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Celebrating a pioneer in geochemical tracer science for groundwater and surface water research: Professor Ian Cartwright

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ABSTRACT

Over a more than 35-year career Professor Ian Cartwright's research has provided advances in the understanding of a wide range of earth-science processes, from metamorphic geology to palaeo-climates, groundwater hydrology, catchment hydrology and geochemistry. His research has predominantly utilised geochemistry, stable and radioactive isotope tracers to understand links between palaeo-climate and groundwater, geochemical processes impacting on groundwater and surface water quality, and metamorphic processes. He has made outstanding contributions to scientific knowledge and training through mentoring numerous PhD and masters students, journal editorial roles – including as a long-time Associate Editor for *Applied Geochemistry*, and active participation in conferences, professional societies and working groups – such as the Applied Isotope Geochemistry group and the International Association of Geochemistry. As he moves into retirement, we take the opportunity to summarise his impact and contributions across many scientific disciplines and reflect on the significance of his distinguished career.

1. Introduction

Professor Ian Cartwright has made significant contributions to knowledge and practice in the use of geochemistry, stable and radioactive isotopes, within the disciplines of geology and hydrogeology. Throughout his career, he has utilised geochemical and isotopic tools to improve the understanding of a broad range of geological, hydrogeological and catchment processes (Fig. 1). Ian's early career as a postdoctoral researcher had a strong focus on metamorphic processes, with many highly cited contributions on metamorphic fluid flow and fluid-rock interaction, utilising stable and radiogenic isotopes (e.g., Buick et al., 2001; Cartwright, 1992). His research focus turned to geochemistry and hydrogeology, soon resulting in numerous grants, collaborations, and journal articles in these research fields.

Examples of his significant contributions include applying isotopic tracers to the major issue of ground and surface water salinity, improving understanding of solute sources and recharge processes in groundwater within Australia's most productive agricultural basin – the Murray Darling surface water and groundwater system (e.g., Cartwright et al., 2007a, 2006, 2004). Ian's growing research group then applied these isotopic tools in other semi-arid regions – including in other parts of Australia and northern China, examining carbon sources, geogenic element enrichment and water-rock interactions in groundwater (Cartwright et al., 2002, 2007b; Currell et al., 2011; Hagedorn et al., 2011; Tweed et al., 2006) as well as groundwater-palaeo-climate relationships (Cartwright and Simmonds, 2008; Currell et al., 2010, 2012).

A substantial body of work followed in the field of groundwater-surface water interactions, examining issues such as the formation and vulnerability of freshwater lenses adjacent to dryland rivers (Cartwright et al., 2010), the identification of baseflow contributions to streams, particularly utilising radon-222 (e.g., Cartwright et al., 2011; Gilfedder et al., 2013; Hofmann et al., 2011; Yu et al., 2013) and studies of catchment processes, including identifying water transit/residence times for different flow contributions to rivers and other dynamics of ground-surface water exchange (e.g., Atkinson et al., 2015; 2014; Cartwright et al., 2017b; Cartwright and Morgenstern, 2015; 2012; Unland et al., 2013). Much of Ian's work has been ahead of the curve on the push for open science. His work typically utilises extensive hydrochemical and isotopic datasets, which are provided in full to easily facilitate further investigation.

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Ian's research largely focused on his home state of Victoria in Australia, with research in the Murray Basin, Corangamite catchment, the Victorian Alpine catchments, Gippsland Basin, and Wimmera-Mallee region, amongst many others. Through his involvement as a Chief Investigator in the Australian National Centre for Groundwater Research and Training (NCGRT), one of the three components of the Australian National Water Plan in 2007, he took a leading role in developing groundwater-surface water interaction research and the development of one of the NCGRT's key field observatories in the Victorian Alps (National Collaborative Research Infrastructure Strategy, 2023). Throughout his career, Ian was well connected with stakeholders who applied insights from his research to catchment and groundwater management (e.g., Victorian Government agencies like the Department of Sustainability and Environment, Department of Primary Industries and their more recent incarnations). His outstanding contributions to Earth Sciences in Victoria were recognised in 2016 with the prestigious Selwyn Medal.

