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SIROTEM – Australia's first locally invented TEM system

A story of continual innovation and improvement in instrumentation over 25 years from 1972

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The need

In the early 1970s, Russia had produced a portable TEM instrument called MPPO-1 (an acronym from its name in Russian) and one was purchased by the then Bureau of Mineral Resources, Geology and Geophysics (now Geoscience Australia) and another by a large Australian exploration company. MPPO-1 was chosen because it had potential to map conductive ore-bodies, especially under the thick conductive overburden typical of most of Australia. This was because the instrument operated in the time-domain and had a large transmitter loop. However, MPPO-1 had analog function and was found to be difficult to operate and unreliable. For example, operators were required to mentally average the reading of a flickering meter display. An easier to use, more reliable instrument with a more objective measurement, preferably digital, was needed.

At this same time, other TEM systems were in operation in North America, however, they did not record signal at sufficiently late times to allow for the delaying effect of Australia's conductive overburden (something that is not commonly encountered in their region). Furthermore, they were not designed to reject the 1000 times higher levels of electromagnetic noise encountered in the tropical regions of Australia.

Meeting the challenge

In 1972, the CSIRO Division of Mineral Physics, under the leadership of Dr K. G. McCracken, took up the challenge to meet the needs of the Australian industry. While learning from the systems existing at the time, it was clear that it was necessary to go back to first principles and establish necessary design goals. These included (a) a large transmitter moment combined with selectable late-time delays to yield deep penetration and (b) signal processing that would provide the highest possible noise rejection in the shortest measurement time. A list of all the original design goals is given in Appendix 1.

Over the next 4 years a team including Ken McCracken, with his previous experience in space physics, Dr Jock Buselli, Brian O'Neill and Phil Pik, assembled a prototype TEM system using available laboratory equipment including a multichannel analyser for stacking data. For a fuller description of this prototype, see Buselli (1974). From that experience, and to make a more field-friendly unit, they designed and tested a digital unit using 8 bit A/D convertors and the latest developments generally in electronics and software including, probably for the first time in a geophysical field instrument, a CMOS microprocessor. This instrument was called SIROTEM recognising it as a TEM instrument from 'SIRO', the colloquial name for the CSIRO. For a full description see Buselli and O'Neill (1977). Some unique aspects of the design were patented in Australia and the USA.

Three prototypes were built and field tests were conducted over ten known ore-bodies, to develop 'case-studies' including at Cloncurry (Buselli, 1974), Woodlawn (Buselli, 1977, 1981) and Elura (Buselli, 1980a). Other sites included Mt. Bulga (Buselli, 1980a, 1991) and Teutonic Bore (Buselli, 1980a; Buselli *et al*., 1986). In August 1977, Jock Buselli took a SIROTEM to the Caucasus Mountains of the USSR to compare it to the latest Russian TEM, MPP-4, which it did very favourably (Buselli, 1980b). In October 1980, Ken McCracken demonstrated a SIROTEM near Hyderabad, India. At such sites some new aspect of the measuring regime was often revealed such as atmospheric ('sferics') noise (see McCracken and Buselli, 1981) and superparamagnetism (SPM), the latter first detected at Elura (Buselli, 1980c, 1980d, 1982, 1991; Clark, 1980). The understanding and resolution of these latter phenomena, in particular, are a whole separate story which may be told elsewhere. The SIROTEM team at CSIRO continued to improve on the system and develop accessories such as a separate borehole probe, a separate receiver, a separate transmitter and improvements to the measurement software and data presentation (e.g. Smith *et al*., 1996). (See also 'Subsequent development of additions and improvements to SIROTEM' and References.)

In 1979, SIROTEM won the prestigious international 'IR-100' award for excellence in industrial design, the first time this award was granted to an Australia organisation for the previous nine years. Examples of the calibre of other recipients of this award are NASA, MIT and GE.

Industry support

In 1975, AMIRA (www.amirainternational.com), an association of mining and exploration companies that sponsors collaborative research projects, funded Project P74 (1975–1977), enabling CSIRO to develop a commercially acceptable version of SIROTEM. This was the first of five AMIRA projects over the next 20 years tasked with developing the SIROTEM system and improvements and accessories. See a full list of project titles and other details in Appendix 2. Twenty mining companies supported one or more of these projects for a total value of nearly $5 million. This was a large amount for one instrument development at this time. See a full list of SIROTEM sponsors in Appendix 2. Developments that resulted from these projects are described in 'Subsequent development of additions and improvements to SIROTEM'.

