

Investigations multidisciplinaires au sein d'aquifères de socle faiblement productifs en Irlande : typologie, propriétés et importance pour le cycle de l'eau irlandais

Multidisciplinary investigations of poorly productive hard rock aquifers in Ireland: typologies, properties and significance in the Irish water cycle

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I. INTRODUCTION

Across the Island of Ireland, hard rock aquifers which are found to underlie over 65% of Ireland (Robins and Misstear, 2000) are commonly referred to as poorly productive bedrock aquifers (PPA), characterised by low well yields (GSI, 2006). Despite their limited role in water supply, PPAs are found to contribute significantly to the maintenance of river baseflow levels, especially in upland catchments during sustained dry periods (Comte et al., 2012). Typically, these units are considered to be devoid of intrinsic matrix porosity: instead, the flow of groundwater is confined to secondary porosity generated through interconnected fractures and fissures. Previous studies have highlighted the challenges in characterising PPA systems due to the heterogeneity of geological structures at micrometre–metre (cf. Neuman, 2005) and regional scales (km to 10s km, cf. Krasny, 2002). This is particularly the case in hard rock environments where the permeability of bedrock is largely dictated by the complexity of fracture networks (Bonnet et al., 2001; Neuman, 2005) and highly variable physical and chemical weathering patterns (Dewandel et al., 2006; Lachassagne et al., 2011). Multi-disciplinary and multi-scale subsurface investigations in these complex subsurface environments provide a means to (1) quantify flow and transport parameters at borehole scale, (2) determine the preferential groundwater pathways and associated geochemical signature at catchment scale and (3) characterise the geological heterogeneity from borehole to catchment scale. In recent years, the development of continuous geophysical imaging techniques has provided an impetus for catchment scale characterisation and modelling of hard-rock aquifers (e.g., Comte et al. 2010; Perrin et al., 2011; Comte et al., 2012 ; Cassidy et al. 2014). In this brief summary, exemplary results from an integrated approach to characterising hard-rock aquifers are presented, based on the strategic application of different complementary investigative tools at varying scales, providing a more comprehensive and robust conceptual understanding of groundwater flow regimes in hard rock aquifers in temperate regions with a legacy of glacial activity.

II. SITE DESCRIPTION

Three sites with geologically contrasting hard-rock aquifers in the northern part of the Island of Ireland (Fig. 1) have been studied as part of the Griffith Geoscience Project at Queen's University Belfast with the specific objective of characterizing groundwater flow regimes and aquifer types, as well as highlighting their

