10.1071/PVv2017n186p42

The development of optically pumped magnetometer systems and their applications in Australia
Part 2

John M. Stanley
john.m.stanley1947@gmail.com

Diversifying the application of optically pumped magnetometers

a. 'High Definition' and 'Broad Spectrum' magnetic mapping

When the first optically pumped magnetometer was developed it was immediately recognised that if the very fast measurement rate attribute could be exploited through automatic recording and the provision of an odometer system for automatically determining the location of each measurement, magnetic mapping would be revolutionised. With these combined developments instead of acquiring magnetic measurements at 20 m intervals or even greater, as was previously the standard, it became practical to record magnetic profiles at sub-metre sample intervals. This could now be done while travelling faster than an operator could walk, and even up to 40 kph with a vehicle-borne platform.

According to sampling theory, a given sample interval can only enable wavelengths of twice that interval, or longer, to be properly defined. Shorter wavelengths, if present, will be under-sampled and will constitute 'magnetic noise'. As a rule of thumb, the shortest wavelength component of a magnetic anomaly will be a wavelength approximately twice the depth to its source below the sensor. It follows that for any given sample interval only magnetic sources originating at greater than that distance below the sensor will be properly defined, while sources closer to the sensor will contribute magnetic noise to the profile.

The consequence of sampling at 20 m intervals (or greater as was more common) at ground level was that all magnetic sources within 20 m (or more) of the ground surface contributed only noise on the magnetic profile. Decreasing the sample interval from 20 m to 0.2 m delivered access to magnetic information in the 0.4 m to 40 m wavelength band, and this is the band that includes anomaly sources occurring between the ground surface and 20 m depth. Instead of magnetic surveys being low-pass limited beyond 40 m wavelength, data acquisition became available covering the entire spectrum arising from surface as well as subsurface sources. The terms 'Broad Spectrum profiles' and 'High Definition imaging' were used to describe the closely sampled data acquired with the magnetometers developed at the Geophysical Research Institute (GRI). The importance of this development to magnetic exploration beneath and within the regolith in Australia cannot be overstated, as our regolith is characterised by accumulations of intensely magnetic, near surface, iron-rich minerals. Only if the magnetic response from such sources can be properly sampled can it be effectively filtered.

Some classic applications of Broad Spectrum profiles to sub-surface mapping include:

- Mafic sills intruding coal seams (Figure 1).
- Thin dykes intruding coal-bearing sediments (Figure 2).
- Deep source exploration beneath a maghemitic regolith (Figure 3).

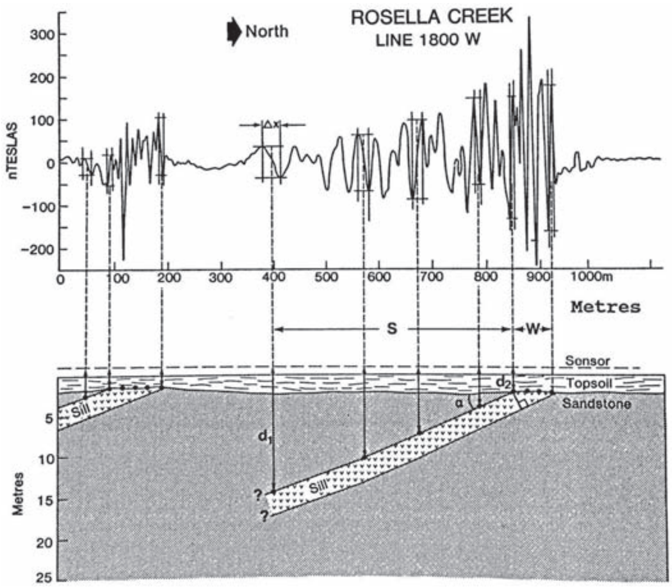


Figure 1. *This profile, recorded across a shallow thin sill, epitomises the significance of Broad Spectrum data acquisition. In close proximity to the surface of a mafic intrusion, magnetic minerals present contribute to a high amplitude 'white noise' spectrum. As the sill dips to greater depth 'upward continuation' progressively low pass filters the white spectrum and in this profile this process can be seen to both decrease the peak-to-peak amplitude of the profile and to increase the wavelength between adjacent peaks. In fact, dividing the distance between adjacent peaks (ΔX) by the tangent of the Earth's magnetic inclination provides a good estimate of the depth to the sill at that point. From two such measurements distance S apart, the dip angle of the sill can be deduced.*