Commercialisation

In 1976, as required of all government developments, the right to commercialise SIROTEM was tendered to private industry. Following an unexpectedly large number of respondents, 36 in fact, Geoex Pty Ltd of Adelaide was awarded the licence to market SIROTEM world-wide. In 1982, the marketing rights to SIROTEM followed Roger Henderson from Geoex to EG&G Geometrics International Corp. in Sydney, and in 1986 to Geo Instruments Pty Ltd, also in Sydney.

The first commercial production of 10 units was designated 'Mk I' and, electronically, was essentially a copy of the prototype provided to Geoex by CSIRO but housed in a robust case. The units were manufactured by MCI Pty Ltd, also of Adelaide, under licence to Geoex. Figure 1 is a photo of a Mk I console and associated battery pack. The assembly was in the form of individual circuit boards in a 'rack-mounted' style case with a separate power supply. In addition to the individual transmitter and receiver electronics, ADC, MPU and interface cards, the unit contained a digital battery-powered printer for data display. Appendix 3 lists the main specifications of the Mk I. A separate cassette recorder was offered for data storage and manipulation, the latter including conversion of signal voltages to apparent resistivities. By now the original design goals (see Appendix 1) were achieved and in most cases exceeded. Some of the early purchasers of the ten Mk I units manufactured were sponsors of Project P74 and other local mining companies but also, three were sold to other countries. See Appendix 4 for a list of all purchasers of the Mk I SIROTEM.

A story may well be true that, because the first unit was not finished in time for the pre-arranged formal handover to the first buyer, a house brick was included in the case so as to simulate the correct weight.

SIROTEM has a rare distinction of being a geophysical instrument mentioned in Federal Parliament as recorded in Hansard on 4 April 1979. In answer to a question from Senator Elstob, the then Minister for Science, Senator Webster, provided details of its development and manufacture, how many had been sold and exported and even the price at the time!

Soon after the completion of the Mk I model, ways of improving the unit and making it more field worthy were devised by Geoex, including the incorporation of a cassette tape for data storage and retrieval in a carry case opening to a flat instrument panel. Figure 2 is a photo of the front panel of this new model, designated 'Mk II'. Appendix 3 lists the main specifications with a comparison to the Mk I. Orders for this Mk II model were received from 1979 and altogether 50 Mk IIs

Figure 1. *Mk I console and battery pack.*

Figure 2. *Front panel of Mk II console.*

were manufactured and sold by 1990 to 20 separate countries. See Appendix 4 for the location and type of organisation of the purchasers of the first 27 Mk II SIROTEMs of which 10 were sold to seven foreign countries.

One customer for the Mk II, Arco Oil and Gas of Texas, had an unusual application; that of measuring the thickness of oil pipelines in the Arctic to reveal their internal corrosion. Due to the extreme cold, the exposed pipelines are normally wrapped with insulation but in this area, to prevent the Caribou eating the insulation, another layer of thin steel was added. This layer prevented the normal use of ultrasound to measure the pipe thickness. Brian Spies, an early Australian exponent of TEM who was working at Arco at the time, recognised the problem as not unlike conditions encountered in the field in Australia in the search for ore-bodies. That is, the thin steel was like the

Figure 3. *Front panel of Mk 3 console.*

conductive overburden and Brian knew that SIROTEM, with its late time delays, had the ability to penetrate this. A US Patent, no. 4 839 593 dated 13 June 1989, with Brian as the inventor (Spies, 1989), described this particular use of the instrument, which was later adopted by Rontgen Technische Dienst, an NDT company in The Netherlands, on behalf of Arco.

Yet again, in the late 1980s, a radical new design was developed and produced as the 'Mk 3' model, which incorporated dual microprocessors, all previous improvements and added a 3-receiver input, solid-state memory and an LCD screen resulting in half the weight of the Mk II and a slimmer case. A sferics reduction algorithm developed by CSIRO was also added (Buselli and Cameron, 1996). Other refinements continued to be added through to the late 1990s. Figure 3 is a photo of the front panel of the Mk 3 and the main specifications are given in Appendix 3, which shows the progressive developments and improvements in specifications from each model to the next. Eventually over 60 Mk 3s were sold around the world making a grand total of over 120 SIROTEMs for all three models. It is interesting that later sales were almost exclusively to foreign countries.