While his almost 200 research articles (Fig. 2a) have had a major impact on a wide range of research disciplines (Fig. 2b and c), his contribution to the scientific community has been extensive in many other ways. He has made many strong contributions to scientific knowledge and training through mentoring over 30 PhD and masters students in a highly supportive environment. He has also motivated countless undergraduate and masters students through teaching hydrogeology, sustainability and environmental geochemistry at Monash University, and through short courses delivered through the NCGRT and Victorian Institute of Earth and Planetary Sciences. Ian's teaching involved developing and running many fieldwork-based projects and other hands-on practical experiences, as well as strong theory-based and research-informed coursework. He has been a highly active member of multiple committees and organisations, having served on committees for the Geological Society of Victoria and Geological Society of Australia, as well as involvement in the International Association of Geochemistry, including a role as president. He also held several journal editorial roles, including as a long-time Associate Editor at *Applied Geochemistry*, and has been an active participant in professional societies and working groups.

2. An overview of the research career of Ian Cartwright

Ian began his research career in Wales, obtaining Bachelor of Science (Geology), and a PhD in geology from the University College of Wales. Upon completing his PhD, he had a two-year postdoctoral position at the University of Wisconsin (USA), funded through NATO. He returned to the University College of Wales (UK), where he held a lecturer position, before moving to Monash University (Australia) in 1990. He spent the entirety of the rest of his career as a valued academic at Monash University. During his time there, he was promoted through the academic ranks, becoming an Associate Professor by 2002, head of the School of Geoscience in 2007 and a full Professor by 2009. As he transitions to retirement, this is a great opportunity to summarise his contributions across five research areas: (1) the study of metamorphic processes, (2) sources of solutes in groundwater, (3) groundwater recharge rates and processes, (4) groundwater-surface water interactions, (5) catchment processes and water residence times (Fig. 1), noting that the discussion is not exhaustive, as it would not be possible to summarise all of his contributions here.

2.1. Metamorphic and geological processes

As a trained geologist, much of Ian's early research had a strong focus on metamorphic geology (Fig. 2b). This focused on using stable and radiogenic isotopes (e.g., analysis of $\delta^{18}O$ in carbonates and U–Th–Pb dating of zircon and monazite) to identify the timing and geological impacts of metamorphic fluid flows in various complexes (e.g., Cartwright et al., 1996; Cartwright and Oliver, 1994; Williams et al., 1996). This research informed a deeper understanding of geological processes in north-western Scotland (e.g., Lewisian and Scourian complexes of the northwest) and in Australia (e.g., the Reynolds Range within the Arunta inlier of central Australia) (e.g., Cartwright, 1988; Cartwright et al., 1985; Cartwright and Buick, 1994). His research activity and interest in geology continued throughout his career, with research focusing on structural geology, sedimentary processes and petrology (e.g., Chenrai et al., 2022; Nasrin Nury et al., 2010; Smith et al., 2007; Warren et al., 2014).

2.2. Solute sources in groundwater

From approximately the year 2000 onwards, Ian's work became more focused on hydrogeology (Fig. 2b). His early groundwater focused work investigated sources of solutes in groundwater within Australia's most productive agricultural basin – the Murray Darling, including areas suffering from serious land and water salinisation (e.g., Cartwright et al., 2007a, 2006, 2004). He utilised a combination of ionic ratios

