# The early history of the induced polarization method

Harold Seigel, Consultant, Toronto, Canada
Misac Nabighian, Colorado School of Mines, Golden
Dattatray S. Parasnis, Lulea Technical University
Keeva Vozoff, University of Sydney, Australia

This paper traces the early development of the induced polarization method, starting with field observations by Conrad Schlumberger in a mining region in France, about 1913. Starting about 1929 he introduced this technique into hydrocarbon borehole logging in the USSR, and this resulted in further development in eastern and western Europe.

A separate, and ostensibly independent, root arose from wartime research by the United States Navy on beach mine detection in 1942. Knowledge of that research provided the incentive for U.S. mining companies to develop the necessary mathematical theory, field equipment, and practice, and, by 1950, to begin IP surveys for mineral exploration.

Further research, at universities and in the mining and oil industries, resulted in significant advances in instrumentation, efficient field practice, data processing, and data interpretation including inversion. However, the ultimate objective—identifying the composition of the source mineral from its IP response—still remains elusive.

Today IP is the primary tool used to explore for several important types of mineral deposits—especially porphyry coppers, bedded lead/zinc and sulphide-related gold deposits. IP is unique among the controlled-source geophysical methods employed in mineral exploration in that it is based on an interface electrochemical phenomenon, rather than on a purely physical property of rocks or minerals.

In this paper, we will trace the first 50 years of the complex history of the development of IP. The story begins with the earliest recorded observation of the basic phenomenon, almost a century ago, and extends until its relative maturity, in terms of quantitative theoretical representation, instrumentation, and field practice. As will be shown, IP has two ostensibly independent roots, well separated in space and time. Developments from these two roots grew essentially in isolation, because of linguistic and political barriers.

**The French root.** The earliest observation of the induced polarization phenomenon associated with sulphide mineralization is attributed to Conrad Schlumberger, the famous French pioneer in electrical prospecting, who, perhaps as early as 1913, observed that if he passed a dc current through rocks containing metallic sulphides and interrupted the current abruptly, the resultant voltages in the Earth decayed slowly rather than instantly. Schlumberger had observed similar effects a year earlier, while making such measurements near a buried iron water pipe. He sensed possible practical application of this phenomenon, but military service in World War I interrupted his experiments.

Schlumberger published a monograph in 1920 (revised in 1930) on electrical prospecting methods, in which he describes the slow decay phenomenon, and correctly attributes it to electrochemical effects at the points of entry and exit of the applied current. However, he also reported that he had found similar long decays in unmineralized rocks and, probably as a result, he did not pursue the phenomenon for mining exploration. However, he continued to regard it as potentially useful for distinguishing diverse rock types. He filed for a U.S. patent in 1934 (granted in 1939) on his method of borehole logging, for hydrocarbon purposes. In this patent he discloses the method of measuring what he called the "coefficient," namely the ratio of the peak transient to the steady-state dc voltage ($V_S/V_P$), as an indicator of the nature of the formations being traversed, but he does not speculate as to the source of the phenomenon.

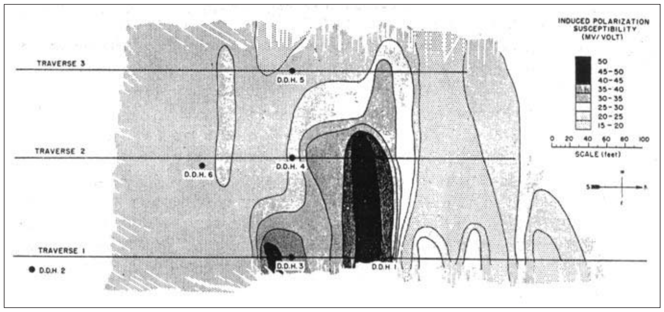

*Figure 1. A contour plan of "IP susceptibility" over a known magnetite body in Lebanon, Pennsylvania, buried under 50 ft of glacial till. These results were obtained using a Wenner array with a spacing of 50 ft. (from Bliel, 1953).*

**Developments in the USSR.** In 1927, D. M. Murashov of the Geologic Committee of the USSR, in Leningrad, observed electrochemical effects in the course of making electrical measurements on samples of sulphides and magnetite in a calcium chloride solution.

In 1929, Conrad Schlumberger was contracted by the Soviet government to carry out an extensive logging program at the Azerbaijan and Chechan oil fields. Among the electrical methods he applied was IP. In conjunction with this work, he published a volume on electric logging methods which came to the attention of Soviet geophysicists who were, presumably, aware of the observations of Murashov. In 1935, E. A. Sergeyev and N. N. Ragulin, both of the Geophysical sector of the Central Research Institute for Geological Prospecting, an offspring of the Geologic Committee, carried out extensive laboratory research on the induced polarization of sulphides. Investigated in detail were the dependence on the density of the polarizing current, the time of establishment, the composition of the sulphides, and the nature of the electrolyte in contact with the minerals. Ragulin correctly foresaw the application of this phenomenon to mineral exploration and suggested that electrode arrays be employed for profiling and depth sounding, and that periodic current pulses be used for establishment of the measurements.

At the same time and in the same institute, A. S. Semenov studied the IP responses of nonsulphide rocks, including sandy clays, and established a correlation between the IP response amplitude and the resistivity of these rocks.

World War II interrupted most scientific developments in the USSR, including IP. However, by 1948 field surveys with IP had begun over ore deposits. A. S. Polyakov promoted the use of very long charging times (3–5 minutes) and high currents (5–10 amperes), and the measurement of the decay transient immediately (typically 0.5 s) after the interruption of the primary current. He also developed nonpolarizing electrodes still used in Russia. He followed Conrad Schlumberger by expressing his results as the ratio of this quantity to the primary field which he named "chargeability"; this ratio and term are still employed by Russian geophysicists.

