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Canadian rock physical property database: first public release

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Introduction

The Canadian Rock Physical Property Database (CRPPD) is a compilation of petrophysical measurements made on Canadian rocks, along with their associated locations and lithologies. The title is ambitious, as the compilation is currently far from complete and not evenly representative of Canadian geology (Fig. 1). Nevertheless, this first public release includes nearly 20 thousand rows of data collected over four decades, and the compilation is useful as-is for the interpretation of geophysical surveys. It does include the common igneous and metamorphic rock types found in the shield, igneous, sedimentary and metamorphic rock types found in the Cordillera and mineralized versions thereof and is therefore fairly representative of the types of rocks to be found across Canada; however it is notably deficient in rocks from the sedimentary basins on the craton.

The purposes of this Open File are: (1) to provide easy access to the CRPPD; (2) to present a simple interpretation of the compilation; and (3) to publicly request data for the continued compilation of the CRPPD. There are likely two or three orders of magnitude more measurements which have been collected by government geological surveys, academia, and especially by private industry, at risk to be lost from public use. After reports have been written and projects have been terminated, these petrophysical data still have utility and can be provided for common usage at little or no cost. Some physical property datasets have been collected and compiled but never even used.

If you or your colleagues have petrophysical data with associated lithologies and locations in Canada, please consider contributing these data to the Canadian Rock Physical Property Database.

For the protection of commercially sensitive interpretations, it is acceptable to reduce the accuracy of sample locations (to ~10 km accuracy) and to remove proprietary sample names.

Physical properties provide the link between geophysical and geological interpretation. One cannot directly apply the geological tools of lithology, mineralogy, and geochemistry without direct access to rock samples. However the lithology, mineralogy, and geochemistry all control the rock physical properties which in turn control the responses detected by geophysical surveys and measurements. Dentith et al. (2017) provide a conceptual framework for petrophysical data by placing the various rock physical properties on a ternary diagram with end members of “Bulk (Overall Composition), “Grain (Amount, Size, Shape of Minority Mineral Species)”, and “Texture (Geometric Relationships Between Grains)”. Density is dominated by the bulk composition, whereas magnetic susceptibility is dominated by the concentration of the minor mineral magnetite. Electric resistivity in sedimentary rocks is dominated by the porosity and permeability, which are textural properties.

In general, geophysical surveys use a naturally occurring or locally generated physical field as an input, and measure its spatial and temporal output after it has been filtered by the distribution of physical properties in the earth. As a forward problem, given the input and the physical property distribution, the output can be calculated. Geophysical interpretation usually involves the inverse problem; that is, given a set of field observations and prior information about the input signal and the physical property distribution, an estimate of the subsurface distribution of physical properties is derived based on achieving an optimum statistical match between the observed and computed signal. Having achieved an acceptable match the investigator is then required to interpret the physical property distribution in terms of geological structure, lithology, mineralogy, and geochemistry.

There are three main applications of petrophysics: (1) Hydrocarbon exploration usually is done on regions with layered stratigraphy where seismic methods are particularly effective. The relevant petrophysical measurements are on elastic properties (bulk and shear modulus and Poisson ratio, seismic attenuation parameters) and on rock-fluid interactions (porosity, pore size spectra, permeability); (2) Geotechnical applications of rocks and sediments, for which the most important measurements are of strength parameters, grain-size distributions and porosity; (3) The current focus of the CRPPD is mineral exploration, for which our understanding of physical property variations and their relationship to common geological processes (mineralization, metasomatism, etc.,) is far less advanced.

Mineral exploration often involves the analysis of gravity, magnetic, electric and electromagnetic surveys. To this end, the CRPPD currently compiles density and porosity, magnetic susceptibility and remanence, and electric resistivity and chargeability. It is likely that other parameters will be included in future releases.

This Canadian compilation is not unique. The most mature compilation of density and magnetic properties has been produced by the Swedish and Finish Geological Surveys (Henkel, 1976, 1991; Airo, 1990, 2005; Airo and Säävuori, 2013). Around the world, there are many more small specific compilations, but not large ones on a national scale with the exception of Uganda performed with the collaboration of the Geological Survey of Finland (Ruotoistenmäki and Birungi, 2015).

Compiling the Canadian Rock Physical Property Database

The author, who has a background in paleomagnetism, began producing rock physical properties measurements for mineral exploration in 2006. Before that time, several regional compilations were made within the Geological Survey of Canada (GSC), comprising over half of the rows in the CRPPD. Mira Geoscience Ltd., a Canadian geological consultancy company with expertize in data integration, incorporated much of the GSC data into their "Rock Property Database System - RPDS" (Parsons and McGaughey, 2007), along with a great deal of borehole-logging data. The Mira Geoscience RPDS was particularly influential on setting the style and scope of the CRPPD.

