A short history of early development of groundwater geophysics in Victoria – the first 70 years

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The earliest mention of groundwater geophysics in Victoria is in the Imperial Geophysical Experimental Survey (I. G. E. S.; Broughton Edge and Laby, 1931), 1927-28 carried out by a field crew consisting of J. C. Ferguson (field leader) and field assistants L. A. Richardson and R. F. Thyer, the latter two are later luminaries in Australian geophysics. The crew carried out resistivity soundings with a "Megger" Earth Tester (manufactured by Evershed and Vignoles, in a classic Cambridge University style wooden box case) using the Gish-Rooney (pole-dipole) and Wenner sounding arrays, in the Mallee (at bores in Murrayville, Manpy near Underbool and Koonda, 20 miles NE of Murrayville) and at Laverton (Truganina 3 & 4 and Newport 1 bores), 12 miles west of Melbourne. A survey over a volcanic covered deep lead at Gulgong, NSW followed these Victorian surveys.

The survey objectives were for "*determinations of water levels and depths and thickness of geological formations*" with the bores providing calibration of the results. The results, were semi-quantitatively interpreted on Ohm. cm. versus feet, linear-linear sounding curve graphs and it was concluded that the resistivity method had potential to distinguish layers, map the depth to water table and perhaps indicate the salinity of the water, heady stuff considering this was pre – type curves or inversion layered models for interpretation. The layer depth interpretation instead relied on the then Gish and Rooney rough empirical rule "*that the depth at which a discontinuity occurs is equal to the electrode-separation corresponding to the turning point on the resistivity electrode-separation curve*".

In terms of early private sector geophysics, remotely connected to groundwater, Croll (1938) refers to two attempts to apply geophysical methods in the Tertiary / Cretaceous hydrocarbon and groundwater basins of Gippsland where Oil Search Ltd carried out a magnetometer traverse and a gravimetric survey from SW of Bairnsdale to NW of Lakes Entrance.

The Petroleum Search Subsidy Act (PSSA) 1957 scheme geophysical surveys and wildcat stratigraphic drilling in Victoria (1957 – early 1970's) was a valuable initiative with numerous investigations based on optimistic hydrocarbon prospectivity projections justifying Government subsidy of the oil and gas sector companies and contractor mapping of all of the Tertiary and underlying Permian and Cretaceous basins in Victoria with seismic, aeromagnetics, gravity and geophysical logging. The legacy of PSSA is a valuable dataset for Victoria's hydrogeological interpretation and understanding purposes for posterity.

The next direct recorded application of geophysics to groundwater studies emerged in the 1960's at the Victorian Mines Department, Geological Survey of Victoria (GSV), with initiation by geologist Bill Esplan of routine use of geophysical logging to support two deep drilling rigs for deep basin stratigraphic and groundwater supply drilling by the Basin Studies group under Dr Bruce Thompson (7 conductor oil field standard Gearhart-Owen truck – 2000 metres depth and side-wall coring capacity) and a large fleet of smaller rotary and percussion rigs for shallow groundwater monitoring bore installations and salinity studies by the Groundwater Section under Dr Charles Lawrence (Widco 4 conductor unit – 300 metres depth capacity). Mid 1980's saw addition of a Comprobe 4-conductor truck mounted unit (1000 metres depth capacity) to replace the Widco logger and the service move to introduction of geophysical log calibration (based on the South Australian Glenside Calibration pits championed by Jim Allender at SADME) and routine logging and development services provided by the Geophysics. Geophysical logging,

though uncalibrated, was carried out with great diligence initially by Bill Esplan and then mostly by technical officers Arthur Pope and Eddie Frankel, servicing the large number of drilling rigs operated by the Geological Survey of Victoria over at least a 30-year golden period of drilling in GSV.

GSV geologists incorporated a qualitative interpretation of gravity and magnetic surveys for basement depth and character, of Portland area in the Otway Basin (Boutakoff, 1963) and the northwest Murray Basin (Johns and Lawrence, 1964).

