AUSTRALIAN MILESTONES IN GROUND MAGNETICS

John M Stanley, and Roger Henderson. October 2023.

INTRODUCTION

This document records milestones achieved in Australia in the measurement and application of ground level magnetics. Marine acquired measurements have been included for the purpose of consistency with contemporary ground magnetics objectives. The milestones document a distinct transition from magnetic field measurement to investigate the properties of the planet Earth to their application to exploration, geological and archaeological mapping. This transition also reflects the evolution of magnetic field measurement technology, the advent of digital recording, GPS positioning and the consequences of these developments to data acquisition methodology. Many of these milestones were not recognised as such at the time, but in retrospect can be seen as significant steppingstones to the next major advance.

1770 JAMES COOK, OBSERVES ERRATIC ROCK MAGNETISM

On 30 Apr: Lt James Cook observes erratic rock magnetism on Pier Head, Quail Island, Queensland. (Morrison, 2017).

1788 MAGNETIC INTENSITY MEASUREMENTS, NORTH SHORE BOTANY BAY

It is believed that scientists from the Laperouse expedition observed magnetic intensity by dip needle oscillation on the north shore of Botany Bay between January and March 1788 as per expedition instructions, and as known to have been carried out earlier in the expedition. An absolute gravity observation by pendulum is known to have taken place and this was almost certainly the first physical science experiment conducted in Australia. (Morrison, 2020).

1792-3 ESTABLISHMENT OF THE FIRST TEMPORARY MAGNETIC OBSERVATORY IN AUSTRALIA

The first documented magnetic intensity measurements were made French scientist Elisabeth Paul Edouard de Rossel. De Rossel was a member of the D’Entrecasteaux expedition sent in search after the disappearance of La Perouse. De Rossel repeated magnetic measurements at Recherche Bay in Tasmania for 26 days in 1792 and another 24 days in 1793 for the purpose of researching the Earth’s magnetic field. The relative magnet field strength was determined by timing 100 oscillations of a vertical dip needle. A significant finding from this study was that the magnetic intensity at Recherche Bay and in Paris was much higher than in Java from which confirmed Lamanon’s discovery that the magnetic force is greater near the poles than at the equator. (Courtillot and Mouël, 2007, Morrison, 2020).

1802 **MATTHEW FLINDERS OBSERVES RELATIONSHIP BETWEEN MAGNETIC FIELD AND GEOLOGY**

Matthew Flinders, confirmed Cook's observations at Pier Head on the Qld coast and he also observed on the Gulf of Carpentaria coast the relationship between magnetism and the local rocks/geology. [Needs to be confirmed]. (Morrison, 2017).

1818 **JOHN OXLEY OBSERVED MAGNETIC FIELD ASSOCIATED WITH THE WARRUMBUNGLE MOUNTAINS.**

The first magnetic observations on mainland Australia outside of the Sydney area are thought to have been conducted by John Oxley. Between 7-9 August. John Oxley climbed Loadstone[sic] Hill near Mount Exmouth and the rugged Warrumbungle Range and found the magnetism on and around the hill affected his compass and was very erratic. He observed these anomalous characteristics over a couple of days. Oxley wrote: "I was surprised with the remarkable effect which the situation appeared to have on the compass … placing the compass on the rock before me, the card flew round with extreme velocity, and then suddenly settled at opposite points". (Oxley, 1820. Morrison, 2020).

1819 **LOUIS-CLAUDE DE SAULCES DE FREYCINET MEASURES MAGNETIC FIELD INTENSITY AT PORT JACKSON**

In December, French navigator scientist Louis-Claude de Saulces de Freycinet of the ship Uranie (probably assisted by Louis Isidore Duperrey) observed the magnetic intensity at Port Jackson (Sydney Harbour) calculating the mean difference between Port Jackson and that at Paris and the magnetic equator. (Morrison, 2020).

1824 **LOUIS ISIDORE DUPERREY CONFIRMS MAGNETIC INTENSITY MEASUREMENT AT PORT JACKSON**

January 1824. French navigator scientist Louis Isidore Duperrey of the ship Coquille at Fort Macquarie, Port Jackson added to and confirmed the magnetic intensity for the location observed on Uranie in 1819. (Morrison, 2020).

1831 **MAGNETIC OBSERVATIONS BETWEEN LONDON AND SYDNEY VIA HOBART**

James Dunlop observed dip circle oscillations (a measure of vertical magnetic intensity) while travelling from London to Sydney via Hobart. Dunlop tied his ship-borne data and an observation made on arrival at Parramatta Observatory to the Makerstoun Observatory in Scotland. (Morrison, 2020).

1831-32 JAMES DUNLOP RECORDS FIRST INLAND MAGNETIC FIELD OBSERVATIONS

James Dunlop observed the first magnetic intensity observations (by dip circle oscillation) away from Parramatta Observatory. He is known to have observed both declinations and inclinations, but these records have not been located. If located, they would be Australia's first inland field magnetic intensity observations. (Morrison, 2020).

1836 COMMANDER ROBERT FITZROY MEASURES MAGNETIC INTENSITY IN HOBART, SYDNEY AND KING GEORGE SOUND (ALBANY)

During January and February, Commander Robert FitzRoy on the second voyage of HMS *Beagle* observed magnetic intensity by needle oscillation at Hobart, Sydney and King George Sound (Albany WA) and tied them to Sabine's value at the magnetic equator. (Morrison, 2020).

1837-8 JOHN CLEMENTS WICKHAM MEASURES MAGNETIC INTENSITY IN SWAN RIVER, THE KIMBERLY REGION AND BASS STRAIT

John Clements Wickham commander on the third voyage of HMS *Beagle* observed magnetic intensity by dip circle oscillation at a number of locations including Swan River Pier, the Kimberley region and Bass Strait. He tied his data to Fort Macquarie in Sydney. (Morrison, 2020).

1839-40 PAUL EDMUND DE STRZELECKI RECORDS MAGNETIC TRAVERSE BETWEEN SYDNEY AND WESTERN PORT

Polish count Paul Edmund de Strzelecki observes magnetic intensity by oscillation, declination and inclination on his discovery horseback trip from Sydney to Western Port Victoria via the Snowy Mountains and then in Tasmania. His oscillation values have not survived. Strzelecki deliberately did not publish any of his inclination and intensity oscillations: he considered them inadequately measured, despite having purchased instruments for the task , "at great expense". (Morrison, 2020).

1840-41. JAMES CLARK ROSS AND FRANCIS RAWDON MOIRA CROZIER MEASURE MAGNETIC INTENSITY NEAR ANTARCTICA

James Clark Ross and Francis Rawdon Moira Crozier commanders of HMS *Erebus* and HMS *Terror* observe magnetic intensity by oscillation throughout their voyage to Antarctica and tied their data to the new Rossbank Observatory in Hobart and to Garden Island in Sydney Harbour. (Morrison, 2020).

1840 **ESTABLISHMENT OF THE FIRST PERMANENT MAGNETIC OBSERVATORY IN AUSTRALIA**

The Royal Society in London chose the Domain in Hobart as the site of a permanent magnetic observatory in the southern hemisphere using an absolute magnetometer designed by Gauss. This was just 8 years after Gauss had established an observatory in Gottengen using an oscillating horizontal magnetic needle to measure the absolute value of the horizontal component of the magnetic field. As with the De Rossel measurements, the purpose of this observatory was to better understand the nature of the Earth's magnetic field. The observatory was established by James Ross in the grounds of the new Government House in Hobart and became known as "Rossbank Observatory" (Morrison, 2020).

