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Author Biography:

Peter J. Hood, B.Sc.(Hons) Physics, Univ. London 1953, immigrated to Canada in 1955 and received an M.A. 1956 and a Ph.D. 1958, both in geophysics, from Univ. Toronto. He spent 18 months in Sri Lanka on a Colombo Plan assignment carrying out a variety of mining geophysical surveys and interpretation of the existing aeromagnetic surveys. He joined the Geological Survey of Canada in 1961 and began an association with the Flight Research Laboratory of National Aeronautical Establishment, National Research Council in Ottawa to study offshore aeromagnetic patterns. He laid out the survey flight lines and flew on all sorties for 25 years of reconnaissance low-level surveys that included the Grand Banks of Newfoundland, the mid-Atlantic Ridge south of Iceland, the Labrador Sea and Baffin Bay to Greenland, Nares Strait, and the Arctic Ocean as far as the North Pole.

Outside of Canada, he was technical supervisor of aeromagnetic surveys in Guyana, Pakistan, and Zimbabwe (funded by the Canadian International Development Agency), and was a technical consultant to the Department of Mineral Resources of Thailand in drawing up the specifications for the airborne geophysical survey of Thailand in 1983. In 1989, he was a member of the GSC team that undertook a feasibility study for a systematic airborne survey of Indonesia (funded by the Asian Development Bank).

He improved aeromagnetic survey techniques and administered the federal/provincial aeromagnetic survey program in Canada from 1974 to 1987. He was program chairman of the second decennial Canadian international symposium on the application of geophysics and geochemistry to the search for metallic ores held in Ottawa in 1977 and was editor of the proceedings volume published by the GSC in 1979. He has lectured in many countries on geophysical topics. He co-chaired the committee that compiled the first Magnetic Anomaly Map of North America. Throughout his public service, he authored and edited 192 publications, including a widely-read annual worldwide review of new exploration geophysical techniques and instrumentation from 1965 to 1992 in the Canadian Mining Journal (26 years) and the Northern Miner (2 years).

Peter Hood retired from the GSC during 1991 following 30 years of service.

History of the Development of the GSC Aeromagnetic Gradiometer

by Peter Hood

May 04, 2009
Contribution to the GSC Historical Archive

The Geological Survey of Canada (GSC) has had an aeromagnetic survey program for more than 60 years. The **genesis of that program and its history** has been described in an article by the author in the November 2007 issue of *The Leading Edge* published by the Society of Exploration Geophysicists [SEG]. The present article is **confined to the development of the GSC aeromagnetic gradiometer** that was also described earlier by the author and Dennis Teskey in an article published in the August 1989 edition of the SEG publication *Geophysics*. That article also contains a more thorough discussion of the technical details and presentation of the vertical-gradient profiles over causative bodies together with survey results that support conclusions herein presented.

It will be appreciated that the carrying-out by the GSC Magnetic Methods Group of a nationwide aeromagnetic survey program for the benefit of the Canadian mining industry and the GSC's own and Provincial mapping geologists required input by a team of people with a wide range of knowledge collectively about aircraft instrumentation and recording equipment, compilation techniques and the drafting and publication of the final aeromagnetic maps. Such technology improved continuously over the years and it was vital that new improvements were incorporated into the contracts of the Federal-Provincial aeromagnetic survey program awarded to the various airborne survey contractors. Accordingly the GSC Magnetic Methods Group headed by the author had a staff of engineers, technicians, computer scientists, compilers and field and map inspectors to ensure that state-of-the-art techniques were employed and improved upon.

With the introduction of alkali-vapour [optical-absorption] magnetometers in the early 1960's that had a much higher sensitivity than those developed earlier, it was realized by the author that vertical gradient aeromagnetic surveys were feasible using two magnetometer sensors separated by a short distance vertically. The advantages of doing so were published in an article by the author entitled "Gradient Measurements in Aeromagnetic Surveying" in the October 1965 issue of the SEG journal *Geophysics*. The advantages that were pointed out included the fact that the diurnal [daily] variation of the earth's magnetic field which is caused by sunspot activity is automatically removed in obtaining the vertical gradient i.e. the difference between the magnetometer readings divided by their separation. It was also pointed out that steeply-dipping geological contacts would be outlined by the zero-gradient contour.

