1. An early "electrical coring" made by Henri Doll in Pechelbronn, Alsace, in 1927 (Allaud and Martin, 1977).

1.3. Borehole Geophysics

Borehole geophysics, in contrast to logging, attempts to probe a considerable distance away from the borehole. Borehole electrical and EM methods have become well established in the mining industry, and include mise-à-la-masse, borehole EM with a surface source, cross-well resistivity and cross-well EM and radar.

In the following sections we will categorize the different borehole electrical and EM methods first by frequency, and then by application. The discussion will jump from the earliest recorded use of a method directly to the present state-of-the-art. Finally, we will review how these methods are adapted for scientific studies in deep crustal boreholes.

2. Classification by Frequency

The purpose of all borehole geophysical methods is to determine, as accurately as possible, the physical properties of the subsurface geology surrounding the borehole. Electrical and EM methods are used to determine resistivity (real, complex, or anisotropic), magnetic and dielectric properties, porosity, fluid content, lithology and fracture patterns. A vast array of tools and techniques have been developed during the last 100 years to make these measurements. The design of the tool, the mode of operation, the physics of measurement, the frequency of operation, signal and noise levels are all interdependent.

Borehole electrical and EM methods cover 17 decades of frequency, from 1000-s geomagnetic measurements for crustal studies, to 1-GHz dielectric and 100 THz optical spectroscopic logging tools used in the oil industry (Figure 2). At the low end of the spectrum are measurements such as SP, d.c. resistivity and magnetometric resistivity, whose lower frequency is bounded by the instrumental switching or observation time, typically a few seconds. Logging tools, which are moved continually in a borehole as data are collected, are limited at the lower frequencies by logging speed. Galvanic resistivity logging tools, which include borehole imaging, operate in the range tens to hundreds of hertz. The frequency range of the other logging tools is determined by the physics of the measurement and practical considerations: induction conductivity devices operate at frequencies from 200 Hz to 40 kHz, whereas dielectric tools range from 20 MHz to 1 GHz. Newly developed optical spectroscopy tools for fluid identification operate in the visible region around 10^{14} Hz.

The frequencies used in borehole mineral exploration depend strongly on the resistivity of the host rock and the distance between source, receiver and target. At or near d.c. are the d.c. resistivity and IP methods, including cross-well resistivity and IP tomography. Surface-to-borehole techniques use frequencies from 10 Hz to 10 kHz. The spectrum of cross-borehole EM measurements is constrained by the skin depth: frequencies as low as 500 Hz are required in conductive formations

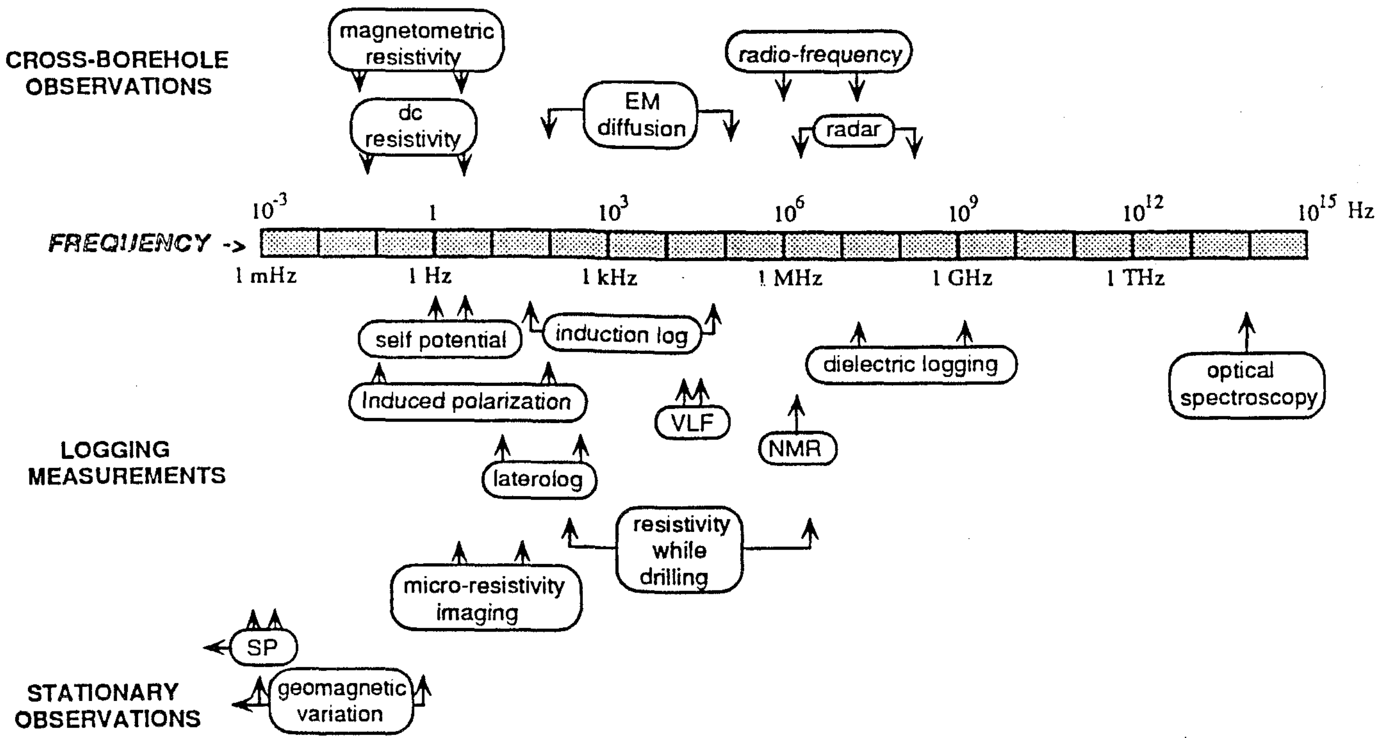

Figure 2. Spectrum of electromagnetic borehole techniques. The frequency of operation is determined by a combination of physics and practical considerations (see text).

($\sim$1 S/m), radio-frequency and radar at frequencies up to 120 MHz are possible in highly resistive rocks ($>$1,000 ohm-m).

3. Borehole Methods in Mineral Exploration

The earliest use of subsurface electrical measurements was in underground mines and workings, where geophysical equipment was taken into the mine to map extensions and hidden sections of ore. A natural development was to deploy electrodes pushed into boreholes and connected by wires to equipment in the mine or at the surface. Most of the techniques in use today bear a very close resemblance to the early methods; the major advances have come in miniaturization and improved reliability of electronics, and of course, modeling and interpretation. Excellent reviews of borehole electrical and EM methods applied to mineral exploration are given by Daniels and Dyck (1984), Dyck and Young (1985), Dyck and Asten (1988), Dyck (1975, 1991), as well as standard texts such as Grant and West (1965) and Keller (1966). Papers specialized in borehole geophysics in the minerals, geotechnical and groundwater industries are contained in the proceedings of a series of conferences (Killeen, 1985; MGLS, 1987, 1989, 1991, 1993).

3.1. Galvanic Methods

Galvanic methods inject d.c. or low-frequency current directly into the rock and measure potentials or potential differences. Many possibilities for electrode arrays exist, including single-borehole, borehole-to-borehole, and surface-to-borehole or borehole-to-surface. The simplest methods are self-potential (SP) and d.c. resistivity, followed by induced polarization (IP) and magnetometric resistivity (MMR). Some work on nonlinear effects at high current densities has also been done.