The problem posed by the chargeabilty of nonmineralized rocks, which had discouraged Schlumberger, was overcome through extensive field experience gained by V. A. Komarov and Y. S. Ryss in many sites, both mineralized and barren. They found, empirically, that the chargeability of specific barren rocks fell within rather low and stable limits, and that the presence of sulphide mineralization could readily be detected through any increase of chargeability beyond the expected limits. Komarov worked at the All-Union Research Institute of Exploration for Prospecting Methods and Techniques (VITR) in Leningrad, then at the All-Union Institute of Exploration Geophysics (VIRG), and from 1980 until his recent death, as professor of geophysics and geochemistry at Leningrad University (now St. Petersburg State University). He was, undoubtedly, one of the leaders of IP prospecting in the USSR.

The mathematical and physical theory of the IP method were first developed in the USSR by Y. P. Bulashevich.

Early instrumentation employed large dc transmitters, rated for currents up to 25 amperes. Transient decay waveforms were recorded on oscillographs. Portable and vehicle-mounted systems were subsequently developed. They used both dc (square waveform) and sinusoidal current waveforms, although the former appears more prevalent. By the middle of the 1960s, IP had become the primary electrical method employed in the USSR in exploration for sulphide-related mineral deposits (Figure 4). Both surface and borehole measurements were made, the latter in the exploration for deep-seated deposits.

Further theoretical and laboratory studies were carried out in the USSR on the nature of both metallic and nonmetallic IP responses. The nonmetallic responses were attributed to diffusion potentials, caused by local solution concentration changes which in turn caused a change in ion transport numbers, in places of capillary cross-section variations. The dependence of the sulphide IP response on the particle size distribution of the mineralization provided the means to determine the textural parameters of ores. Equations were developed which could express the polarizability of any type of rock as functions of kinetic and structural parameters of their capillary system. Nonlinear electrochemical effects at mineral anodes and cathodes were also investigated, and this became the basis of other methods (e.g., those known as "contact method" of polarizing curves, KSPK and "contactless method" of BSPK) for the qualitative and quantitative determination of the specific mineral content of sulphide deposits.

Although there is no documentation, by the late 1950s there was already some cross-fertilization in IP between USSR geophysicists and their counterparts in North America, including visits between Komarov and Ted Madden.

Before we leave the Russian chapter, we add an interesting footnote concerning the application of IP to oil exploration in the USSR. As indicated, the method was first introduced into the USSR (by Schlumberger) for well logging, and it continued to be used for this purpose. Surface IP measurements in the USSR unexpectedly revealed IP anomalies over oil and gas deposits. Further investigation revealed pyrite mineralization in the rocks capping the hydrocarbon deposits. This association was later followed up by the Chinese. Thus, by the middle 1960s, the theoretical basis and field practice of the IP method of mineral (and hydrocarbon) exploration had reached a relatively high level in the USSR.

**Early activity in western Europe.** Following Schlumberger, several workers in western Europe, among them Mueller, attempted to measure the decay of so-called "polarization" emfs, through the distortion of sinusoidal voltage waveforms. Unfortunately, they used a single pair of electrodes for the passage of primary current and the measurement of polarization effects, thus introducing sources of error larger than the effects they were attempting to measure.

By the middle of the 1950s, likely inspired by their close relationship with USSR, workers in East Germany, Yugoslavia, and Sweden started to investigate the use of the IP method, both in theory and practice. Papers on the theory of the method were published by Buchheim in 1957 and Malmqvist in 1960. In the latter, Malmqvist solves the diffusion equation and derives an expression for the time-domain response involving Gauss' error integral. His theoretical presentation proved to be in excellent agreement with laboratory experiments on mineral samples.

Buchheim and Malmqvist collaborated in the application of IP to exploration for mineral deposits in Sweden. Also at this time, Frank Sumi in Yugoslavia published a number of IP case histories, the earliest publications in English in Europe.

**Developments in North America.** Important research on IP did not begin in the United States and Canada until World War II, but it quickly became widespread, and important advances resulted from work by the military, private industry, and academia.

*The U.S. Naval Ordnance Laboratory.* The seed which led to development of the IP method in North America was planted during World War II, apparently without knowledge of the prior Soviet work or the monographs and 1939 patent of Conrad Schlumberger. Driven by the urgent wartime need to develop a detector for mines along enemy shores, in anticipation of the amphibious landings in Europe and the Pacific, the U.S. Navy established, in 1942, a section in its Naval Ordnance Laboratory (NOL) to carry out research on "underwater electric potential (UEP) phenomena." This research was top secret during the war and for some years thereafter, although breaches of security developed shortly after the war's end. Scientists involved with the UEP program included physicist/geophysicist William Rooney (codeveloper of the Gish-Rooney method) of the Carnegie Institution and William Keck, a physicist/geophysicist from Michigan State University with experience in electrical measurements in the marine environment, who was the project supervisor. Joining the project in May 1943 was David Bleil, a student in the Physics Department of Michigan State.

The UEP project successfully developed a device to detect beach mines that could be towed by a Navy frogman. The device was pole-like, with a current electrode at each end, through which an interrupted square wave current was passed, each pulse being 1–2 s in duration. Transient decay voltages were measured across two nonpolarizing potential electrodes. The presence of a buried metal mine was indicated by a significant increase in the observed transient decay voltage. The principle on which the device functioned was designated "induced electrical potential" or IEP. It is not known who originated the concept for this device. Keck vigorously denied any knowledge, at that time, of the early work of Conrad Schlumberger.

One of the frogmen who participated in testing this device was Edgar O. McAlister, an experienced mining engineer with Anaconda Copper Company. Shipments of the first production models, designated the RX-1 Beach Mine Locator, were made to Okinawa in May 1945, presumably to be used in the invasion of Japan. Fortunately or otherwise, the RX-1 never saw active deployment, as the war ended abruptly in August 1945. The UEP project was terminated, and McAlister returned to Anaconda, where, for some years, he kept his wartime IEP work in total secrecy.

Bleil, on the other hand, became interested in the possible application of the IEP method to the detection of buried mineral deposits, and proposed this as his PhD research at Michigan State. NOL, however, wished to retain Bleil on staff and offered assistance and facilities for his thesis work. In the first year of this research (1945), Bleil became aware of Schlumberger's paper trail. He conducted laboratory tests of polarization effects on many types of metallic targets and graphite. He commenced field work in the following year on three sites in Virginia and Pennsylvania, which had been selected with assistance from the USGS and which contained deposits of pyrrhotite and magnetite. Bleil completed his field and laboratory work by October 1947. His PhD dissertation, accepted in the spring of 1948, demonstrated significant IP responses over known sulphide bodies, and provided an experimental basis for the method and an understanding of the underlying electrochemical phenomenon.