Initial Instrumentation Development

One of the important associations in the subsequent development process that was undertaken was the assistance of a group led by Lee Godby in the Flight Research Laboratory, National Aeronautical Establishment [NAE], NRC who were involved in the development of airborne magnetometry for anti-submarine warfare. The NAE group specialized in the magnetic compensation of military aircraft to reduce the magnetic noise produced by the steel components e.g. engines as an unavoidable result of the small rolls, pitches and yaws that all aircraft undergo in flight. Such magnetic noise reduces the range of detection of submarines and degrades the quality of the signal in aeromagnetic surveying and in fact determines the effective recording sensitivity.

The first joint project of the two groups was a low-level [200-foot elevation] aeromagnetic survey of an area of the Nova Scotian continental shelf south of Halifax using an RCAF Argus submarine patrol aircraft [No.722] based in Summerside, P.E.I. during the summer of 1962.The aircraft was flown along the purple Decca navigation lines of Chain 7 which were hyperbolae approximately oriented in a SE direction from the coastline. The magnetometer utilized was an AN/ASQ-8 military fluxgate magnetometer mounted in the tail stinger of the anti-submarine aircraft. The author and Margaret Bower, an experienced data monitor and compiler in the GSC Magnetic Methods Group, took part in the flying of the survey, and the latter compiled the resulting data into contour map form that were published as GSC 1:50,000 aeromagnetic maps in 1964. A number of sharp anomalies due to shipwrecks were removed from the published data whose positions were located on the classified Marine Wreck Charts and included a German U-Boat sunk in World War II — its position differed somewhat from that recorded by the accurate Decca navigation fix. Margaret Bower remained attached to NAE for the rest of her career and even past her retirement in 1988. She took part with the author in subsequent reconnaissance offshore surveys in the Atlantic Ocean, Labrador Sea, Baffin Bay, Nares Strait, Greenland and the Arctic Ocean as far as the North Pole over a period of 25 years. Many of these low-level flights were also a contribution to maintaining Canada's sovereignty in her Arctic islands.

At the end of the Scotian Shelf survey, it was decided to carry out some low-level offshore reconnaissance flights with the RCAF Argus aircraft, which being designed for long anti-submarine sorties, was ideally suited for such work. Flight lines for two such sorties were laid out by the author, who with Margaret Bower operated the data-recording equipment during the flights. The first traversed the large Grand Banks continental shelf area east of Newfoundland and included the Tail of the Banks and the shallow Flemish Cap. Depth determinations on the resultant profiles indicated sediment thicknesses in excess of 25,000 ft [7600 metres] between Newfoundland and the Flemish Cap. The results were published in the November 1965 issue of the Canadian Journal of Earth Sciences and were duly noted by the oil companies in Calgary. Much follow-up seismic work and drilling resulted in the discovery of the prolific Hibernia, Terra Nova and White Rose oilfields in the Jeanne d'Arc Basin.

The second sortie consisted of two low-level [305 m or 1000 ft] traverses across the Labrador continental shelf to the coast of Greenland. A series of distinct anomalies in the central part of the Labrador Sea repeated themselves on both flight lines. These results were communicated in a letter to the journal Nature published June 13, 1964[No. 4937] in which it was concluded that the linear pattern was indicative of typical sea-floor spreading anomalies similar to those that had been found off the west coast of North America by Scripps Oceanographic Institute. These interesting results obviously pointed out the value of an expanded offshore program but any further work using the Argus aircraft was abruptly stopped by the advent of the Cuban missile crisis. The RCAF was obliged to return Argus 722 aircraft to a state of military readiness. Thus to pursue the offshore work and carry out further magnetometer development, it was necessary for NAE to acquire a suitable long range aircraft.