Borehole resistivity applications in mineral exploration and development are described in Ogilvy (1983, 1985b) and Daniels (1977, 1978, 1983). More recently, developments in borehole resistivity have focused on tomographic techniques, which are discussed later in this paper.

Induced polarization has always played an important role in mineral exploration, because of its high sensitivity to metallic minerals. The theoretic basis of IP is well summarized in the works of Wait (1959, 1989) and Madden and Cantwell (1967). The primary mechanism for IP in mineral applications is electrode polarization effects at the boundaries of electrolyte and conducting mineral grains. Borehole IP measurements have successfully been applied in mineral exploration by Wagg and Seigel (1963), Bacon (1965), Brant (1966), Mathisrud and Sumner (1967), Sumner (1976), Glenn and Nelson (1979) and more recently Ogilvy (1985a,b) and Poirmeur (1987).

In the mise-à-la-masse or applied potential method, current is injected directly into conductive ore intersected in the borehole, and the potential mapped either on the surface (Jakosky, 1933; McMurray and Hoagland, 1956; Edwards, 1988; Edwards and Howell, 1976; Tyne, 1980; Witherly, 1980; Mwenifumbo, 1986; Asten, 1991) or in another borehole (Parasnis, 1967; Nabighian *et al.*, 1984; Lo and Edwards, 1986; Mwenifumbo, 1987; Ushijima, 1989; Reed, 1993).

A reciprocal geometry to mise-à-la-masse is to map the potential distribution in a borehole a from surface electric source. Shima (1992; 1993) use the term "vertical electrical imaging" for such an array to map the resistivity distribution away from the borehole. Cross-borehole MMR is described by Nabighian *et al.* (1984) and Mwenifumbo (1987).

3.1.1. *Resistivity Tomography*

The foundations of resistivity tomography were laid in the 1970s both for geophysical (Stefanescu, 1970) and medical applications, where it is also known as electrical impedance computed tomography (Lytle and Dines, 1978; Henderson and Webster, 1978; Price, 1979; Henderson and Brown, 1984; Brown *et al.*, 1985; Dijkstra *et al.*, 1993).

Resistivity tomography between boreholes requires the collection of a large matrix of d.c. electrical measurements from electrodes in both boreholes, and inversion of the data to form a resistivity image of the interborehole region. The data can also be collected between the surface and boreholes, or between subsurface engineering or mining tunnels. Geophysical applications of d.c. resistivity tomography include Daily and Yorkey (1988), Daily *et al.* (1992), Shima (1992a), Shima and Saito (1988), Shima and Sakayama (1987), Sasaki and Matsuo (1990), Hishida *et al.* (1992), Shibamoto *et al.* (1992), Ramirez *et al.* (1993), Spies and Ellis (1995). An example of an image from a 3-D resistivity tomogram is shown in (Figure 3).

Variations on the tomographic theme include anisotropic resistivity tomography (Sasaki, 1994), IP tomography (LaBrecque, 1991; Iseki and Shima, 1992), magnetic susceptibility tomography (Sakashita and Shima, 1993), and tomographic imaging of SP differences induced by fluid injection (Ushijima *et al.*, 1992). Resistivity tomographic schemes are also used to image core samples (Daily *et al.*, 1987; Dines and Lytle, 1981).

3.2. INDUCTIVE METHODS

Borehole induction methods with very large radii of investigation have been developed to search for deep ore deposits not intersected by drilling. To attain a large source moment, the transmitter is normally located at the surface, and the frequency is chosen low enough to prevent excessive skin depth attenuation in the host rock. This configuration is known as surface-to-borehole, and has successfully been used to depths as great as 3,000 m. Frequency-domain systems employing a surface loop include Noakes (1951), Ward and Harvey (1954), Salt (1966), Hohmann *et al.* (1978), and Worthington *et al.* (1981).

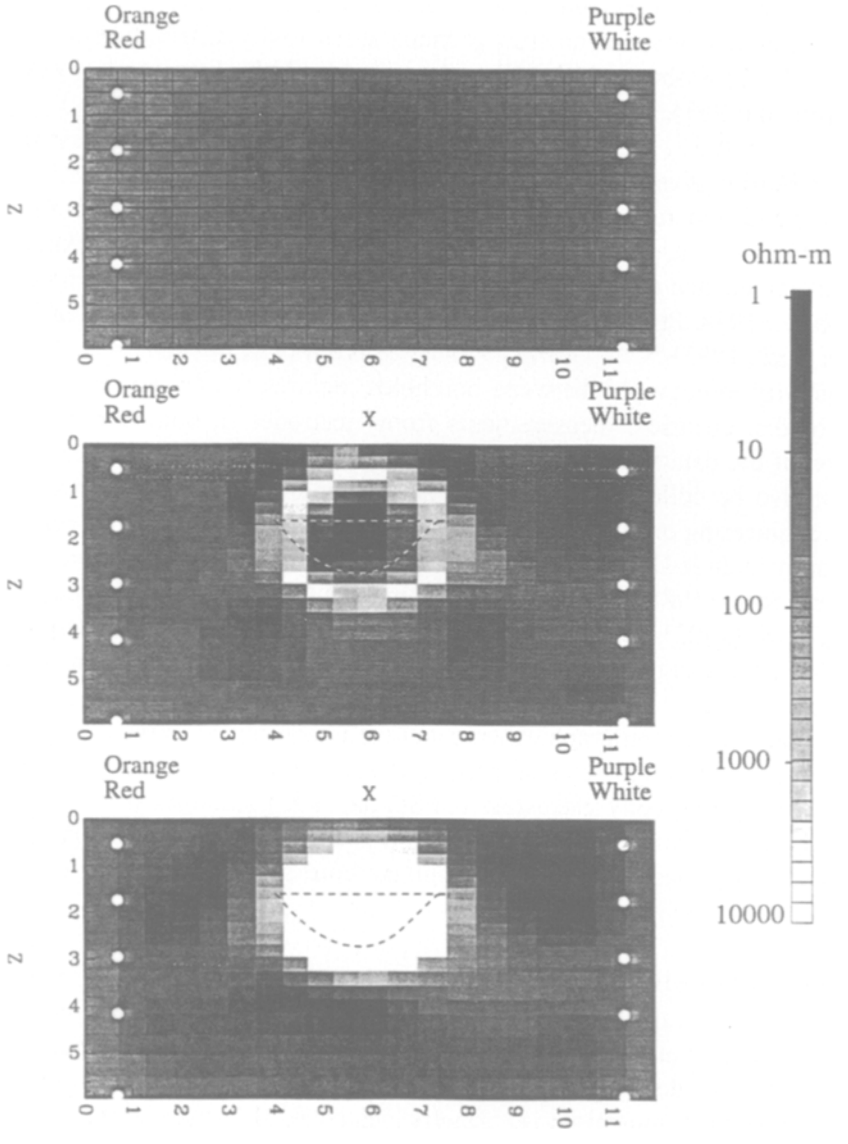

Figure 3. Cross-well resistivity images from three phases of an in-situ vitrification experiment. The three images were obtained from data collected before melting (top), during melting (middle), and after solidification (lower). White dots represent electrodes. 3-D resistivity data were collected in six boreholes surrounding the melt (Spies and Ellis, 1995).

