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An overview of some of CSIRO's "Underground Science" capabilities

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Abstract. CSIRO is a multi-disciplined, Australian Government funded, science organisation whose major aims include the investigation of science issues that are of particular relevance to Australia in a global context. The organisation has over 5700 employees. This review paper contains a broad outline of some of the "underground science" capabilities found within CSIRO, with an emphasis on SQUID-based sensors developed within the CSIRO's Superconductivity Group and the general capabilities to be found within CSIRO's Petroleum Geoscience Program.

1. OVERVIEW OF CSIRO

The Australian Government funded science organisation, the CSIRO (Commonwealth Scientific and Industrial Research Organisation), was formed in 1926. Within CSIRO, there exists a broad range of science capabilities based on the individual and collective expertise of scientists and technicians working in the fields of agricultural, information science, environment, health, mining, energy, manufacturing and materials sciences. Structurally, common capabilities are collected together within CSIRO "Divisions".

Many of CSIRO's physical science capabilities are housed in the Division of Material Science and Engineering (CMSE). Some science disciplines of relevance to underground science found within CMSE include understanding and application of the properties of metals and ceramics, thin films, textiles, forest polymers and wave physics, superconductivity and fluid dynamics. Currently this Division has over 880 staff members.

CSIRO's Petroleum Geoscience and Petroleum Engineering science capabilities are housed within the Earth Science and Resource Engineering Division (CESRE). Currently this Division has over 450 staff members. Within both CMSE and CESRE, there exist a number of capabilities relevant to "underground science".

2. CMSE – SUPERCONDUCTING SCIENCE

Over a period spanning four decades, CSIRO was instrumental in developing and maintaining primary reference standards for Australia. Implementing both temperature and electrical standards required the use of liquid helium. CSIRO scientists were amongst the first to implement a working voltage standard based on the superconducting quantum behaviour observed via the Josephson/Shapiro constant-voltage steps. This early work contributed significantly to the refinement in the value of the constant $2e/h$. CSIRO also contributed significantly to the field of metrology via the invention of the superconducting

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Figure 1. LT SQUID system used for mineral prospecting in Western Australia by BHP Billiton.

cryogenic current comparator, a device that allows the ratio of currents to be determined with accuracies of order a few parts in 10^{10} [1].

For the past two decades, the focus of the CMSE superconductor group has been on applications other than metrology. Projects undertaken by the group include the use of SQUIDs for bio-magnetometry (magnetic mapping of brain activity), detection of metal contaminants in food [2], SQUID sensors for Time Domain Electromagnetic geophysical prospecting [3], magnetic anomaly detection for Geophysical and Defence applications [4], and THz imaging using Josephson Junction-based detectors [5] to name a few. An overview of these activities follows:

2.1 Low temperature SQUID magnetometers

The earliest CSIRO Josephson junctions were formed via the connection of a simple point-contact of niobium wire onto bulk niobium material [6]. This simple junction technology was sufficient for the realisation of the Josephson volt and for the early SQUID magnetometers used in the original superconducting cryogenic comparator developed within CMSE. However it was not suited to manufacture of the smaller scale devices that are required for multi-sensor systems. Thus in the late 1980s, as part of a bio-magnetometer project, CMSE developed a tri-layer process for use in SQUIDs that followed Ketchen and Jaycox's square-washer design [7]. In order to facilitate the manufacture of these devices, in the mid-1990s, CMSE installed a class 100 clean room facility at its Lindfield site. Since its completion, this facility has played a vital role in ensuring a steady flow of superconducting devices for both research and commercial applications.

CMSE have recently built a Low Temperature (LT) SQUID system targeted at geophysical prospecting. This system is currently being used by BHP Billiton for prospecting for massive nickel sulphide deposits. With a white noise floor of less than 50 fT $/\sqrt{\text{Hz}}$, this system has proven capable of the detection of the natural magnetic phenomena known as Schuman resonances. It is anticipated that this system, or one similar in construction, could be used for trialling long-base line magnetometry, as a part of the magnetic network that is currently being championed by the Low Noise Underground Laboratory (LSBB), Apt.