Bleil made an oral presentation on this subject at SEG's 1948 Annual Meeting, and an abstract was published in GEOPHYSICS. A condensed version of his thesis was published in GEOPHYSICS in 1953. These publications constituted the first in the North American literature about the possible application of IP to mineral exploration. Bleil coined the phrase "induced polarization" for this method, and the term has stuck. Figure 1 shows a contour plan of "IP susceptibility" over a known magnetite body in Lebanon, Pennsylvania, buried under 50 ft of glacial till. These results were obtained by Bleil in 1947, using a Wenner array with a spacing of 50 ft.

Bleil returned to NOL on the completion of his PhD and abandoned work on IP in favor of aeromagnetic detection methods, a subject of more pressing importance to his employer. However, the publication of the abstract of his SEG talk in 1948 sparked ongoing academic interest and research in the IP method. In addition, other members of the UEP project were central figures in two independent streams of IP development which occurred in the private mining sector.

**The Newmont chapter.** In the 1940s, Arthur Brant was an associate professor of physics at the University of Toronto. He was dynamic, forceful, very dedicated to the development of mining geophysical methods, and with strong convictions about many things other than geophysics. This is well described by Norman Paterson:

> Nothing got him more stirred up than what he considered to be the blindness on the part of government, business, and the general public to the numerous benefits provided by the mining industry. He had no respect for brokers, lawyers, accountants, administrators, bankers, salesmen, politicians and all who dealt in "shuffling papers around." Farmers, loggers, manufacturers, engineers, oilmen and, above all, miners, were the only ones adding to the economy, since they were creating value out of unused material. Arthur had a keen appreciation of the factors behind successful mineral exploration, one of which was, "You don't find mines without drilling holes."

Brant also enjoyed a thriving consulting practice (somewhat to the detriment of his academic commitments). One client was Newmont Canada Limited. In 1946 the senior management (particularly Fred Searls Jr.) of the parent corporation, Newmont Mining Corporation based in New York, was interested in sifting through the wartime scientific advances to determine if any might be applied in mining. Radio Frequency Laboratories (RFL) of Boonton, New Jersey, was retained to do the study. RFL selected three technologies for further investigation, one of which was dubbed "ionic potential." The suggestion for this technology sprang from R. Kraft, an employee of RFL who had worked on the NOL mine detection project. RFL, at Newmont's request, conducted further laboratory study of the phenomenon. These experiments by Everett A. Gilbert, using samples of porphyry copper ores as target material, demonstrated the polarization response of such samples.

Newmont immediately requested that RFL construct field equipment to carry out in-situ tests and, in 1947, Brant was retained to consult on the research. A 20 kW, 1000 V dc generator was constructed and mounted in an Army surplus radar truck. Switching was manual, using high-voltage vacuum switches. An oscilloscope measured peak transient voltages immediately after the interruption of the charging current. Field tests began in the fall of 1947, at Tintic, Utah, and Kimberley, Nevada, with Walter Heinrichs, a geophysicist with the U.S. Bureau of Reclamation, as party chief. Results were somewhat confusing, with polarization responses observed over both mineralized and unmineralized areas, and it was apparent that peak measurements were inadequate, no doubt because they emphasized electromagnetic effects. Based on these results, a Grassot fluxmeter replaced the oscilloscope. This was a critically damped galvanometer which integrated the charge passing through it, using optical amplification of the galvanometer mirror displacement to achieve high gain. The field procedure involved passing current through the Earth via two electrodes for about 30 s, manually interrupting the current, and then manually recording the deflection of the fluxmeter—i.e., the integral of the voltage under the transient decay curve—for 3 s. All timing was by stopwatch.

Patents were applied for on the approach at this stage (Brant and Gilbert, 1952). The disclosure to these patents is interesting, as it makes no reference to the earlier published work of Schlumberger (Schlumberger, 1920) or to his 1939 U.S. patent in the mineral field, while acknowledging a U.S. patent using a similar approach in the hydrocarbon field (Potapenko, 1940).

In 1947, Brant informed Harold Seigel, a graduate student in physics at the University of Toronto, that the U.S. Navy had developed a method for the detection of mines, by observing the transient decays after the passage of current through the water. He suggested that Seigel investigate the basic phenomenon involved, and how it might be applied to detect the distribution of metallic particles in the Earth. At that time, porphyry copper deposits were an economically important resource which did not respond to the available roster of mining geophysical methods (electrical, electromagnetic, gravity, and magnetics). Seigel reviewed the electrochemical literature and identified the responsible phenomenon as "overvoltage." By experiment in a water tank with a magnesium sphere as model and a ballistic galvanometer as detector, he was able to observe the anticipated overvoltage response of a metallic body in an electrolyte. He presented his findings in a thesis for the National Research Council of Canada in 1948. His thesis also included his first attempt at a representation of the response from a volume distribution of metallic particles, in anticipation of the application of the phenomenon to mineral exploration.

With Brant's encouragement, Seigel began his PhD research on the theory and application of the overvoltage phenomenon to mineral exploration. Through the summer and fall of 1948, under the auspices of Newmont, Seigel conducted extensive field tests of the method on a copper/molybdenum porphyry deposit at San Manuel, Arizona, then under an early stage of investigation by drilling. The field equipment employed on these tests was that developed by RFL, first employed in Utah and Nevada the year before, and later modified. As Schlumberger had before him, Seigel encountered polarization responses from all rocks and soils, whether mineralized or devoid of metallic sulphides. However, after numerous tests under diverse geologic environments, Seigel concluded that by ratioing each polarization response by its corresponding dc primary field (i.e., ohmic voltage), the polarization responses in nonmineralized rocks and soils (which he called the "normal effect") fell within a relatively small range of low values. Both Schlumberger and Bleil (independently) had adopted this same ratio for presentation of their polarization measurements and Polyakov, following the lead of Schlumberger, also used it. Seigel found that polarization responses from as little as 1% by volume of metallic sulphides were readily detectible, over and above the limits of the normal effect background. Thus, by the fall of 1948, he was able to demonstrate that IP was a viable tool in exploring for porphyry copper type deposits.