Time-domain surface-to-borehole systems, first used in 1970 (Nabighian, 1984), have become more popular because of their broadband nature and relative ease of interpretation. Field examples of large-loop source, borehole receiver time domain EM surveys are given by Witherly (1980), Ogilvy (1983), Boyd and Wiles (1984), Dyck *et al.* (1985), Crone (1986), Boniwell (1986), Reed (1986), Levy and McNeill (1986), Eadie and Staltari (1987a), Asten *et al.* (1987), Bishop *et al.* (1987), Eadie (1987), Eadie and Staltari (1987b), Irvine (1987), Lane (1987), Mutton (1987), Richards (1987), Crone (1987), Robertson and Ascough (1991), Doe *et al.* (1991). The recent introduction of three-component receivers in the time-domain (Lee, 1986; Duncan and Cull, 1988; Hodges *et al.*, 1991; Cull, 1993) and frequency-domain (Worthington *et al.*, 1991; Pantze *et al.*, 1986; Cull and Cobcroft, 1986; Bourgeois and Bernard, 1991) has added much-needed directional capability.

Variations of the large surface source, borehole receiver geometry are possible. One interesting modification with a fixed borehole receiver and moving surface transmitter is described by Coggon and Clarke (1987). Applications of surface-to-borehole techniques in other fields include saline contaminant mapping (Asch and Morrison, 1989; Bevc and Morrison, 1991), and enhanced oil recovery (Spies and Greaves, 1991).

3.3. Logging tools in mineral exploration

Logging tools used in mining are similar to their petroleum counterparts described in Section 6, but are usually smaller in diameter and are not designed to be operated under high pressure. Borehole logging is routinely used for exploration for coal (Hoyer, 1991; Jiajin and Harvey, 1982; Kayal and Chistoffel, 1989; Peeters and Kempton, 1977; Reeves, 1976), and other minerals (Zablocki, 1966; Reeves, 1972; Reeves, 1976); Killeen and Mwenifumbo, 1987; Emilsson and Wanstedt, 1993; Hollyer *et al.*, 1991; Schoen, 1993). Descriptions of mineral logging in specific countries are Russia (Czubek, 1971), Czechoslovakia (Kobr, 1990) and France (Labert, 1981).

Induction logging tools developed specifically for mineral exploration are Clerc *et al.* (1983), Frignet (1986), Straub and Valla (1987). Attempts to increase the depth of investigation of induction logging tools by increasing the separation of source and receiver are described by Elliott (1961) and Smith and Hallof (1971). Simultaneously measurement of magnetic susceptibility and electrical conductivity can be made with an induction device (Scott *et al.*, 1981; Bristow, 1987).

Other mineral exploration logging tools are combined resistivity and IP (Tyne and Daggar, 1990; Tyne *et al.*, 1985; Webster, 1986; Mwenifumbo, 1989).

Induction logging tools are finding an important application in environmental studies, e.g., contaminant mapping with induction logs (DeSimone and Barlow, 1993), and tracking salt in groundwater (Church and Friesz, 1993).

4. Radar

Borehole radar systems, which typically operate at frequencies of tens to hundreds of MHz, are used to probe rocks of very high resistivity, such as salt and granite. At these frequencies dielectric properties become important, the physics is best described by wave propagation, and relatively simple concepts such as ray paths and travel time can be used for interpretation. Borehole radar systems can operate in single-well mode (Bradley and Wright, 1987), detecting reflections from scatterers, or in cross-borehole mode (Lager and Lytle, 1977; Olhoeft, 1988), measuring attenuation or travel time. Standard tomographic inversion techniques (Dines and Lytle, 1979; Lytle and Dines, 1980) are readily applied to cross-well radar data.

Radar system were first used in boreholes in the early 1970s to detect the boundaries of salt domes hundreds of meters distant (Holser *et al.*, 1972; Stewart and Unterberger, 1976; Halleux *et al.*, 1992; Nickel *et al.*, 1983; Unterberger, 1978), and have also been applied in coal seams (Cook, 1977; Coon *et al.*, 1981) and mining (Cook, 1977; Coon *et al.*, 1981; Nilsson, 1986). Borehole radar is routinely applied in such geotechnical applications as tunnel detection (Kong *et al.*, 1993; Lytle *et al.*, 1979; Moran and Greenfield, 1993) and characterization of fractures (Cook, 1977; Okada *et al.*, 1980; Coon *et al.*, 1981; Andersson *et al.*, 1989; Olsson and Nilsson, 1986; Olsson *et al.*, 1989; Olsson *et al.*, 1992; Chang, 1989; Sandberg, *et al.*, 1991; Holloway *et al.*, 1992).

5. Cross-borehole Electromagnetics

Tests of the underground detection of radio waves have been carried out intermittently since the 1920s, including measurements of the attenuation of radio-waves between boreholes in Germany in the 1930s (Rust, 1940). However, it was not until the Lytle and others in the late 1970s laid the theoretical foundation of geotomographic imaging that interest spread in the geophysical community. The earliest cross-well experiments in an oilfield environment used frequencies in the 1- 30 MHz range (e.g., Kretzschmar *et al.*, 1982; Witterholt and Kretzschmar, 1982; Witterholt and Kretzschmar, 1984), but covered relatively short distances.

Parallel to the developments in resistivity tomography, theoretical studies on electromagnetic propagation in resistive crustal layers (e.g., Wait, 1970; Wait and Spies, 1972) showed that the layers often form an efficient waveguide for propagation of EM waves over long distances. It was known that coal seams formed an effective waveguide that could be used for radio communication (e.g., Wait, 1976; Hill, 1984). The fact that radio waves could also be used to detect geological inhomogeneities in coal seams was soon recognized and the necessary technology developed (Shope, 1987; Shope *et al.*, 1986; Rogers *et al.*, 1987; Stolarczyk and Fry, 1989; Stolarczyk *et al.*, 1988; Stolarczyk, 1990). The technique, often termed the Radio Imaging Method (RIM), is being used in several countries (Thomson *et* *al.*, 1990; Vozoff *et al.*, 1993; Takacs, 1993; Young and Rogers, 1994) and employs hand-held loop antennae in mines or probes in boreholes. The RIM measurement is based on attenuation of the EM signal in the frequency range 50–500 kHz. Applications of RIM to other mining problems are described by Thomson, *et al.*, (1990), Thomson and Hind (1993), Thomson *et al.* (1992); McGaughey, 1991), and to tunnel detection by Mahrer and List (1995). There is, of course, an overlap in frequencies between RIM and cross-well radar referred to earlier. The term RIM is normally confined to continuous-wave measurements of signal attenuation, whereas radar measures discrete pulses in the time domain.

Radio-wave methods are also widely used in the (former) Soviet Union, and include borehole-to-surface and borehole-to-borehole attenuation (radio-wave shadowing) and reflection variants (e.g., Petrovsky, 1971; Chmelevskoy and Bordarenko, 1989).

Until recently, interpretation of EM tomographic data has normally employed standard ray-tomographic inversion techniques, which may not be accurate at the frequencies employed. Nekut (1994) describes the conditions under which ray-theoretic approaches are valid. Improved interpretation techniques for the diffusion regime are described by Sena and Toksoz (1990); Rogers *et al.*, 1993; Alumbaugh, 1994; Alumbaugh and Morrison, 1994, 1995; Torres-Verdin and Habashy, 1994; and Newman, 1995).