1845 **PAUL EDMOND DE STREZELECKI IDENTIFIES PALAEOMAGNETISM IN TASMANIAN DOLERMITE**

„Its colour in the recent fracture is blackish green; on the surface, yellowish brown. The Iustre of the paste waxy; that of the homblende which it contains vitreous; it does not adhere to the tongue, and exhales an argillaceous odour; its streak is dissimilar and dull; its colour a brownish grey; when strack with a hämmer, it gives a metallic sound: it is compact, hard, its fracture is somewhat concoidal. The structure is prismatic, the prisms having three, four, five, six, or seven sides. Their diameter varies from three to eight feet; the length of two or three columns, which are still entire, exceeds 100 feet. The clustered columns are sometimes very closely united; sometimes they are only in close contact, and are separated by the fall of the masses. Some of the columns have but a slight influence upon the magnetic needle; and in these the axes ränge east and west. The columns lying parallel with the meridian, or nearly so, disclose a strong polarity; a phenomenon worth noting, as the property seems to be more dependent on the bearing of the axes of these columns than on their constituents. The discovery of this polarity was consequent upon the anomalous results which the observations of the magnetic intensity furnished me by the prismatic greenstone on Ben Lomond *(Strzelecki 1845 p. 104).“*

The above account given by Paul Strzelecki in 1845 is probably the earliest reference to rock magnetism in Australian literature. The 'greenstone' on Ben Lomond he refers to is clearly the Tasmanian Dolerite. Strzelecki recognised and described the dependence of magnetic effects on the Orientation of fallen columns. These observations were not simply mundane compass deflections. It would appear that Strzelecki measured the total field anomalies of a number of columns while taking routine magnetic intensity measurements. Indeed, had Strzelecki been distracted further by his curious observations, and had he the fortune of understanding Contemporary developments in the research of electromagnetic phenomena, he would have concluded that the Tasmanian Dolerites were magnetised in a steep-upward direction. Of course he would then have deduced that Tasmania was near the magnetic south pole when these rocks formed and wondered if the pole came to Australia or Australia to the pole. (From Schmidt, 1997).

1858 **GEORG NEUMAYER TAKES MAGNETIC MEASUREMENTS AT FLAGSTAFF HILL OBSERVATORY**

Between 14-15 September, German scientist Georg Balthaser von Neumayer made magnetic observations at seven locations within 300 feet of his Flagstaff Hill Observatory to determine the local magnetic interferences there. He decided it was not a good location for a magnetic observatory. In December Neumayer and Ellery carried out magnetometer field tests near Kilmore, north of Melbourne. (Day, 1966-67).

1859-62 GEORG VON NEUMAYER RELATES AND INTERPRETS MAGNETIC INTENSITY WITH SUB-SURFACE GEOLOGY

In 1859 Georg von Neumayer commenced extensive regional magnetic measurements around the Colony of Victoria and a number of these specifically related to geology. In December he observed the horizontal magnetic intensity underground at the Black Hill mine at Ballarat. In 1861 he interpreted and recorded the magnetic properties and orientation of the largest of the buried meteorites at Cranbourne, southeast of Melbourne. In November 1862 he observed magnetism associated with quartz reefs at Little Wombat and Granite Flat gold diggings in the alpine region. Von Neumayer used a theodolite magnetometer designed by Johann Lamont for his regional magnetic survey of Victoria but to produce his descriptions and calculations determining the orientation, depth, dimensions and mass of the Cranbourne meteorite he used a simple magnetised needle on a thread. This is the first record of a geological interpretation of magnetic data having been undertaken in Australia. (Morrison, 2020).

1860 NEW SITE FOR MELBOURNE MAGNETIC OBSERVATORY

Between May-June, Georg von Neumayer and LJ Ellery carry out magnetic and geological studies to determine site for the new Melbourne Observatory. The site near Government House and botanic gardens deemed the most suitable. (Morrison, 2020).

1865-70 MAGNETIC SURVEYS IN NSW PROPOSED BY GEORGE SMALLEY

NSW government astronomer George Smalley 1865-70. It seems he wished to carry out a magnetic survey of NSW similar to that carried out by Neumayer in Victoria. The survey was halted by Smalley's death in 1870. (Day, 1966-67).

1891 MAGNETIC PROPERTIES OF A SHOAL NEAR CAPE LAMBERT, WESTERN AUSTRALIA

Between 22–25 April, Lt James W. Combe RN and commander and crew of HMS Penguin precisely position and measure the magnetic properties of a shoal near Cape Lambert, Western Australia. The report, along with a contour map of declination, included detail on the adjacent and along strike onshore rock types and general geological structure. (Morrison, 2020).

1909 LOCATION OF THE SOUTH MAGNETIC POLE

The 1908/09 British Antarctic Expedition led by Britain Ernest Shackleton had as an objective the task to find the South Magnetic Pole. Shackleton divided his expedition into two parties, each to explore different regions in Antarctica, but both were to include if possible, the location of the South Magnetic Pole. Ernest Shackleton and Frank Wild formed one party while Australians Tannatt W Edgeworth David and Douglas Mawson, joined by Scot, Alistair Mackay formed the other party. Chief officer of Shackleton's ship the Nimrod was Australian John K Davis. At the end of these expeditions, the Nimrod was to rendezvous with the explorers. Davis first found Shackleton and Wild who informed him that "we got within 97 miles of it". The search for the other party almost proved disastrous. The Nimrod searched the coast where the rendezvous was proposed without success. Davis was on watch at one point where visibility of a small section of the coast was hindered by some icebergs and poor weather. As the exploring party had not been located, although dangerously low on coal, the decision was made to return to the location where the search had been imperfect. They located David, Mawson and Mackay but they had only just reached the coast. Had visibility not hindered the search on the first pass, the Nimrod would not have returned, and the three men would have perished. And what was their news? "We got to the Magnetic Pole at 72^{o} 25' S, 155^{o} 16' E." They raised a flag on 16th January 1909 at the site where using a vertical dip needle (vertical plane compass) they determined the Pole to be (Davis, 1962). The accuracy of this determination has since been questioned, but given the rate at which the pole is moving, their position was within experimental error and certainly a significant magnetic milestone.

Left to Right: Mackay, David and Mawson at the South Magnetic Pole on 16th January, 1909. (Photo: from Davis, 1962)

1912 LOCATION OF THE SOUTH MAGNETIC POLE TO WITHIN 63 KM

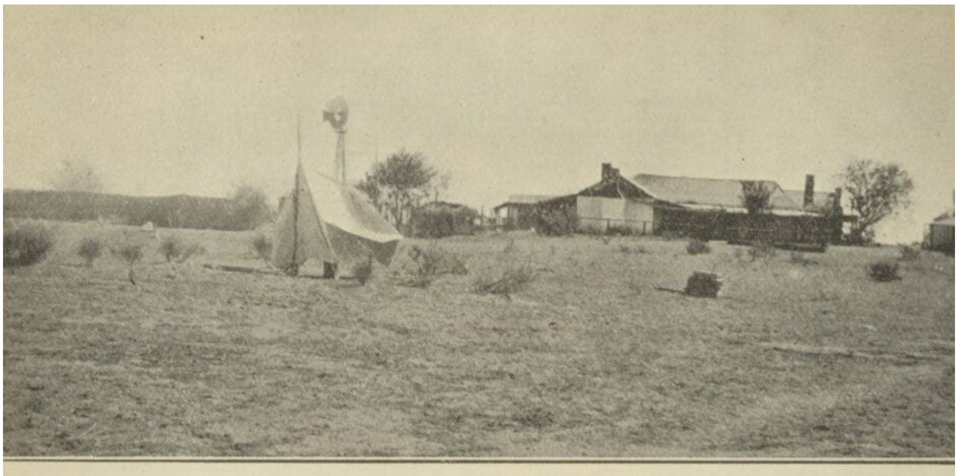
The 1911/14 Australian Antarctic Expedition was led by Australian Douglas Mawson. Captain of the Aurora and second in command of the expedition was Australian John K Davis. In January 1912, Australians Robert Bage, Eric Webb and Frank Hurley reached a site where, using a vertical dip needle, they determined their position to be within 16.5 minutes of the vertical field, an estimated 63 km radius of the magnetic pole. (Mawson, 1930). Also on this expedition was another party lead by Frank Wild and this included A. L. Kennedy who was operating a horizontal component, theodolite magnetometer on loan from the Carnegie Institute. (Jack, 1915). The purpose of Kennedy's measurements were almost certainly to acquire basic information about the Earth's magnetic field. In the absence of detailed information, one can only speculate what conclusions were reached from measurements of the horizontal component made so close to the magnetic pole.

1914 MAGNETIC ANOMALIES MEASURED IN THE MUSGRAVE RANGES

In 1915 the Geological Survey of South Australia published in its Bulletin No 5, a report by R Lockhart Jack entitled: "The Geology and Prospects of the Region to the South of the Musgrave Ranges, and the Geology of the Western Portion of the Great Artesian Basin". (Jack, 1915). This report contains details of "magnetic and other observations" conducted by the Government astronomer, G. F. Dodwell during 1914 (and detailed in his section of the report dated 29th June, 1915), "which form an addition to the world wide investigation of Terrestrial Magnetic inaugurated by the Carnegie Institute". These observations were the first record of a ground magnetic survey to map variations due to underlying geological structure in Australia.