In 1970, at the request of Dr Charles Lawrence at GSV, the 3rd year geophysics class of Melbourne University, School of Geology and Geophysics under the supervision of Dr Lindsay Thomas (Power and Thomas, 1971) carried out for GSV, a test geophysical survey of seismic refraction, gravity and magnetics for basement profiling in the Kiewa River valley, concluding seismic and possibly gravity could be useful geophysical methods for GSV to employ for their groundwater investigations.

In the summers of 1971 to 1974, a geophysical team from the Bureau of Mineral Resources (BMR geophysicists - Eddie Polak, Jock Taylor, Doug Ramsey and Geoff Pettifer) carried out the first major groundwater geophysical survey in Victoria, surveying the entire Northern riverine plains of the Goulburn River Valley and the Broken Creek using 1.6 km grid and detailed 100m spacing traverse gravity surveys, aeromagnetics over the Barmah Forest and the Shepparton 1:250,000 map sheet, numerous deep seismic refraction and reflection traverses, electrical VES and dipole-dipole traverses. All this was to support the Geological Survey of Victoria's Shepparton-based Steve Tickell's comprehensive drilling program and groundwater study across the Goulburn Valley (Tickell, 1977; Tickell and Humphrys, 1979 & 1987). This data together with ESSO Australia's extensive deep resistivity soundings for uranium exploration over the south west of the survey area (by Jim Hussin and Associates), enabled production of an integrated drilling / geophysical interpretation of the Tertiary aquifer system and the underlying newly mapped Permian sub-basin troughs (Pettifer, 1973; Polak and Ramsey, 1974; Pettifer and Kerec, 1975; Pettifer, 1980, Pettifer et al., 1980; Pettifer and Polak, 1980; O'Brien, 1981; Pettifer et al., 1987; Holdgate, 1995).

The Bureau of Mineral Resources in 1973 (Dolan et al., 1975), followed up with the first deep resistivity sounding survey in Australia for MT sounding reconnaissance purposes at Mildura with soundings mapping 700+m deep sub-Permian basement.

The apparent value of the Goulburn Valley and Murray Basin geophysical surveys and also with early work for GSV by Melbourne University, helped the case for addition of geophysicists to the staff of Geological Survey of Victoria and the progressive growth from a modest start with initially under-powered resistivity equipment providing systematic shallow groundwater geophysical resistivity surveys. This work commenced initially under Dr Peter Gunn (Gunn, 1975; Gunn, 2015) in Mornington Peninsula and Westernport Bay sunk lands in collaboration with David Isles, then a Melbourne University BSc Hons student, who in 1974 completed his thesis with a gravity survey of the Westernport sunk lands which also helped illustrate the benefits of groundwater geophysics for GSV. Ian Lilly (1976), commenced the GSV resistivity work in the Shepparton area and this was scaled up particularly with Peter Elliott Master's degree studies (1978 to 1982; Elliott, 1978), with his GSV surveys for shallow salinity and aquifer dewatering studies introducing routine dipole-dipole surveys (pre-multi-core cables) in the Shepparton irrigation area for the State Rivers and Water Supply Commission (SRWSC) Tatura office dewatering programs, under two key proponents of routine use of geophysics: SRWSC engineer Bill Trewhella and hydrogeologist David Ife.

Geoff Pettifer joined the GSV in 1980 and GSV continued this dewatering program geophysical work with the bulk of the ongoing work carried out for SRWSC by Geoff Speedy under contract to GSV, post-departure of Peter Elliott (who moved on to form his own mineral geophysics exploration company and develop the innovative FlairTEM system). Supported by successive GSV Directors: John Knight, Peter Kenley, Keith Bowen. John Cramsie and Bob Dalgarno, rapid growth of the geophysics team in the Geological Survey of Victoria occurred from 1980 to 1993 under Geoff Pettifer, with appointment, of geophysicists Alan Willocks, Bruce Simons, Paul McDonald, Julie Withers, Suzanne Haydon and briefly Bill Killey, John Ashworth and Geoff Speedy (contractor) and field technical officers: Barry Cambridge and Ken Sherry (gravity mapping and other general geophysical field duties), and electronics technical officers: Arthur Pope, Ben Spencer-White, and Phil Robinson (seismic, geophysical logging, resistivity).