To extend the application of cross-well electromagnetics to a conductive or lossy earth it is necessary to employ lower frequencies. Field systems designed for low frequencies (1 kHz to 50 kHz) are currently being developed (Wilt *et al.*, 1991,1995; Osato and Takasugi, 1992; Gasnier *et al.*, 1994; Sakashita *et al.*, 1994; Sasaki *et al.*, 1994) for reservoir characterization and geotechnical applications. There is trade-off between resistivity, borehole separation and optimal frequency (Spies, 1992; Spies and Habashy, 1995); however, even in relatively conductive sedimentary rocks, measurements are possible between boreholes spaced many hundreds of meters apart. Several groups are also developing three-component receivers.

5.1. Electromagnetic measurements though steel casing

The presence of steel well casing in most oil fields has hindered the use of cross-well electromagnetics. Various numerical studies and field tests (Uchida *et al.*, 1991; Spies, 1992; Wu and Habashy, 1994; Wilt and Ranganayaki, 1990) suggest that it may be possible to measure magnetic fields though steel casing at sufficiently low frequency. Nekut (1995) describes the use of resistive sections between casing joints that can be used as electric dipoles for high-frequency cross-well measurements.

5.2. Use of steel well casing as a source for surface measurements

Steel casing used as a source electrode is a blend of mise-à-la-masse and d.c. tomography, and is often used to increase the depth of investigation of electrical studies around an injection or production well. Examples in oil exploration are given by Rocroi and Koulikov (1985); Le Masne and Poirmeur (1988), Goldman (1990), Ushijima *et al.* (1992b), Sugimoto (1992).

6. Petroleum Well Logging

The prime catalyst for the rapid technological development of borehole electrical and electromagnetic logging has been the need to accurately assess hydrocarbon content in boreholes drilled for petroleum. Unlike the small-diameter mineral exploration boreholes that are usually cored, the larger-diameter boreholes employed in the petroleum industry have multiple uses: exploration for hydrocarbons, assessment of productivity of reservoirs, and production of the hydrocarbons.

Well logging technology now supports a major industry. Literature searches reveal at least 10,000 references in English related to borehole logging techniques and interpretation, many of which are in publications of the Society of Prof. Well Log Anal. and its European counterparts.

This section will give a very brief overview of the electrical and EM techniques used in petroleum well logging, in order of increasing operational frequency. Only key references are given; the reader is referred to the many excellent texts (e.g., Serra, 1984, 1986; Hearst and Nelson, 1985; Jorden and Campbell, 1986; Ellis, 1987; Labo, 1987), reprint volumes (SPWLA, 1992) and bibliographies (SPWLA, 1985; Maute, 1992; Prensky, 1992) for more detailed information.

6.1. THE DRILLING ENVIRONMENT

Electrical and EM well logging tools are adapted to the drilling environment encountered in petroleum provinces. Petroleum wells are routinely drilled to depths of 5,000 m or more; often multiples wells are drilled from the same platform and deviated to intersect different parts of the reservoir. Heavy drilling mud is used in the drilling process to prevent blowouts and excess fluid loss into the formation, and its density is such that overpressure is maintained during the entire drilling process. Drilling mud can be water-based or oil-based, and is charged with dense minerals like barite and conditioned with gels such as bentonite. Oil-based muds are used to prevent shales from spalling and blocking the well. The resistivity of the drilling mud varies widely, from less than 0.1 ohm-m for salty muds, to thousands of ohm-m for oil-based muds. The range of resistivities of sedimentary formations is also large, from less than 0.1 ohm-m in many brine-filled sands, increasing to 1 to 10 ohm-m in many shales, to tens of thousands of ohm-m in some carbonates.

In permeable formations the drilling fluid rapidly flows into, or invades, the formation. Clay platelets in the drilling mud build up on the borehole wall, eventually forming a relatively impermeable barrier (the mud cake) that inhibits further fluid loss. The mud cake can reach thicknesses of several centimeters opposite high-permeability zones. The invaded fluid, known as the mud filtrate, forces the natural or connate formation fluids some distance back into the formation, leaving behind a certain amount of irreducible fluid. In some cases the invaded zone can be up to 1 or 2 m in diameter.

Historically, the primary purpose (but not the first use) of electrical and EM logging methods was to identify hydrocarbon-bearing sands. Sands and shales are discriminated with the SP (and gamma-ray) logs, and oil or gas zones identified by their higher resistivities. Resistivity and induction logs are used to determine the true resistivity of the formation and, together with independent estimates on the rock porosity obtained from other techniques, determine the percentage of oil or gas filling the pore space, or conversely, the water saturation.

Logging tools evolved to deal with dramatic variations in resistivity of drilling mud and formation, environmental realities such as borehole breakouts and changes in borehole diameter, variable invasion, and the need for detailed information on a wide range of lithologies. Logging technology and geological interpretation has advanced rapidly, and electrical and EM techniques now provide detailed resistivity images of the borehole wall, estimates of pore size distribution and fracture and hydrocarbon analysis.

6.2. Electrical properties of sedimentary rocks

The electrical properties of sedimentary rocks have been studied for many years (Archie, 1942; Wyllie, 1957; Waxman and Smits, 1968; Sen, 1991; Sen *et al.*, 1981). Electrical conduction at low frequencies is dominated by ionic conduction in the pore fluids, and depends strongly on water salinity and saturation, porosity, and the effective conduction path length, or tortuosity. In shales the relationship becomes more complex; conduction is largely due to exchangeable ions on the surface of clay particles (charge polarization). At higher frequencies dipolar, atomic and electronic polarization play important roles.

The electrical properties of a rock are normally described in terms of electrical conductivity σ and electric permittivity or dielectric constant ϵ. In the most general case, both quantities are complex and dispersive, and cannot be separated. The choice of terminology is not clear, and has led to many discrepancies in the literature (Fuller and Ward, 1970).

Depending on the frequency regime, most workers choose specific terms for the in-phase and quadrature components that relate the measured electric field intensity and current density. Below 100 MHz, where $\sigma/(\omega\epsilon)$ is normally less than 1, the in-phase component is normally described as a conductivity term, and the quadrature as an electric permittivity term. Above 100 MHz it is customary to express the electrical properties as complex permittivity, where the imaginary part of the measured quantity is the conductivity (divided by frequency).

The conductivity of most rocks increases slowly with frequency until around 100 MHz, due to dipolar relaxation of water at a length scale much smaller than the pore size. Around 1 GHz, conductivity becomes proportional to water fraction. Above 1 GHz, conductivity increases further due to the contribution of relaxation of water molecules, which peaks at about 16 GHz.

The effective permittivity at low frequencies is dominated by surface effects due to interstitial clays (often termed induced polarization below 1 kHz). Electric permittivity is related to the pore concentration of clays in sand pores, and allows estimation of the cation exchange capacity of the rock (Vinegar and Waxman, 1984). It reaches stable values between 0.2 GHz and 2 GHz, and is much higher for rocks saturated with water than with hydrocarbons. Logging measurements of permittivity made at frequencies between 20 MHz and 1 GHz are used to evaluate hydrocarbons in the presence of fresh, resistive formation water.

At still higher frequencies the interaction of the rock's material with electromagnetic radiation leads to absorption peaks or resonances at frequencies characteristic of various molecular oscillations, including vibrational and electronic modes. Molecular oscillations of water and hydrocarbons are utilized in optical logging methods, described later.