The equipment used consisted of Carnegie theodolite magnetometer No 6 used for the measurement of the horizontal component, a Barrow dip circle loaned by the NSW Government astronomer Professor W. E. Cook to measure magnetic inclination, a trough compass theodolite for measuring magnetic declination, an altazimuth instrument for latitude and longitude determination, a box chronometer, a siderial watch and three mean time watches and a barometer and thermometers for altitude determination. They also had the use of a portable wireless apparatus (crystal set) for the reception of longitude (time) signals from Adelaide.

Horizontal field data were recorded at nine stations with infill measurements between stations performed to record magnetic declination. Clearly, magnetic surveying in 1915 was a very involved and time-consuming operation.



Site of Magnetic Station, Mount Todmorden Station, looking W.S.W.

Dodwell's magnetic station at Todmorden Station in 1914. (Photo: from G. F. Dodwell in Jack, 1915).

1928 **IMPERIAL GEOPHYSICAL EXPERIMENTAL SURVEY (IGES)**

The IGES was commenced in 1928 and continued into 1931. The aim of the study was to test the applicability of geophysical methods in a range of conditions which were seen as representative of different parts of the British Empire. Magnetic, electrical, gravimetric and, to a limited extent, seismic methods were examined as exploration tools in areas containing sulphide and other ores, brown coal, graphite and saline waters. (Broughton Edge and Laby, 1931).

The magnetic investigations conducted as part of this project used two Schmidt type, vertical balance magnetometers manufactured by Askania Werke of Berlin plus a Thalen-Tiberg magnetometer made by Berg of Stockholm. The Thalen-Tiberg magnetometer also measured the magnetic inclination. The Schmidt type balance was first built by Adolph Schmidt in 1915 and several manufacturers produced similar instruments through to 1940.

This Schmidt type balance, made by Askania in about 1930 would be similar to those used in the IGES. Setup and measurement time at each station would take several minutes for a skilled operator. The relative measurement accuracy was approximately 2 nT.

Four magnetic surveys were conducted for the IGES project.

Survey A.
Gelliondale, Victoria. Area of brown coal.
470 stations were recorded along 13 E-W traverses of approximately 500 m (1600 ft) length and averaging about 10 minutes per station including the time to traverse the approximate

distance of 14 m (45 ft) between stations. A contour map was produced from which a narrow, linier anomaly was identified and attributed to a dipping, basalt dyke. This was confirmed by a bore in 1930. This was arguably the first "engineering" application of magnetic exploration in Australia.

Survey B.
Gulgong, NSW. Alluvial gold in deep leads.
At this location deep leads were known to have been infilled with basalt and then covered by overburden. 430 stations averaging six minutes per station were recorded using one Askania magnetometer. Intense positive anomalies were detected due to the basalt and the strong gradients flanking these anomalies indicated the edge of the deep leads. A contour map clearly delineated the basalt flows filling the deep leads. Previously unknown leads were detected this way and confirmed by drilling. The success of the method suggested it should be applicable to other areas in N.S.W., Victoria and Tasmania. This survey was arguably the first application of magnetic exploration for minerals in Australia, and it was successful.

Survey C.
Kadina, S.A. in the Moonta-Walleroo copper field.
At this location the Thalen-Tiberg magnetometer was used. Stations were recorded at 7.6 m (25 ft) intervals along five parallel traverses. At the site of a 5000 nT anomaly in the vertical component of the field an exploration shaft was dug. This encountered highly susceptible magnetite in a mica schist. It was believed not to be an indicator of copper mineralisation.

Survey D.
Renison Bell. Tasmania.
A magnetic survey was conducted in close conjunction with an electrical survey but no further details were reported.

1932 A MAGNETIC SURVEY FOR BASEMENT HIGHS

A magnetic survey searching for basement highs was conducted for Oil Search by J. M. Rayner in 1932. Details are presently not available.

1935-37 SUCCESSFUL APPLICATION OF MAGNETIC SURVEY FOR COPPER-GOLD MINERALISATION

Lewis (Lew) Albert Richardson stands out as a milestone developer of the magnetic field measurement technique for mineral exploration, pioneering both data acquisition and interpretation. With a previous background introduction to surveying, Lew was employed in 1928 as a "Field Assistant" with the No 1 Electrical Party of the Imperial Geophysical Experimental Survey (IGES). (Richardson, R., 2016). The objective of the IGES program was to assess the applicability of geophysical methods in a range of conditions. Lew quickly recognised the potential of the magnetic method to locate mineralisation associated with iron. Between 1935 and 1937 when employed as an Applied Geophysicist with the Aerial, Geological and Geophysical Survey of Northern Australia (AGGSNA), Lew applied himself to both the data acquisition (using a Watts Torsion Balance Variometer) and the even more challenging task of data interpretation when the target source exhibited strong remanence and demagnetisation. Lew found such targets in the Tennant Creek region. These were often quite deep, relatively small, and often steeply dipping and “pipe like”. For drilling to reliably hit such targets required very complicated magnetic analysis and Lew acquired the skills to do this using ellipsoid modelling that included remanence. This achievement alone was a significant milestone.

An A. E. Watts torsion balance magnetic variometer as used by Lew Richardson when exploring for copper/gold in the Tennant Creek region of the Northern Territory, 1935 – 37.

1961 MAGNETIC EVIDENCE FOR CONTINENTAL DRIFT

In 1961 Continental Drift was still very contentious but Ron Green and Ted Irvine had already proposed a migration of Australia north of the Antarctic in 1957 based upon palaeomagnetic measurements of the Tasmanian Dolerite. In 1961, Ron joined the voyage of the research vessel “Argo” from Fremantle to New Zealand assisting Vic Vacquier operate a magnetometer. The magnetometer on board the R. V. Argo was one of the first proton precession magnetometers produced by Elsec in Oxford. One of the results of the cruise showed no continuation of the Darling Fault through the oceanic floor and a second was the observation of mirror image magnetic anomaly stripes paralleling the ‘50°S degree’ Ridge. Each of these findings supported continental drift. Another outcome of this operation was Ron becoming convinced of the future importance of proton precession and electron spin resonance magnetometer technology. He recognised the need to replace the relative, component measurements of preceding magnetometer systems with absolute, total field intensity measurement. This detail proved to be a significant steppingstone in the history of magnetics in Australia.

1969 DEVELOPMENT OF A VEICHLEBORNE MAGNETOMETER WITH NAVIGATION SYSTEM

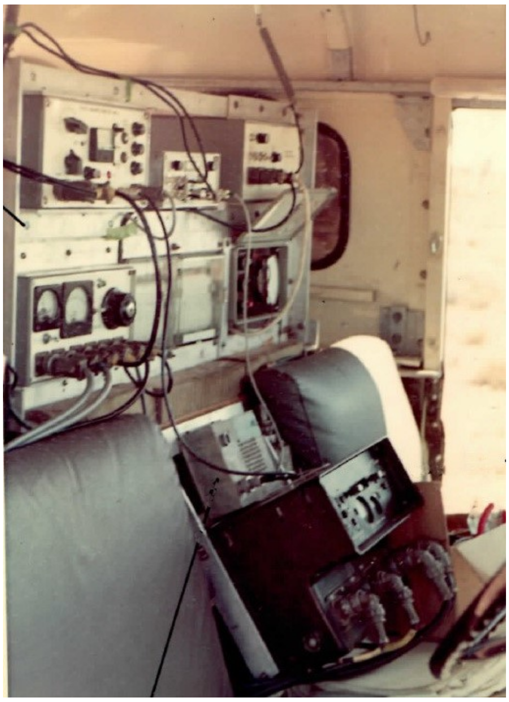
From Bob Richardson, August 2022

In the late sixties, exploration by Geopeko, the major client of L.A. Richardson and Associates (LAR), ranged beyond Tennant Creek to more remote areas, where available maps were poor quality and the terrain flat and featureless, such as Tanami-Granites, and the Rover field some 80-100kms SW of Tennant Creek. Navigation to locate anomalies that had been revealed by aerial survey was very difficult. Bob Richardson had the task of locating and assessing magnetic anomalies of interest selected from very broad brush BMR aeromagnetic contours. The standard technique had been to use compass and odometer to navigate during the day, trying to drive in straight lines, but inevitably having to veer around obstacles. By the time he had veered around several mulga forests, claypans, and creeks he could be kilometres away from the planned destination. He would then have to camp the night and undertake star observations using a theodolite to get a location using four stars (if you got three stars to agree that was good enough). At best this would give an accuracy of only about 500 metres, so then it was necessary to walk the area back and forth with an Askania magnetometer to find and outline the anomaly. The initial objective in the Rover field was to find the Rover 1 anomaly. Bob and his team eventually found another bunch of anomalies in the Rover field, all of which were associated with mineralisation. (The Rover 1 deposit is currently undergoing development by WestGold.)