Fortunately in 1963, the RCAF was willing to supply NAE with a North Star aircraft, which is essentially a DC-4 aircraft with [noisy] Rolls Royce Merlin engines but with an endurance of some 13 hours; actually the North Star was able to fly directly from Gander, Newfoundland to Shannon, Ireland at 1000 feet but because of the prevailing westerly winds had to land at the tip of south Greenland to refuel on the return to Gander. The North Star came with a RCAF air and ground crew who were seconded to NAE to fly and maintain the aircraft which was housed in the NAE hangar at Uplands airport in Ottawa, part of the NRC complex there that includes the NRC wind tunnel. A rubidium–vapour magnetometer had been purchased by the GSC from Varian Associates of Palo Alto, California and had been made available to the NAE group who soon satisfied themselves that it had the sensitivity claimed.

The rubidium magnetometer was initially towed in a bird from a winch on the starboard wing of the North Star to avoid magnetic compensation problems and demonstrated the repeatability and quality of the recorded data. After that demonstration the next step was to equip the North Star with a 30-foot long tail boom that extended from the tail of the aircraft in order to mount a second rubidium magnetometer in addition to that installed in the towed bird; this development was completed in 1964.The North Star with the trailing bird appeared in a 1966 film about the various endeavours of the Geological Survey of Canada entitled 'The Continuing Past'. Ile Haute Island in the Bay of Fundy was used as a backdrop on September 3, 1966 to photograph the North Star flying at low-level past the island. The movie camera used was mounted in the Plexiglas nose of an Argus aircraft kindly provided for the occasion by the RCAF. A scene in the film of the author operating the magnetometer recording equipment in the North Star was later filmed on the ground in Ottawa outside the NAE hangar at Uplands. While the film indicated that the author was in the North Star operating the magnetometer recording equipment, in actual fact he flew in the Argus to liaise between the RCAF crew and the NFB film director, Stephen Ford, on the various shots to be taken which included flying closely behind the towed bird. Fortunately the bird was on a long towline so it was well below the level at which the North Star flew and that meant that the Argus was not in the slipstream of the North Star with the consequent turbulence that the camera would have undergone. There were some very interesting sequences taken but most ended on the cutting-room floor.

In 1965, Peter Sawatzky, an electrical engineer and head of the GSC Magnetic Instrumentation Section and his two technicians, Aurele Dicaire and Howard Knapp, were attached to NAE and helped in the assembly of a digital system to record the output of the two high-sensitivity magnetometers, time and navigational data on a magnetic tape recorder. They also took part in an aeromagnetic survey of central Hudson Bay in 1965 that utilized the Decca Navigation System belonging to the [then] EMR Polar Shelf Project as the prime positioning system. The area surveyed was in the deepest part of the sedimentary basin that had been delineated by the author from 1961 sea magnetometer results and that interpretation was published in the December 1964 issue of the SEG journal *Geophysics*. That year a number of companies contracted by both government and oil-company organizations undertook geophysical surveys in Hudson Bay and that included marine seismic profiling. Many of the 1965 Hudson Bay results were presented at a symposium in Ottawa in 1968 organized by the author who edited the resulting proceedings volume published in 1969 as GSC Paper 68-53.

Much valuable experience in instrumentation and surveying practice was gained by GSC personnel as a result of the Hudson Bay and later offshore surveys such as those in the Labrador Sea and across the mid-Atlantic Ridge to profile the sea-floor spreading anomalies. Another resultant end product was the delineation of sedimentary basins on both the Labrador and SW Greenland continental shelves. The former were later drilled after follow-up seismic surveys were done by oil companies and yielded both natural gas and hydrocarbon fluids. Accordingly Peter Sawatzky began the design of a high-sensitivity digital-recording aeromagnetic survey system suitable for use in a small twin-engine aircraft. There was much testing of the system during the North Star flights and as a result in 1966, the system was redesigned and rebuilt for further testing. Further iterations continued during 1967 and 1968, and then with the experience acquired in successful test surveys it was decided to acquire an experimental survey aircraft in order to pursue the goal of building an inboard aeromagnetic gradiometer; in addition it was also clear that digital recording would result in many improvements in the compilation and interpretation of aeromagnetic surveys.