2.2 High temperature SQUID magnetometers

Following the discovery of high-temperature superconductivity (HTS) in 1987, CMSE developed an active HTS research program based on our earlier research on low-temperature superconductivity. An important outcome of this program was the development of a step-edge Josephson junction (SEJ)

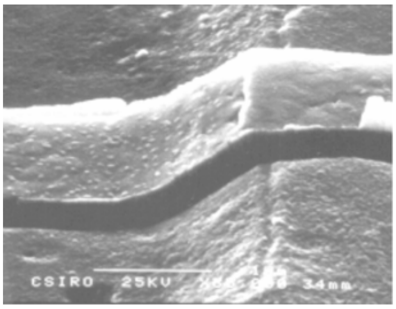

Figure 2. SEM picture of a CSIRO Step-Edge Junction.

Figure 3. Prototype LANDTEM system pictured in Canada, 2001 (left) and a production model shown in operation in Western Australia, 2004 (right).

technology that allows a junction to be positioned anywhere on a MgO (001) substrate and is suitable for fabricating multiple devices or arrays on a single chip [8, 9]. This technology has proven to be a cost effective process for fabricating HTS SQUIDs and other junction-based devices. A consequence of CMSE's patented SEJ process is that only one junction is formed at the top of the step, formation of a second junction at the bottom of the step is avoided by ensuring a rounded bottom on the step return. Variation of the junction's step angle enables the SEJ critical current to be adjusted over four orders of magnitude. This highly versatile junction technology is core to many of CMSE's HTS sensor applications.

CMSE developed an HTS SQUID-based sensor for ground-based TEM with the first field trial occurring in 1991. In 2000, CSIRO was contracted by Falconbridge (now Xstrata) to build two ruggedized and portable SQUID systems to be used for mineral exploration at their Raglan, Quebec exploration lease. These systems have been in almost continuous use since 2003 and have been used to survey hundreds of line kilometres at their Raglan prospect. In 2004, CMSE licensed this technology to a local engineering company for manufacture and use for geophysical prospecting. Currently ten such systems, known as LANDTEM, have been manufactured and are in use on four continents: Australia, Africa, America and Europe.

2.3 High temperature SQUID gradiometers

Measuring the full magnetic gradient tensor provides many potential advantages for the detection of magnetic anomalies. This is particularly relevant when attempting to localise magnetic anomalies

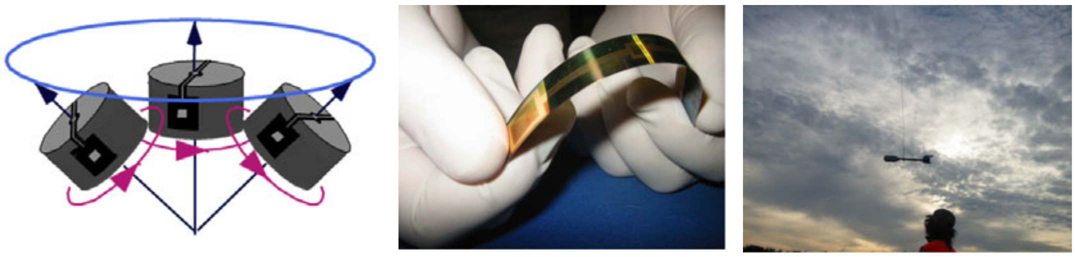

Figure 4. Schematic representing the concept of a rotating gradiometer (left) and a picture of a HTS patterned tape used in the realisation of this concept (centre) and the system being flown slung under a helicopter (right). This work was part-funded by the Australian Defence Department.