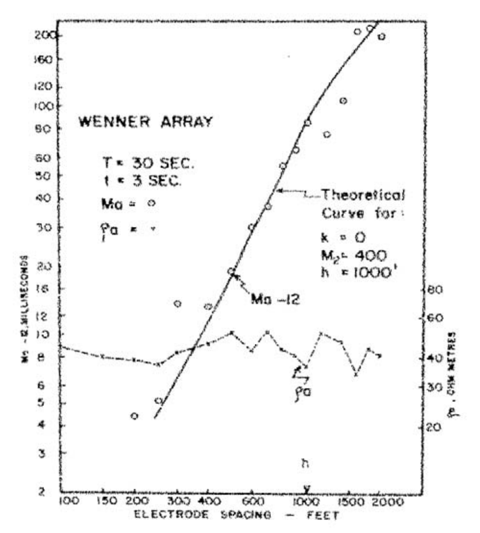

***Figure 2.*** *The results of an IP and resistivity depth sounding over an extension of the San Manuael porphyry copper deposit in Arizona, using a Wenner array, a charging time of 30 s, and a transient integration time of 3 s. This site was about 400 m in advance of the existing drilling on the deposit at the time (October 1948) of the survey. The geologic environment consisted of Tertiary Gila conglomerate overlying mineralized quartz monzonite porphyry. The two-layer IP interpretation predicted mineralization to occur at a depth of 1000 ft depth. Later drilling found the depth to be 1100 ft. This case history may be the earliest example of an IP base metal "discovery," at least in North America. The small resistivity contrast between the mineralized porphry and the overlying conglomerate demonstrates the importance of the IP information (from Seigel, 1971).*

That fall Seigel conducted the first actual exploration "wildcat" IP surveys, in the form of Wenner array depth soundings, on areas of unknown but prospective geology in the San Manuel area. One sounding, well away from the San Manuel exploratory drilling grid, revealed indications of high polarization from considerable depth. Using a two-layer mathematical model which he had developed, Seigel interpreted the depth to the upper surface of the unknown source to be about 300 m. Later drilling revealed the source to be an extension of the vast San Manuel porphyry copper deposit, under 330 m of Gila conglomerate (Figure 2). Seigel incorporated his mathematical development and field experimental results into his 1949 dissertation. At the request of Newmont, his thesis remained unpublished and even withheld from library circulation for some years, a rather unprecedented restriction on a PhD dissertation.

It was only while preparing his dissertation that Seigel became aware of the work of Bleil, then only available as the abstract of his SEG address. Needless to say, this caused Seigel some concern until it became clear that Bleil's field investigations were quite limited, and that he had not really recognized nonmineralized responses, nor confronted the need to resolve them from metallic mineral responses.

In 1949 Brant left the University of Toronto and joined Newmont full time, induced by a mandate to set up a research-oriented geophysical division, later named Newmont Exploration Limited. A geophysical laboratory was established in Jerome, Arizona. In 1949 further investigations were carried out in the IP method, including theory, rock property studies, improved instrumentation, and actual field exploration surveys. Brant recruited a talented team of recent graduates in physics, geophysics, and electronics. The large group from the University of Toronto included Robert Baldwin, Ewart Blanchard, Leonard Collett, John Dowsett, Ken Ruddock, Seigel, Don Wagg, and Jim Wait. Geophysicists Walter Heinrichs and Bob Thurmond came from the United States. Other talented geophysicists and electronic engineers who were added in the following two years included Bob Uffen, Earl Bell, Robert Searls, Duncan Crone, and Gordon Wieduwilt. Under Brant's dynamic leadership, and with the full support of Searls, this group made major advances in mining geophysical theory and technology over the ensuing decade. These advances were not restricted to the IP method but included time-domain and frequency-domain EM prospecting, both ground and airborne.

For the first half of the 1950s, Newmont kept its new IP method totally confidential and used this period of exclusivity to gain leverage in joint exploration programs with other companies. The first publication on the subject, a 1959 monograph edited by Wait, summarized the results of the IP field work by the Jerome group to that time. Among the highlights of this research were Seigel's mathematical formulation for the IP response of a medium with regions with diverse resistivity and IP "chargeability" which established the fundamental theoretical basis of IP interpretation. The physical properties laboratory, under the direction of Collett, made important contributions to the understanding of the IP phenomenon, including the influence of such factors as current density, type and amount of electrolyte, the response from diverse metallic minerals and graphite, metallic particle size, and mineral concentration. Until 1950, all Newmont IP measurements were in the time domain (transient). However, laboratory measurements that year by Collett and Seigel showed that the ac apparent resistivity of sulphide samples decreased markedly as the frequency was increased. The equivalence of this approach to IP measurements with the time-domain IP excitation was quickly recognized, and Wait developed the appropriate theory for this approach. Some frequency-domain field tests were carried out in 1950–1951 in the Jerome area, but this research was discontinued in favor of the time domain, because of considerations of sensitivity and instrumental complexity (at that time).

Those who pioneer with a new geophysical method will be the first to encounter the perils of the unknown. As Newmont's field experience with IP accumulated in different locations and in geologic environments, unexpected