Acquisition of GSC Beechcraft Queenair Aircraft

The aircraft chosen by the Magnetic Methods Group in 1968 [and held as an item on the author's field equipment inventory in the departmental stores for the next 21 years!!] was a light twin-engine Beechcraft B80 Queenair aircraft which had sufficient range to operate from local landing strips in the Canadian North. The aircraft was initially equipped by Peter Sawatzky, an electrical engineer and his group [later joined by Dwayne Olson and Dick Flint] with a single rubidium-vapour magnetometer installed in a single tail stinger. A vertical-pointing frame camera was used for flight-path recovery. An active magnetic-compensation system manufactured by Canadian Aviation Electronics for the military was employed that was based on development work done at NAE. Actually provision for the recording of data from two sensors was made in designing the first Queenair data acquisition system, which also employed digital recording techniques on magnetic tape that were new at that time, and were later incorporated as a requirement into the standard Federal/Provincial contracts after the technique was well proven in inhouse surveys.

A number of high-sensitivity single-sensor surveys were carried out in the period 1970-73 and the results were contoured at 2nT[nanoteslas formerly called gammas] and even 1nT intervals demonstrating that the Beechcraft twin-engine aircraft could be utilized as an acceptable single-sensor high-sensitivity aeromagnetic survey platform.

Development of the Aeromagnetic Gradiometer

Thus after several years of survey work and fine-tuning of the magnetic compensation to reduce the figure-of-merit[FOM] to as low a value as possible, it was decided to proceed in 1973 with a two-sensor vertical-gradiometer installation on the tail of the aircraft. The design was initially based on the requirement to delineate the vertical gradient at a height of 305 m [1000 feet] above a dipping contact that had a measurable but small susceptibility contrast between the adjacent formations. The contact case is the most frequently encountered geometric model for geological formations in the Canadian Shield and is actually the worst case model in that the rate of fall-off of the total field is least than for other geometries. The vertical separation was chosen to be approximately two metres and was the maximum that could be easily achieved using a rigid stinger structure on the tail of the Queenair aircraft. It was found that the magnetic signatures that could be measured at the standard 305 m [1000 foot] flight elevation over the Precambrian Shield were significantly increased by reducing the survey height to 152 m [500 feet]. Because the inverse rate of fall-off with height of vertical gradient anomalies increases by one power over that of total field anomalies and consequently have shorter wavelength, it was also necessary to reduce the flight-line separation from the standard 800 m [0.5 mile] to 400 m [0.25 mile] to improve the contouring accuracy across flight lines. The basic recording sensitivity of the system was 0.005nT at a 0.5 second sampling interval. The uncompensated FOM of the aircraft using the US Navy definition was 3.4nT, but using the CAE 16-term active compensator, this was reduced to 0.4nT. With this FOM, a noise level of 0.02nT was achievable in the recorded data.

First Test Aeromagnetic Gradiometer Surveys

The first gradiometer survey was carried out in the Spring of 1975 in the White Lake area immediately to the west of Ottawa and the compiled results well demonstrated the improvement in resolution and the other desirable properties of aeromagnetic gradiometer data. A series of experimental surveys were then carried out to demonstrate the efficacy of the vertical-gradient technique in various geological environments. The Radioactive Waste Disposal program was getting underway at the same time, and the aeromagnetic gradiometer soon proved its value in unraveling areas of complex geology at the various possible disposal sites under investigation. Another particular highlight was the survey in the Wollaston Lake area on the east side of the Athabasca Sandstone. The gradiometer results were easily able to delineate the metasedimentary units at the edges of the uranium orebodies. Leslie Kornik in the Magnetic Methods Interpretation Section was also able to highpass filter the data to indicate the dominant glacial movement direction [because eskers are slightly magnetic]. Use of glacial flow direction to trace the origin of radioactive boulder trains was a prime exploration technique in the area.