In the late 1990s, advances in computers suggested the possibility of a version incorporated into a rugged PC (Mk 4?). This possibility was not pursued at the time, due to a change in company ownership, but it was essentially achieved a later time by another group (see ' 'Son' of SIROTEM').

Demonstrations and exhibitions

The value in physically demonstrating the attributes of the instrument to prospective users was recognised at the outset, and this was assisted by a number of case-studies developed by the CSIRO (see the section on 'Meeting the challenge'). Also, a large number of field demonstrations and exhibitions were made by Geoex. Within 3 months of the licence being awarded in October 1977, Geoex personnel conducted a SIROTEM survey over the Cavendish test site in Ottawa, Canada to display its attributes to Canadian TEM users. Geoex also exhibited SIROTEM at 'Ottawa 77', the second decennial mineral exploration conference in Ottawa. The need for such demonstrations applied particularly in the early stages when the system was not well known outside of Australia. Later on, some repeat orders were received without any more need for a demonstration.

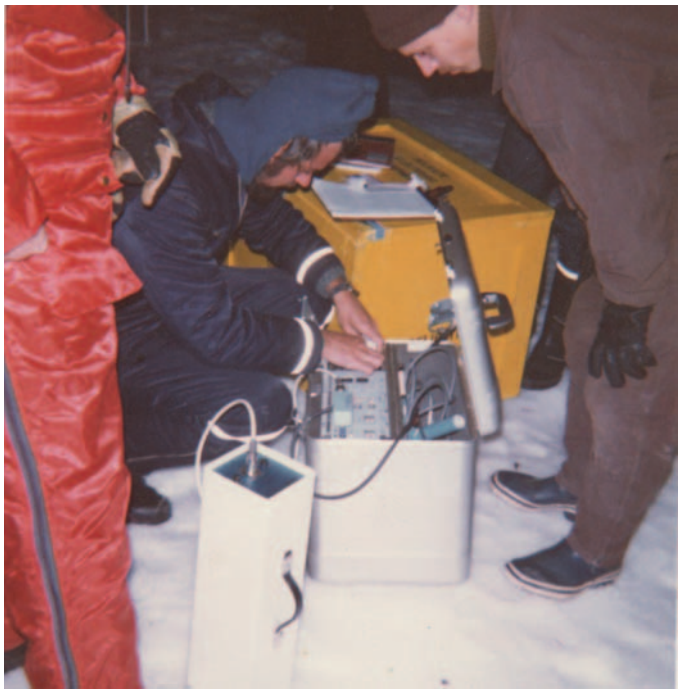

Figure 4. *A Mk I and battery pack being demonstrated north of the Arctic Circle in Finland in 1978.*

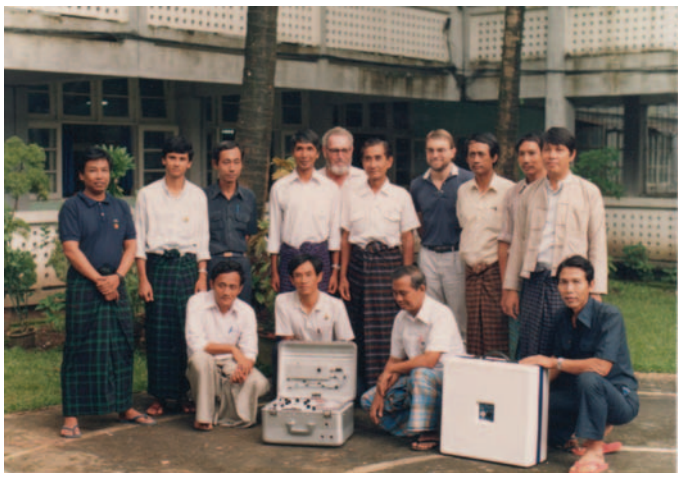

Figure 5. *Geologists from the Geological Survey of Myanmar receiving training on their Mk II and RVR-1 in 1987.*