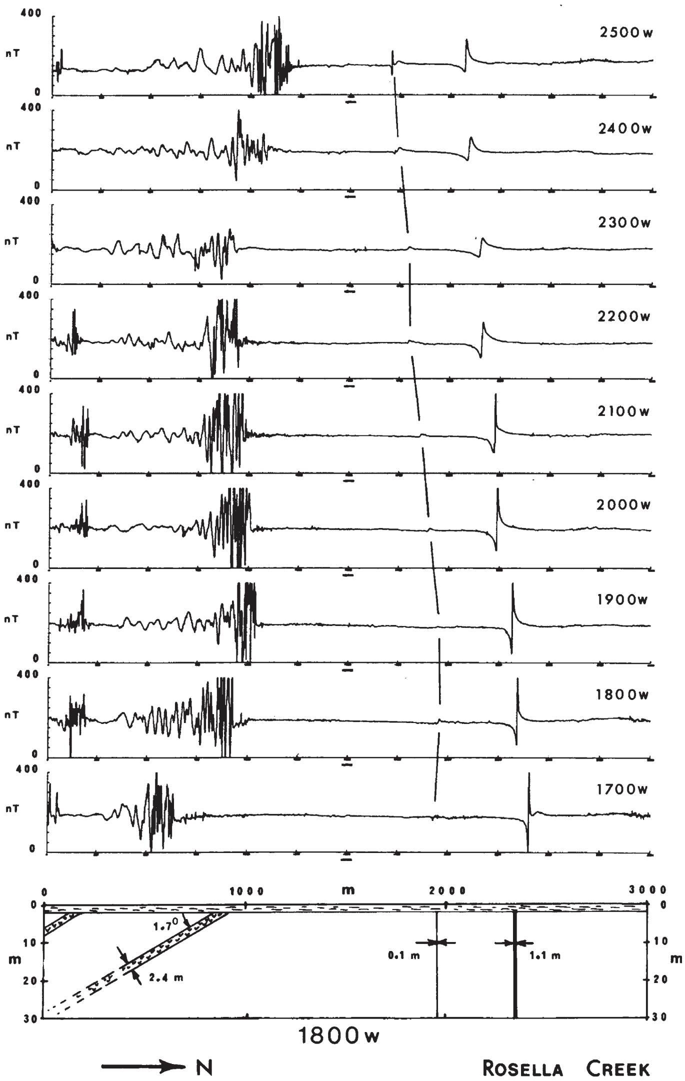


Figure 2. *Even very thin dykes can pose an expensive problem to longwall mining if their presence is not expected. This series of broad spectrum profiles clearly identifies near surface dykes down to 0.1 m in thickness. A pair of thin sills can also be recognised from this data.*