With the decline of base-metal exploration in the late 1970’s, the only significant activity was gold exploration. In September 1979, the Association of Prospectors of Quebec requested a test survey in the well-known Abitibi mining camp. Because the Val D’Or 1:50,000 scale map area contains many gold mines, it was chosen for the test survey and this was carried out during June 1980. The resultant coloured vertical gradient and total field maps were published using the Applicon colour plotter. The correspondence of the Val D’Or mapped geology with the coloured gradiometer imagery was striking and it was readily apparent that many of the diorite plugs that are associated with gold have a magnetic expression and thus could easily be delineated by the gradiometer. The release of the published maps caused a flurry of exploration in the area and resulted in at least one new discovery, the New Pascalis prospect.

Development of Digital Compilation Methods

New computer-based techniques for the compilation of vertical gradient and its accompanying total field data also had to be developed and consideration given to their presentation in the final published maps. Michael Holroyd led the Compilation Section until his departure in 1980 to join Data Plotting Services in Toronto. His position was then filled by Dennis Teskey ably assisted by Dwight Dods, Ichbal Butt, Ken Anderson and Larry Lawley. In the late 1970’s, the first ink jet printer was introduced into North America by the Applicon Company in Boston. This revolutionary colour printer derived from a Swedish invention in which three ink jets, each for a different primary colour, shot computer-controlled bursts of ink onto a spinning drum around which a large sheet of absorbent paper, the map sheet, had been tightly wrapped. Thus the fifth Applicon printer manufactured [and the second sent to North America] was purchased by the GSC Geophysics Division for the departmental Computer Science Centre in 1979. The resultant colour-contoured magnetic maps were clearly an impressive step forward in presentation and therefore immediately acceptable to end users. However there were several practical problems to overcome in being able to print multiple copies of such coloured pixel maps for general distribution. The first was the tendency for the ink to clog in the small-diameter orifice of each ink jet [an ongoing problem for ink jet printers even today]. Other problems were that only absorbent paper could be utilized for printing purposes rather than a stable non-absorbent plastic sheet. Also the colours in the ink-jet prints faded fairly rapidly when exposed to sunlight. In order to make colour separations for printing coloured maps which would not have the fading problem, each primary colour sheet was printed separately with the necessary lettering and surround in black. The resultant four paper sheets containing all the required map information were immediately photographed before changing humidity could alter the dimensions of the paper sheets so that four colour separations on stable film were available for map printing. It was subjectively decided to use the spectrum of white light as the colour scheme for total field maps and by experimental observation of a series of end products that the spectrum could be divided into a maximum of 39 colour levels each of which could just be discerned separately by the human eye. However to maximize the information content of the magnetic data, it was necessary to abandon the equal spacing [5nT] used for line-contoured total field maps and use colour-contour intervals determined by equal area considerations of the middle values [not the extreme values] in order to get maximum colour-contour information. Compromises had to be made such as the selection of whole integer contour values and the contour values could not be different between adjacent sheets or the colour map data would not be continuous across map boundaries. It was also decided to remove the main earth's field using the International Geomagnetic Reference Field [IGRF] which produces a regional slope to the total field data especially in the Maritime and West Coast areas of Canada. Whereas the colour scheme adopted for total field maps produced a coloured map that was gradational and the colours blended one into the next, a colour scheme was chosen for the vertical gradient that was somewhat contrasting but generally followed the white-light spectrum with red being positive, blue being negative gradient values and yellow being the zero-gradient value. This was done because, as mentioned earlier, the zero-value vertical-gradient contour closely tracks the steeply-dipping geological contacts of the Precambrian Shield because the dip of the earth's field is in excess of 70 degrees everywhere in Canada. Thus the coloured vertical-gradient map data were in essence a contact-mapping tool of direct value to the mapping geologist. Since much of the Precambrian Shield is drift-covered, the percentage of outcrop may be only a few percent of the total area mapped. It has become increasingly apparent in such areas that the utilization of vertical-gradient maps results in a much more reliable and accurate geological map. There were indeed a number of examples of field mapping where vertical-gradient results indicated that the position of contacts had been interpolated inaccurately due to the paucity of outcrop data.