6.3. Spontaneous Potential Log

Spontaneous potentials arise from a variety of sources, including gradients in ionic concentration (electrochemical potential) and filtration (electrokinetic potential). The SP measurement (Doll, 1948; Wyllie, 1948) is very simple – basically a recording of the potential difference between an electrode in the borehole and an electrode at the surface – but is one of the most widely used for petroleum well logging.

The electrochemical potential originates at the junction of two solutions with different salinity (the mud filtrate and the formation fluid), at the outer boundary of the invaded zone. The concentration difference sets up an ionic current path through the formation into adjacent beds with different electrochemical properties (such as shale), forming a closed current path through the fluid-filled borehole. In sands and shaley sands SP values vary from −120 mV to +40 mV, compared to values measured next to adjacent shale beds. Filtration potential (Gondouin and Scala, 1958) is normally smaller than the electrochemical potential, and is highly dependent on the water conductivity.

The SP log records the difference between the shale and more permeable formations, and generally gives a good approximation of the electrochemical potential. It provides an independent estimate of the water resistivity or clay cation exchange capacity in the formation, as well as a permeability indicator.

6.4. Low-Frequency Electrode Tools

The evolution of electrode tools, from the normal array used in the 1920s to the focussed laterologs developed in the ensuing fifty years is shown in (Figure 4).

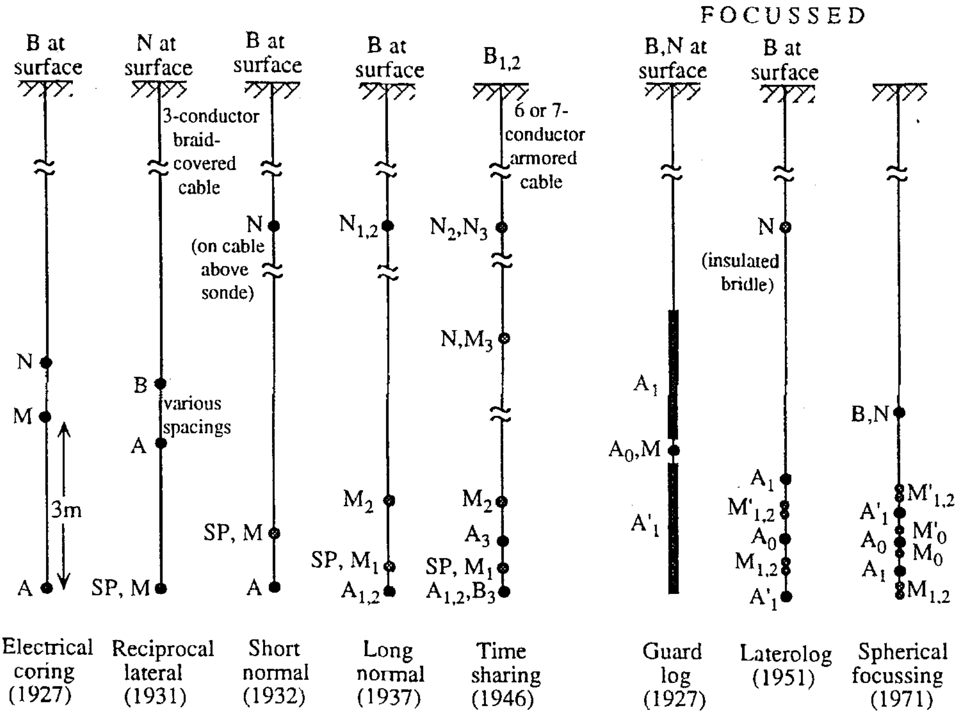

Figure 4. Evolution of logging electrode arrays. Unfocussed arrays are shown on the left; focussed on the right. A and B are current electrodes, M and N are potential electrodes (after Segesman, 1980).

6.4.1. *Unfocussed Devices*

The earliest electrode configuration, the normal array, consisted of a single current and potential electrode in the well, with returns at the surface (Figure 4). Low frequency a.c. currents (a few tens of hertz) are used to prevent electrode polarization. The equipotential pattern is strongly influenced by the borehole and invaded zone, and has a relatively shallow depth of investigation. The lateral array effectively measures the potential gradient downhole, and has a greater depth of investigation than the normal array. For many years the term electrical coring (Schlumberger *et al.*, 1932) was used to describe the combination of normal and lateral devices. The Microlog (Doll, 1950) is a pad tool with a very shallow depth of investigation (less than 5 cm), used to identify mud cake buildup that characterize permeable zones

6.4.2. *Focussed Resistivity*

Devices that incorporate passive or active focussing were developed to minimize the undesirable influence of the borehole and provide a deeper, more reliable measurement. The concept of passive focusing using long guard electrodes dates back Schlumberger's work in 1927. The guard electrodes force current into the formation perpendicular to the hole by keeping all electrodes at a constant potential

(Owen and Greer, 1951). Early passively focused tools include the Guard and Proximity (Hamilton, 1960) logs.

Other passively focussed tools were devised to provide more detailed information on sedimentary features. The high resolution dipmeter (Allaud and Ringot, 1969) is a four-pad device that records four resistivity measurements around the borehole wall. Formation dip is determined by cross-correlation of the four resistivity tracks. The concept of high-resolution pad measurements evolved into electrical resistivity imaging tools, described in later in Section 6.7.

Active focusing techniques employ an array of electrodes that continually balance the potential along the tool so that current is directed into the formation perpendicular to the measuring current electrode. Also, small focussing electrodes can be used, and they can be combined with SP and induction tools. The success of the focusing concept can be seen by tracing the current line paths (Figure 5).

The Laterolog-7 (Doll, 1951) was the first short-electrode laterolog, and employed 7 electrodes. This was followed by the Laterolog-8 (Doll *et al.*, 1960) and spherically focussed tool. The dual laterolog (Suau *et al.*, 1972) combines deep and shallow measurements in a single tool, and is most suitable for high-contrast resistivity logging and salty muds. Other actively-focused tools, too numerous to mention here, have been introduced for specific markets. The basic requirements for these designs are a multiple depth of investigation that enables accurate computation of the invaded zone resistivity and deeper true formation resistivity, a reduced sensitivity to borehole effects, and good thin-bed resolution.

6.4.3. *Deep Measurements*

Several tools have been built to measure large distances from the well. A scaled-up normal array with electrode spacings up to 300 m and frequency lowered to 0.1 Hz known as ULSEL (ultra-long spaced electrical log) is described by Runge *et al.*, (1969). Its main use is to determine the distance to the flanks of salt domes.

6.5. ELECTROMAGNETIC LOGGING

Despite the success of the low-frequency electrode tools, induction tools have become the prevailing resistivity tool because of their greater depth of investigation and efficacy in high-resistivity oil-based muds. Doll invented the first induction tool in the 1940s (Doll, 1949); it was a three-coil device operating in the low-induction number regime (typically around 10 kHz), where the depth of investigation is proportional to source-receiver separation. The device operates with one source coil and two receiver coils wound in opposition so that the net free-space signal is zero. Later, additional transmitter or receiver coils were added to focus the zone of greatest sensitivity deeper in the formation (e.g., the deep induction). Two depths of investigation are provided by the dual induction design (Tixier *et al.*, 1963).