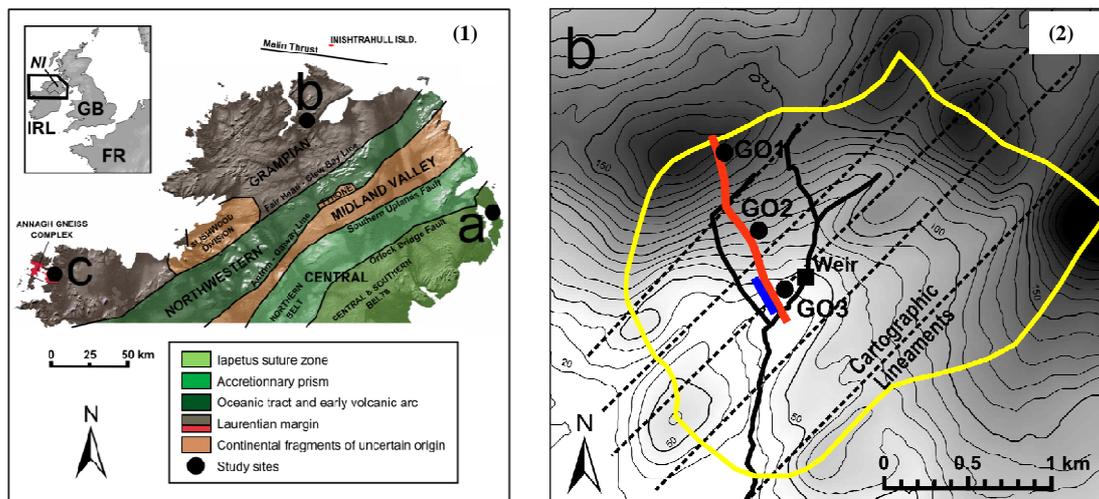


Figure 1 – (1) Setting of Study Sites (a,b,c); (2) Gortinlieve Catchment, yellow line=catchment boundary, black dots/boxes=monitoring well/weir, red line=ERT profile, blue line=SR profile, black dashed line=lineaments (Comte et al., 2012)

major hydrogeological similarities and differences. The three study sites (Fig. 1) include the Mount Stewart (MS) site (a; Co. Down, Northern Ireland), the Gortinlieve (GO) site (b; Co. Donegal, Rep. of Ireland) and the Glencastle (GC) site (c; Co. Mayo, Rep. of Ireland). This paper focusses on key findings from the Gortinlieve (GO) site (Fig. 2b). The Gortinlieve site is underlain by Precambrian psammitic micaschists, with occasional marbles (Lough Foyle Succession), of the Dalradian Southern Highland Group (McConnell and Long 1997). Regional faults trend in a NE–SW orientation, parallel to the Highland Boundary fault, which was active during the Caledonian Orogeny. Several fault scarps and cartographic/topographic lineaments in line with the regional structural trend occur in the upper catchment and are indicated in Fig. 1-2. Annual rainfall in the area ranges from 1,000 to 1,200 mm (Met Eireann 2011). The Gortinlieve (GO) site was instrumented with three borehole clusters installed at different elevations along a valley slope profile. Each cluster (Fig. 1-2) comprises up to 4 separated wells, each isolated and screened across different depth-distinctive zones commonly encountered in Irish bedrock aquifers and conceptually described by Moe et al. (2010) as: subsoil SS, transition zone T, shallow bedrock S and deep bedrock D. To facilitate comparison with both the geological observations and the geophysical signatures, the authors will refer to these different hydrogeological units as: overburden (= SS), decomposed bedrock (= top of T, present only in GC), broken bedrock (= bottom of T), fissured bedrock (= S) and massive bedrock (= D).

III. METHODOLOGY

The multi-disciplinary study completed across the study sites included a range of field and laboratory methodologies to characterise the aquifer systems and to investigate the groundwater flow regime and underlying key processes across varying scales of interest, including:

- Geophysics – borehole geophysics, ground based surveys (ERT, seismic, EM, GPR), airborne geophysics (AEM); e.g. Comte et al. (2012), Cassidy et al (2014), Nitsche (2014).
- Hydraulic Testing – Integral Borehole Pump Testing and Packer Testing; e.g. Comte et al. (2012), Nitsche (2014).
- Tracer Testing – Borehole Injection and Dilution Tests; e.g. Heintz (2012), Nitsche (2014).
- Structural Geology Mapping – outcrop mapping and borehole imaging; e.g. Cassidy et al. (2014), Nitsche (2014).
- Hydrodynamic Monitoring – long-term groundwater & surface water level monitoring; e.g. Pilatova (2014), Cai & Offerdinger (in prep).
- Hydrochemical Analysis – major and trace element analysis; e.g. Pilatova (2014).
- Geochemical Analysis – Rock-water interaction studies; Caulfield et al. (2014).

- Isotope Analysis (2H, 3H, 18O, 13C, 14C) in precipitation, groundwater & surface water; e.g. Pilatova (2014); Pilatova & Offerdinger (2011, 2015).
- Geochemical Modelling (NetPath); e.g. Pilatova (2014).

The following summary will focus on exemplary key findings from the hydrogeophysical and geochemical investigations completed at the Gortinlieve (GO) site.