Faults are often more readily apparent on vertical-gradient than on total field maps. In addition to producing offsets in magnetic anomalies where there has been transcurrent movement, faults can also produce a narrow line of magnetic lows because the magnetite present in the rocks is oxidized in the immediate vicinity of the fault and lose their ferromagnetic properties. When such faults cut a conspicuous magnetic linear formation, the intersection point is often marked by a distinct indentation [or nick point] in the magnetic contours of the linear anomaly. Because most orebodies occur at or close to geological contacts, vertical- gradient data were also of considerable value in mineral exploration programs. The accurate delineation of circular intrusions of kimberlite intrusions for diamond exploration is also an obvious application for gradiometer surveys and one favoured by mineral exploration companies because the tops of such intrusions are often deeply weathered causing the tops to be covered by lakes and therefore totally hidden to a prospector.

Additional advantages of measuring the vertical gradient is that the main earth's field and any diurnal activity are automatically removed in the subtraction and any offset in the values due to an uncompensated magnetism of the aircraft can be corrected by averaging along the flight lines since the average gradient value should approximate to zero.

The vertical gradient and total field maps were published using colour contour intervals of 0.05nT/m and 5nT respectively in the middle ranges and at a map scale of 1:25,000. These complimented the standard 1:50,000 10nT line contour interval maps and 1:250,000 maps published for the national aeromagnetic survey program.

Transfer of Aeromagnetic Gradiometer Technology to Canadian Industry

By 1980, the time was ripe for a technology transfer to the Canadian aeromagnetic survey contractors, although a number of the companies were reluctant to build a system without an assurance of a market for the end product. Fortunately that year, a vehicle for the technology transfer manifested itself through the Canada-Eastern Ontario Subsidiary Agreement, which was administered by the Ontario Geological Survey [OGS]. Roger Barlow of OGS and the author were co-leaders of the project, and Norman Paterson of Paterson, Grant and Watson Ltd. was retained by OGS as a consultant for the project. The specifications for the Commercial Aeromagnetic Gradiometer System were prepared by the GSC Magnetic Methods Group and proposals were invited from contractors.

Two companies responded, namely Kenting Earth Sciences Ltd. of Ottawa and Questor Surveys Ltd. of Toronto. After a considerable evaluation of the proposals, a contract was awarded to Kenting in the spring of 1982. Under the terms of a Memorandum of Understanding between the various parties, the GSC Magnetic Methods Group undertook to provide Kenting with technical support on a day-to-day basis including the provision of technical drawings and compilation software. Kenting spent about 15 months fabricating their system, and it was accepted for survey work in August 1983. The company did two test surveys as part of the OGS contract before the system was offered commercially. Subsequent work included GSC contracts in Nova Scotia, Quebec, Manitoba and Saskatchewan, which were funded under various Federal/Provincial Mineral Development Agreements.