Demonstrations were especially necessary in countries where the initial belief that 'it can't be much good if made in Australia' had to be overcome. This necessitated many trips to most other countries where the capabilities of the technique were understood. Roger Henderson alone, as the primary SIROTEM salesperson, conducted field demonstrations in 15 countries and presented papers and exhibited SIROTEM at over 20 conferences throughout the world. Roger's second such overseas trip (the first being to Ottawa as mentioned above) was to north of the Arctic circle in Finland (see Figure 4). In addition, workshops and training sessions were organised. Figure 5 is a photo of geologists of the Geological Survey of Myanmar in July 1987 who received training on their newly acquired Mk II SIROTEM and its associated receiver coil, RVR-1. Figure 6 is a photo of geologists in Taipei, Taiwan in June 1992 participating in one of the many workshops on Mk 3 SIROTEM performed

Figure 6. *Participants in a workshop on Mk 3 in Taipei, in 1992.*

Figure 7. *A Mk II in use in Mexico in 1987.*

Figure 8. *A Mk 3 in use in the desert of Egypt in 1990.*

throughout the world. Figures 7–9 are of demonstrations and training activities in field situations in Mexico, Egypt and Sumatra respectively.

Subsequent development of additions and improvements to SIROTEM

In 1978, in AMIRA Project P94 (1978–1981), CSIRO started development of a single-component down-hole receiver probe. Also, some of the sponsors of P94, by now, users of SIROTEM, noticed some unusual transients where the signal decayed more slowly than usual at late times, a phenomenon which was investigated by CSIRO and resolved in 1980 to be due to superparamagnetic (SPM) material close to the then coincident transmitter and receiver loop cables, providing additional signal (SPM has also been discussed in 'Meeting the challenge'). This gave impetus to the development of a separate receiver coil that could be positioned away from the transmitter loop, which was the generator of the SPM.

Thus, in 1980–1982, tests were conducted at Mt Bulga and Elura on a small multi-turn receiver coil for component measurements other than vertical. This coil also proved useful to avoid SPM (Buselli, 1982). After extensive field testing by CSIRO, both a single-component down-hole probe and the multi-turn receiver coil were made available commercially by

Figure 9. *A Mk 3 in use in Sumatra in 1993.*

Figure 10. *A Mk II with a SATX-1 (on the right) and an RVR-1 (behind).*

Geoex and designated DHR-1 and RVR-1 respectively. In 1980–1985, development of a very high power transmitter supplying up to 50 Amp was undertaken by other members of the CSIRO team (Buselli, 1991; Buselli *et al*., 1983). In 1982–1984, an early-time measurement version of SIROTEM was evaluated and subsequently incorporated in SIROTEM Model II. This allowed for shallow investigations such as soil salinity and geotechnical targets (Buselli, 1985; Buselli *et al*., 1990; Davis *et al*., 1991). In 1984, development commenced on a medium-power transmitter (20 A) with crystal clock synchronisation to the SIROTEM. This was later made available commercially and designated, SATX-1. Figure 10 is a photo of a SATX-1 with an RVR-1 behind it.

Many of these subsequent developments were sponsored by AMIRA Project P136 (1981–1984) which also included development of an induced polarisation (IP) receiver plug-in. This latter addition was never offered commercially. Aids to interpretation in the form of analogue model studies were sponsored by Project P212 (1986–1989) and software developments for rejecting noise such as sferics by statistical algorithm were provided by Project P250A (1990–1994).

As Mk 3 SIROTEM now had three receiver inputs, a 3-component downhole probe was a logical addition to the SIROTEM accessories and in 1990 a prototype was devised by Jim Cull of Monash University. In 1993 this was developed as a commercial product by John Pope and Phil Palmer of MCI and designated 'Vectem'.

Airborne SIROTEM

The operation of SIROTEM as an airborne system would greatly speed up survey coverage. However, the merit of SIROTEM as a type of TEM system would rely heavily on the area of the transmitter loop: the bigger the better. Ideally therefore, a large aircraft or a powerful helicopter would be used to fly the survey, but this would add to the overall cost and difficulty of the operation. Also, to comply with the increased speed of an aircraft, the stacking time, a great improver of signal to noise ratio, had to be reduced. This generally meant that an airborne operation would only be possible semi-airborne, either with the large transmitter loop on the surface and the receiver flown over it, or with a not so large transmitter loop towed by an aircraft. However, in 1989, the value of an airship, which was available at the time, was recognised by Jim Cull (Cull, 1989) for the large area it provided for the transmitter loop together with slow speed – which provided close-spaced sampling. One trial of this platform out of Sydney was featured in the ABC-TV science program *Beyond 2000*. In the early 1990s, SIROTEM technology was applied to a fixed-wing platform in an off-shoot development called SALTMAP (Duncan *et al*., 1992).