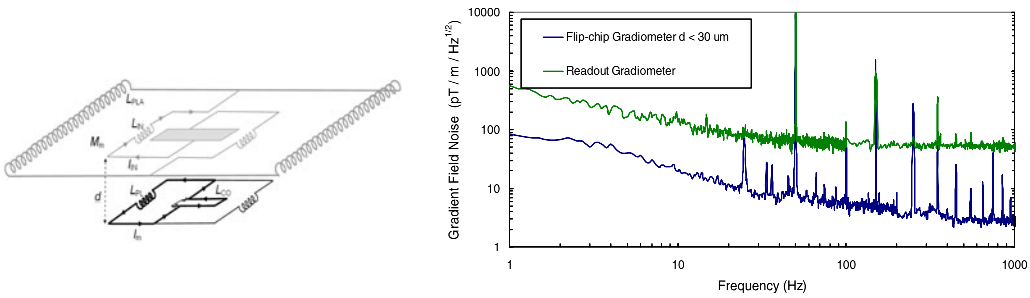

Figure 5. Schematic (left) showing a gradiometer antenna (upper structure) flip-chipped to a planar gradiometer (lower structure). The accompanying graph (right) shows the improvement in noise performance gained by flip-chipping the antenna to the planar gradiometer (lower of the two traces).

via measurement made from a moving platform, where the use of a vector magnetometer is severely compromised by their inherent sensitivity to movement in the Earth's magnetic field.

CMSE has developed two forms of HTS-based magnetic tensor gradiometers. The first system trialled was based on the concept of rotating three axial gradiometers to measure the five independent components of the magnetic tensor. While trials over a large magnetic anomaly proved the feasibility of this concept to measure gradients of the order of 1 nT/m, improving the sensitivity by two orders of magnitude to 0.01 nT/m has proven difficult, possibly due to the occurrence of hysteretic effects in the HTS material used to form the axial gradiometer [10].

CMSE have adopted a more conventional approach for a gradiometer design for the detection of unexploded ordnance (UXOs). In this design, six planar gradiometers are arranged in a hexagonal pyramid configuration. SQUID magnetometers are used to compensate the non-ideal common-mode rejection of the Earth's field. This system, which is being funded by the US Government Agency, SERDP and is being undertaken with a commercial partner, SkyResearch, is currently in the laboratory test phase [11].

3. HIGH RESOLUTION, SUB-SURFACE RADAR

Over a period of many years, CSIRO has built up a capability in a pulsed, low-power, sub-surface radar system (SIROPulse) that typically operates over the frequency band of between 200 MHz to 2 GHz. This radar can probe solid structures over distances ranging from less than one centimetre to several metres. The system weighs less than two kilograms and is thus quite portable. This system has been used for searching for concealed devices including fine wires and plastic landmines. It has also been applied to

Figure 6. An image produced by high-resolution, sub-surface radar is shown overlayed onto a concrete floor that is being scanned by a SIROPulse radar operator.

structural health monitoring of concrete walls particularly in cases where it is necessary to detect the presence or absence of reinforcing materials.

In recent years, CSIRO has focussed on the development of data processing packages and software that generates a three dimensional image of the target thereby making it easier to visualise the hidden structure.

4. PETROLEUM GEOSCIENCE

The CSIRO Earth Science and Resource Engineering Division (CESRE) hosts a number of capabilities with application to "Underground Science". These capabilities are broken down into two major research programmes termed Petroleum Geoscience and Petroleum Engineering. These capabilities are based across three sites in Perth, Sydney and Melbourne.

The petroleum geoscience research programme comprises around 75 researchers divided into five major groups which include:

- Basin Timeframes, where K-Ar, Ar-Ar and Sr-isotope dating are used to unravel sedimentological, structural and stratigraphic events occurring in sedimentary basins.
- Geofluid Sciences, where reservoirs deep in the subsurface are characterised using fluid inclusion technologies and hydrodynamic data. In addition, fluids seeping from those reservoirs into the ocean at the present day can be discovered, identified and quantified through the development of novel nanochemical sensors.
- Predictive Geoscience, through the use of stratigraphic forward modelling code termed SEDSIM, a computer-based technique provides 3D simulations of the arrangement of sediments in the Earth's crust over a range of time scales. This modelling helps geoscientists and engineers understand basin fill processes, the location of stratigraphic traps for oil and gas and to predict the reservoir quality.
- Organic Petrology and Geochemistry, where analysis of source rocks, coals and oils can be applied to understand basin evolution, migration of hydrocarbons, the development of coalbed methane resources and subsurface storage of CO_2.
- Rock Properties, where rock mechanics, rock physics and petrophysical properties of rocks are evaluated through world class laboratory facilities and modelling approaches for application to petroleum, geothermal and CO_2 storage issues.