The advantage of operating in the low-induction number regime is that the received signal in-phase signal with the transmitter current (the so-called R-signal)

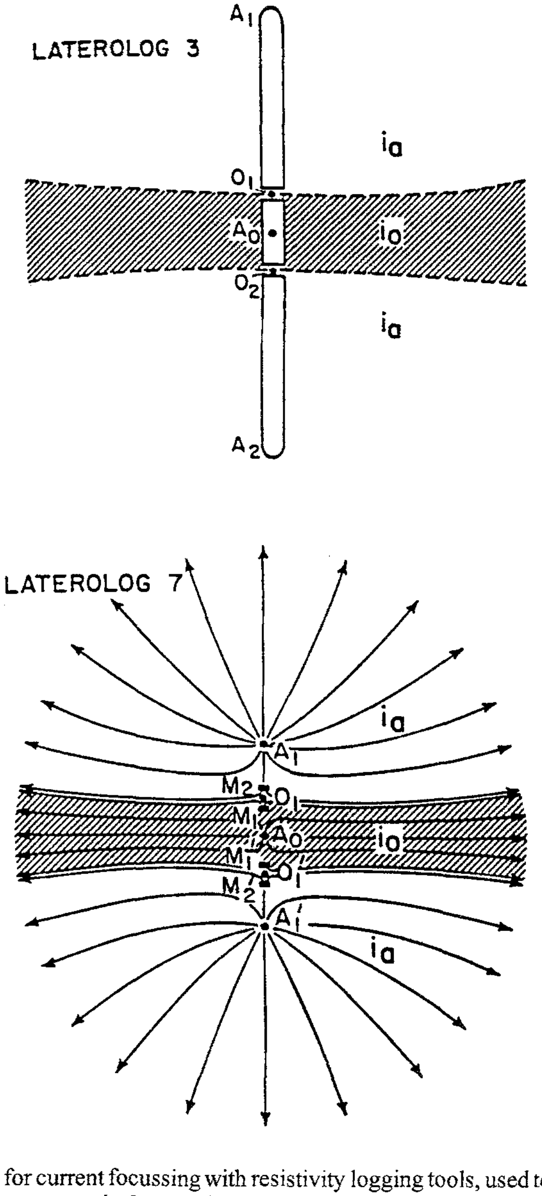

Figure 5. Two designs for current focussing with resistivity logging tools, used to reduce sensitivity to borehole effects and increase vertical resolution. An early three-electrode design from the 1920s (top) used two long guard electrodes (A1, A2) kept at the same potential as the measuring electrode A0 to passively focus the measuring current into the formation. Later designs utilized active focussing: the 7-electrode laterolog design (bottom) maintains a zero potential difference between the two pairs of potential electrodes M1–M2 by continually adjusting the currents leaving A1 and A1'. Since the potential drop along the sonde in the vertical direction is zero, current from the measure electrode A0 is focussed deep into the formation (from Suau *et al.*, 1972).

is directly proportional to formation conductivity. With the advent of better electronics and processing software it became possible to measure the small out-of-phase signal (quadrature or X-signal) caused by eddy currents in the formation and incorporate skin effect in interpretation (e.g., Barber, 1985). Recent developments include array induction tools operating with multiple coil spacings and frequencies with 5 or 6 depths of investigation (e.g., Martin *et al.*, 1984; Barber and Rosthal, 1991). With these tools it is possible to construct axisymmetric resistivity images of the first 1 or 2 m surrounding the borehole, considerably assisting with geological interpretation and simplifying identification of invasion.

6.6. Electromagnetic propagation tools

Electromagnetic propagation tools are used to distinguish between oil and resistive fresh formation water based on the large contrasts in their dielectric constants. The earliest tools (Calvert *et al.*, 1977; Poley *et al.*, 1978) were pad devices operating at 1.1 GHz, with a penetration depth of 2 to 10 cm. Later, mandrel tools operating at lower frequencies (around 25 MHz) with an array of receivers increased the depth of investigation up to 1 meter. However, interpretation is often complicated by strong dispersion in the MHz frequency range.

6.7. Electrical imaging

Borehole imaging is one of the most rapidly advancing fields in wireline logging. Wireline imaging devices produce images of the borehole wall that can be used to infer detailed geological information such as the geometric arrangement of rock layers, or structure, and sedimentological data on rock texture, fabric and facies type.

6.7.1. *High-resolution Shallow Devices*

Electrical imaging of the borehole wall emerged in the 1980s as an extension of dipmeter technology. Electrical imaging tools have multiple arms with an array of small buttons electrodes that contact the borehole wall and inject current into the formation (Ekstrom *et al.*, 1986; Straub *et al.*, 1991). Their maximum vertical and horizontal resolution is of the order of 5 mm. The current leaving each button is assumed to be directly proportional to the local conductivity. The conductivity data are displayed as a color image, which is unwrapped onto a projection of the borehole wall (Figure 6). A planar dipping feature shows up as a sinusoid from which the dip and strike can be uniquely determined.

The image contains bedding information crucial in sedimentological analysis (McGann *et al.*, 1988; Plumb and Luthi, 1986), facies characterization, and reservoir zonation (Luthi and Banavar, 1988). Also, porosity and mineralogical variations affecting the resistivity image are clearly seen in the image texture. An important application, especially in crystalline rocks, is mapping and characterizing fractures. Very thin fractures, filled with conductive drilling mud, become

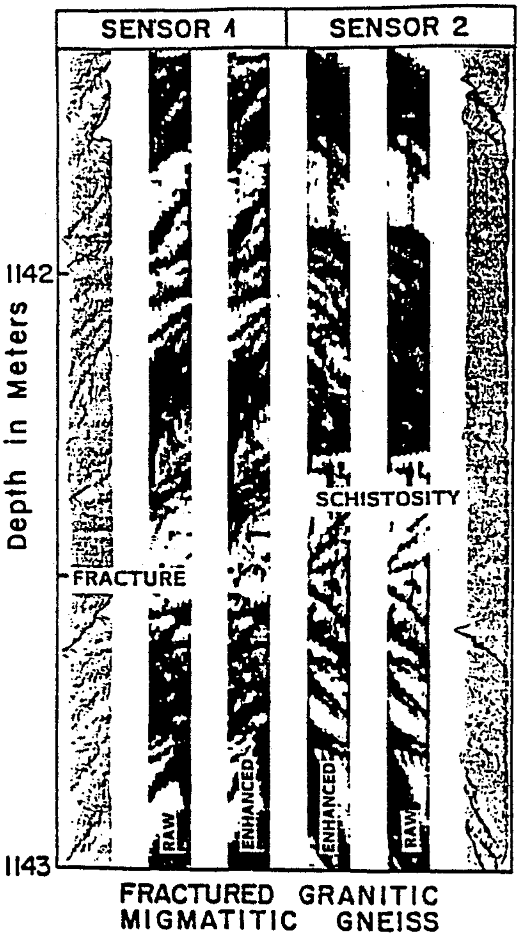

Figure 6. High-resolution resistivity image of the borehole wall recorded in the Cajon Pass scientific drillhole, California, showing fracture and foliation patterns in crystalline granitic gneiss (from Pezard and Luthi, 1988).

prominent features on microelectrical images (Dennis *et al.*, 1987; Laubach *et al.*, 1988; Luthi and Souhaité, 1990). The same is true of carbonates and other rocks with dissolution macro- porosity (Badr and Ayoub, 1989). Other applications are identification of faults (Koepsell *et al.*, 1989) and characterization of crystalline rocks (Pezard, 1992; Pezard and Luthi, 1988; Draxler *et al.*, 1990). Key papers on borehole imaging are reprinted in Paillet *et al.* (1990).