Surface geophysics allows investigations at larger (macro) scales (m-km) using both ERT and SR while borehole geophysical investigations provides high-resolution measurements at borehole (meso) scale (cm-m; e.g., Parasnis 1997). ERT proved useful for hydrogeological investigations as it is sensitive to the aquifer lithology (i.e. clay mineral content), the pore-water content and pore-water mineralisation; it allows the spatial distribution of these important hydrogeological features to be characterised (e.g., Fetter 1988; Singhal and Gupta 2010). Differentiating among these features is difficult on the basis of the ERT results alone. However, this can be achieved through coupling ERT with other methods of investigation or datasets (e.g. hydrogeological monitoring, geological observations, borehole geophysics, geochemistry, etc.). In this study, ERT was used to undertake 2D tomographic sections at catchment scale. Acquired dipole-dipole (DD) and multi-gradient (mGD) apparent resistivity data were processed and jointly modelled to calculate the 2D distribution of (specific) resistivities (Comte et al., 2012b). ERT profiles were aligned perpendicular to relevant geological structures and along boreholes lines for comparison with borehole data. Profiles were extended to the inferred hydrogeological boundaries of the aquifers.

At local scale within each catchment, outcrops, boreholes and quarry exposures were used to map geological discontinuities and establish possible common sets in the catchment area. Regional structural trends were determined from interpretation of the geological maps and field sheets where available and compared with the digital elevation models for the areas. Within each catchment, scanline surveys were conducted along a line on suitable rock outcrops or quarry faces (Singhal and Gupta, 2010).

Open-hole constant rate pumping and recovery tests were carried out at all boreholes across the three study sites. Both pumping and recovery data were jointly interpreted for each well using informing regarding aquifer and well geometries. Single and double porosity/permeability analytical solutions with AQTESOLVE software were applied to obtain the best fits to the field data. When model outputs provided values of transmissivities (i.e., for single porosity solutions), the respective hydraulic conductivities were calculated using the observed unit aquifer thicknesses from borehole data, ERT data and geophysical logging data. Combining these three sources of information increased the accuracy for the assessment of thickness and thus the estimates of representative hydraulic conductivity values for each relevant aquifer unit.

Rock samples and overburden deposits were recovered from outcrop localities across the study site. Composite rock samples were taken comprising splits of both fresh and variably weathered bedrock, along with secondary clay weathering products where present. Where possible rock samples were oriented and marked in the field to aid with the characterisation of structural features. Polished thin sections of fresh and weathered material were prepared. Clay samples were analysed using X-ray Diffraction (XRD) and Fourier Transform Infrared (FTIR) Spectroscopy techniques in order to identify and characterise secondary mineral weathering products.

Groundwater hydrochemical samples from individual wells at each well cluster across the three sites were collected as bulk samples from the open-hole wells and piezometers in accordance with the British Standards (BSI 2009) as well as during the later stages of the above hydraulic well tests described above. Groundwater sampling was carried out at nominal 4 monthly intervals between 2008 and 2010. Concurrent to the sampling, in situ water quality parameters such as pH and EC were measured using a TPS FLMV 90 Multi-Parameter Water Quality Meter with an accuracy of 0.01 pH and 1 $\mu\text{S cm}^{-1}$ respectively.