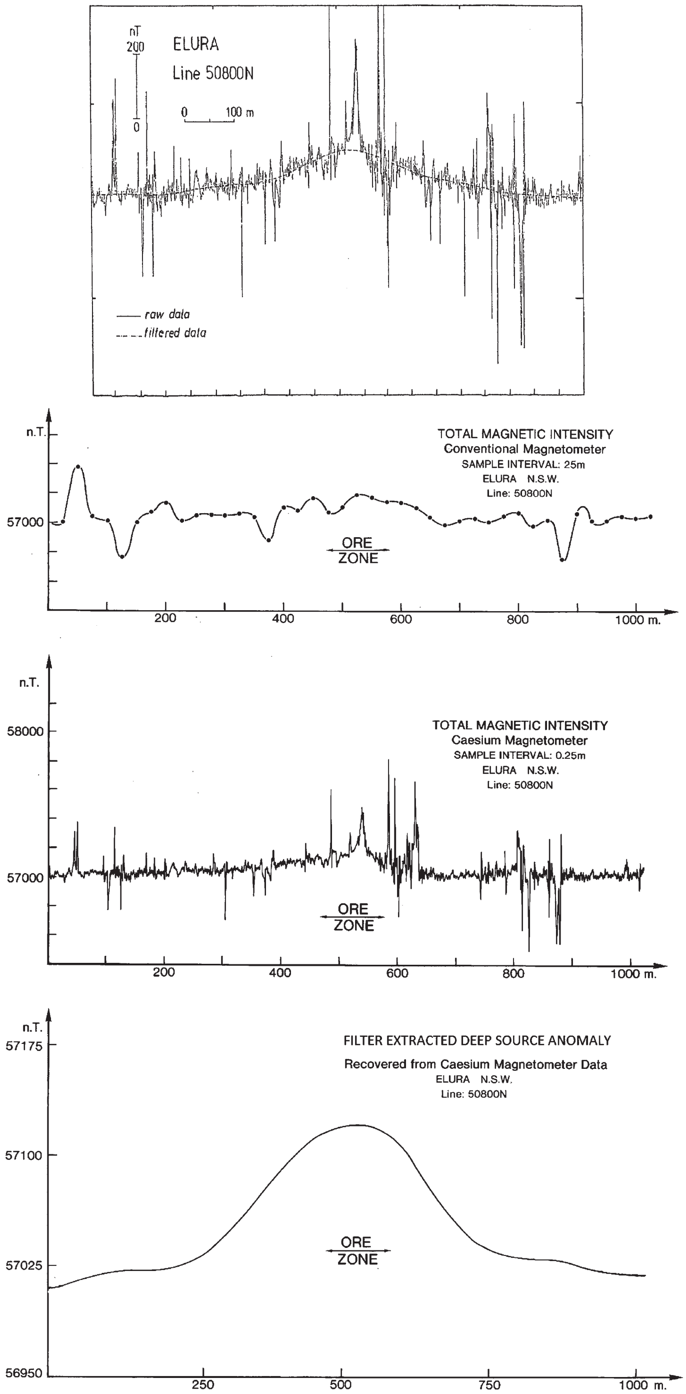


Figure 3. *The Elura Ag/Pb/Zn orebody consists of siliceous, pyritic and pyrrhotitic materials weathered to a depth of approximately 100 m. Overlying this orebody is a maghemitic layer rich in intensely dipolar magnetic gravels. Only after properly sampling the full spectrum of the magnetic noise profile from these gravels could it be effectively filtered and a quality profile representing the magnetic response of the deep orebody extracted.*

Classic examples of High Definition imaging include:

- Magnetic signatures of sandstone and conglomerate (Figure 4).
- A magnetic image of an intrusive pipe, ring dykes, uplifted stratigraphy, streambed alluvials and even buried 76 mm artillery projectiles (Figure 5).

These examples were documented in detail by Stanley and Cattach (1990) and Stanley et al. (1992, 2005).

b. The upgrade to TM-4

In 1988, after a period working in industry, Stephen Lee returned to the GRI and developed a new concept in period counters based upon the statistical analysis of a large number of overlapping, short duration, windows of the Larmor period using Programmable Logic Array technology. The result was a count resolution of 0.005 nT at approximately 40 Hz sampling, or 0.1 nT resolution at approximately 400 Hz sampling. This counter formed the basis of a new magnetometer system, the TM-4 (Figure 6).

The upgrade from TM-3 to TM-4 in 1989 was significant in many ways that would influence new applications. It had an interface with a DGPS for both data positioning and navigation functions, and its frequency counting specifications were improved over the TM-3 by a factor of 20 for resolution and a factor of 40 for sample rate. Up to four Cs magnetometer sensors could be logged simultaneously. The period counter and data logging functions required the power of a new Motorola 68030 CPU with a 68881 co-processor. Data were logged on a

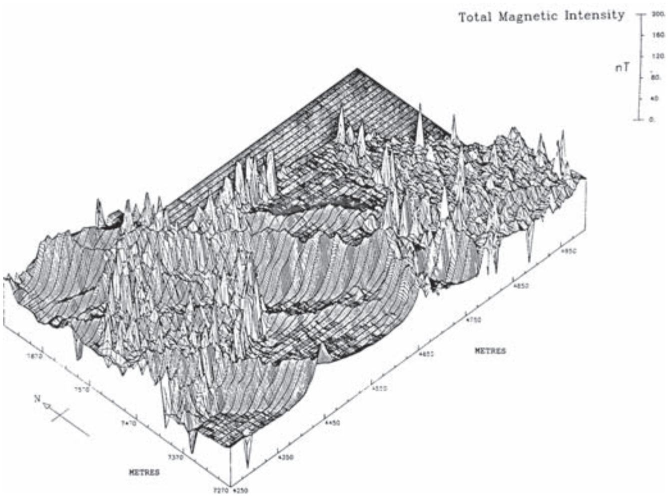


Figure 4. *An isometric image of high definition magnetic data in this location defines the distinctly different magnetic signature of a relatively iron rich conglomerate interbedded between horizons of sandstone. Four linear features reveal the location of thin intrusive dykes that effectively prohibited longwall mining of the underlying coal seam.*