Bob soon realised that a better form of navigation was required and after some digging around through any publications he could find on navigation (no google in those days) he discovered information about the Chobham Navigator, manufactured by Sperry Instruments in the UK. It had been developed for the British army and one was being used on the Woomera rocket range to locate and recover spent rocket casings. The system uses two fluxgate compasses on a boom on the rear of a Land Rover to obtain heading information from the earth's magnetic field. This heading information was combined with information from the odometer cable and interfaced to a mechanical computer called a "ball resolver" that calculated and displayed north-south and east-west displacement. Two compasses were used at different distances from the vehicle so that the differences in heading could be used to correct for the vehicles effect on heading. By setting the known starting coordinates of the vehicle the device would then indicate a position on mechanical readouts, in AMG coordinates with an accuracy of about 0.25% of the distance travelled. The British army used them in Land Rovers, and heavier vehicles in which case they used gyro compasses for direction. Bob met with the Woomera people and became convinced that this was what was needed, and LAR ordered one from Sperry.

Before using it in any region it was necessary to calibrate the system by driving between points of known AMG coordinates and making appropriate adjustments. In the Tennant Creek region, I used a north-south leg between Tennant Creek and the Threeways Roadhouse (a distance of 25km) and a similar East-West leg between Threeways and a point of known coordinates on the Barkly Highway.

With boom fully extended. The two black compasses further forward on the boom. Under the compasses was a coil to measure the NW Cape VLF signal (gave that away in a hurry).



Rack for magnetometer and other control instruments. The Choblam Navigator mounted between the front seats.

The magnetometer astatic sensor at the end of the boom.

It was a beautiful piece of equipment, built to milspec standards. It revolutionised GeoPeko's navigation in remote locations particularly Rover and Tanami, before the advent of GPS. Two vehicles were fitted with these navigators, and were christened 'Blossom 1' and 'Blossom 2'

The most common purpose for navigating to remote areas was to locate, measure, and assess specific magnetic anomalies. Based on these initial surveys one could decide whether to do a detailed pegged grid survey. LAR equipped the Chobham-navigated vehicle with a magnetometer. The obvious technical choice was the proton precession instrument that measured the total field so that the sensor did not require orientation – essential for a vehicle bumping along in the spinifex. The principle of proton precession, and its use for magnetic measurement, was invented by Varian Corp in the early 1950's, but there was no suitable instrument for our purposes on the market.

LAR's brilliant engineer Mike Palmer designed and built a proton precession magnetometer with one second cycling and Bob fitted this onto the Navigator vehicle, with the sensor mounted on an aluminium boom projecting from the rear of the vehicle and extended to minimise the vehicle's magnetic effects. That rear section of the boom could be telescoped back and locked to reduce its length for road travel.

The system, as mounted in the Land Rover, consisted of Chobham Navigator (between the seats), magnetometer, chart recorders, and various control units. All units were mounted on shock absorbing mountings. The AMG coordinates and heading could be read easily by the driver and passenger. Electrical noise from the engine electrics created too much noise and corrupted the magnetometer precession signal so Mike made an astatic sensor, ie a sensor with two coils so that electrical noise was cancelled out. The precession signal was outputted to a speaker so that signal quality could be monitored. Magnetic field strength was recorded on a chart recorder that was slaved to the vehicle odometer.

The magnetic effect of the vehicle was reduced or at least modified to a simple sine curve relationship between vehicle heading and the magnetic effect at the sensor, by fitting a large de-gaussing coil carrying DC current mounted on the lower tailgate of the vehicle. This idea came from Lew Richardson's experiences during WII that involved work on degaussing ships to make them less attractive to floating mines.

After the discovery of the Ranger 1 uranium deposit in 1971, Bob fitted a 3x3in NaI Xtal detector and Nuclear Enterprises spectrometer to the navigator vehicle with chart recorder output and this was used in the East Alligators province to follow up airborne spectrometer anomalies

As far as known, LAR was the first, and possibly the only outfit, to build and use such a system in Australia (who knows, maybe the world??).

1970 DEVELOPMENT OF AN OPTICALLY PUMPED MAGNETIC SENSOR

Post WWII, magnetic field measurements on land for geological mapping and exploration were generally made using a vertical component fluxgate magnetometer at grid locations established using optical surveying. The fluxgate was popular because it was light and relatively inexpensive. However, in hand-held operation each measurement required the magnetometer to be stationery so that the sensor could be vertically oriented. A relative field intensity value was then hand recorded after being read off an analogue scale. Accuracy was typically about 5 nT. Although the principle of using proton precession frequency as a measure of the absolute value of the total field intensity was established in 1946, it was not until 1958 that an instrument became commercially available. The Elsec Proton Precession Magnetometer measuring the total field was developed at Oxford University and commercialised by the Littlemore Scientific Engineering Co. The proton precession frequency, scaled in units of nT was displayed on 5 analogue meters graduated 0 to 9. With this instrument a measurement to 1 nT resolution could be obtained in a 3-second period at locations defined by a pre-established survey grid. Each measurement was then then hand recorded. Very few Elsec proton precession magnetometers were used in Australia but Ron Green appreciated its importance and acquired one as the first acquisition for his new Geophysics Department at UNE in late 1967.

The Jalander vertical component fluxgate magnetometer manufactured in Finland was a popular choice for magnetic exploration on land during the 1960's. Measurements were recorded while stationary, hand recorded and read off the analogue dial.

Ron Green acquired this Elsec, Proton Precession Magnetometer, S/N 316, for his Geophysics Department at UNE in late 1967.

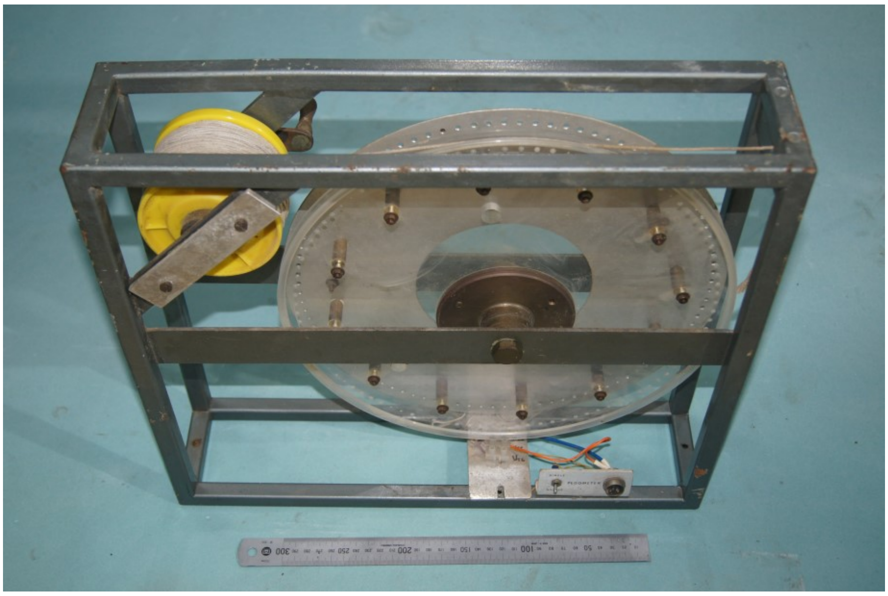
Inspired by his experience with the deficiencies of the 3-component fluxgate magnetometer on board the R.V. Argo in 1961, Ron Green suggested in 1969 that Jim Cull and John Stanley jointly conduct an Honours research task at the University of New England to build an optically pumped magnetic sensor using Caesium. At that time, optically pumped sensors had been developed under military classification in both the US and France. Concurrently but further advanced, a team at Imperial College in the UK were also developing an optically pumped sensor using Rubidium. The UNE sensor development proved too ambitious for an Honours year and John continued it into a PhD research program and in 1970 an optically pumped Cs sensor was functioning. (Green and Stanley, 1973, Stanley 1975a.)

The prototype UNE self-oscillating Cs magnetometer sensor first operated in September, 1970. Lamp driver electronics on the right, feedback electronics on the left.

1971 DEVELOPMENT OF AN OPTICALLY PUMPED DIGITAL MAGNETOMETER WITH ANALOGUE RECORDING

With an optically pumped Cs sensor now functioning, a digital period counter was built in 1971 that delivered 0.01 nT resolution in a 2.2 second period or 1 nT in a 22 mS period. This represented over a 100 times improvement in either resolution or sample rate over the proton precession magnetometer. (Stanley et. al., 1976).