IV. RESULTS & DISCUSSION

Results of fracture measurements both from outcrops and boreholes show dominant meso-scale (millimetre to metre) fracture occurrence and orientations which correlate well with past tectonic regimes in Ireland. The Dalradian micashist in Gortinlieve displays two dominant fracture sets: a major set with fractures oriented WNW–ESE with two dip angles of about 35 ° NNE (parallel to the schistosity plane) and 60–70 ° SSW and a secondary set corresponding to a NE–SW/NNE–SSW trend with a high dip angle of about 70–90 ° towards the ESE. The fracture measurements suggest that fracture controls on groundwater flow at mesoscale may be influenced by Alpine tectonic fabrics whereas the pre-Alpine Grampian/Caledonian/Variscan fabric would act as a secondary control at this scale. Recent work suggests that Alpine NW–SE to NNE–SSW fracture systems could act as a major control on groundwater yields in post-Variscan formations (e.g., Worthington and Walsh 2011). At macro-scale however (catchment and regional scale), cartographic lineaments, and features preferentially affected by glacial erosive action and weathering are typically associated with the pre-Alpine NE–SW trend. This is clearly observable in the Gortinlieve catchment. Structural measurements for oriented Gortinlieve rock samples indicate that foliation planes have a WNW-ESE strike with an average dip angle of 26° to the NNE. It is apparent from petrographic observations of thin sections taken from oriented blocks that the bedrocks contain two sets of interconnected microfractures. Both sets share the same WNW-ESE strike as the foliation planes, with one set dipping 25–32° to the NNE (parallel to the foliation plane) and the other 65–72° to the SSW. These structures are commonly lined by iron oxides and appear orange/brown stained in plane polarised light. The build up of secondary alteration minerals has resulted in localised reduced porosity, whilst ‘pinch-out’ terminations indicate their discontinuous nature. These structures are also visible within borehole and outcrop profiles, therefore spanning micro- to mesoscales. Importantly, these fractures are seen to act as micro- to mesoscale pathways for the introduction of weathering solutions and the subsequent transport of dissolved species away from the sites of mineral breakdown.

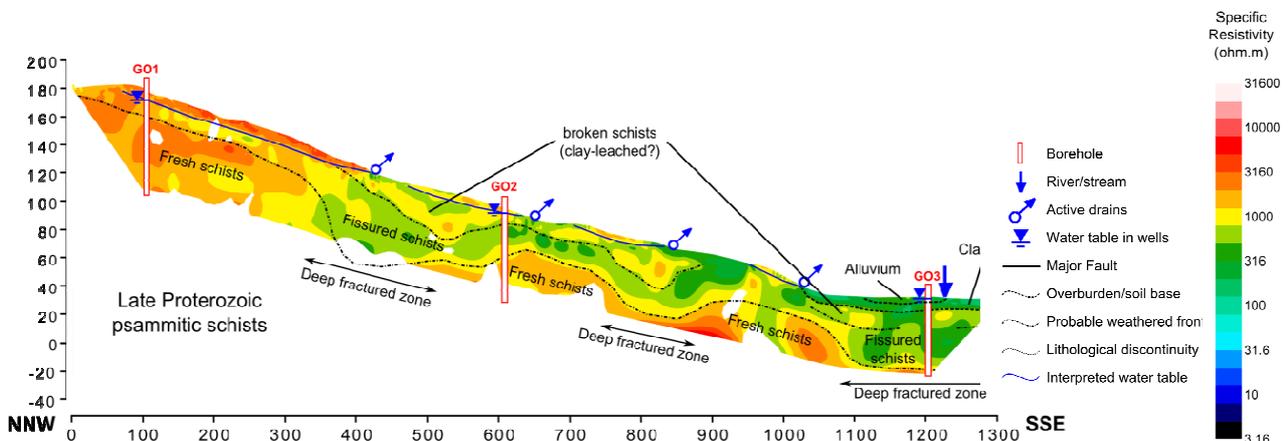


Figure 2 – Resistivity Model with hydrogeological interpretation for Gortinlieve; elevations are in metres amsl and horizontal distances in metres (Comte *et al.*, 2012)

Among the three ERT profiles carried out at the GO site (cumulative length of 3,040m), the profile presented in Fig. 2 is considered representative of the catchment; the profile was located both to coincide with the borehole transects and aligned perpendicular across the main geological structures (Fig. 1). The hydrogeological interpretation is superimposed on the specific resistivity distribution obtained through the inversion of measured apparent resistivities, and is supported by field outcrop observations, borehole geological logs, geological maps and water table measurements as well as the results provided by SR and borehole geophysical logging. The specific resistivity distribution is clearly dominated by an irregular layering in specific resistivity values. Higher specific resistivities at the bottom of the section are interpreted as the signature of the massive to poorly fissured micashist bedrock (deep bedrock), whereas intermediate