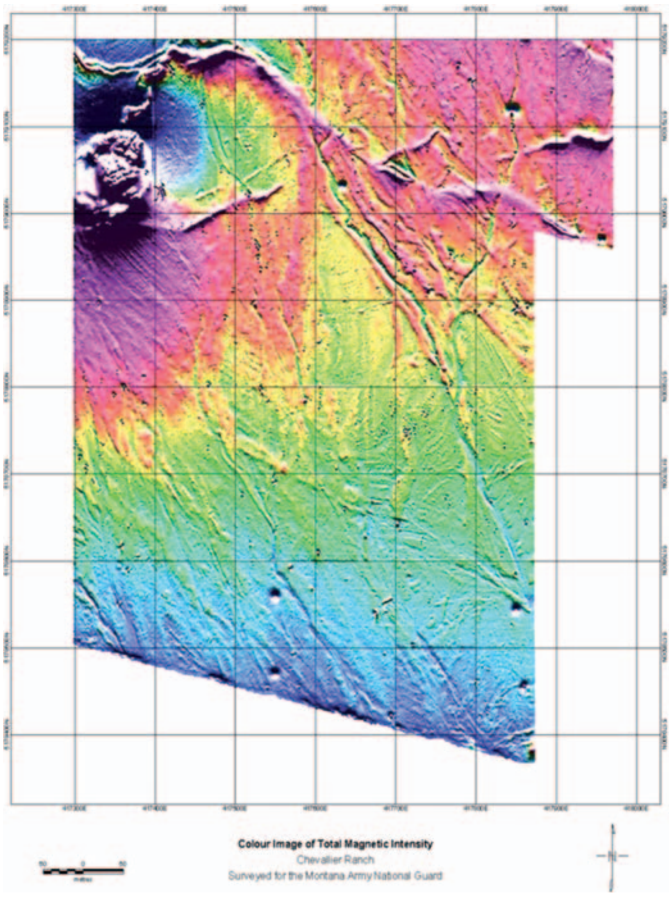


Figure 5. *This high definition magnetic image represents 9 million, DGPS positioned measurements of the Total Magnetic Intensity covering a 45 ha area. Data acquisition using a hand-held, quad-sensor TM-4 magnetometer took 20 crew days. Interpretable from this data are an intrusive pipe, ring dykes, uplifted sedimentary stratigraphy and alluvial drainage. Small speckles revealed the presence of buried unexploded ordnance, predominantly 76 mm artillery projectiles. The four circular features in the lower section were each due to a steel fence post.*

Figure 6. *The TM-4 magnetometer with odometer attached. Seen also in quad-sensor application in the search for unexploded ordnance 2000 m above the Missouri valley in Montana.*

battery-backed RAM. In 2016, after 25 years of service, a TM-4 remains in use at Comenius University for archaeological and environmental investigations.

In 1989, differential GPS using a local base station delivered an absolute positional accuracy of around 1.5 m. In Broad Spectrum survey applications requiring precise relative sample interval accuracy a cotton thread type odometer was still used to control the sample interval along line, while the DGPS was used to position the course of the survey line and to facilitate navigation within a survey area. A vehicle-borne system using a quad-cycle was built for mineral exploration applications and this combined the relative accuracy of a digital odometer to control sample intervals along line with the absolute position of survey transects and navigation aids being controlled using DGPS.

c. Sub audio magnetics for simultaneous electrical and magnetic mapping

The significance of 'High Definition' magnetic mapping for resolving great detail in near surface geological structures was recognised from the early vehicle-borne magnetic profiles and various archaeological investigations. It left a significant impression. This immediately raised the question as to what might be the benefits for the exploration industry if similar spatial resolution could be economically achieved measuring other useful parameters such as electrical conductivity, electromagnetic coupling, induced polarisation and even gravity. Malcolm Cattach joined the GRI team in 1980 and with sponsorship and access to the latest instruments provided by Newmont Exploration, Mal commenced a Master's program to evaluate, compare and perhaps suggest improvements to, the current state-of-the-art induced polarisation receivers. He explored means to increase the speed with which closely spaced measurements might be acquired, but remained frustrated by the inherent fact that if the depth of exploration was to be maintained then the electrode spacing had to be large. With a large receiver electrode separation measurements could only reflect an average current flow through the large volume of ground between the electrodes and this would prohibit high spatial resolution. But, important seeds were sown; there had to be a better way.

The benefits of high definition magnetic mapping and the desire to expand this to include other parameters of geophysical mapping remained at the forefront of John's and now Mal's minds. Mal proposed: 'can we use a magnetometer to measure the electromagnetic response of a time-varying current in the ground? If we can, then we should be able to filter between the spatially varying magnetic field and the time varying electromagnetic field.' It sounded too good to be true. 'If it were possible then someone would surely have already done it'. Then one day in 1988, John and Mal were using a TM-3 in an area also being investigated using CSAMT and there, visible on the TM-3 signal, was the CSAMT waveform. This convinced Mal to commence a PhD program under John's supervision to investigate this new application (it is beside the point, but what was actually observed was the primary field from the wires feeding the CSAMT electrodes, not the ground response. But that is the luck of the draw in research, and Mal was convinced to pursue his conviction.)