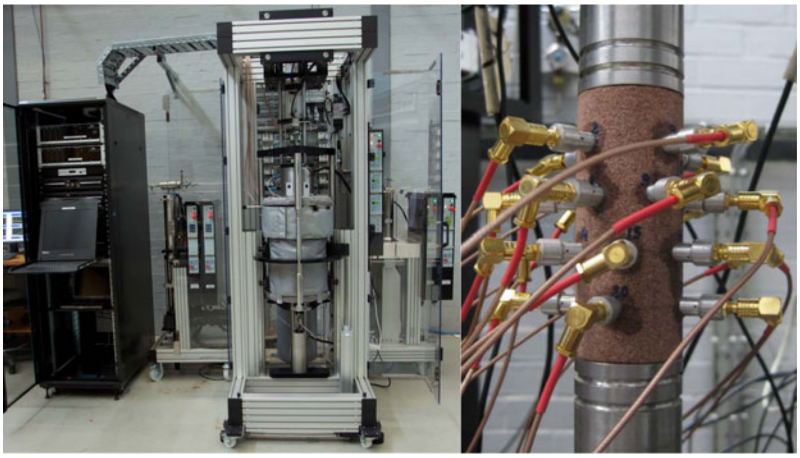

Figure 7. High pressure, high temperature rig equipped with 20 channel active/passive transducer system for measurement of ultrasonic velocities and acoustic emission (left). Ultrasonic transducer arrays for uniaxial tests on rock samples and measurement of acoustic emissions (right).

The petroleum engineering research programme is broken down into four groups, two of which are concerned with the subsurface:

- Geomechanics, where experiments and modelling are used to investigate hydraulic fracturing for application to both hydrocarbon recovery and the mining industry, plus drilling mechanics where research into bit-rock interactions and drillability of rocks are also applied across these two industries.
- Reservoir Engineering, where the properties of both conventional and unconventional reservoirs (e.g. coal bed methane, shale gas) are investigated through coupled mechanical and chemical experiments and modelling.

These capabilities are focussed on refining integrated petroleum system analysis and reservoir characterisation. The research aims to add benefit to industry via the optimisation of well siting, maximising production and recovery, and minimising recovery loss. Industrial partners and clients who draw on these capabilities include BP, Statoil, Schlumberger, Petronas, ConocoPhilips, BHP Billiton, Woodside, Origin Energy, Chevron, Anadarko plus many other oil and service companies. Strong links are also maintained with Australian state governments and other federal agencies such as Geoscience Australia (GA) and the Australian Government Co-operative Research Centres.

CESRE is renowned for its world-class experimental facilities which in subsurface terms generally revolve around characterisation of rock and fluid properties. The Rock Mechanics laboratory has at least ten rigs capable of simulating in situ pressure and temperature conditions (up to 300 MPa and 200 °C), a number of which have additional capability such as ultrasonic velocity measurements and/or acoustic emissions. The petrophysics laboratory comprises experimental facilities for nuclear magnetic resonance (NMR) at frequencies from 2 MHz to 400 MHz, including core flooding under stress. Electrical properties of rocks can be measured across 12 decades of frequency from mHz to GHz, using both electrical impedance and dielectric spectroscopy. This is combined with wireline log interpretation, allowing powerful interpretation of subsurface formation properties through core-log integration. A medical CT scanner is also used for evaluation of mm to cm scale microstructure and for monitoring core flooding experiments in core holders also equipped with ultrasonic transducers. Exotic petrophysical characterisation can also be carried out using National Facilities such as the Synchrotron and the OPAL Neutron Source. The coal seam gas laboratory has facilities for measuring coal permeability, geomechanical properties, swelling and cleat compressibility, techniques which can also be applied to geological CO_2 storage.