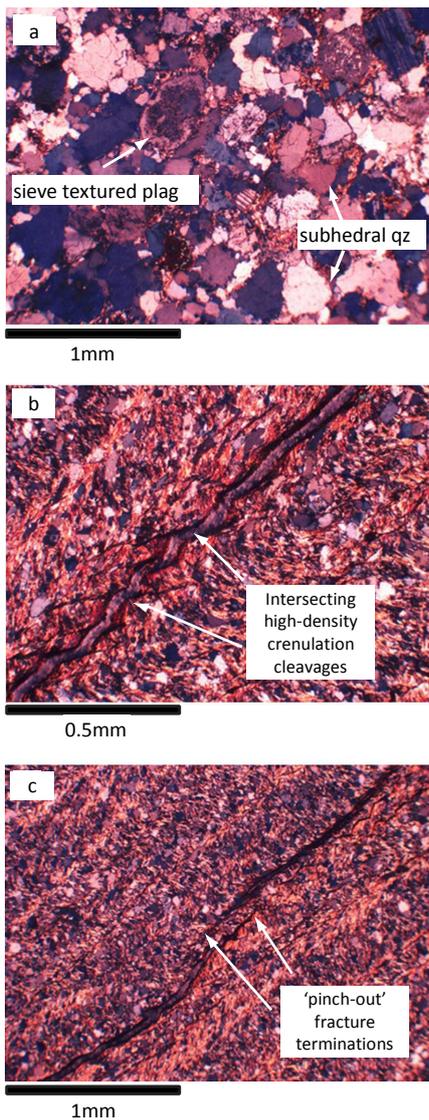


Figure 3- Key petrographic observations in GO bedrock; a) from weathered rind with subhedral QZ grains with irregular grain boundaries and sieve-textured plagioclase with cloudy sericitic overgrowth; b) & c) from strongly foliated mica-schist showing development of micro-fractures through the intersection of high-density crenulations. The discontinuous nature of the structures is high-lighted by 'pinch-out' fracture terminations (Caulfield et al., 2014)

lower horizon within the weathered zone (Comte et al., 2012). This structure is believed to reflect the eluviation of secondary clay weathering products from the upper part of the weathering profile and subsequent accumulation in the basal portion as identified in the ERT profiles. This process is thought to be the result of rainwater recharge transporting clays as a suspension, downward through the interconnected network of fractures, with deposition as an illuvial layer as fracture density decreases with depth.

Table 1 summarises the pumping and associated recovery test results for the bedrock boreholes and generally confirms a significant decline in both hydraulic conductivity and storativity with depth. Across the three catchments, bulk hydraulic conductivities and storativities clearly decrease with depth of about one

specific resistivities are characteristic of the fissured to broken upper part of the bedrock (transition and shallow bedrock). In the valley floor, specific resistivities <500 ohm.m correspond to the glacial till infill of the valley, also observed in the cutting from the transition well of the GO3 cluster; a slightly higher specific resistivity zone above the till corresponds to modern alluvial infill with clayey sand and gravel deposited by the river. A particularly noteworthy feature in this section is the variation in thickness of the boundary between the fissured (weathered) and massive (unweathered) micaschist across the transect, ranging from approximately 15 m to more than 60 m across the section. Deeper zones indicate localized deep weathering with furrows visible between GO1 and GO2 (400–500 m), GO2 and GO3 (800 m) and below GO3 (1100 m and further). This suggests the presence of deep fracture zones with higher weathering potential within the bedrock, each corresponding well with the catchment topographical lineaments highlighted on the Fig. 1-2. A common feature across the three study sites is that the weathered (fissured to broken/decomposed) bedrock unit sometimes appears to be composed of two zones of lower (500–1,000 ohm.m, bottom part) and higher specific resistivity (1,000–2,000 ohm.m, upper part). Based on the corresponding borehole gamma logs, this superposition could be related to a clay-rich weathered unit underlying a clay-poor (or clay-leached) weathered unit, respectively.