Distributed acquisition

A final innovation to SIROTEM, before it was superseded by the latest computer based system, was to have multiple receivers throughout the survey area recording transients from one large transmitter loop. This technique is similar to that used in seismic acquisition with arrays of geophones. To have a quantity of receivers required them to be less expensive than existing 'RVRs' and this was achieved using coils wound as circuit track on 50 cm square circuit boards. The receivers were synchronised to the transmitter pulse and readings were stored in them for subsequent 'harvesting' by a main acquisition computer. This development was called ARTEMIS (Array Receiver TEM Intelligent System). Such multiple receiver arrays would also improve on semi-airborne operations (see 'Airborne SIROTEM').

'Son' of SIROTEM

When it was apparent that a radically new model (a 'Mk 5') could be developed with the latest computing technology, Dr Jim Cull and Dr Duncan Massie at Monash University made this a reality using a full Pentium processor with 500 kHz sampling and a touch-screen for operation and display. This enabled display and interpretation software to be installed to allow for initial interpretations to be done in the field with colour displays. Apart from this, and other advances in improving data quality, the fundamental field operation of the system is the same as for SIROTEM. The new model was commercialised as 'terraTEM' and in just the first 5 years of production more units were exported than for SIROTEM in total.

SIROTEM look alikes

'Imitation is the sincerest form of flattery'

In the early stages of SIROTEM's development, when its use of microprocessors was a rarity, an institution in China purchased a SIROTEM complete with a full set of spare circuit boards. While they were not able to obtain the particular microprocessor separately, they duplicated the SIROTEM using the microprocessor on the spare board. It was then accepted by the local users that this 'Chinese SIROTEM' was better than the other locally made TEM units (Chinese SIROTEM agent, pers. comm.).

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Appendix 1. Original design goals of SIROTEM

- Digital signal processing
- Minimum 20 windows to be sampled simultaneously
- Windows contiguous to cover entire transient
- Stacking depth of up to 256 transients
- Bipolar pulse for noise cancellation
- Repetition rate a multiple of mains frequency
- Printer output
- Light weight, yet large transmitter moment
- Single, separate, small battery power pack

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Appendix 2. AMIRA projects related to SIROTEM and sponsor companies

Projects

Project name, period, cost to each sponsor and no. of sponsors shown.

(1) P74 – Improvement of Electromagnetic Exploration Techniques and Interpretation, 1975–77, $30 000, 5.
(2) P94 – SIROTEM Technology, 1978–81, $123 000, 8.
(3) P136 – Advanced EM & IP Techniques, 1981–84, $327 000, 12.
(4) P212 – Field and Model Studies for TEM Interpretation, 1986–89, $146 000, 8.
(5) P250A – Improved TEM Detection of Massive Sulphide Orebodies, 1990–94, $67 000, 6.

Sponsor companies (listed alphabetically)

Company: Projects supported

Aberfoyle Ltd: 2, 3, 4 & 5
Anaconda Aust. Inc.: 3
BHP: 1, 2, 3 & 5
Billiton Australia: 4
Carpentaria Exploration Co.: 1, 2 & 3
Chevron Exploration Corp.: 4
CRA Exploration P/L: 2, 3, 4 & 5
CSR Ltd: 2
Esso Aust. Ltd: 3
Goldfields Exploration P/L: 4
Jododex Aust.: 3
Mt Isa Mines Expl. P/L: 5
Noranda Aust. Ltd: 3
North Broken Hill Ltd: 1 & 4
Pacminex P/L: 1
Peko-Wallsend Ltd: 2 & 3
Seltrust Mining Corp. Ltd: 3
Shell Co. of Aust. Ltd: 2 & 3
Swedish Geological Co.: 4
Western Mining Corp. Ltd: 1, 2, 3, 4 & 5