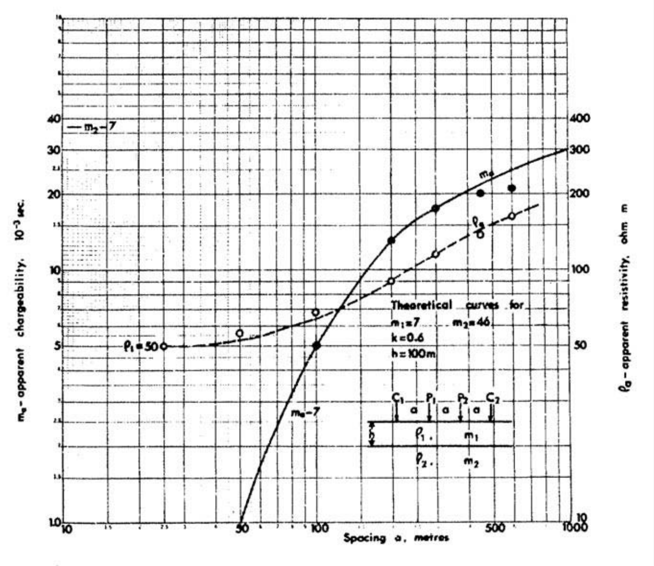

***Figure 3.*** *The results of an time-domain IP and resistivity Wenner array depth sounding obtained on a porphyry copper deposit in the Cuajone area of southern Peru in 1952. The current cycle was 3 s on/off and the transient voltage was integrated over 1 s. The deposit lies in an intrusive porphyry, overlain by a later unmineralized volcanic flow. The purpose of this and other depth soundings over this deposit was to map its areal distribution, depth, and sulphide content under the volcanic cover. The two-layer interpretation indicated that mineralized porphyry lies under 100 m of volcanic cover, and has a higher resistivity than the overlying volcanic flow. This was, undoubtedly, the first IP survey executed in South America (from Seigel, 1958).*

responses were encountered. For example, strong (nonsulphide) IP responses were almost invariably found in the vicinity of manmade metal structures, such as grounded metal fences, pipelines, and railway tracks (underground surveying in mines). After some erroneous conclusions, these were finally acknowledged to be due to the current gathering effects of these long, man-made conductors. One humorous and humbling experience helped establish this conclusion. A Newmont IP crew, working on an old road along a section of Mingus Mountain near Jerome with numerous small copper showings, kept getting exciting responses in a number of places. Phelps Dodge Copper, a joint venturer on this project but not privy to the IP technology, sent E. E. "Red" Maillot (mining engineer) and George Rogers (geophysicist), from their exploration staff, to observe the survey. They made a few SP measurements in the vicinity of the Newmont IP responses and found corresponding strong SP indications, whose source was discontinuous sections of an old pipeline. It was now clear why the mountainside road on which the survey was being done was called the Pipeline Road!

Certain rock types, such as ultramafic rocks, even without appreciable sulphides or magnetite, typically showed higher than normal IP responses. Also, although IP responses from graphite were anticipated, certain dark limestones were found to have a high IP response. On chemical analysis, these proved to have several percent of free carbon content, presumably somewhat electronically conducting.

Under Ruddock and Bell, continuous improvements continued in transmitters and detection systems. By 1950 drillhole IP arrays were developed and used in surveying surface and underground boreholes in mines in Jerome and in Leadville, Colorado. Electromagnetic coupling effects arose in this work but were quickly recognized and circumvented by appropriate shielding of the cables. Electrode arrays were devised for surface and borehole applications. Depth soundings employed the Wenner array. Profiling employed the "three-electrode" array, (pole-dipole) for surface and borehole, or the "two-electrode" array (pole-pole) on surface only. For each type of array, theoretical type curves were developed for the responses of two-layer earths and tabular bodies, to assist interpretation. Wait provided indispensable theoretical support, both in relation to the IP responses and the analysis of electromagnetic effects intruding into the IP transients. Of course, Wait is even better known for pioneering the theoretical development of the propagation of electromagnetic waves in the Earth, particularly as applied to mineral exploration. He also was the first to suggest the use of the impulse function waveform in EM exploration (time domain).

By 1951 Newmont IP crews were at work in the United States, Canada, Peru, and several countries in southern Africa. The IP survey in the Cuajone area of southern Peru, with Bob Baldwin as party chief, was particularly rewarding, in its material contribution to the delineation of the major porphyry copper deposit there (Figure 3).

Many of the original group of geophysicists and engineers later pursued distinguished careers elsewhere. Seigel (Scintrex), Ruddock and Bell (SpectraPhysics), Wagg (Geoterrex), Heinrichs (Heinrichs Geoexploration Company), Wieduwilt (Mining Geophyical Surveys), and Crone (Crone Geophysics) founded companies. Wait (National Bureau of Standards and the University of Arizona), John Dowsett (INCO), Uffen (Queen's University, Kingston), and Collett (Geological Survey of Canada) advanced to senior positions at major companies or other institutions. Brant continued to direct Newmont Exploration, with emphasis on research in geophysical methodology until his retirement in 1975. In summary, within a very few years, under Brant's direction, the group of young scientists and engineers that he assembled in Jerome, had accomplished their basic task of establishing the IP method, in theory, in instrumentation, in field practice, and in interpretation, as a sensitive and effective geophysical tool for the exploration for porphyry copper deposits. In order to do so, they overcame numerous obstacles, chief among which was the ubiquitous polarization responses from all rocks. They concentrated on the time domain but were the first to recognize the equivalent frequency-domain approach, although, after due study, they found it advantageous to persevere in the time domain.

**The Anaconda chapter.** The Anaconda chapter takes us back to the wartime NOL research in which Ed McAlister was a frogman who tested prototype mine detectors. After the war, McAllister returned to Anaconda, where he founded a Geophysics Division. Mac's formal education was in mining engineering, which means that he started his career with a good working knowledge of ore deposits and the economics of their extraction. However, he had an excellent grasp of geophysics, and no fear of delving deeply into mathematics, electrochemistry or electronic design. These attributes made him well qualified to direct the Geophysics Division of Anaconda.

The beach mine project was classified top secret, and it is a tribute to the McAlister's integrity that he kept his wartime experience fully confidential, even from his employer, although he was aware that the technology developed in that project held considerable promise for mineral exploration. This self-imposed confidentiality ended with Bleil's SEG presentation in 1948. Mac thereafter felt free to pursue IP research at Anaconda.