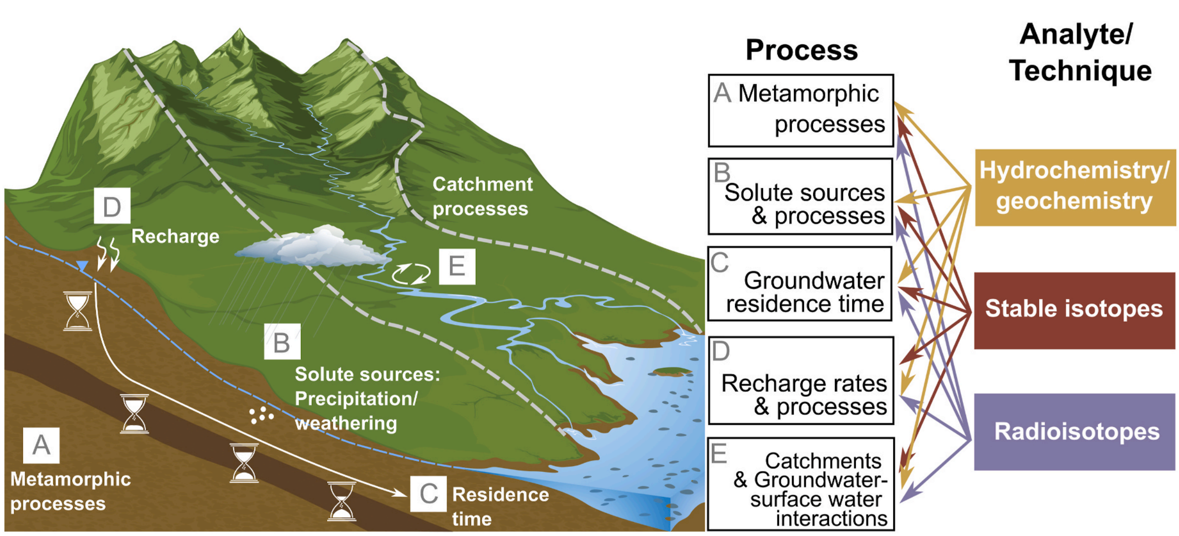

Fig. 1. Geological, hydrogeological, and surface hydrological system, highlighting the research contributions of Professor Ian Cartwright, and the use of analytes/ data analysis techniques. Catchment diagram from iStock Photos, ID:174380242. Symbols from Jane Hawkey, Tracey Saxby, Integration and Application Network (ian.umces.edu/media-library).

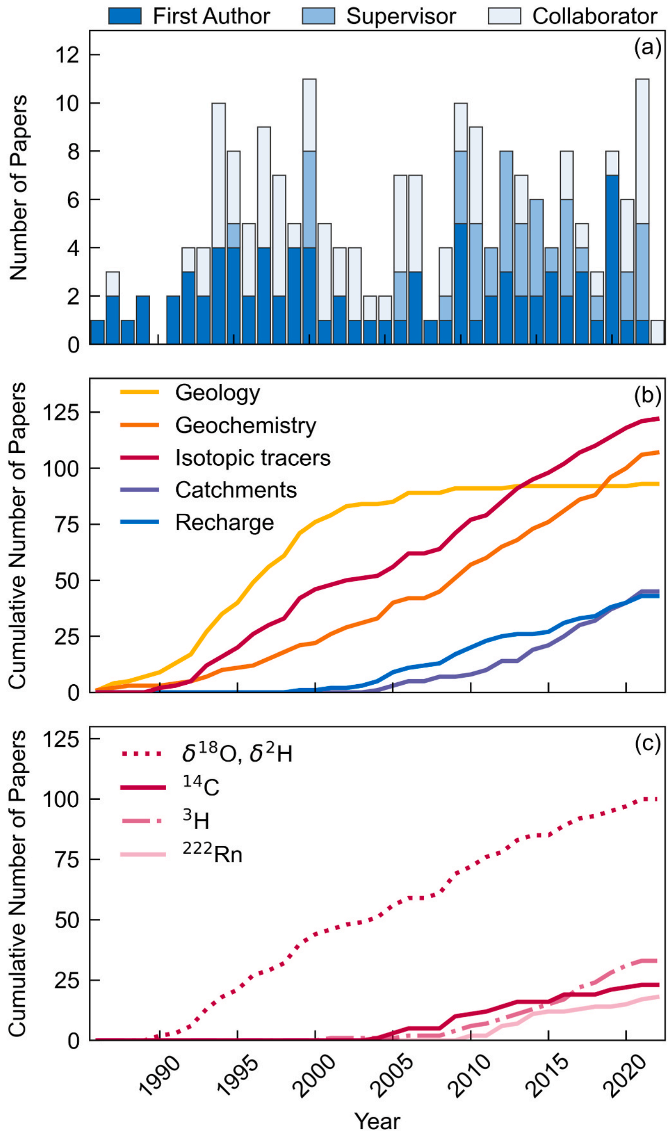

Fig. 2. Overview of publications by Professor Ian Cartwright. (a) Publications by year, separated by the role (first author, supervisor of the first author, or a collaborator). (b) Number of papers by research focus. (c) Number of papers that utilise different isotope techniques. $\delta^{18}O$ and $\delta^{2}H$ denote stable isotopes of water, ^{14}C denotes carbon-14, ^{3}H denotes tritium, ^{222}Rn denotes radon-222.

