1. Introduction to research

I received PhD degree at Department of Earth and Planetary Sciences, McGill University, Canada in 2019, and am now a visiting researcher at Kyoto University. The PhD research was titled "Global Compilation and Analysis of Fault Zone Permeability". The review of available data from 10,000 publications was used to perform statistical exploration of permeability trends, the ratios of fault and protolith permeability, development of permeameter device for testing of drill core and outcrops over a wide range of permeability values, and testing of fault zone in-situ and on drill core transects at the Gryphon U deposit in north-central Canada. The field site was in Precambrian pelites and pegmatites under the Athabasca Basin, where the fault zone permeability structure and hydrothermal alteration patterns are well-preserved since the Proterozoic age. I also contributed to a review paper on the topic of fault zone hydrogeology (Bense et al., 2013), and helped to map pseudotachylite networks on outcrop of exhumed fault zone in mylonitic rocks (Rowe et al., 2018).

Over the past 20 years, the research topics were:
- Permeability testing on drill core and in-situ in fault zones;
- Statistical analysis, world-wide depth-trends and permeability contrasts in fault zones;
- Hot spring groundwater flow systems and fault conduits;
- Mapping of hydrogeologic units in fractured and faulted rocks at mine sites;
- Geospatial and numerical groundwater flow simulations in shallow aquifers affected by climate change.

This article has four sections that introduce those research topics, and presents some typical results from my publications and projects that are in progress. The spatial scale of these projects ranges from single drill core pieces to 10 km sized study sites, and world-wide statistics. Some aspects of Geoinformatics are involved in each study topic.

2. Permeability testing on drill core and in-situ in fault zones

Routine permeability and porosity tests on drill core, with adequate detection limits and accuracy, can provide new insights into present-and paleo-fluid flow processes and deposit formation in sedimentary basins and permeable fault zones (e.g. uranium deposits, sub-sea hydrothermal ore deposits) (Figure 1).

New research at Kyoto University now focusses on testing of drill core of fault zones, and appropriate geostatistical methods.

We are presently developing a new version of a practical and versatile pressure-decay permeameter probe, and testing the...
capabilities. Early results show that such gas probe and method can change how drill core and outcrops are routinely tested and it will provide new data at drill core scale for geostatistical work on fractured rocks.

Such detailed new data are very important for other studies:
- Hydrogeology of underground radioactive waste repositories;
- Geophysical and earthquake studies in active faults (involvement of fluids);
- Paleo-fluid flow in fault zones and the formation of many mineral deposits;
- In-situ recovery ("leaching") of some mineral deposits such as uranium (dissolving and pumping out the deposit);
- Environmental aspects of hydrogeology, contaminant transport, water resources, and geotechnics.

3. Statistical analysis, world-wide depth-trends and permeability contrasts in fault zones

In a recent article by Scibek (2020) in Scientific Data, a multi-disciplinary world-wide compilation and database was prepared that contains the bulk and matrix permeability of fault zones: 410 datasets, 521 reviewed sites, 379 locations, >10000 publications searched. The review covers studies of faulting processes, geothermal engineering, radioactive waste repositories, groundwater resources, petroleum reservoirs, and underground engineering projects. The initial statistical study of biases of various permeability observation methods was published in Scibek et al. (2016).

The objectives of such research are to stimulate the cross-disciplinary data sharing and communication about fault zone hydrogeology, document the biases and strategies for testing of fault zones, and provide the basic statistics of permeability values for models that require these parameters. Such results are useful as reference values and for geostatistical work in the future on faulted rocks (Figure 2). For example, the permeability ratio is important for understanding and modeling of fluid flow in fault zones. The ratio is typically 100 to 1000, attains a maximum at a depth of about 2 km, and may decrease with depth. In Japan, the permeability ratios at 32 geothermal and scientific drilling locations are all bounded by the proposed permeability ratio curve.

4. Hot spring groundwater flow systems and fault conduits

The discharge and temperature of thermal and hot springs provide important information about hydrothermal flow systems, especially regarding the convective heat flow and permeability of fault zones. This is known in Japan, however, in other regions of the world, the nature of this discharge-temperature relationship is poorly described, and no regional patterns have previously been investigated. In this on-going study, Japan is compared to other regions of the world (data references in Scibek et al. (2018)). (a) Statistical analysis of hot spring data from Japan, and other regions of the world (data references in Scibek et al. (2018)). (b) Example of review process for hot spring areas in Japan (from presentation by Scibek et al., 2018).
other regions of the world along active margins where there are Quaternary volcanic areas (Figure 3).

I am helping to review all hot spring areas in Japan and worldwide, and to integrate the hot spring data with deeper geothermal data at Kyoto University. Recently, I co-authored a study by Luijendijk et al. (2020), on the thermal spring discharge, temperature, the contribution to the groundwater and heat budget. The completion of world-wide thermal spring database, and the progress on modeling of flow systems can help estimate the permeability of fault zones and convective heat flow in many areas.

5. Mapping of shallow sedimentary aquifer properties and simulating the impacts of climate change on groundwater levels

From 2002 to 2006, at Simon Fraser University, I studied the alluvial aquifers in mountain valleys in British Columbia, Canada. At that time, I developed 3D models of two regional aquifers: Abbotsford-Sumas and Grand Forks aquifers (Scibek and Allen 2006b; Scibek et al., 2008). Numerical models were used to link the spatial distribution of groundwater recharge and water levels (Figure 4, and Scibek and Allen, 2006a). This method is now used by the Environment Canada government agency to simulate the climate change impacts on groundwater resources. One of the main observations was the effect of river and stream flow hydrographs on groundwater levels (i.e. shifting of hydrograph peak) (Scibek et al., 2007). An example of local study is at Gabriola Island, consisting of folded sedimentary rocks, near Vancouver Island, west coast of Canada (Scibek et al., 2013).

However, regional aquifers are very heterogeneous and many geospatial tools and databases are used to model the 3D distribution of hydraulic properties and of averaged hydrogeologic units (Scibek et al., 2003, and Figure 5). The data quality of sediment logs from commercial drilling wells is highly variable, thus the well logs must be standardized and the sedimentary structure modelled (e.g. Allen et al., 2007 based on my work).

The collaboration between the mineral resource exploration industry and the hydrogeologic scientists is recommended, because this can lead to good access to deep drilling projects, to rock drill core, and to in-situ hydraulic tests in many drill

Figure 4. Simulations of impacts of climate change on groundwater resources (from Scibek and Allen, 2006b).

Figure 5. Geospatial work on mapping of sedimentary hydrogeologic units of aquifers at Grand Forks and Abbotsford (after Scibek et al., 2003).
holes. However, most of the conceptual and numerical models of groundwater flow in faulted and fractured rocks are poorly characterized and most of the parameters are assumed (not tested). Therefore, it is important to transfer the academic knowledge and new test methods to the industry.

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