Petrographic observations show that quartz is the most resistant mineral present in the catchment bedrock. Grains in the outermost weathered rinds and those on fracture surfaces are typically subhedral with irregular grain boundaries (Fig.3a). Samples taken from highly fractured/fissured zones contain a higher proportion of strained grains recorded by undulose extinction. The weakened crystal structure and proximity to microfractures renders them particularly vulnerable to weathering (Tucker, 1991). The alteration of sodic feldspar (albite) is the main source of Na released as a result of bedrock weathering in Gortinlieve. Ubiquitous sieve-textured feldspar grains are consistent with the preferential dissolution of more calcium rich grain cores and replacement with sericite resulting in a characteristic cloudy appearance (Fig. 3a). Secondary weathering products are dominated by illite, montmorillonite and their admixtures. Clay samples taken from an outcrop of the upper part of the transition zone within the NE-SW oriented fractured zone located between borehole clusters GO1 and GO2 show a low clay mineral content and is consistent with inferences from specific resistivity profiles that delineate a clay poor upper layer and clay enriched

order of magnitude between each bedrock unit. Across the catchments, it appears that the hydraulic conductivities obtained from single permeability/porosity models are well correlated with the nature of the hydrogeological unit tested (Fig. 4).

Table 1 – Mean values and ranges of bulk hydrodynamic parameters classified by bedrock unit (Comte et al. 2012)

| | Geometric mean | Range | No. data |
|---|----------------------|---|----------|
| Hydraulic conductivity K ($m\ d^{-1}$) | | | |
| Transition (broken/decomposed) zone | 0.9×10^{-1} | $1.5 \times 10^{-2} - 2.2 \times 10^{-1}$ | 4 |
| Shallow (fissured) bedrock | 1.6×10^{-2} | $3.8 \times 10^{-4} - 2.2 \times 10^{-1}$ | 12 |
| Deep (massive) bedrock | 1.2×10^{-3} | $1.1 \times 10^{-5} - 7.8 \times 10^{-3}$ | 8 |
| Storativity S (-) | | | |
| Transition (broken/decomposed) zone | 3.7×10^{-2} | $2.8 \times 10^{-2} - 4.9 \times 10^{-2}$ | 4 |
| Shallow (fissured) bedrock | 1.7×10^{-3} | $1.0 \times 10^{-4} - 2.8 \times 10^{-2}$ | 12 |
| Deep (massive) bedrock | 3.8×10^{-5} | $1.2 \times 10^{-8} - 5.2 \times 10^{-3}$ | 8 |