6.7.2. *Deeper-reading Calibrated Imaging Devices*

High-resolution imaging devices have a shallow depth of investigation and are uncalibrated. These issues are addressed in a new calibrated azimuthal resistivity tool based on a dual laterolog design, which incorporates 12 or more electrodes arranged circumferentially around the tool (Davies *et al.*, 1992). Images from these tools are not as sharp as those provided by the high-resolution devices, but are useful for quantitative estimates of small-scale resistivity structure not resolvable on conventional electrical logs (Rauen and Lastovickova, 1994).

6.8. Nuclear magnetic resonance (NMR)

Nuclear magnetic resonance, originally termed nuclear induction (Bloch, 1946; Bloch *et al.*, 1946), is based on the precession of atomic nuclei in a d.c. magnetic field. NMR logging tools first became available in the 1960s (Brown, 1960; Hull and Coolidge, 1960). The basic NMR tool measures the relaxation time of hydrogen nuclei in the pore space of a rock and hence gives a direct measure of the free fluid in the rock (the hydrogen in water and hydrocarbons), as well as viscosity and permeability. The decaying magnetic field amplitude can be interpreted as a superposition of a suite of exponentials, each corresponding to a typical pore size. By a suitable choice of observation window it is possible to determine the pore size distribution and discriminate between fluids bound to surfaces (such as the water in shales) which have much faster relaxations, and fluids in pore space.

Early NMR logging tools measured atomic precession in the earth's magnetic field, and required doping of the drilling mud to reduce its signal. New pulsed NMR tools (Cooper *et al.*, 1980; Jackson, 1984) use strong permanent magnets. NMR logs can provide robust estimates of porosity that is independent of lithology (Miller *et al.*, 1990; Morriss *et al.*, 1993). Jackson and Matthews (1993) gives a bibliography of 500 references related to NMR logging.

6.9. Optical methods

A new development in borehole measurements is optical spectroscopy, based on the absorption of light as a function of wavelength. Measurements of the absorption spectra in the near-infra red and visible range ($\sim$ micron or 10^{14} Hz) are used to differentiate between fluids sampled in a borehole (Mullins *et al.*, 1992; Smits *et al.*, 1993).

6.10. Corrosion in casing

Corrosion of steel casing is a major expense and hazard in hydrocarbon, geothermal and water wells. Wireline logging tools that detect corrosion include mechanical (caliper), acoustic, electromagnetic and electrochemical (Cryer *et al.*, 1987; Monrose and Boyer, 1992). One electromagnetic corrosion tool employs flux leakage detection using a low-frequency magnetic field and a second measurement at 1 kHz to delineate inner surface defects (Cuthbert and Johnson, 1974). A second group of tools measures the in-phase and quadrature response at a frequency low enough (typically 10 Hz) that the response varies with the casing thickness (Smith, 1981). Other tools measure polarization potentials on the inner casing surface due to corrosion electrochemical cells.

7. Emerging Technologies

7.1. LOGGING WHILE DRILLING (LWD)

In standard logging the sonde is lowered on a wireline cable down the borehole after drilling. It was recognized in the early 1930s that information on the drilling process could be conveyed to the driller via the drilling mud using mud pulse telemetry. The first downhole drilling measurements were directional (azimuth, inclination, and tool face), progressing to resistivity (basically a 16-inch short normal) in the late 1970s (Buchholz, 1982). In the mid-1980s 2-MHz electromagnetic propagation tools were introduced (Rodney *et al.*, 1983; Coope *et al.*, 1984), which were well-suited to conductive formations and oil-based drilling muds.

In the last few years LWD resistivity technology has evolved rapidly (Allen *et al.*, 1989) to include both multi-spacing and multi-frequency propagation tools and resistivity tools similar to laterologs which can operate in oil-based muds. These tools use toroids to induce currents on the drill collar which then leak out into the formation. The sensing elements in all LWD tools up until recently were spaced 15 to 30 m behind the drill bit, which meant that geological information from the bit location was not received in real time. Most recently the resistivity measurement has been moved within 1 m of the bit, with the bit itself becoming part of the electrical circuit. The ability of measuring resistivity "at the bit" has motivated a major change from "geometric steering" to "geological steering" (Figure 7) (Bonner *et al.*, 1993). This technology now makes it possible to steer a horizontal well within a meter of a geological horizon, over distances of many kilometers, and dramatically improve the efficiency of draining oil reservoirs.

7.2. RESISTIVITY THROUGH CASING

Measuring the resistivity of rocks behind steel casing is a formidable challenge, because the conductivity of steel casing (6×10^6 S/m) is 6 to 8 orders of magnitude higher than that of typical formations. The concept of injecting current into casing and measuring the very small potential changes due to current leakage into the formation can be traced to the 1930s (Alpin, 1939). However, the measurements have only recently become feasible due to advances in electronics and techniques for compensating for variations in casing resistivity and thickness. Numerical and practical studies are described by Kaufman (1990); Kaufman and Wightman (1993), Klein and Martin (1993) and Schenkel and Morrison (1994). Experimental tools that measure resistivity through steel casing with stationary measurements are currently in the testing phase (e.g., Vail *et al.*, 1993), and initial results are encouraging.

The possibility of making inductive measurements through casing has also received attention (Augustin *et al.*, 1989; Uchida *et al.*, 1991).

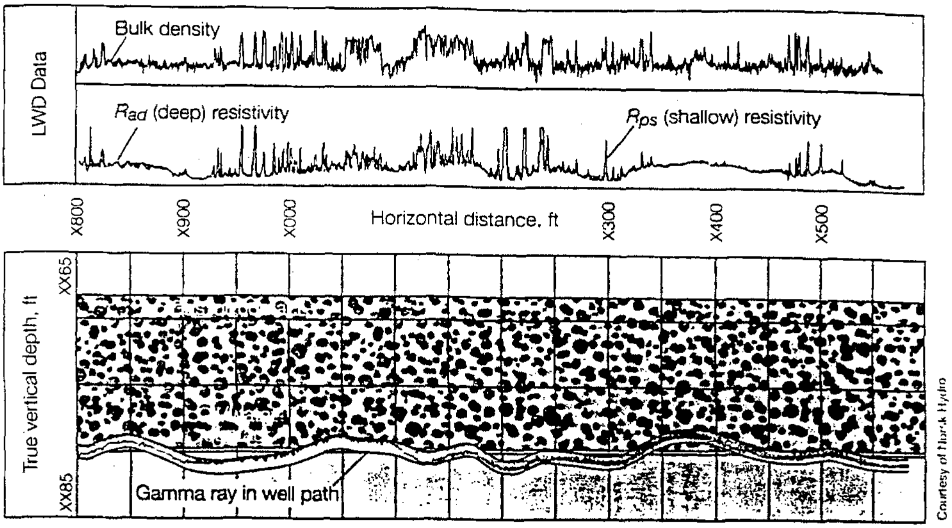

Figure 7. Geological steering along the top of an oil-water contact in the North Sea using resistivity and density logging-while-drilling measurements (from Bonner *et al.*, 1993)

8. Measurements in Deep Crustal Boreholes

Many of the deep boreholes drilled for purposes of scientific research are fully or partially cored, but data on rock properties in-situ (at borehole temperature and pressure) can only be obtained from logs. Borehole electrical and EM techniques used in deep crustal boreholes are similar to those used in commercial applications, except tools must usually be modified to withstand the very high temperatures and pressures encountered in deep wells, and the size must be reduced for the slim holes (<12.7 cm) often used in scientific drilling programs. Standard logging tools developed for the petroleum industry are rated to 175 °C and 140 MPa. Certain tools developed for hostile environmental logging (HEL) conditions are designed to operate at 260 °C and 170 MPa. Government and research institutions working with vendors have modified many of the standard tools, and designed new tools, to meet the needs of deep scientific drilling.