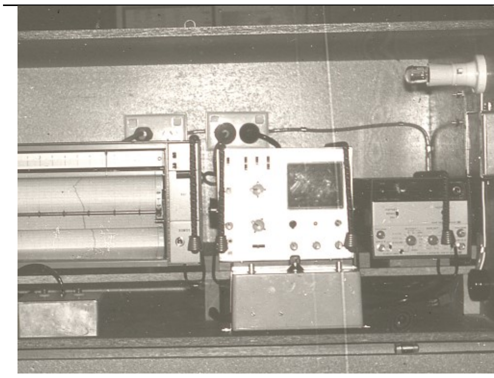
In order to take advantage of the improved magnetometer performance in exploration mapping applications it was necessary to devise a technology for automatically establishing the position where measurements were made and a method for automatically recording the magnetic field measurements. 1971 pre-dated portable digital recording. Initially, the position where measurements were acquired was determined using a rewindable string drawn out with the sensor along a survey transect and in so doing rotating a pully wheel which in turn controlled the chart movement of an analogue recorder. Survey lines were limited by coaxial cable properties to 30 m length restricting this technology to archaeological scale surveys. But in this application, data to 1 nT resolution could be acquired and plotted at 20 mm intervals (or to 0.1 nT at 200 mm intervals) while continuously traversing at up to 1 m/s. (Stanley, 1978).



An odometer system devised to acquire positioned measurements along traverses limited to 30 m by the properties of a coaxial cable linking the sensor to the counter and chart recorder.

1974 DEVELOPMENT OF AN ANALOGUE RECORDING VEHICLEBORNE MAGNETOMETER

Since Bob Richardson at L A Richardson and Assoc. pioneered the use of a vehicleborne magnetometer system using a proton precession magnetometer, the significant technological advancement of a rapid sampling Cs sensor led to an enhanced vehicleborne system, albeit without the benefit of a navigation system. Successful, auto plotting of magnetic data at an archaeological site scale stimulated the demand to apply the technology to regional and mineral exploration scale mapping where very closely sample data could enable near surface magnetic signatures to be identified as well as broader structural anomalous features. A solution to the problem of automatically acquiring positioned data was found by replacing the string and pully wheel odometer with a magnetic switch (Hall device) mounted on the tail shaft of a Land Rover. Magnetic interference was minimised by the strategic placement of the magnetic sensor on a non-magnetic stinger of 6 m length and 1.2 m above ground, behind the vehicle. A peak-to-peak heading error of 25 nT was measured during a 360 degree turn. If the highest resolution data were required, the sensor could be hand-carried 30 m behind the vehicle and connected by a cable. In the vehicle, the digital data were plotted to scale on chart. In 1974 long traverses were conducted across NSW with measurements plotted to 1 nT resolution (with a maximum 20 nT heading offset) at 400 mm intervals while travelling at 30 kph. A feature of these transects was the observation of a distinct, high frequency magnetic signature associated with prior water courses (Stanley, 1975b). With a hand carried sensor, mineral exploration surveys were also performed to 1 nT resolution without heading offset, at 50 mm sample intervals. (Stanley, 1975c.)



The vehicleborne magnetometer in 1974. Inside the cabin a chart recorder with stepper motor driven by a magnetic switch on the vehicle tail shaft recorded scaled plots of the magnetic field at 400 mm intervals independent of travel speed.

1976 APPLICATION OF A VEHICLEBORNE MAGNETOMETER TO OPAL EXPLORATION IN QLD

The success reported in using a continuously recording vehicleborne magnetometer to locate a signature indicating the present of buried prior streambeds, led to a collaboration between B. E. Long and R.J Whiteley at the University of NSW, with B. R. Senior and W. H. McColl of the BMR to replicate the construction of a vehicleborne, chart recording Cs magnetometer. They used a Varian 4937A sensor sampling at 1Hz and mounted upon a 6 m tail boom that similarly reduced the heading error to a maximum of 25 nT. Measurements at approximately 1.5 m intervals were plotted while traversing at about 5 kph (Senior et al, 1977).

UNSW Vehicleborne system RHS

UNSW Vehicleborne system LHS

In this project, the significant milestone was the innovative application of high spatial resolution ground magnetic measurement to the detection and location of boulder opal. The spatial resolution acquired enabled the distinction to be made between remanently magnetised, near surface host ironstone and surrounding, ferruginous sandstone components that were normally magnetised by induction. While no commercial grade opal was recovered from costeans sited by ground magnetic methods, this milestone documents a significant advance in the understanding of a "non-textbook" application in magnetic exploration.

1978 DEVELOPMENT OF A DIGITAL RECORDING VEHICLEBORNE MAGNETOMETER

In 1978 a Z80 based digital data acquisition system developed by Sonotek in Canada was added to the Series 1 Land Rover vehicle-borne magnetometer system. For the first time, positioned digital data were able to be automatically recorded along vehicleborne traverses. This system was commercially applied to exploration mapping projects using both the stinger and hand-held sensor modes of operation. Real-time plotting of the data on chart was retained but the digital data could now also be downloaded to a main-frame or personal computer for further post processing. Success of this system led to an upgraded instrument rack being fitted to a Range Rover in 1980 and the sensor being exclusively hand carried, 30 m behind the vehicle and connected by a coaxial cable.

The upgraded instrument rack fitted to a Range Rover in 1980. Data at regularly acquired distance increments were concurrently plotted to scale on a chart recorder and digitally logged on cassette tape for later post processing on PC or mainframe.

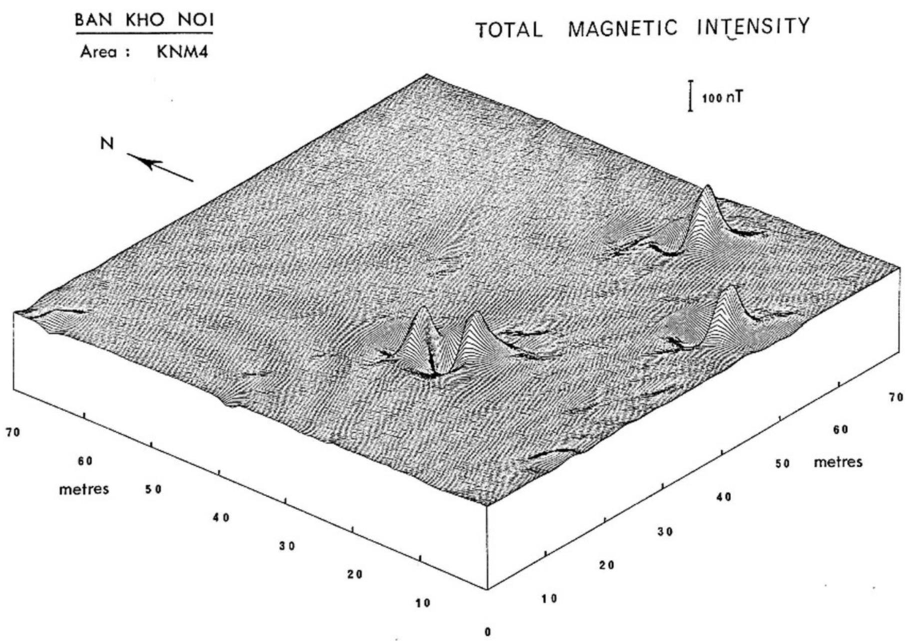
1979 DEVELOPMENT OF A HAND-HELD, DIGITAL RECORDING MAGNETOMETER

The first hand-held, digital recording magnetometer with automatic position measurement in the World was developed in Australia in 1979. Stephen Lee built a frequency shift keying encoder that enabled digital data from the UNE caesium magnetometer to be relayed by CB radio to the vehicleborne data logging facility ("Telemetric", TM-1 magnetometer). This development coincided with Sony's release of their first Walkman miniature cassette tape recorder and this was used as a replacement for the unreliable radio link to the vehicleborne logger. In this application, the reusable string odometer was replaced by a lost cotton system enabling survey transects of virtually any length to be conducted. Error in the cotton thread odometer accuracy was observed to be approximately linear with survey line length and so when control lines were recorded, a correction could be made in post processing, resulting in a maximum positional error along line of about 0.2% of the distance between control lines. In mineral exploration applications, control lines at 500 m intervals resulted in less than 1 m along-line positional error. In archaeological and later, ordnance detection surveys, control lines at 50 m intervals delivered an accuracy of better than 100 mm. The TM-1 and its successor the TM-2 system both required the use of the Sonotek data acquisition system as an interface with a PC or mainframe. (Stanley, 1982).