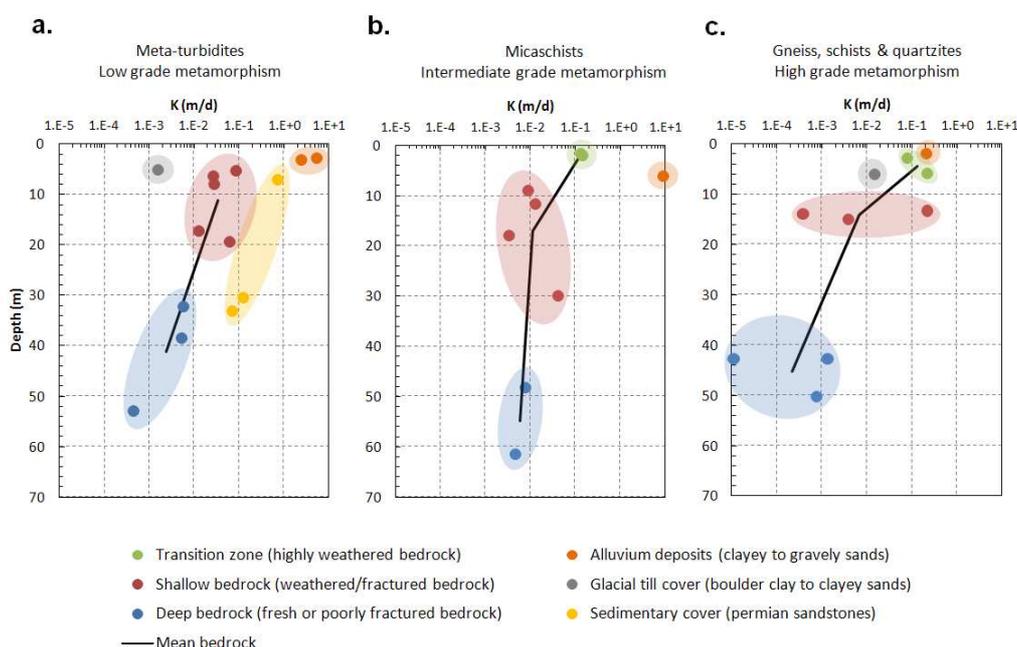


Figure 4 – Variations of hydraulic conductivities with depth obtained from specific pump tests (single porosity models) for bedrock and overburden units at a) Mount Stewart, b) Gortinlieve and c) Glencastle (Comte et al., 2012)

While the bedrock turbidites at Mount Stewart display a decrease of one order of magnitude with increasing depth, the schists at Gortinlieve decrease by only half an order of magnitude, while the Glencastle bedrock units exhibit a marked decrease of approximately two orders of magnitude. The relatively low decrease in Gortinlieve is attributed to the deep weathering, as observed on the resistivity sections (Fig. 2). It is also noteworthy that the hydraulic conductivities in the shallow bedrock (fissured zone) show significant variability compared to those of both the transition and the deep units. This variability can be explained by (1) an observed overall increase in hydraulic conductivity in the shallow bedrock from the catchment divide, i.e. the hilltop, towards the catchment outlet, i.e. the valley (reaching a factor 4–5 in Gortinlieve) which can be attributed to an overall increase in the degree of fissuring and weathering and/or (2) local variations in the degree and associated depth of weathering related to the local presence of either deep fracture or low permeability zones.

The depth referenced box plots in Fig. 5 illustrate the variation of pH and electrical conductivity between the various conceptual units within each aquifer, i.e. the drift deposits (undifferentiated glacial or alluvial overburden), the transition zone where present, and furthermore the shallow and deep bedrock across the key lithological units encountered at the three sites. Overall, the pH and EC appear to be robust tracers that are strongly controlled by aquifer hydraulic properties and associated groundwater residence times and, to