In the absence of viable, interested local near-surface geophysical contract service providers at the time, given the demand for contract services for mineral exploration geophysics, this GSV geophysics team enabled major expansion of in-house geophysical services to State Government agencies SEC, SRWSC, VicRoads and some local Shires and to GSV groundwater and engineering programs for groundwater, salinity, geotechnical, infrastructure, brown coal, deep basin studies and geophysical / geological mapping employing in-house provided seismic refraction and shallow high resolution reflection, vibration studies, Geonics EM34, resistivity, gravity and geophysical logging services. The BMR seismic truck and equipment donated to GSV from the Engineering and Groundwater Services group of BMR, led by Eddie Polak, helped initiate the groundwater geophysics program growth in GSV Victoria. Early use of BMR, by then AGSO-loaned LaCoste-Romberg and Sharpe gravimeters employed with conventional topographic surveying by GSV surveyor Reg Fox and his team, followed by purchase in 1994 of a Scintrex CG3 gravity meter and Trimble differential GPS surveying equipment by GSV (first survey by Haydon, 1994), enabled numerous gravity surveys initially for groundwater (a large regional survey starting in 1982 in the Kerang Northern Plains area; Withers and Cambridge, 1991). This foreshadowed and made possible the massive systematic and opportunistic detailed gravity mapping program supporting geological mapping of the State that has continued up to the present day, transitioning of late from ground surveys into airborne gravity mapping.

GSV Geophysics team, with collaboration with Melbourne University geophysics Masters candidate Paul Geissler who developed UNISEIS, a Fortran-based shallow high resolution reflection seismic data processing system, formulated and employed a 6-fold, roll-along, high resolution seismic reflection system with shallow shot hole, Betsy Seisgun and weight drop sources, for river valley and shallow Tertiary basins seismic reflection mapping (<50 m to >600 m bedrock depths) in the Campaspe valley and for the Geelong water supply investigation at Yeodene (Pettifer et al, 1983).

Geophysical and geological databases (GSV GEDIS system; Allwood, 1994) and private exploration data (particularly in the Murray Basin by CRA under CRA Chief Geologist Tom Dickson, Chief Geophysicist Bob Smith and geophysicists Rob Harvey and Theo Aravanis), greatly informed groundwater and salinity geophysical studies across Northern Victoria and in the deep leads in the basin margin highland valleys. GSV Otway Basin studies over 3 years mainly in collaboration with SADME and AGSO, systematically mapped the deep Tertiary and Cretaceous basin stratigraphy and structure using available petroleum seismic, regional gravity and magnetics data. One deep seismic survey in the Mildura area was a collaboration between GSV and the NSW Water Resources Commission Hydrogeophysics seismic services team of Joe Odins, David O'Neill, and Noel Merrick.

Of note was one of the first airborne EM surveys for groundwater in Australia in 1984, commissioned by SRWSC, using the Catalina PBY Super Canso flying boat-mounted Geoterrex Input 6 system (geophysicists Martin Schneider and Graham Butt), at Tatura in the Shepparton irrigation area (Ife et al, 1987) and further west at Kamarooka dryland salinity area for the SRWSC / GSV client. The Tatura inversion outputs were simple half-space models, and it was specifically the depth to the half-space that was the diagnostic parameter that defined the targets, ironically but logically, mapping the lower elevation of the base and the tortuous shape of the meandering, higher resistivity, shallow sand channel near-surface aquifers in the top of the underlying highly salinised landscape (half-space).