The TM-1 magnetometer to which had been added a Sony Walkman cassette recorder upon which to log positioned, digital data. Frank Ludbey (Geophysics Department technician) leads holding a Varian made sensor, John Stanley follows with the digital counter, cassette recorder and cotton thread type odometer.

A TM-2 magnetometer using an inbuilt cassette recorder was used in Thailand in January 1981 to successfully locate and map 1000-year-old pottery kilns. A BBC documentary recording this success was noted by the Australian Defence Department who recognised the importance of this technology to the detection of unexploded ordnance (UXO). The ability to record digital data created the opportunity to both filter near surface geological noise that had plagued their use of analogue metal detectors in lateritic environments and to establish a quality control and audit process in UXO remediation. Australian Defence contracted a TM-2 to map the former bombing range in Darwin as part of remediation leading to the hand-over of this site for civil use. Globally this was the first contaminated site remediation project that was accompanied by a digital audit trail with associated quality assurance and quality control.

This sequence of events highlights an evolutionary process in the development of the application of magnetics and establishment of significant milestones. In response to technical innovations, a device first conceived for mineral exploration and geological mapping applications was applied to archaeological scale investigations which in turn opened the door to UXO remediation and the broader application in environmental remediation geophysics.



Four approximately 1000 year old buried pottery kilns in Thailand identified in 1981 from magnetic mapping using a hand-held, digital TM-2 magnetometer with automated data positioning.

1986 DEVELOPMENT OF TM-3, A SMART HAND-HELD, DIGITAL RECORDING MAGNETOMETER

After the TM-2 had been contracted in 1985 to perform the first ever digital detection survey for unexploded ordnance, the Australian Defence Department recognised the significance of this technology in facilitating a QA/QC strategy for contaminated site remediation. The Geophysical Research Institute was contracted to develop the next generation of "smart" magnetometer and data interpretation software to fulfil this requirement. John Stanley and Malcolm Cattach developed the TM-3 which retained the cotton thread odometer but now included a frequency counter supplied by Varian Associates (available after the military declassification of the Varian magnetometer and replacing the earlier period counter) an inbuilt Z80 based data acquisition system using a robust Huskey Hunter miniature PC and a suite of software for real time grid survey data management including control line odometer corrections. Data from the TM-3 could be directly downloaded to a PC or mainframe for data processing, imaging and interpretation. John and Mal were awarded the inaugural Grahame Sands Award for Innovation in Applied Geoscience for the TM-3 in 1988. (Stanley and Cattach, 1990).

The TM-3 magnetometer with microprocessor controlled survey management aids, inbuilt odometer and digital recording from up to two optically pumped sensors.

1987 POTENT SOFTWARE – AN HISTORICAL CONTEXT

Throughout his career in BMR (which started in 1970) Richard Almond had an interest in computer applications, particularly in the field of potential field modelling (i.e., creating magnetic and gravity models that represent sub-surface structures). As he was mainly with the Metalliferous Exploration group, the models tended to the orebody (hard-rock) side of the modelling spectrum, rather than the layered models used in petroleum (soft-rock) exploration.

In Richard's earlier career the computing infrastructure comprised mini (e.g., HP1000, Vax) or mainframe (e.g., Control Data, IBM) computers. While computationally powerful for their day, the limiting factor of these systems was their lack of interactivity; the software developer or modeller communicated with them via punched cards, teletype terminals or (later, and a big improvement) dumb CRT terminals.

In those days the choice of computer language was effectively limited to Fortran. Unfortunately, Fortran, while capable, tended to encourage poor programming. (Richard wrote more than his fair share of spaghetti code!) In 1982, by way of self-development, he completed some programming units at ANU and became aware of the simulation language Simula. This was an object-oriented language which, it seemed to Richard, would be ideal for writing potential field modelling applications.

In the mid 1980s there was an explosion in technology, spearheaded by the IBM PC, that introduced affordable desktop computing. Mainstream software applications such as word processors and spreadsheets, flourished. Compilers for software development languages such as Basic were not far behind. Then, to Richard's delight, Borland introduced the Turbo-Pascal compiler, which used a fully functional object-oriented language.

Richard resigned from BMR in 1987, set on a career in software development, preferably with a geoscience flavour. He wrote the first version of *Potent* (**Potent**ial field modelling) using Turbo-Pascal, and even managed to sell a few licences. This was *Potent* version 3.

Compiler development flourished, and Microsoft developed Visual C++, (their version of C++, first developed by Bjarne Stroustrup). It was apparent that C++ was superseding Pascal as a mainstream development language, so *Potent* was re-written in Visual C++. This was *Potent* version 4, the direct ancestor of the current version 4.17.01.

Although *Potent* was developed for modelling gravitational and magnetic models in a geological context, other applications soon appeared. Geotechnical engineers use it for diverse purposes such as modelling the magnetic effect of old steel pilings and buried drums. Archaeologists use magnetic models for locating buried hearths, while gravity models can detect sub-surface cavities such as crypts. Several universities and other educational institutions use *Potent* in their geophysics courses and in support of doctoral research projects.

1988 DEVELOPMENT OF TM-4, AN UPGRADED DIGITAL RECORDING MAGNETOMETER

In 1988 Stephen Lee returned from working with industry to re-join the Geophysical Research Institute at the UNE. His challenge was to develop a new concept in period counters based upon the statistical analysis of a large number of overlapping, short duration, windows of the Larmor period (the signal produced by the optically pumped Cs sensor) using Programmable Logic Array technology. The new counter would deliver 0.05 nT resolution at approximately 5 mS intervals from signal delivered from up to 4 independent sensors. A new digital magnetometer was developed around this counter using a high-performance Motorola 68030 CPU and 68881 co-processor. Data were now logged on battery backed RAM. With DGPS positional accuracy still limited to about 1.5 m, the use of the cotton thread odometer was retained in many applications for its relative positional accuracy. In combination, the cotton thread odometer providing high relative accuracy between individual measurements with DGPS absolute accuracy, the two systems delivered a good solution for all applications. As a steppingstone to important future applications, TM-4 data were precisely time-tagged in synchronisation with GPS time. (Cattach et.al., 1993).

Malcolm Cattach operating a TM-4 magnetometer in 1988. His right hand is resting on the cotton thread odometer box.

1988 POSITION CONTROLLED, AUTOMATIC DATA RECORDING USING GPS

As DGPS accuracy improved, software operating on the TM-4 was tailored to replace the cotton thread odometer entirely in mineral exploration applications with DGPS-only data positioning. The survey data management software pioneered for use on the TM-3 was now upgraded to provide off-track warnings and navigation control encompassing the entire survey path within a defined, arbitrary shaped survey area. This software pre-empted that which today is used globally in farm ploughing and harvest operations where a tractor is required to follow a defined path of tracks and position is determined by GPS.

1991 DEVELOPMENT OF SUB AUDIO MAGNETICS

Sub Audio Magnetics (SAM) is the concept whereby a total field, optically pumped magnetic sensor may be used to simultaneously acquire spatially varying total magnetic intensity and time varying electromagnetic field signals in the 5 to 200 Hz (Sub-Audio) range. (Cattach et.al., 1993). Malcolm Cattach, John Stanley and Stephen Lee were granted a Provisional Patent for SAM in 1991. The SAM Patent recognised that after applying a time varying current (in the form of a bi-polar square wave, each pole separated by an equal “Off” time) to the ground through distant electrodes fed by a cable surrounding the area of investigation, precisely timed total field measurements could theoretically be used to simultaneously acquire:

- The spatially varying total magnetic intensity, (TMI)
- Magnetometric electrical resistivity (TFMMR) acquired during the “ON” time
- Magnetometric induced polarisation (TFMMIP) acquired during the “OFF” time
- Electromagnetic induction response (TFEM) acquired during the “OFF” time, where in this case the EM source is the current in the cable feeding the grounded electrodes

Malcolm deserves recognition for the concept of SAM and in a PhD commenced at the Geophysical Research Institute in 1991 under the supervision of John, Mal developed all the theoretical aspects of the method and proved the concept by acquiring case study TMI and TFMMR data using a Zonge GGT-10 current source. (Cattach, 1992). The first field trial of SAM took place in May 1992 over the Orlando Au-Cu-Bi Deposit near Tennant Creek. (Cattach and Foley, 2005). Critical to the application of the SAM theory was the performance of the TM-4 magnetometer. An upgrade to the TM-4 had enabled data to be synchronised with the current transmitter using GPS time. (Cattach et.al., 1995). The TM-4 magnetometer and its application to SAM resulted in Mal and John receiving the 1995 Grahame Sands Award.