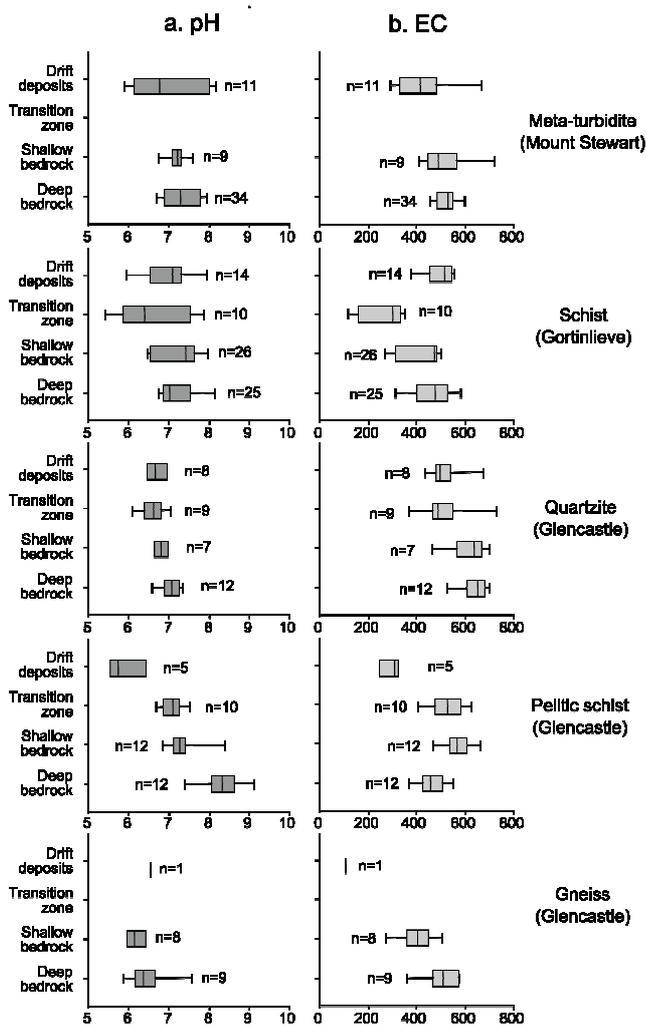


Figure 5- Depth-referenced box-plots of (a) pH (in pH units) and (b) electrical conductivity (EC, in $\mu\text{S cm}^{-1}$) for key lithologies across the three sites; box-plots indicate the median, quartiles (25,75%) and range (Pilátova 2014)

parameters at macro-scale and the control of the aquifer internal (meso-scale) fabric by recent (postmetamorphic) tectonics. At the catchment scale, access for the development of deep weathering profiles is controlled by NE-SW regional scale fracture zones associated with mountain building during the Grampian orogeny. In-situ chemical denudation of mineral phases is controlled by micro- to mesoscale fractures oriented parallel to the foliation plane. These younger structures are considered to be related to regional strike-slip faulting as a consequence of Alpine compression. The alteration of primary muscovite, clinocllore and albite along the surfaces of these small-scale fractures has resulted in the precipitation of illite, montmorillonite and their admixtures. The interconnected but discontinuous nature of the small-scale fractures highlights the role of larger scale faults and fissures in the supply and transportation of weathering solutions to/from the sites of mineral weathering. The two layered structure of the weathered zone identified from resistivity profiles is confirmed by the presence of a clay-poor upper zone within the broken/decomposed bedrock. This distribution is inferred to result from the suspension and removal of secondary clays via the flow of groundwater recharge through shallow-level interconnected fractures and fissures. As the density and aperture of these structures decreases with depth, the clays are deposited within the basal part of the weathering profile.

a lesser extent, by lithology type. As demonstrated across the three catchment sites as well as in the five different litho-types, the relatively neutral pH is largely detected in bedrock aquifers composed of mica-schists, meta-turbides, gneisses, quartzite and shallow pelitic schists. Interestingly, across these litho-types, the closely similar permeability distributions are also a common denominator (Fig. 4). In contrast, the deep pelitic schists in Glencastle are characteristic of the most alkaline pH and were also notably found to be remarkably the least permeable litho-type. As a result, longer residence times are plausible with additional silicate weathering (as opposed to predominant carbonate dissolution in the other litho-types), which acts as a trigger for the pH increasing to a value as high as pH 9. Similar to the pH distribution, electric conductivity measured in the bedrock across the five different lithological types is within a range of 400 to 600 $\mu\text{S cm}^{-1}$ with the exception of groundwater within the deep quartzite. This is consistent with the interpretation that the weathered/fractured zone is a more important control on the groundwater flow than the litho-type directly, the latter remaining an indirect control through its impact on the weathering depth (i.e., the differential weathering).

V. CONCLUSION

Across the study sites, similar patterns in aquifer structure, hydraulic properties and groundwater chemistry confirm the complexity of hard-rock aquifers. These include the strong spatial, and particularly, depth variability of hydrodynamic

VI. REFERENCES

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