Development of Helicopter-borne Gradiometers

It is difficult to carry out aeromagnetic gradiometer surveys in areas of mountainous terrain. The GSC Magnetic Methods Group had utilized the technique of flying regional total-field surveys of mountainous areas at a constant barometric elevation; these areas included the Cordillera of British Columbia and the Torngat Mountains of Labrador. However, this procedure did not yield useful results when flying vertical-gradient surveys over rugged areas, because gradient surveys are much more sensitive to varying distances between the gradiometer sensors and the causative magnetic bodies than is the case for total-field surveys. It is clear that gradiometer surveys must be drape-flown to yield the most useful end product. Accordingly, in 1983 the GSC Magnetic Methods Group began fostering the development of helicopter-borne gradiometer systems through research and development contracts to the Canadian airborne geophysical industry. The companies that initially received funding were Geotech Ltd. of Markham, Ontario and Geophysical Surveys Inc. of Ste. Foy, Quebec. Geotech built a system using Overhauser magnetometers developed under a previous GSC-sponsored contract by GEM Systems Ltd. of Toronto. Two proton oscillators [GSM-11A] were installed in a mast-like structure above an electromagnetic [EM] bird with a 3-metre separation. The fourth-difference noise envelope achieved was about 0.1nT for two readings per second for a single sensor and 0.033nT per metre for the gradient measurements.

The second helicopter-borne system developed by Geophysical Surveys utilized two V-200 Scintrex split-beam cesium-vapour magnetometers mounted on a towed bird with a 2 metre separation. The system measured the vertical gradient twice a second with a sensitivity of 0.005nT per metre. The total-field and vertical-gradient noise levels were less than 0.02nT per metre and 0.025nT per metre respectively.

Both systems were first field tested in the relatively flat Carleton Place area west of Ottawa previously flown by the Queenair fixed-wing system to ensure that repeatable survey results could be obtained. Then a survey of Mount Megantic, Quebec, which is about 700 m. high, was carried out in March 1984 to ascertain whether the technique would produce useful results in steep terrain areas. Mount Megantic had been previously surveyed in 1951-1952 by a fixed-wing aeromagnetic survey flown by the GSC. In general, the experimental survey demonstrated the excellent repeatability of total-field data, but in the fine detail there were many differences that would have affected its geological interpretation. There was an even more striking comparison with the resultant vertical-gradient colour-contoured map. This map showed that Mount Megantic consists of two concentric rings of magnetic rock that extend about 270 degrees in azimuth, and that have significant magnetization and a central nonmagnetic core. This was confirmed by a comparison with the existing geological map which showed an outer ring of syenite, an inner ring of gabbro, and a central core of granite.

In 1984, an invitation to tender for the first helicopter-borne vertical-gradiometer contract was issued for a survey in the Gaspe Peninsula of southeastern Quebec, and the successful contractor was Geophysical Surveys Inc. The published results demonstrated that the technique was an excellent geophysical tool to assist detailed geological-mapping programs in areas of rugged terrain. Moreover the results showed a significant improvement in resolution of the anomalies over the older, drape-flown survey.

Two other companies also produced helicopter gradiometer systems. Aerodat Ltd. of Mississauga, Ontario fabricated a vertical gradiometer that utilized Scintrex split-beam cesium-vapour magnetometers. Sander Geophysics Ltd. of Ottawa, Ontario completed a system that utilized Overhauser magnetometers of their own design. The sensor separation was 3 m and the 7 m-long bird structure was towed by an Aerospatiale AS 350D Astar helicopter at the end of a 30 m cable. Sander Geophysics carried out their first GSC gradiometer contract in the Gaspe Peninsula in 1985.

Development of the Queenair aeromagnetic gradiometer continued and in the spring of 1985 transverse and upper booms were installed on the aircraft to produce a trigonal configuration so that the transverse gradient could be measured in addition to the vertical. Three high-sensitivity self-orienting cesium-vapour magnetometers and three nine-term CAE compensators were installed in the three booms. Several compensation flights were made to reduce the aircraft magnetic interference to a minimum. Then in June, a small 348 line km survey was flown in the Carleton Place area. It was clear from the resultant data that both vertical and transverse gradient could be measured effectively using such a short-base gradiometer system and that it was possible to compensate the three cesium magnetometers to provide the required sensitivity. Moreover the transverse data improved the contouring of the data between the flight lines as an exercise in contouring with and without the transverse data easily demonstrated. Unfortunately the trigonal gradiometer development could not be pursued further due to lack of funding and the requirement for the Queenair aircraft to survey the Great Lakes [except for Lake Michigan] across the international boundary in order to fill in that hole in the aeromagnetic survey coverage of North America and better tie the US and Canadian data together. This requirement was imperative for the production of the first digitally-compiled Magnetic Anomaly Map of North America. The author was co-chairman of the international committee for the compilation of that map which the GSC had promised as one of a number of contributions to celebrate the 1987 centenary of the Geological Society of America.