Contract detailed airborne magnetic / radiometric surveys of the onshore Otway Basin provided high quality airborne radiometrics data which was analysed and interpreted by Paul McDonald to interpret soil salinity risk and also identify groundwater recharge areas in the largely volcanic soils of Western Victoria (McDonald, 1991). The Otway Basin and accompanying Ararat 1:100,000 map sheet airborne surveys lead in 1994 to the start of the systematic Victoria-wide Victorian Initiative for Minerals and Petroleum (VIMP) higher spatial resolution magnetics / radiometrics and gravity program. Under GSV Directors Bob Dalgarno, Tom Dickson, Kathy Hill and currently Paul MacDonald, the geophysics team lead by Alan Willocks and later Suzanne Haydon, moved the emphasis of the geophysics team initially to VIMP, and then to increasingly more target basin studies and regional and systematic geological mapping support with GSV in-house gravity and contract airborne geophysics, rather than groundwater and other near-surface geophysical services.

The GSV Groundwater Section, including drilling rigs and geophysical logging by technicians, was moved to and merged with, the Groundwater Section of the Rural Water Commission (RWC) under Dr. Rick Evans in the early 1990's. This transfer followed a long period of geopolitics over governance of groundwater matters endured by most groundwater geoscientists, where the groundwater function had been split in the Victorian Government between the Mines Department (GSV) and the SRWSC (later the RWC). Gunn (2015) mentions that this groundwater politics soured his efforts to get groundwater geophysics off the ground and his enjoyment of carrying out hydrogeological work in Government in Victoria and this contributed to his early exit from GSV. Rural Water Commission took over the groundwater regulation and investigation responsibility for Victoria, but unfortunately did not continue with groundwater ground geophysical services, which in hindsight was a setback in terms of regular use of groundwater geophysics in Government in Victoria.

Rob Harris, from the early 1980's, at the then Melbourne and Metropolitan Board of Works (MMBW now Melbourne water), carried out the occasional groundwater geophysics survey, but mainly geotechnical surveys for MMBW water supply and sewerage projects.

In the late 1980s and early 1990s World Geoscience Corporation (WGC) Environmental Group headed up by Greg Street was trailing the use of airborne electromagnetics for salinity mapping in Western Australia. Their work drew the attention of the National Soil Conservation Program director Lindsay Northrup who made available funds to do demonstration surveys in other states. Despite reluctance from Rural Water Commission to use geophysics Victoria took up the offer and an area near Serpentine north of Bendigo and on the edge of the Murray Darling Basin was selected. No follow-up work was conducted by RWC.

Further developments by WGC led to development of the SALTMAP system (Street and Roberts, 1994). In 1997 lobbying of the Federal National and Liberal Parties (then in opposition) by Pat Cunneen and Greg Street of WGC resulted in $1,000,000 being made

available, when they came to government, for further demonstration surveys. An area near Willaura east of the Grampians was selected and WGC conducted SALTMAP, magnetic and radiometric surveys and interpreted the data (Street et al., 1998). Although in this case a report was prepared by the National Landcare Program there was minimal follow-up by RWC and no on-ground works to combat salinity resulted. CRA Exploration also made available QUESTEM data flown for mineral exploration in the Black Range west of the Grampians and WGC interpreted the data and made a presentation of the results to the local landholders. This work was sponsored by CRA under Chief Geologist Robert Hayden.