The concept was quite simple. If a fast-sampling magnetometer was operated one metre above the ground surface, where the shortest wavelength of the spatially varying magnetic field is about two metres, at a walking speed of up to say 2 m/s (7.2 kph), then the spatially varying field would be observed in time as frequencies lower than 1 Hz. If a time varying current were introduced to the ground by either a galvanic source or an electromagnetic loop using a square wave generating source at a frequency greater than 1 Hz, then the spatially and time varying components of the magnetic field could be separated by filtering. Naturally occurring temporal changes in the magnetic field could be removed by reference to a base-station magnetometer. It was envisaged that the current source would deliver a bi-polar, square wave in the 5 Hz to 200 Hz range and hence the name Sub Audio Magnetics (SAM) was proposed (Cattach et al., 1993).

Hypothetically, if current were applied using grounded electrodes, four total field parameters could be extracted. These were:

- The spatially varying magnetic field intensity (TMI)
- Magnetometric electrical resistivity (TFMMR) acquired during the 'ON' time
- Magnetometric induced polarisation (TFMMIP) acquired during the 'OFF' time
- Electromagnetic response (TFEM) acquired during the 'OFF' time, where in this case the EM source was the current in the wire feeding the electrodes

Alternatively, if the excitation source used was a closed wire loop, then an enhanced electromagnetic response could be measured at the expense of the resistivity and induced polarisation parameters.

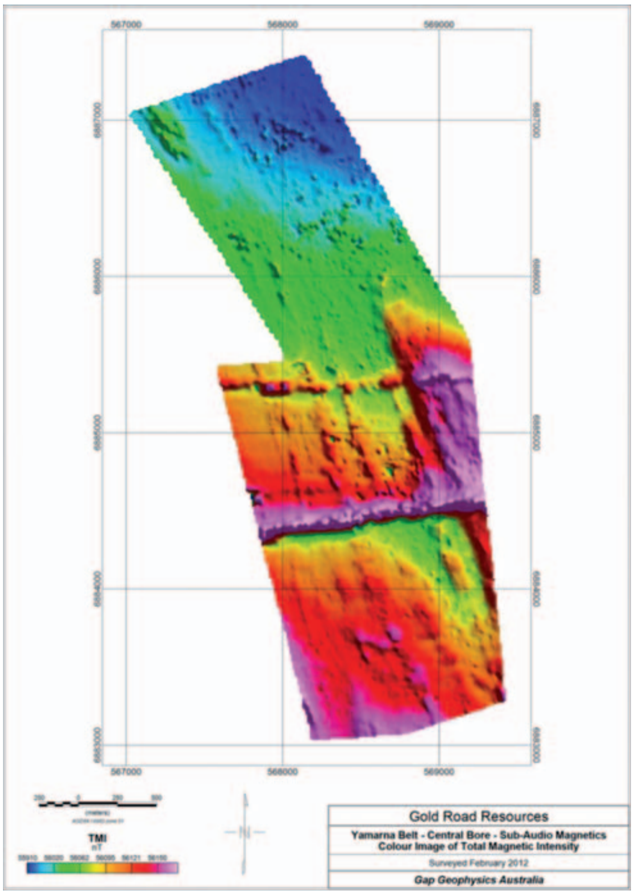
During the course of his PhD research into the SAM method, Mal focused on the use of the TM-4 magnetometer with a galvanic source where several amperes of current were introduced through electrodes initially separated by 1000 m. Mal diligently applied the laws of physics to calculate corrections that would be necessary if the electrical response due to changes in sub-surface conductivity properties were to be isolated. These included the subtraction of the primary field due to the current in the wire feeding the electrodes and subtraction of the normal field that would occur if the ground were homogeneous.