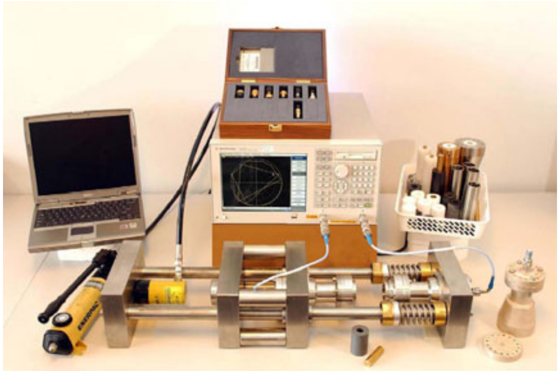

Figure 8. Network analyser and pressure rig for making measurements of dielectric properties of rocks under in situ pressure conditions.

One of CSIRO's strengths is its ability to draw on a wide range of staff capability not just within divisions but across the whole organisation. This allows us to conduct highly multi-disciplinary research projects across various scales, from micro-to-macro, laboratory-to-field and experiment-to-theoretical. Such powerful approaches have been strongly supported by industry in a number of recent projects such as:

- The Turbidite Research Initiative (TURI): a project in which the impact of structural and stratigraphic architecture on fluid flow in turbidite reservoirs was investigated based on an approach of integrating fieldwork with 2D and 3D seismic data, ground penetrating radar, flow tests, bore hole data, laboratory data and reservoir modelling.
- Integrated Predictive Evaluation of Traps and Seals (IPETS): this project, looked at factors governing trap integrity in the subsurface, including capillary trapping of hydrocarbons, likelihood of faulting and fracturing breaching trap integrity, predicting shale geomechanical properties and wettability in clay-rich systems. This collaborative project was sponsored by seven Australian and international companies and was undertaken within a consortium that included three Australian tertiary institutions, an oil-field service provider and drew on multi-disciplinary capabilities located within three CSIRO Divisions. These capabilities included structural geology, seismic attributes, hydrodynamics, rock mechanics, petrophysics and modelling.
- Geological Storage of CO_2: CSIRO's multi-disciplinary capabilities are being deployed to work on geological storage of CO_2. These capabilities have all been deployed on Australia's first demonstration site for the technology located in the Otway Ranges, Victoria. Full geological, geophysical and rock properties characterisation of the reservoir and seals took place before injection in order to develop initial geological models of the site. 65000 tons of CO_2 were injected into the trap and dispersion rates monitored with seismic, microseismic and geochemical methods. Surface methods have also been deployed to monitor CO_2 build-up in soils, groundwater and the atmosphere. To date, the CO_2 plume has been detected subsurface using 4D seismic and geochemical techniques, including novel tracer studies. The Otway project provides an opportunity to undertake research on storage at commercial levels of CO_2 sequestration.

Within CSIRO's Petroleum and Geothermal (P&G) Portfolio, there are numerous other ongoing strategic and applied research projects tackling subsurface geoscience. Specific areas of interest include shale behaviour, 4D seismic technologies, regional studies such as a collaboration with GA on the geology of the Perth Basin and with the Victorian Department of Primary Industries looking at resource competition between hydrocarbons, groundwater and subsurface CO_2 storage. The P&G Portfolio's current major growth areas for research include unconventional hydrocarbons (such as coal bed methane and shale gas), subsurface CO_2 storage and geothermal energy (both engineered geothermal systems and hot sedimentary aquifers). Similar multi-disciplinary approaches as noted above will be brought to bear on these upcoming (for Australia) research topics.

5. SUMMARY

Two of CSIRO's Divisions, "Materials Science and Engineering" and "Earth Science and Resource Engineering", contain extensive capabilities in superconductor science, sub-surface radar technology and Petroleum Geoscience and Petroleum Engineering science capabilities. CSIRO has undertaken and completed a large number of projects in collaboration with Universities, Commercial partners and other Government Departments (both national and international). CSIRO has a strong interest in furthering our future collaboration with international partners, for example by partnering with members of the I-DUST community. We welcome approaches from any-one interested in accessing our capabilities for the purposes of further research into "Underground Science".

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