Two TM-4 crews conducting the first SAM survey at Orlando near Tennant Creek in May 1992. (Photo: Kim Frankcombe.)

1991 DEVELOPMENT OF THE SQUID MAGNETOMETER SENSOR

After the discovery in 1986 of a ceramic material that became superconducting at liquid nitrogen temperatures, Catherine Foley at CSIRO led a collaborative program with mining company BHP in 1991 to develop SQUIDs as B-field sensors for TEM soundings. The two-junction SQUID (Superconducting, Quantum Interference Device) sensors were fabricated in-house at CSIRO. The first ground-based field trials were conducted in December 1992. (Foley et. al., 2006).

1994 IN-SITU MAGNETIC PROPERTIES MEASUREMENT USING VECTOR GRADIOMETER

A recognised major source of ambiguity in the interpretation of spatially varying magnetic data is the uncertainty of the Koenigsberger Ratio (Q value) and the direction of remanence in the source structure. In 1994, David Clark at CSIRO Nth Ryde proposed overcoming this ambiguity by conducting an in-situ measurement of Q and the direction of remanence using a vector gradiometer. One vector magnetometer would be located near the peak of the observed magnetic anomaly, and the second would be established as a base-station, out of the influence of the anomaly.

Clark argued that the induced magnetisation of a magnetic source is proportional to the ambient magnetic field and varies in response to natural geomagnetic variations, such as diurnal changes, storm fields and pulsations. In contrast, the remanent magnetisation is independent of changes in the ambient field. Stephen Lee at the Geophysical Research Institute was engaged to construct two, synchronised vector magnetometers using optically pumped Cs sensors, TM-4 magnetometers and orthogonal Helmholtz coils sequentially switched to measure each component of the field.

Monitoring of all three field components at the on-anomaly and base station allowed the components of the second order gradient tensor of the pseudo-gravitational potential to be determined. CSIRO showed that the following information could be obtained from the components of this tensor without making any assumptions about source geometry or location:

- the Koenigsberger ratio (Q), which is the ratio of remanent magnetisation intensity to induced magnetisation intensity,
- the direction of remanence,
- the direction of total (remanent+ induced) magnetisation.

Furthermore, the direction to the centre of a compact source could be determined directly from diagonalisation of the tensor. Repeating the procedure at another location within the magnetic anomaly could uniquely determine the location of a compact source, prior to drilling. Thus, the information provided by this method could substantially improve geological interpretation of magnetic anomalies and aid prioritisation of targets.

The outcome was a milestone that verified the concept, but logistical difficulties in operating the gradiometer with sufficient separation and independence of the base station led to the investigation of alternative solutions to the problem addressed. The final report on this project (CSIRO-AMIRA P446) was published in 1997. (Schmidt, et. al., 1993).

1996 THE APPLICATION OF SAM TO ACQUIRE TFEM DATA

David Boggs commenced a PhD with the Geophysical Research Institute in 1996 under the supervision of Malcolm Cattach and John Stanley. His research was to investigate the feasibility of applying SAM to the acquisition of total field EM data (TFEM) as anticipated in the SAM Patent. David focused upon the acquisition and interpretation of the transient decay from a square wave energising signal, measured during the "Off" time with precise synchronisation using GPS timing. Having confirmed the viability of measuring the TFEM decay simultaneously with the acquisition of TMI and TFMMR data when using a grounded electrode energising source, David varied the procedure and replaced the electrodes with a closed loop surrounding the area being investigated. Specifically, he surrounded a 1 ha square area with a closed loop measuring 110 m x 110 m. In a case study, he demonstrated that the magnetic and electromagnetic response from buried unexploded ordnance could simultaneously be acquired. An important significance of this was the potential for a SAM survey to provide discrimination between highly magnetic fragmentation and whole UXO on the basis of the compatibility of the magnetic dipole with the conductor dimensions. (Stanley, et. al., 2005). David's thesis also delivered another significant steppingstone as it defined shortcomings in the TM-4 counter technology which if overcome would enhance the measurement of transient EM decay responses. (Boggs, 1999, Boggs et.al., 1998)

2001 IN-SITU MAGNETIC PROPERTIES MEASUREMENT USING TENSOR GRADIOMETER

Following on from the success but with limitations of the vector gradiometer project using optically pumped sensors to determine in-situ magnetic properties, CSIRO undertook an investigation into the use of SQUIDs (Superconducting Quantum Interference Devices).

After the successful testing of a SQUID sensor made in-house in 1991, development at CSIRO continued and included the construction of a tensor gradiometer system. Tensor gradiometry yields desirable mathematical properties of true potential fields, allows rigorous continuation, RTP and magnetization mapping. Furthermore, redundancy of tensor components gives inherent error correction and noise estimates.

Inversion using Euler deconvolution was developed for locating and characterising dipole sources and identifying a wider set of sources generally encountered in mineral exploration, such as spheres, sheets and pipes. A wide range of new types of processed data became available, including invariants, directional filters and depth slicing.

The final report on this development was delivered in 2007. The technology has not been evaluated as delivering a cost-effective solution but its contribution to scientific knowledge was significant. The final report on this project (CSIRO-AMIRA P446) was published in 1997.

2006 THE TM-6 MAGNETOMETER

David Boggs' confirmation that high-definition transient EM data could be acquired simultaneously with TMI data led to the recognition of specific desired enhancements to the TM-4 performance. In particular, a frequency counter with a precisely regular count rate rather that a period counter with variable count rate was desired. In 2006 Ron Bradbury engineered an upgrade to Steve Lee's period counter making it a true frequency counter. Moreover, the new counter delivered 5 pT resolution at 120 Hz or 0.04 nT at 2400 Hz. Each measurement was able to be time tagged to 10 µS precision synchronised with GPS time. The TM-6 was a purpose-built SAM receiver. Unlike the TM-4 which had its own inbuilt screen and keyboard, the interface with the TM-6 was via a Bluetooth connection with an off-the-shelf hand-held device. Using a TM-6, Gap Geophysics have demonstrated that an induced polarisation signal can also be confidently distinguished from electromagnetic coupling thus confirming that all four parameters defined in the SAM Patent can be simultaneously acquired.

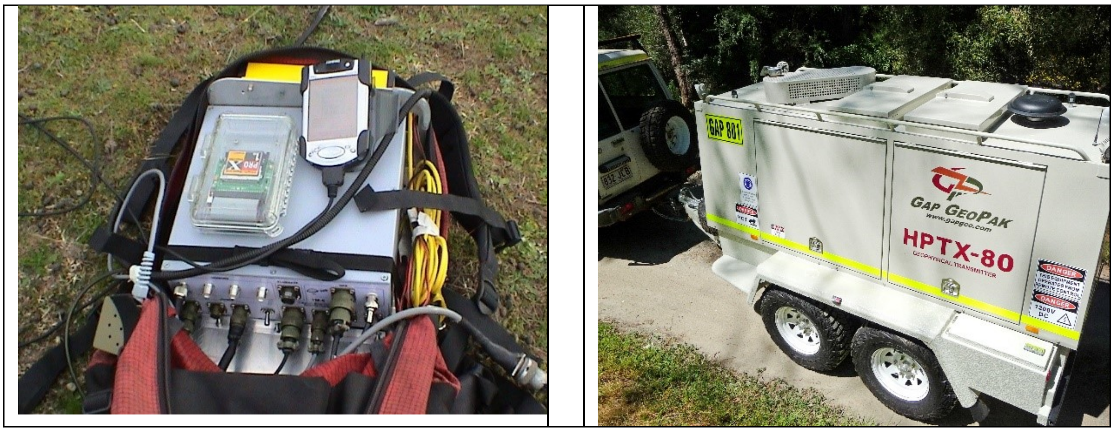
A TM-6 crew acquiring SAM data near Kalgoorlie in 2006. (Photo: Kim Frankcombe.)

2007 THE DEVELOPMENT OF SAMSON, DEEP PENETRATION TFEM

A strength of the SAM measurement strategy was that it simultaneously delivered independent parameters associated with sub-surface structure at measurement intervals along line that adequately sampled the response from near surface sources. While many such sources may be considered noise, if their response is properly sampled it may be removed by filtering. If not properly sampled, the noise energy will be folded back into the spectrum occupied by deeper sources of interest. However, the long period transient EM response from a large conductor outlives the response from small near surface sources. In exploring for deep conductors using transient EM measurements, emphasis is not upon close sampling but upon the signal to noise ratio of the late-time decay. "SAMSON" (Son of SAM) was conceived by Malcolm Cattach to address this specific application.