(particularly Cl/Br and cation/Cl ratios), together with stable isotopes, radiocarbon, and tritium. This work confirmed the meteoric origins of the majority of groundwater solutes within important groundwater and surface water resources, highlighting the significance of evapotranspiration (as opposed to extensive mineral dissolution) as the key salinisation mechanism. Recharge processes were further illuminated through this work, highlighting the importance of dual-porosity flow (e.g., Cartwright et al., 2007b) and providing important insights for the management of dryland salinity. His further work in the Murray Darling and other Victorian aquifer and lake systems focused on identifying sources of strontium, carbon and rare earth elements in groundwater and surface water (e.g., Cartwright et al., 2007b; Hagedorn and Cartwright, 2009; Tweed et al., 2006); while a project collaboration with the Chinese Academy of Sciences led to further contributions on the sources of arsenic, fluoride and nitrate in heavily utilised groundwater sources in northern China (e.g., Currell et al., 2011, 2010), along with their links to groundwater recharge history and palaeo-climate (e.g., Currell et al., 2012).

2.3. *Groundwater recharge rates and processes*

Groundwater recharge is a vital component of the water balance that poses significant challenges in water resources management (Healy and Cook, 2002; Scanlon et al., 2002). Ian's research utilised a wide range of techniques to quantify recharge rates and mechanisms to navigate these challenges, with the use of the water table fluctuation method, chloride mass balance, radioisotopes and temperature (e.g., Barua et al., 2021; Cartwright et al., 2020b, 2007b; Cartwright and Weaver, 2005; Irvine et al., 2017; Irvine and Cartwright, 2022). A key feature of his research is in the application of multiple techniques to inform the estimates of both modern and historical recharge (e.g., Cartwright et al., 2020b, 2007b; Cartwright and Morgenstern, 2012). The analysis of palaeo-climatic influences on groundwater recharge, including analysing the utility and limits of groundwater isotopes in palaeo-climate reconstruction was another key focus throughout Ian's hydrogeology research career (e.g., Cartwright, 2020a; Currell et al., 2010).

Much of his recharge-focused research was in the state of Victoria (e.g., Atkinson et al., 2014; Barua et al., 2021; Cartwright et al., 2020b, 2007b, 2006; Cartwright and Morgenstern, 2012; Irvine and Cartwright, 2022). However, his work has informed recharge rates and mechanisms across Australia (Cartwright et al., 2019; Hofmann et al., 2020; Irvine and Cartwright, 2022; Tweed et al., 2011) and in China (e.g., Currell et al., 2012, 2010). In particular, his extensive experience in recharge estimation utilising radioisotopes led to the synthesis of current knowledge, and outlined future research directions in the use of radioisotope tracers to estimate groundwater recharge (Cartwright et al., 2017a).

2.4. *Groundwater-surface water interactions*

The formation of the Australian NCGRT, started Ian's research engagement in groundwater-surface water (GW-SW) interaction studies as one of the major academic contributors to the GW-SW interaction program. A large component of Ian's work focused on the uses of geochemical tracers (e.g., major ions, radon, cosmogenic isotopes, Fig. 2c) for baseflow separation. Within this context, he advanced the conceptual understanding of GW-SW interactions in a variety of stream and catchment setting (e.g., Atkinson et al., 2014; Unland et al., 2013) but he also led advancement in the use of radon for baseflow estimations (Gilfedder et al., 2015; Hofmann et al., 2011). He worked extensively on bank storage, parafluvial flow and hyporheic exchange, and the temporary store of groundwater in riverbanks and riverbeds. These investigations utilised both field observations and numerical modelling. For example, he investigated parafluvial flow including riverbank flow in the Avon River in eastern Victoria using a combination of major ion tracers and radon over a 6 year study period (Cartwright and Hofmann, 2016) and parafluvial flow and hyporheic exchange in Australian alpine catchments (Cartwright et al., 2014). In the study by Howcroft et al. (2019), he investigated residence time of bank storage using cosmogenic isotopes. Gilfedder et al. (2019) utilised numerical modelling to investigate emanation, decay and transport of radon in a pool-riffle sequence. They found that large underestimations of apparent water age were caused by mixing of regional groundwater and recent event waters, highlighting that numerical modelling can provide a powerful approach to interpret field data. Cartwright and Irvine (2020) utilised cross-section stream-aquifer models to investigate the role of stage height, regional hydraulic gradients, and aquifer heterogeneity on bank storage processes. They used the outputs from numerical models to assist the interpretation of head-EC relationships in near-stream piezometers in the Ovens catchment from the Victorian Alps.