Summary of the Advantages of the Vertical Gradiometer and Conclusions

The advantages of the aeromagnetic gradiometer may be summarized as follows:-

[1] Resolution of anomalies that are produced by closely spaced geological formations e.g. diabase dykes, is superior to that obtained by total-field measurements;

[2] Anomalies produced by near-surface features are emphasized with respect to those produced by more deeply buried features;

[3] Direct delineation of vertical contacts by the zero-gradient contour value that were purposely designed for the mapping geologist to coincide with the narrow yellow pixel bands on the colour maps; this vertical contact mapping property means that a vertical gradient map is in essence a pseudogeological map;

[4] Regional gradient of the Earth’s magnetic field and diurnal variations are automatically removed.

It follows from the above advantages listed that vertical-gradient survey results are a better aid to geological mapping programs than standard total-field results. Moreover because many orebodies are located at or near contacts, the vertical-gradient technique can also be utilized as a direct aid to mineral exploration.

It is also clear that helicopter-borne gradiometer surveys flown at low levels result in a more useful and coherent set of data than are obtained from ground magnetic surveys. Such airborne-survey coverage is certainly much faster and cheaper to obtain in forested terrain. Moreover the greater distance from the sensors to the ground minimizes local disturbing effects due to glacial debris and bedrock topographic features that in addition may have been subject to lightning strikes that will affect their magnetization. The separation distance also results in recording anomalies that are more representative of the average magnetic properties of the associated causative bodies. The magnetic properties of Precambrian rock formations can be quite variable at say the 1.0 m cube size. For the magnetic survey method to work most effectively, it is necessary to sample the fields due to average magnetic properties at the 10 m cube size at a minimum. That is what airborne magnetic surveys are so effective in doing. Such averaging is their great advantage, albeit with increasing loss of detail at higher and higher flight elevations.

The development of the aeromagnetic gradiometer extended over two decades. It could not have been accomplished without a team of dedicated and knowledgeable persons. An essential ingredient was the possession of an in-house survey platform, namely a twin-engine Beechcraft Queenair aircraft. It was also abundantly clear that in the introduction of a new airborne geophysical survey technique, it was not sufficient just to present some limited experimental results at a scientific meeting and expect commercial airborne survey contractors to adopt the new method with its associated development costs and without some assurance of a commercial demand for such a service and a likelihood of profit.

One of the results of the aeromagnetic gradiometer program was that digital recording of the data was made mandatory in both domestic and overseas [CIDA-funded] contracted surveys. This was first done in the 1973 tender issued for the aeromagnetic survey of northern Quebec which was carried out by Photographic Surveys of Quebec City and Geoterrex. Consequently there was a general switchover to digital acquisition systems by the Canadian aeromagnetic survey contractors that gave them a competitive advantage in bidding for work overseas.

The introduction of the digital recording of aeromagnetic survey data had many other benefits. The resultant gridded data sets produced to make the interpolated colour pixel maps were also available to end users to apply quantitative interpretation techniques and to make various kinds of end products of their own choosing such as derivative and shaded-relief maps useful in the qualitative interpretation of the data. This resulted in the GSC establishing a Geophysical Data Centre for the distribution of these and other geophysical data sets — a facility much utilized over the years by the mining industry and copied around the world by other national geoscience organizations.