Private sector groundwater geophysical services for Victoria however progressively developed. Geoff Speedy worked on contract in GSV delivering salinity and groundwater dewatering geophysics to SRWSC and can arguably be credited with starting up on a modest scale, the first commercial groundwater geophysical services in Victoria, during the 1980's. Jim Cull at Monash University developed a team that contracted some groundwater geophysics services. Geoff Pettifer joined the private sector (Geo-Eng, now GHD) in 1998 and the GHD team provided groundwater and other geophysics services from GHD's Morwell and later Shepparton offices. SKM's WA-based Greg Street consulted in hydrogeophysics for SKM in Victoria (Street et al. 2003) and elsewhere in 2000-2002. Greg's work included a study of irrigation channel seepage in Western Victoria and Southern NSW using a towed resistivity array provide by Zonge and David Allen then a PhD student. A short study of saline ingress into the Murray River near Mildura was conducted around the same time using the resistivity array. Later Dubbo-based David Allen (Ground Water Imaging Pty Ltd) made this into a business and mapped irrigation channel leakage in Northern Victoria and the Murray and Latrobe River's surface-groundwater interactions with resistivity mapping contract services. Street and Harrison (2004) of SKM interpreted airborne radiometric, magnetic and DTM data along with Landsat imagery to identify recharge areas in the Bengworden Catchment near Bairnsdale. In this case the interpretation outlined areas identified as a priority for revegetation to control salinity.

All this development of groundwater geophysical services in Victoria was underpinned by the training, assistance and collaboration of the Geophysics Department of Melbourne University under Colin Kerr-Grant (1958-1977), Dr Lindsay Thomas (1968-2001) and Gary Gibson (1968-1970) who either trained, nurtured, graduated, employed or mentored: Peter Gunn (PhD), Ian Lilly (Demonstrator/Tutor), Peter Elliott (Masters candidate), Geoff Pettifer (BSc). Eddie Polak (student)

From 1974 to 2001, key post-Bachelor degree students in groundwater geophysics at Melbourne University included: Paul Geissler (Masters candidate: UNISEIS high resolution reflection processing system used by GSV); and BSc Hons students: David Isles (Gravity survey of Westernport sunk lands); Arthur Koelle (Dipole resistivity transformations); Rob Hewson (Seismic refraction and groundwater); Barry Chalmers (Deep Leads geophysics and gravity surveying as a vacation student for GSV in the Dookie-Cobram area); Mike Bucknill (Reinterpretation of CRA deep lead gravity data); Margery Perkins (Northern Victorian Gravity Interpretation); David Heislers (Murray Basin magnetics interpretation); Tom Forrest (Resistivity studies at Mitre Lake); Peter Corrie (Groundwater application of shallow subsurface geophysics); and Richard Griffin (Groundwater geophysics at Honeysuckle Creek).

The Melbourne University geophysics program was followed by other key contributors to development of groundwater and general geophysics in Victorian universities including Jim Cull and later Mike Asten who have developed a geophysics program at Monash University and Graham Granger and later Jim MacNae who have developed a geophysics program at RMIT University.

Finally Victoria has the first Australian State-wide hydrogeophysical study (Department of Sustainability and Environment, State Government of Victoria, 2012) of major geological structures that are possibly impacting the Tertiary groundwater system and affecting the State's SAFE project estimates of State Groundwater Resources – quantity and quality-wise (saline bedrock waters impacting Tertiary aquifer salinities). Existing Geoscience Victoria structural interpretations, the complete State-wide geophysical data sets (gravity, magnetics, radiometrics, topography, basin seismic mapping) and the State-wide groundwater database data were interpreted in an integrated manner and analysed by GIS to map structures and rank likelihood and degree of impact on the groundwater system, particularly in key highland valleys and basin margin areas of the State. Publication of State-wide GIS layers showing all datasets and likely impacted areas and definition of pilot study areas for follow-up, were the project outputs.

Victoria is fortunate to have a good foundation for ongoing hydrogeophysical work in terms of a large groundwater, geophysical log database and core library, full State-wide coverage with topography, gravity, magnetics and radiometrics and numerous groundwater geophysical, hydrocarbon and minerals exploration reports and datasets, archived in GSV, suitable for re-interpretation in an integrated fashion to bring a fresh-eyes approach to groundwater mapping utilising geophysics in Victoria.

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