The TM-6 magnetometer has a capacity to perform real time signal processing and this was applied to the stacking of multiple transient EM decays while the sensor was stationary. Because the source was deep, the sample interval could be extended, justifying the increased measurement time. Complementing the receiver technology was the development of the HPTX-70 (soon after upgraded to HPTX-80), a very high power (70 kW, later 80 kW) square wave transmitter with a fast cut-off. This development was led by Keith Matthews working with Mal Cattach at Gap Geopak and they and their colleagues were recognised for this achievement with the Grahame Sands Award in 2012. Delivering such power through a closed loop of dimension several sq km would generate an electromagnetic primary field of high intensity and uniform to many 100’s of m depth.

The first SAMSON survey was conducted at Honeymoon Well in WA in October 2007. In combination the TM-6 and HPTX-80 have routinely delivered interpretable TFEM signal above noise background as low as just 0.005 pT/A.



A TM-6 magnetometer and HPTX-80 transmitter first used to acquire SAMSON TFEM data at Honeymoon Well, WA, in 2007 where signal was detected above a noise floor of just 0.005 pT/A.

2007 MAGNETIC PROPERTIES MEASUREMENT USING THE Q METER

The importance of magnetic properties measurement was clearly identified in Chapter VI of "Application Manual for Portable Magnetometers" by S. Breiner at Geometrics (Breiner,1973). where "Magnetic Susceptibility, Magnetization and Magnetic Moment Measurements" were discussed. Inspired by this, an outcome of the investigation at CSIRO of advanced technologies to acquire in-situ measurement of the magnetic properties of sub-surface sources, was the development by Phil Schmidt of an elegantly simple and field portable device for determining the Konigsberger ratio (Q) and direction of remanence from a rock sample. (Schmidt and Lackie, 2014). To determine the Q of a rock sample normally requires the measurement of its magnetic susceptibility, k, and its remanent magnetisation, Jr (Q = Jr/kH, where the ambient magnetic field, H, is an assumed known). While the susceptibility, k, and remanence, Jr, are usually measured on different instruments, more often than not the latter is ignored because the measurement of Jr requires sending samples to a laboratory which is time consuming and can cause delays to the exploration workflow. However, it is possible to measure both susceptibility and remanent magnetisation using the Q- meter at the exploration camp or even the drill site. The instrument has one moving part and is entirely powered by a single USB port.

The susceptibility is determined from the induced magnetisation (kH) since H is known. The procedure involves making two measurements of the magnetisation of a sample in the ambient field, H, one where the total magnetisation is a maximum and the other where it is a minimum. When the magnetisation is a maximum, both the induced and remanent magnetisations are aligned, whereas when the magnetisation is a minimum the remanent magnetisation is opposed to the induced magnetisation. The addition of the two values derived from the magnetic measurements yields twice the induced magnetisation, while the difference yields twice the remanent magnetisation. A slightly more involved set of measurement can determine the direction of the remanence of a sample when unknown. For the development of the Q-Meter into a commercial product now marketed by MagneticEarth Pty Ltd, Phil Schmidt received the 2015 Grahame Sands Award for Innovation in Applied Geoscience.

The Q-meter is an elegantly simple and field portable device that can be used to determine the Konigsberger ratio (Q) and direction of remanence from a rock sample. (Photo: Phil Schmidt).

REFERENCES.

Boggs, D.B., 1999
"The Theory and Application of Sub-Audio Magnetic Data Acquisition and Numerical Modelling"
PhD Thesis. University of New England.

Boggs, D.B., Stanley, J.M. and Cattach, M.K., 1998
"Feasibility studies of TFMMIP and TFEM surveying with Sub-Audio Magnetics."
Exploration Geophysics, **29**. 290-295.

Breiner, S., 1973
"Application Manual for Portable Magnetometers"
Geometrics Inc, in-house publication.

Broughton Edge, A. B. and Laby, T,H., 1931
"The Principles and Practice of Geophysical Prospecting."
Oxford University Press.

Cattach, M.K., 1992
"Sub Audio Magnetics – In theory and in practice."
PhD Thesis. University of New England.

Cattach, M.K. and Foley, A., 2005
"A Sub-Audio Magnetics case study: Orlando Au-Cu-Bi deposit, Tennant Creek, Australia."
Exploration Geophysics, **36**. 147-156.

Cattach, M.K., 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.

Cattach, M.K., Boyd, G.W., Bradbury, R. Stanley, J.M., 1995
"Recent developments in Sub-Audio Magnetics (SAM)."
Preview, August.

Courtillot, V. and Mouël, J.L., 2007
"The study of Earth's magnetism (1269 – 1950): A foundation by Peregrinus and subsequent development of geomagnetism and paleomagnetism."
Reviews of Geophysics, **45**,

Davis, J.K., 1962
In: High Latitude. Melbourne University Press. 106 – 109.

Day, A.A., 1966-67
"The development of geophysics in Australia."
Journal and Proceedings, Royal Society of NSW, **100**, 33-60.

Foley, C.P., Leslie, K.E. and Binks, R.A., 2006
"A history of the CSIRO's development of high temperature superconducting rf SQUIDs for TEM prospecting."
ASEG Extended Abstracts, **2006:1**.

Green R. and Stanley, J.M., 1973
"The application of the technique of optical pumping for the precise measurement of weak magnetic fields."
The Australian Physicist, **10**. 52-54.

Jack, R.L., 1915
"The Geology and Prospects of the Region to the South of the Musgrave Ranges, and the Geology of the Western Portion of the Great Artesian Basin".
https://nla.gov.au/nla.obj-1411613854/view?partId=nla.obj-1411680138#page/n2/mode/1up

Mawson, D., 1930
"Bage's Narrative."
In: The home of the blizzard. Hodder and Stoughton, London. 213.

Morrison, W. D., 2017.
"Geophysical surveying in Australia by navigators James Cook and Mathew Flinders"
ASEG Preview, **189**, 38-41.

Morrison, W. D., 2020.
"Measuring terrestrial magnetism"
Geoscience Australia/ASEG.

Oxley, J., 1820.
"Journals of two expeditions into the interior of New South Wales, undertaken by order of the British Government in the years 1817-18". London

Richardson, R., 2016
"Lewis Albert Richardson: a pioneer f exploration geophysics in Australia"
Preview. April 2016.

Schmidt, P.W., Clark, D.A., Coward, D.A. and Huddleston, M.P., 1993
"Development and application of differential vector magnetometers."
Exploration Geophysics, **24**. 312-319.

Schmidt, P.W., 1997
"The sesquicentennial of palaeomagnetism and rock magnetism in Australia"
AGSO Journal of Australian Geology & Geophysics, 17(1), 32-143.

Schmidt, P.W. and Lackie, M.A., 2014
"Practical considerations: Making measurements of susceptibility, remanence and Q in the field"
Exploration Geophysics, **45**. 305-313.

Senior, B. R., McColl, D. H., Long B. E. and Whiteley, R. J., 1977
"The geology and magnetic characteristics of precious opal deposits, Southwest Queensland."
BMR Journal of Geology and Geophysics, **2**, 241-255.

Stanley, J.M., 1975a
"A caesium vapour magnetometer and its applications."
PhD Thesis. University of New England.

Stanley, J.M., 1975b
"Empirical observations in locating present and prior streambeds with a magnetometer"
Geophysics, **40**. 684-685.

Stanley, J.M., 1975c
"The application of a rapid sampling vehicle-borne magnetometer."
Bull. Aust. Soc. Explor. Geophysicists, **6**. 100-103.

Stanley, J.M., 1978
"The application of geophysical methods to hunter/gatherer prehistory in Australia."
Archaeo Physika 10 – Proc of 18th International Symposium on Archaeometry and Archaeological Prospecting, Bonn, 14-17 March. 692-699.

Stanley, J.M., 1982
"New magnetometer technology and its application to archaeological exploration."
In: Archaeometry – an Australian perspective, ANU Press. 151-155.

Stanley, J.M. and Cattach, M.K., 1990
"The use of high definition magnetics in engineering site investigation."
Exploration Geophysics, **21**. 91-103.

Stanley, J.M., Cattach, M.K., Griffin, S.M. and Townsend, J.A., 2005
"Environmental applications of Sub-Audio Magnetics."
Exploration Geophysics, **36**. 198-205.

Stanley, J.M., Ludbey, F.C. and Green, R., 1976
"An alkali vapour magnetometer using integrated circuits."
Space Science Instrumentation, **1**. 471-492.