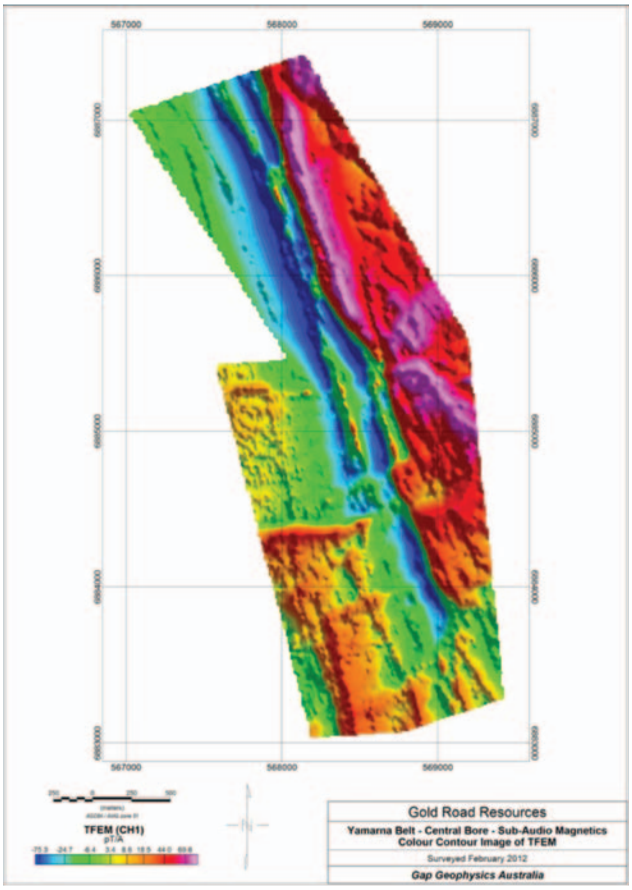
Malcolm achieved his goal using a galvanic source with resounding success and the simultaneous acquisition of high definition TMI and TFMMR was quickly adopted by the exploration industry. Under the supervision of Malcom Cattach and John Stanley, David Boggs, in his own PhD research, used TM-4 data to confirm the predicted viability of also acquiring the transient decay signal from an electromagnetic source (Figure 7). From this it was inferred that the transient decay from an induced polarisation source would also be measurable (Boggs et al., 1998).

The TM-4 and its application to SAM earned Malcolm Cattach and John Stanley the 1995 ASEG Grahame Sands Award for Innovation in Applied Geoscience.

d. SAM to provide discrimination between UXO and Non UXO

David Boggs' feasibility assessment, confirming that high definition transient electromagnetic data could be acquired simultaneously with spatially varying TMI and TFMMR data using the SAM technology principles, led to the recognition of specific desired enhancements to the TM-4 performance. Driven by these results development of the first specialised SAM receiver, the TM-6, was commenced in 2002. Ron Bradbury engineered an upgrade to the Steve Lee statistical period counter making it now a true frequency counter with a precisely regular count rate. He was also able to raise its performance to 0.005 nT @ 120 Hz and 0.04 nT at 2400 Hz. Each measurement was able to be time tagged to 10 µS precision synchronised with GPS time. Up to four Cs magnetometer sensors cold be logged simultaneously. Unlike the TM-4, which had its own display screen and keyboard, the interface with theTM-6 was via a Bluetooth connection with an off-the-shelf, hand-held device.





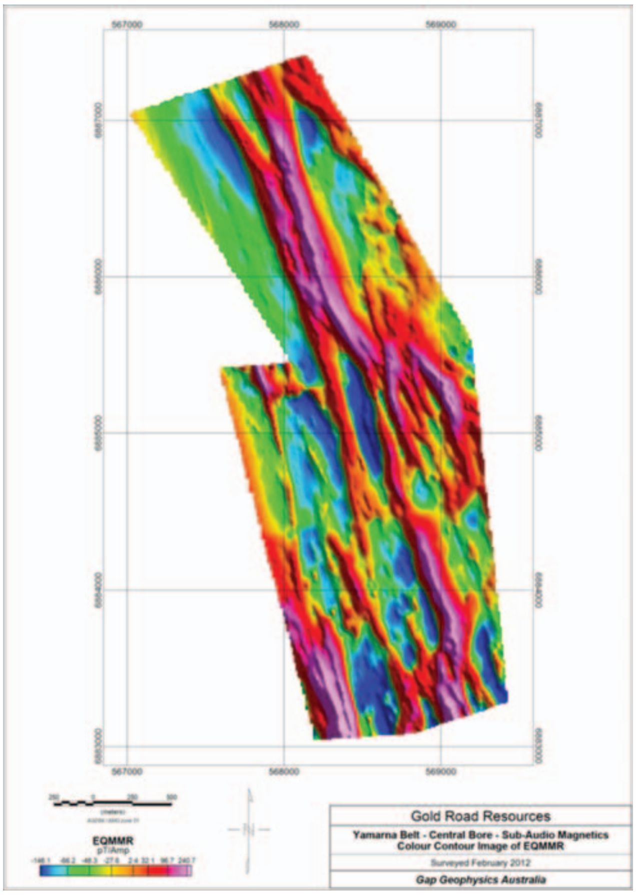


Figure 7. *Images of TMI, TFMMR and TFEM acquired simultaneously with a TM-7 magnetometer using SAM.*

This enabled the TM-6 to be more conveniently carried in a backpack, leaving the operators hands free (Figure 8). With DGPS now capable of delivering cm positional accuracy, the requirement for an odometer system was overcome in even the most demanding sampling applications. The processing power and storage capacity were also increased permitting the use of real-time navigation aids, real-time signal stacking where required and digital recording at very high data rates.