At the request of Reno Sales, chief geologist of Anaconda, Mac's initial IP research objectives were to develop criteria for detecting copper sulfide deposits and distinguishing between pyrite and chalcopyrite, a major problem in porphyry copper exploration. Mac and his staff conducted considerable research in the nonlinear electrochemical characteristics of these two minerals and others which exhibited IP responses. This was called the EC (for electrochemistry) method. Mark Halverson was hired to assist in this research. One approach to EC measurements, applied to excite and detect these nonlinear mineral characteristics, was to superimpose two simultaneous square waveforms in the ground, one with a long period (e.g., 250 s on-off) called the modulation component, and the other a much shorter period (e.g., 3 Hz), continuous wave, called the carrier component. The nonlinearity of the impedance measurement of the carrier signal signified the EC effect. Extensive field tests of this mineral discrimination approach were made at 184 sites in Canada and the United States, which contained both pyrite and chalcopyrite (or other copper minerals). In about 80% of these tests, copper minerals were correctly identified through analysis of their IP responses. However, Halverson concluded that, overall, this approach would have had limited success in actual exploration programs, due to the effects of mineral grain size, particle interconnection, and sulphide body shape. He also concluded that the practical depth of excitation of EC effects was limited to a few tens of feet, due to the need to create the necessary threshold current density, and therefore was not amenable to areas covered with thick alluvium. Eventually, Mac decided to abandon research in EC in favor of linear spectral IP.

Under Mac's direction, significant advances were made in IP instrumentation and field practice. The early field instrumentation employed rather high-frequency (time domain) waveforms, of the order of 3 Hz. When these were found to be prone to EM effects at larger electrode spacing, the operating frequency was progressively reduced, to 0.125 and to 0.025 Hz. One important development made by Mac was the improvement of signal/noise when searching for very deep exploration targets, such as porphyry copper deposits, under considerable valley fill. For the large electrode spacings required for deep exploration, the measured signals decrease as the inverse first power of the spacing. The telluric noise, however, commonly increases in proportion to the spacing. To minimize this S/N problem, in the late 1950s, Mac devised a telluric canceling system, using the signal from a reference bipole, in line with the electrode array. This scheme effected telluric cancellation for one potential dipole. One electrode of the bipole was the potential electrode farthest away from the current electrode. The second electrode of the bipole was placed at a large distance further along the direction of the array (i.e., "at infinity"). The potential dipole and the telluric-cancellation bipole were then connected to a resistance bridge. The bridge was balanced prior to the IP measurement, so that the telluric noise on the potential dipole was cancelled by the telluric noise from the bipole. The IP reading would then be taken, with the telluric cancellation bridge in place. There will be some ohmic and IP signal in the bipole cancellation signal (e.g., 1:1 for a pole dipole array), resulting in some distortion of the desired IP measurement from that dipole. In theory, however, the telluric signal from the bipole will be much larger than that from the dipole, so that a proportionately smaller corruption of the latter's ohmic and IP signals would result from the bridge cancellation process. The process would, in the 1970s, be adapted to what Anaconda referred to as real time telluric cancellation. It was in essence the bridge-based cancellation concept adapted to digital acquisition across a line of potential dipoles: the tellurics cancelled from the potential-dipole data with no preliminary noise monitoring period needed, the telluric bipole now bracketing the roving current electrode and line of potential dipoles.

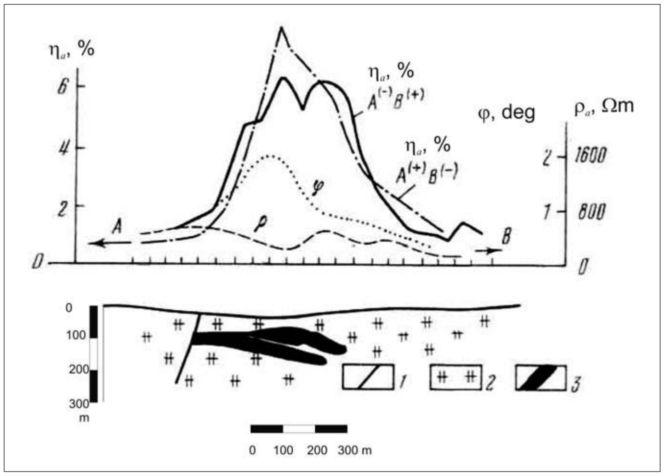

*Figure 4.* *The results of dual time-domain and frequency-domain IP and resistivity traverses over a known polymetallic deposit in the Altai region (USSR) in the late 1960s. The deposit lies in volcanics and comes within about 30 m of the ground surface. These traverses employed the Schlumberger array with AB = 1200 m and MN = 20 m. For each measurement, charging current flowed for two minutes and the residual transient after 0.5 s was measured. Dual time-domain profiles of apparent polarizability (nk) are shown, for different polarities of the charging current flow. The small differences in nk for the different current polarities are attributed to nonlinear effects. Also shown are the results of the corresponding frequency-domain profile. The IP parameter measured was the phase shift of the measured voltage, using a frequency of 2.44 Hz. The deposit does show as a minor resistivity depression, but is much more clearly indicated by its IP response, both in the time and frequency domains (after Komarov, 1980).*

Other advances made by Mac's Anaconda group during the 1950s and 1960s included the development of a spectral IP model by Halverson, based on particle radius R and a second parameter k, which he has shown to be transformably equivalent to the parameters t and c of the Cole-Cole model proposed by Pelton et al. (1978). Using this mathematical model, IP transient decay curves were analyzed by computer to derive the R and k parameters, in the hope of mineral differentiation, not only in particle size but also in kind. Anaconda's advances in IP and EC during these two decades were kept proprietary.

Thus, starting from McAlister's direct experience with the NOL beach mine project and totally independent of Newmont's activities, Anaconda developed its own IP theory and practice by the middle of the 1950s. Their research emphasized basic IP responses (linear and nonlinear) of metallic minerals, with the objective of differentiation of responsive mineral species. Field tests of the theory met with some success. Inversion to 1D and 2D models was applied, and telluric noise cancellation was developed and effectively applied using reference bipoles, which was very valuable in IP exploration for deeply buried deposits.

**The MIT chapter.** In our story thus far, we have seen two productive IP development streams, each supported by a major U.S. mining company. Each sprang, directly or indirectly, from a member of the wartime NOL beach mine detector team. In addition, a third member of the NOL team, David Bleil, was the first in North America to actually investigate the mineral exploration possibilities of the NOL research. Bleil abandoned this line of investigation in favor of ASW aeromagnetic research but his 1953 paper struck a responsive chord with Ted Madden, then a lecturer at the Massachusetts Institute of Technology. Madden was a bright, charismatic individual and a great lecturer. He was also an ardent sportsman, with a keen interest in hockey, tennis, and lacrosse. Oceanography was another interest, and he participated in several cruises with Maurice Ewing.