Appendix 3. Specifications of SIROTEM Models I, II, and 3

Specification	Mark I	Mark II	Mark 3
Internal transmitter			
Waveform	Rectangular, bipolar. On time equals off time		
Repetition rate	25 Hz to 1.39 Hz	25 Hz to 1.39 Hz	25 Hz to 0.12 Hz
Current output	10 Amps	10 Amps	10 Amps
Voltage output (max.)	24 Volts	24 Volts	24 Volts
Receiver			
Input channels	1	1	3
Measurement range	0.4–165 msecs	0.4–165 msecs	0.05–2000 msecs
(later option)		0.05–165 msecs	0.008–2000 msecs
No. of Windows (max.)	32	32	53
Window width	0.4–25.6 msecs	0.4–25.6 msecs	0.05–410 msecs
(later option)		0.05–25.6 msecs	0.006–410 msecs
Voltage resolution	1 nanovolt	1 nanovolt	1 nanovolt
Stacking	2 to 4096	512 to 4096	2 to 9999
Gain	N/A	0.1,1,10,100	0.1,1,10,100
Data entry	Switches	Switches	Keyboard
Mains frequency rejection	By cancellation from repetition rates		
Sferics rejection	20 pulses/min.	Software	Software
Display and Interfaces			
Display	Printer	Printer	LCD
Data Storage	Optional	Cassette	Solid state
Resistivity Calculation	For 100 m Tx loop	For 4 loop sizes	Any loop size
External Interface	N/A	RS232C	RS232C
Synchronisation	N/A	OXCO	OXCO
Physical			
Operating temperature	–20 to +45°C	0 to 45°C	0 to 45°C
Weight of console	8 kg	13 kg	7 kg
Dimensions of console	44.5 × 34 × 14 cm	46 × 34 × 26 cm	46 × 34 × 16.5 cm
Options	Cassette Rec.	2 time series	4 time series
Accessories		Down-hole probe	Sep. surface coils
		Sep.surface coils	20 A extnl. Tx
		20 A extnl. Tx	Down-hole probes

Tx = transmitter. OCXO = Oven controlled crystal oscillator.

Appendix 4. Early users of SIROTEM

Purchasers of the 10 Mk I SIROTEMs produced (includes 3 in other countries, 1 in Finland, 1 in Sweden and 1 in UK. All others are Australian companies * denotes an original sponsor)

BHP (2)*
CSIRO/BMR
Geopeko*
Institute of Geological Sciences, UK
Shell Metals*
Soumen Malmi, Finland
Univ. of Adelaide
Univ. of Lulea, Sweden
Western Mining Corp.*

The first 27 purchasers of the MK II SIROTEM (by Country and type of Organisation)

Country: Organisation: Number

Australia: Exploration Company: 7
Australia: Contractor: 7
Australia: Government: 3
USA: Government: 2
China: Government: 2
Germany: Government: 1
South Africa: Exploration Company: 1
South Korea: Government: 2
UK: Contractor: 1
Thailand: Government: 1

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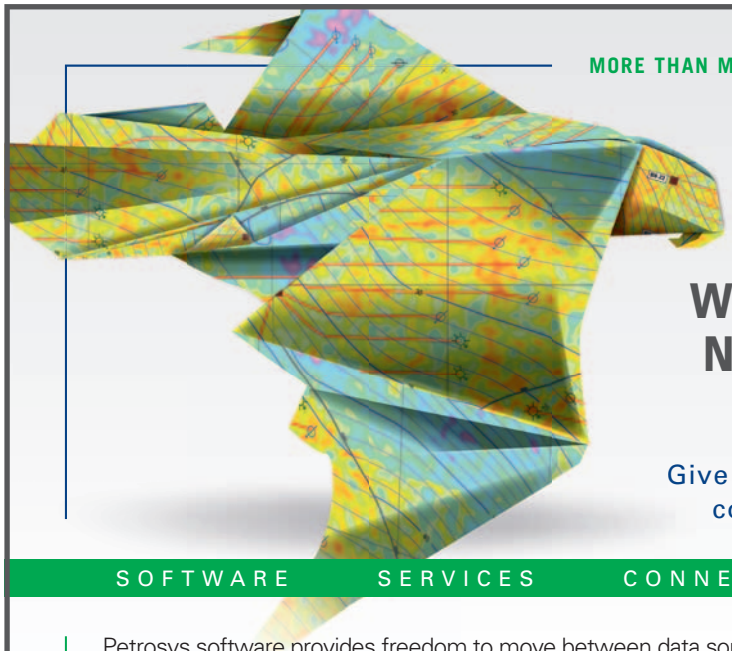

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