Figure 8. *The TM-6 magnetometer system with ports for up to four Cs sensors and a frequency counter capable of delivering measurements to 0.04 nT resolution 2400 times per second with each measurement time tagged to 10 µS precision synchronised to GPS time. Data positioning with cm accuracy and survey navigation aids was provided by DGPS. On-board signal stacking delivered a noise floor of just 0.05 pT for electromagnetic exploration applications.*

At the time of the TM-6 development the major cost in remediating contaminated military sites was recognised as arising from the labour intensive investigation of false alarm sources. Magnetic field mapping was effective in detecting ferrous items to a depth in most environments beyond the expected penetration depth. But highly remnant magnetised fragmentation could not be distinguished reliably from dangerous UXO items. Electromagnetic metal detectors were relatively cumbersome to use but were more discriminating against fragmentation as they responded in a manner more proportional to the target dimensions. Electromagnetic detectors also had an advantage in being capable of detecting non-ferrous items. However, electromagnetic systems deploying a small, roving coil transmitter were inherently limited in their detection depth. The energising signal decreased nominally with the inverse cube of the depth to target and the induced signal also diminished with an approximate inverse cube relationship with distance back to the receiver. Consequently, detection depth using a small coil energising source decreases with nominally an inverse 6th power. A magnetometer achieves a greater detection depth primarily because the source is passive and its response decreases only with a nominal inverse cube relationship. SAM technology was seen as a viable solution for both reducing the false alarm rate and for increasing the electromagnetic detection depth. Not only could the magnetic and the electromagnetic response be acquired simultaneously with a single sensor, but the energising field could be applied using a very large loop surrounding, for example, a whole ha. From such a source the energising field remains constant beyond the depth of concern and so the electromagnetic response follows just the inverse cube law instead of the inverse 6^{th} power experienced with a roving coil transmitter. Using SAM the detection depth of both magnetic and electromagnetic responses would be equivalent, both measurements would be precisely co-located and in combination would deliver enhanced discrimination capability.

The TM-6 specification was defined such that it would enable a large loop SAM system to detect UXO targets as small as a 20 mm projectile (approximately 20 mm diameter, 100 mm length). In order to meet this specification a current transmitter had to be designed and built capable of driving up to 350 Amp current through a square loop of dimension 110 m surrounding a 1 ha search area. Keith Matthews brought his experience with high power, fast shutoff transmitter technologies to the team and the result was the MPTX-500 transmitter (Figure 9). Calculation of the transient electromagnetic response from a 20 mm projectile in the energising field produced from such a loop revealed that the TM-6 magnetometer frequency counter now had the performance to detect the transient response from a source as small as the 20 mm projectile target. The predicted performance of SAM in this application was confirmed during an evaluation program sponsored by the US Environmental Security Technology Certification Program (ESTCP, 2003).

Figure 9. *The MPTX-500 transmitter was developed as an EM source capable of delivering up to 350 Amp current through an energising square loop of 110 m x 110 m. When such a loop surrounded a 1 ha search area SAM technology, using a TM-6 magnetometer, was capable of detecting UXO targets down to 20 mm projectile size.*

e. Identifying induced polarisation using SAM

The simultaneous measurement of Total Field Magnetometric Induced Polarisation together with TFMMR and TMI was always specified in the hypothetical concept of SAM. But it was not until the TM-6 technology had evolved that an induced polarisation signal could be confidently distinguished from electromagnetic coupling. Recent case studies by Gap Geophysics have confirmed David Boggs' prediction that all four parameters could in practice be simultaneously measured with a single, Cs magnetometer sensor.

f. SAMSON for deep penetration electromagnetic surveys

The successful application of the TM-6 magnetometer and MPTX-500 transmitter to electromagnetic detection of UXO targets was the precursor to the next stage of SAM development for mineral exploration applications. In 2005 Malcolm Cattach brought together a development team under the new organisation of Gap Geophysics. During the years 2006 to 2008, the TM-6 magnetometer/SAM receiver underwent ongoing development, evolving into the TM-7, with significant enhancements to acquisition electronics and firmware as well as processing software (Figure 10).