Madden talked to Arthur Brant and Victor Vacquier to gain some insight into the IP research in which Newmont and others were engaged. From the beginning, as a departure from the precedents of Newmont and Anaconda, Madden determined to use sine wave current forms in his research, and to develop portable equipment.

Initially Madden made ac resistivity tests on rock samples in the laboratory. Then, in the summer of 1954, he and two students, Keeva Vozoff and Philip Hallof, made field tests over the South Ore Zone of Mindamar Mine on Cape Breton Island, Nova Scotia. In this field program, Madden developed the dipole-dipole array for profiling, and the practice of presenting profile results in 2D pseudosection form for both resistivity and IP response. The latter were presented both as percent frequency effect (PFE) and the PFE normalized by the apparent resistivity—i.e., the metal factor (MF). This profile presentation permits the separation of lateral and depth physical parameters and has been widely employed in IP surveying ever since. The equipment, also developed by Madden, used a small dc generator and battery-operated voltmeters. To produce the ac currents, choppers were made using mechanical switches and motors taken from hand-cranked phonographs, then to be found only in Salvation Army shops around Boston. The transmitter was operated from a small motor-generator in the back of Madden's station wagon. On the road, the latter consumed as much oil as gasoline.

In subsequent years, Madden continued his IP work with a series of unusually bright students—Yed Angoran, Tom Cantwell, Tony Hauck, Randy Mackie, Don Marshall, Dale Morgan, Phil Nelson, Tony Neves, Bijan Nourbehecht and Bill Sill. The Division of Raw Materials of the U.S. Atomic Energy Commission, sponsored IP research at MIT from 1956 to 1959. This research led to four reports, authored by Madden and colleagues, which focused on theoretical and laboratory studies of induced polarization effects in nonmetallic minerals, and their causes. The last AEC report was published in GEOPHYSICS in 1959. In the course of this work, Madden's group adopted the electrochemical term "membrane polarization" for some nonmetallic sources, "percent frequency effect" for the amplitude of the basic IP measurement, and "metal factor" as a ratio of two electrical physical properties to normalize for resistivity and emphasize the IP response from bodies of increased conductivity. To describe the entire process, they incorporated the electrochemical Warburg impedance into an electrical circuit model of IP effects.

In 1954–1957, the MIT group collaborated with geophysicists in several mining companies, including Ralph Holmer and George Rogers at Bear Creek Mining (Kennecott Copper Company), Calumet and Hecla Mining, National Lead Co, Stan Ward at Nucom (American Metals), and John Sumner at Phelps Dodge Copper, and introduced them to the MIT brand of frequency-domain IP technology. Through these companies and these individual geophysicists, IP became widely disseminated and put into mineral exploration practice. Madden's work also led to much smaller, portable IP equipment, which facilitated the use of the IP method in diverse geologic and logistical conditions.

Finally, starting in 1969, on behalf of Anaconda, Madden and Dick Harter developed, demonstrated, and delivered efficient 1D and 2D IP inversion code, and Vozoff provided telluric cancellation algorithms, all growing out of the MT modeling and inversion at Geoscience Inc.

Vozoff joined McPhar after receiving his PhD in 1955. He brought finite difference numerical modeling and inversion to Canada, prompting Stan Ward to claim he would "invert everything." Later, Vozoff teamed up with Tom Cantwell and Madden, who had formed Geoscience. He then went on to a career in academia and consulting, with special emphasis on magnetotelluric exploration. In the course of this work, he attempted to measure IP effects using natural magnetotelluric fields, over a deep porphyry copper deposit at Safford, Arizona, where he had done conventional IP surveys earlier. However, the technology of 1960 did not have the sensitivity required. In 2005, Gasperikova et al. reported limited success in their attempt to do the same.

Hallof completed his PhD and joined McPhar in 1956. He ultimately helped that company become the world's foremost contractor of frequency-domain IP surveys. In conjunction with Pelton, Ward, Phil Nelson, and Bill Sill, Hallof subsequently extended the application of spectral analysis to extract EM coupling and Cole-Cole parameters from IP data.

Sumner joined the University of Arizona faculty in 1963, where he continued his research on IP. Ward went to the University of California at Berkeley and later to the University of Utah, where he and his students contributed greatly to the understanding of the IP phenomenon through rock property measurements, improved modeling, and inversion.

**Other early IP activity in North America.** Bleil's article in GEOPHYSICS and the migration of personnel from the two major mining companies that had developed and actively applied IP provided the impetus for other entities to enter the field.

A group at the New Mexico Institute of Mining and Technology, under Victor Vacquier (one of the wartime developers of the first airborne total field magnetometer) and which included Paul Kintzinger (an ex-Newmont geophysicist), applied IP to groundwater exploration. The specific objectives were to differentiate strata, on the basis of the content of dirty sands and clays, to explore for potential aquifers. IP responses from clay-bearing horizons were attributed to membrane effects in the clays.

By the middle of the 1950s, several companies had been established, in the United States and Canada, to provide contract IP services to the mining industry. These included McPhar Geophysics, Seigel Associates, and Huntec in Canada, and Mining Geophysical Surveys and Heinrichs Geoexploration in the United States. Zonge Engineering and Research Organization followed shortly. Each conducted some research and development activity, with emphasis on instrumental development and efficiency in conducting field surveys. McPhar and Zonge preferred to work in the frequency-domain; the others remained devoted to the time-domain approach. For competitive purposes, each service company extolled the relative advantages of its preferred approach—the frequency-domain people emphasizing their better signal/noise, and the time-domain people emphasizing their sensitivity and broadband information content. When caught off guard, each group might admit that the two approaches, when properly performed, really yielded equivalent geophysical data, but the debates between the groups enlivened many otherwise boring meetings.