The following section summarizes electrical and EM logging measurements used in several of the deep scientific drilling boreholes. Many are standard logging tools, but some measurement such as magnetic variations are unique to research boreholes.

8.1. KTB, Germany

An extensive literature exists for the two KTB (Kontinentales Tiefbohrprogramm der Bundesrepublik) boreholes in Germany, in the form of formal reports and many papers in the journal *Scientific Drilling*. The first borehole is known as the KTB-VB, was drilled as a pilot to a depth of 4 km. The main borehole, the KTB-

Oberpfalz HB was spudded in 1990. It has passed 8 km and is planned for 10 km (the original plan was for 12-14 km but the temperatures were found to be much hotter than expected). A good review of progress in recent scientific drilling is give by Andrews and Pyle (1991).

Major suites of logging tools that have been run in the KTB boreholes include galvanic and inductive EM, as well as density, spectral gamma, thermal conductivity, remanent magnetization and magnetic susceptibility, porosity, stress relaxation, acoustic emissions, sonic and nuclear geochemical logging (Bram and Hänel, 1991). Borehole EM and electrical methods applied include 3-D magnetics, gradient magnetics, IP, SP, and electrical imaging (Draxler *et al.*, 1990).

Surface geophysical investigations in the vicinity of the KTB, which include over 100 MT and CSAMT soundings, identified a large SP anomaly (900 mV) and anomalous low conductivity with lateral variations below 4 km depth (Haak *et al.*, 1991). Resistivities determined from logging range from 1000 to 100,000 ohm-m to about 4 km depth, when they abruptly drop to values as low as 1 ohm-m where the borehole intersects sub- vertical pyrite- and graphite-bearing cataclastic zones. Bremer *et al.*, (1992) discusses differences in electrical conduction mechanism in sedimentary rocks and crystalline rocks found in the KTB. Crystalline rocks are dominated by surface effects caused by the very small ($<$ 100 nm) pore size rather than volume effects that influence rocks with larger pore sizes.

The average resistivity of the upper 4 km from surface EM is between 100 and 500 ohm-m, much lower than the borehole logs which are above 1000 ohm-m for 80 percent of the depth interval. Kück (1992) reconciles the discrepancies between surface EM and borehole measurements by analyzing resistivity data from laterologs, induction logs and microfocussed logs, which cover a wide range of spatial scales. By using a model of parallel conductance to integrate data at different scales, the average resistivity is interpreted to be 300 ohm-m.

The high conductivity at 7 km depth is determined from core samples (Rauen *et al.*, 1994) to be caused by increased graphite and sulphide mineralization, and saline inflows from pores and cracks. However, Rauen *et al.* (1995) also found that in situ resistivity from 6 km to 3 km depth, measured with a deep-reading resistivity imaging log, is higher than that measured on core samples, and attributed the disparity to pressure release during core recovery and the filling of microcracks with water. Rauen *et al.* (1995) also used the deep resistivity image to study electrical anisotropy, which ranged between $\lambda = 1$ and 1.5 (core measurements were 1.2 to 1.3 for amphibolites and lamprophytes to 2.8 for foliated gneiss). High-resolution resistivity image were used to study fractures, dip and the post-orientation of cores (Draxler *et al.*, 1990).

An improved SP tool rated at 300 °C and 150 MPa was developed (Winter *et al.*, 1991) to map extension of the surface SP anomaly to depth. The SP anomalies were attributed to oxygen fugacity and graphite in combination with redox potential. SP was also used to monitor electrokinetic effects stimulated by hydraulic pumping (Stoll, 1994).

IP logging measurements in the KTB pilot borehole (Grinat, 1991; Vogelsang *et al.*, 1992) identified strong metallic polarization from sulphide and graphite, which is evenly distributed throughout the crystalline rock, with higher concentrations in fracture zones.

A mise-à-la-masse experiment using the steel casings of the pilot and main boreholes as current electrodes and mapping the potential at the surface is described by (Stoll, 1993). He traced a conductive zone 100 m wide intersecting the main borehole between 250 m and 1500 m depth.

Measurements of the time-varying vertical electric field (Ez) were made by (Bahr and Eisel, 1990) who observed 4 mV of excursion between the surface and 4000 m depth, indicating lateral changes in conductivity. One of the few successful tests of the vertical magnetic gradient method (VGM) was conducted in the KTB (Spitzer, 1993; Steveling *et al.*, 1991). Magnetic-field measurements were made at the earth's surface and at 3000 m depth using a triaxial fluxgate magnetometer rated to 70 MPa and 100 C, at periods between 10 and 6000 s. Analysis of the VGM data showed that the surface telluric fields at the KTB site are strongly distorted by local conductivity anomalies, biasing conventional MT data interpretation.

8.2. Gravberg, Sweden

A detailed study of the electrical resistivity of the Gravberg-1 deep well in the Siljan impact structure in Sweden is described by Pedersen, *et al.*, (1992), where laterologs were run to a depth of 6100 m. MT interpretations were that the upper crust to be 10,000 ohm-m to a depth of around 6 km, where the resistivity of an impact-related unit decreased to about 1000 ohm-m. Below 6 km the resistivity was interpreted to be about 300 m. The borehole measurements confirmed the MT interpretations and showed that zones of increased conductivity are related to fracture zones with increased porosity, and that below 5.4 km the pore fluids are highly saline.

8.3. Cajón Pass

High-resolution resistivity imaging logs were run in the Cajón Pass scientific well in California, between 850 m and 1820 m depth (Pezard *al.*, 1988). The images were used for textural analysis of the igneous rocks, and identification and mapping of open or mineralized fractures.

8.4. Toa Baja, Puerto Rico

An intriguing use of resistivity logs in the Toa Baja Scientific Drill Hole, Puerto Rico, is described by Maltezou and Anderson (1991), who identified Milankovich cycles in sedimentary history from an analysis of the power spectra of resistivity logs of interbedded limestone, sandstone and shale in the upper 600 m of the borehole.

9. Summary

By locating sources or sensors in boreholes, the earth scientist can vastly improve the utility and range of investigation of geophysical techniques compared to what can be achieved when measurements are restricted to the earth's surface. On the smallest scale, detailed resistivity images of the borehole wall reveal sedimentological textures and fabrics that often substitute for core. Larger scale measurements provide bulk rock properties up to and above reservoir scale. Source and receivers may be located in separate boreholes to image the resistivity distribution between the boreholes, and map the migration of fluids over time.

Borehole electrical and electromagnetic logging technology has reached the level of technological sophistication that we can determine detailed electrical properties as well as lithology, dip, fracture pore size distribution and fluid content. Indeed, it can be argued that accurate petrophysical assessments can only be made in boreholes, where rocks are under natural conditions. The fastest growing area in borehole techniques is that of measurement while drilling, which enables many of the conventional logging techniques to be applied in real time during the drilling process, and the borehole to be steered along narrow stratigraphic intervals.

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