Total Field Electromagnetic measurement became practical as an offspring of the SAM concept. In 2007, SAMSON ('Son of SAM') was developed as a collaboration between Gap Geophysics and ElectroMagnetic Imaging Technology (EMIT). The distinguishing feature of SAMSON was the use of stationary measurements and real-time signal stacking in order to enhance the signal-to-noise ratio of weak transient responses from very deep sources. In the application of SAMSON to very deep exploration it is practical to achieve late time noise levels of 0.05 pT with a typical measurement station occupation time of 5 minutes. But while the measurement time might now be relatively long, the requirements of deep source exploration can be met with measurement stations 50 m apart. This is a distinctly different application of the Cs magnetometer sensor to those previously focused upon the high definition mapping of near surface sources. Such is the diversity in applications of the Cs sensor. SAMSON earned for Andrew Duncan, Malcolm Cattach and Steven Griffin the 2007 ASEG Laric Hawkins Award for the most innovative use of a geophysical technique from a paper presented at the ASEG Conference (Duncan et al., 2007).

Figure 10. *The TM-7 magnetometer system is the current generation. Its performance is similar to that of the TM-6 but advantage has been taken of advanced acquisition electronic components, firmware and processing software.*

g. High-power transmitters to support SAM technologies

When using the TM-7 magnetometer SAMSON methodology was able to achieve a measurement sensitivity that was well within ambient noise when transmitters available at the time were used. It soon became clear that further improvements to sensitivity would not improve the signal-to-noise ratio. However, if higher powered transmitters could be made available then improvement in signal-to-noise using the TM-7 could be expected.

Gap GeoPak (GeoPak) was established in 2007 as a joint venture between Australian companies Gap Geophysics Pty Ltd and Kayar Pty Ltd (engineering company).The objective in establishing the company was to develop a range of high performance geophysical transmitters that would:

- Significantly exceed the performance and reliability of commercially available transmitters
- Optimise the signal-to-noise ratios achievable by Gap Geophysics proprietary and non-proprietary survey techniques.
- Significantly increase the depth of exploration for electrical techniques.
- Reduce station occupation time thereby increasing survey efficiency.
- Incorporate enhanced safety features which meet and exceed the more stringent requirements of today's mining exploration industry.

Gap GeoPak's flagship products are the HPTX-70/80 range of high power transmitters. With the ability to achieve up to 350A and power output up to 80kW, these transmitters have pioneered high power, deep penetrating EM surveying in Australia (Figure 11).

The GeoPak HPTX-70 earned Malcolm Cattach, Keith Mathews, Ed Campbell and Symon Bouwman the 2012 ASEG Grahame Sands Award for Innovation in Applied Geoscience.

Figure 11. *The HPTX-80 transmitter is capable of delivering 80 kW of electrical power to either a galvanic source, where electrodes may be separated by several km, or to an electromagnetic loop of several square km area. With such a transmitter, and the TM-7 magnetometer, very deep electromagnetic exploration can be achieved using SAMSON technology or the survey efficiency of a helicopter-borne platform can be applied to TMI and TFMMR exploration using SAM technology.*

h. HeliSAM

The development of high powered transmitters such as the HPTX-80 has made feasible the supply of high current to galvanic electrodes that are separated by several km. The area between these electrodes that can be explored using TMI and TFMMR maybe several square km, and the use of a towed bird sensor can deliver excellent spatial resolution in a fast and economic manner. Similarly, the use of a large area electromagnetic loop to energise the ground can make available a large prospective area capable of benefitting from the efficiency and speed of airborne data acquisition measuring TMI and TFEM.

References

Boggs, D. B., Stanley, J. M., and Cattach, M. C., 1998, Feasibility studies of TFMMIP and TFEM surveying with sub-audio magnetics: *Exploration Geophysics*, **29**, 290–295. doi:10.1071/EG998290

Cattach, M. C., Stanley, J. M., Lee, S. J., and Boyd, G. W., 1993, Sub-audio magnetics (SAM) – a high resolution technique for simultaneously mapping electrical and magnetic properties: *Exploration Geophysics*, **24**, 387–400. doi:10.1071/EG993387

Duncan, A., Cattach, M. C. and Griffin, S. M., 2007, Total field EM for highly conductive targets: *ASEG Extended Abstracts*, No. 1.

ESTCP, 2003, Project 200322 Annual Report, Sub-audio magnetics: technology for simultaneous magnetic and electromagnetic detection of UXO.

Stanley, J. M., and Cattach, M. C., 1990, The use of high definition magnetics in engineering site investigation: *Exploration Geophysics*, **21**, 91–103. doi:10.1071/EG990091

Stanley, J. M., Sertsrivanet, S., and Clark, P. J., 1992, Magnetic exploration beneath a near surface magnetic noise source: *Exploration Geophysics*, **23**, 323–326. doi:10.1071/EG992323

Stanley, J. M., Cattach, M. C., Griffin, S. M., and Townsend, J. A., 2005, Environmental applications of sub-audio magnetics: *Exploration Geophysics*, **36**, 198–205. doi:10.1071/EG05198