Also starting in the 1950s, several universities (University of California at Berkeley, Michigan Technological University, Missouri School of Mines, University of Utah) and the U.S. Geological Survey became interested in IP research. George Keller, at the Colorado School of Mines, developed a large field survey facility and trained many international students. He was also one of the first in North America to take a serious interest in activity in the USSR. He learned Russian and translated, with USGS support, many papers. For many in the West, this was the first indication of the high quality and quantity of the Russian work (Figure 4).

**Later developments.** In 1965, Kennecott Copper Corporation formed a subsidiary, Kennecott Exploration Incorporated (KEI), to carry out research in geology, geochemistry, and geophysics. Under G. D. Van Voorhis and G. W. Hohmann, KEI did extensive research on IP properties of rocks, receiver design, borehole logging, and numerical modeling.

By the middle of the 1960s, IP technology had been exported to Australia, Africa, South America, and Europe, either through the overseas activities of the North American mining community, or through the contract service companies. Also by this time, much closer communication had been established between the IP development streams in the USSR and North America, allowing cross-fertilization of their respective ideas. The Soviet geophysicists and their publications spread time-domain IP technology throughout the USSR satellite countries and China, and stimulated research in IP in these countries. As mentioned earlier, in Yugoslavia, Frank Sumi applied the method to the exploration for metallic deposits but also experimented with it for clays, bauxite, barite, chromite, and groundwater.

By 1965, IP had become the worldwide tool of choice in the exploration for buried porphyry deposits and bedded lead-zinc deposits, and discoveries followed swiftly. The earliest documented example of IP's contribution to the exploration for buried mineral deposits was in 1948, the extension of the San Manuel deposit, at 300 m depth (Figure 2). Shortly thereafter was the delineation of the Cuajone porphyry copper deposit in southern Peru, under 100 m of later volcanic flows, in 1950 (Figure 3) by a Newmont crew directed by Bob Baldwin. An early lead-zinc discovery with IP was the Pyramid deposit in Canada's Pine Point area, Canada. These case histories illustrate the best application of IP, namely the detection of disseminated sulphide ore deposits which are not clearly distinguishable by other electrical techniques. In addition to its early application to the exploration for porphyry copper and lead-zinc deposits, IP has been very fruitful in the search for sulphide-related gold deposits (e.g., in the Carlin area of Nevada).

**Conclusion.** Having traced the history of IP to a very healthy plateau of theoretical understanding and field practice in 1965, we have arrived at a convenient point to end our chronicle. Of course many advances have been made in the science and practice of the IP method in the last four decades—in the theory of the phenomena involved; in the instrumentation, including multichannel receivers and improved signal processing; in interpretation (e.g., computer programs for forward modeling of complex geology); in inversion; and even through the measurement of the magnetic fields, rather than the electric fields, associated with IP polarization current flow (MIP). This last development opened up the possibility of the use of mobile, or even airborne, IP receiver systems. Under certain geologic conditions, there are recognizable IP effects in time-domain electromagnetic transients, both terrestrial and airborne. The problem of IP source discrimination stimulated considerable investigation. The use of a three-parameter Cole-Cole model was proposed and adopted, initially for multifrequency measurements. The same model was also adopted for time-domain measurements, derived from an analysis of the transient decay voltages. Characterizing observed IP responses in terms of their Cole-Cole parameters has proven useful in resolving different IP sources, but primarily through differences in their average particle size. Grounded metallic structures have been easily recognized by the long time constant of their IP responses. However, despite much effort, attempts to predict the mineralogical composition of an IP source by analysis of its IP response characteristics have not been very fruitful. Mineral discrimination has been shown to be feasible, but only when the source body is sufficiently accessible that nonlinear electrochemical responses can be created.

Data presentation and interpretation has been simplified, through evolution of Occam inversion of crosshole measurements, to give heavily smoothed images. A major trend is the attempt to relate detailed IP effects to rock physics for petroleum, environmental, and engineering applications. Enormous cumulative effort has been expended in trying to extract permeability, porosity, and clay content from electrical measurements on rocks and in wells. However, since the major breakthrough by Archie in 1942 in developing his (empirical) law, further improvements have been marginal at best. Simply trying to predict the dc resistivity of a specific clay-free, water-saturated rock on the basis of detailed microphotographs has not been successful, on account of the complexity of real rocks and pores. There has been more success in qualitative location of anomalous subsurface regions in wells and from surface (Olhoeft, 1992).

Thus, although still not fully understood about 90 years after the first recorded observation of the basic phenomenon, IP is firmly established, worldwide as a primary mineral exploration tool and one that is uniquely instrumental in the search for several important types of mineral deposits. We may anticipate progressive improvements being made in software and electronic hardware, but whether there will be basic advances in understanding the phenomenon remains to be seen.

**Suggested reading.** The authors have made extensive use of published references, listed below and organized according to the appropriate section. Particularly useful for our purposes has been "History of the induced polarization method" by Leonard Collett which was chapter 1 in SEG's 1990 publication *Induced Polarization, Applications and Case Histories*, and from which we have borrowed shamelessly. Extensive references were also obtained from this book and its editors—J. B. Fink, E. O. McAlister, B. B. Sternberg, W. G. Wiederwilt, and S. H. Ward. Ward's 1980 article in GEOPHYSICS, titled "History of geophysical exploration—electrical, electromagnetic, and magnetotelluric methods," was a thorough review on electrical methods which, however, lacked information about many central but important unpublished developments and the recognition of Russian and other European contributions. Konstantin Titov provided valuable input on the USSR developments. Finally, in addition to published material, we have been fortunate to have received recent input, in the form of personal reminiscences, of events and people, from many individuals who were central figures in the development of the IP method. These include Ed McAlister, Norman Paterson, Walter Heinrichs, Leonard Collett, Mark Halverson, Phil Nelson, and John Kingman. These interviews were particularly important in tracing Anaconda's role.

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***Figure 5.*** *Composite of photographs of contributors to the early development of the IP method: (a) Conrad Schlumberger, (b) Vladimir Komarov, (c) David Bleil, (d) Arthur Brant, (e) Harold Seigel, (f) Jim Wait, (g) Edgar McAlister, (h) Ted Madden, (i) Phil Hallof, (j) John Sumner, (k) Mark Halverson, and (l) Leonard Collett.*

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*Corresponding author: hseigel@rogers.com*