2.5. *Catchment processes and estimation of water residence times*

The GW-SW interaction studies on catchment scales lead to one of his most recent research fields; the understanding of water residence times and catchment processes. Ian has significantly contributed to the understanding of mean residence time distributions in catchments and the use of cosmogenic isotopes to characterise catchment water stores and runoff behaviour. Amongst many, examples of his work on catchment processes include documenting river flow-concentration relationships and the processes that control the geochemistry of streamflow (Cartwright, 2020b). This work showed notable differences in the behaviour of nitrate with large flow events, relative to other ions, and highlighted challenges in the application of chemical mass balance approaches in hydrograph separation. He also investigated the correlation between catchment attributes and ^{3}H-based mean residence time estimations (Cartwright et al., 2020c). Working across four Victorian catchments, this work explored whether catchment attributes could be used to predict mean residence times, identifying that complex catchment processes prevent the use of knowledge from one catchment to predict behaviour in others, even those with similar geology, topography and land use.

Ian utilised ^{3}H analyses, including in the estimation of mean water residence times, in over 30 studies (Fig. 2c). For example, residence times determined from ^{3}H data were utilised to inform hydrogeological processes many regions throughout Australia, including the Murray Basin (Cartwright et al., 2007b, 2010), the Ovens catchment (Cartwright et al., 2020c; Cartwright and Morgenstern, 2012, 2015) and numerous other catchments and basins (e.g., Cartwright et al., 2020c, 2018; Hofmann et al., 2018; Howcroft et al., 2018). The ability of ^{3}H to inform short residence times (e.g., up to 100–150 years), allows it to be used in conjunction with other tracers to inform distributions of residence time. The use of tritium proved particularly fruitful due to the fact that bomb peak tritium (^{3}H) activity was several orders of magnitude lower in the southern hemisphere relative to the northern hemisphere (e.g., Cartwright et al., 2020b; Morgenstern et al., 2010), allowing direct dating of waters.

Ian also worked extensively with ^{14}C to estimate residence times in a range of aquifer settings (e.g., Cartwright, 2010; Cartwright et al., 2010, 2007b; Currell et al., 2010) and ^{222}Rn to determine the contribution of groundwater discharge (e.g., Cartwright and Hofmann, 2016; Gilfedder et al., 2019; Unland et al., 2013). Much this work culminated in comprehensive reviews of the use of radiocarbon to estimate groundwater residence times in semi-arid regions (Cartwright et al., 2017a, 2020a) and radon to infer groundwater discharge (e.g., Adyasari et al., 2023). As is the case for many of the tracers and approaches discussed here, a key feature of Ian's work has come through the use of a broad range of other tracers in conjunction to inform the understanding of catchments and groundwater systems.

3. Summary

Professor Ian Cartwright is a widely respected member of the geochemistry and hydrogeology communities, both internationally, and within Australia. His use of geochemical and isotopic tracers helped in the quantification of groundwater recharge and surface and groundwater residence times, the determination catchment processes, and groundwater-surface water interactions (Fig. 2b). This short overview only scratches the surface of contributions from a research career spanning over 35 years. On his contributions to research, it is impressive that Ian is the first author of over 40% of his publications (Fig. 2a), a feat, not matched by many academics. The fact that a further 20% of his publications were written by students and postdoctoral researchers while under his supervision (Fig. 2a), further demonstrates his research contributions. However, his legacy goes well beyond the extensive knowledge generated through his research, with his students and postdoctoral researchers going on to work in a broad range of sectors, including in consulting and government organisations and universities. With increasing pressures on water resources from both climate change and development, the knowledge generated through Ian's research, and the numerous scientists that he has trained will ensure that he will continue to impact the study of water resources into the future well after he retires. On behalf of the scientific community and many organisations, we take this opportunity to thank Professor Ian Cartwright for his meticulous research, supportive mentoring, and generous dedication of his time.

Declaration of competing interest

The authors declare that they have no known competing financial interests that could have appeared to influence the work reported in this paper. We note that Prof. Cartwright has been a supervisor of either our PhDs or postdoctoral positions.

Data availability

Data will be made available on request.

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