A few legacy datasets deserve comment (Fig. 1a):

A major mapping operation in the Yukon Crystalline Terrane, led by Dirk Templeman-Kluit (1974) from 1970 to 1972, resulted in 2½ 1:250K geological map sheets in Yukon Territory. Tempelman-Kluit and Currie (1978) published GSC Paper 77-8 with density and magnetic susceptibility measurements, along with major element geochemical concentrations of their sample collection archive. While the paper concludes that the major element geochemical information of that epoch is of little exploration utility, the physical properties provide a wonderful record. The data was compiled on computer punch cards, which have long been lost. The 30 microfiches published with the paper summary are too low quality for optical character recognition digitization. Fortunately, Lowe et al. (1994) summarized means from that compilation by lithological classifications, which indicated that she had access to the original digital data. Although she has since left the GSC, we still have her digital records. On an obsolete JAZ drive, using an old computer which had a functioning reader, there was a spreadsheet with locations in UTM coordinates rather than the original latitude and longitude, and magnetic susceptibilities in SI rather than the original CGS units. Nevertheless, the data were recognizable. In order to link the corresponding geological formations and lithologies to each sample, Mira Geoscience hired a student who painstakingly typed in the character data from the microfiches. Finally, Tark Hamilton went through the formations and lithologies as identified in the early 1970s and updated them to more recent understanding of Yukon geology as mapped by Colpron and others (Colpron and Nelson, 2011). Thus, passing from computer punch cards and poor quality microfiches, through an obsolete mid-1990s computer medium to today, we have recovered an important petrophysical data set comprising 2374 rows.

The largest data set included in the CRPPD is from the NatMap Nechako Project (1996–1999), which resulted in two 1:250K geological map sheets in north central British Columbia (Struik, MacIntyre, Williams, 2007). This project was one of the first that had geologists map with portable dataloggers, and they set the protocol to measure magnetic susceptibility at every outcrop. Magnetic susceptibilities were compiled at the site level, while densities measured on hand samples by Marianne Quat were compiled on a separate table at the sample level. The combined results are clearly compatible with the rest of the CRPPD, so this sample/site inconsistency is deemed insignificant, and this study adds 6085 rows, 31% of the complete compilation.

The substantial rock storage facilities across the GSC represent a huge investment of our collective work. As part of the first 5-year Geo-mapping for Energy and Minerals (GEM) program, the densities and magnetic susceptibility of 629 samples were measured from samples collected during the Franklin project in the 1960s from the Chantrey region in the north of mainland Nunavut, complemented by measurements on 156 recently collected samples. The difficult issue with the archive collections is many samples lack digital metadata of locations and lithologies. Given the huge expense of remapping huge tracts of Canada, a very efficient strategy for the GSC is to perform work in our rock collections and add value by making systematic physical properties and complementary geological measurements on the samples. After the current compilation was frozen in June 2018, a substantial compilation of GSC physical properties data was introduced to the author, housed on the Geoscience Data Repository (gdr.agg.nrcan.gc.ca). These data will be incorporated in the next release of the CRPPD.

The original scope of this data collection was British Columbia (Enkin et al., 2008; Enkin, 2014), incorporating several collections made by Carmel Lowe (Bowser and Sustut basins, Lowe et al., 2004, unpublished collections on the Queen Charlotte Islands, Eagle Bay Assemblage and the Kootenay Arc) and several new studies in conjunction with contemporary mapping projects (e.g., Anderson et al., 2010). Measurements on sample archives from paleomagnetism studies going back to the 1970s by the lab founder, the great GSC paleomagnetist Ted Irving, were included complemented by the compilation of locations and lithologies by Judith Baker.

In 2008, equipment from the GSC Petrophysics lab led by John Katsube was transferred from Ottawa to the GSC Paleomagnetism lab in Sidney, British Columbia, to establish the Paleomagnetism and Petrophysics Laboratory. Particularly important are integrated studies where lithology, mineralogy and geochemistry are combined with the physical properties (e.g., BC Porphyry Deposits, Mitchinson, et al., 2014, Great Bear Magmatic Zone Iron-Oxide Copper Gold setting, Enkin, et al., 2016).

Prominent in the field of integrated mineral exploration studies is the Canadian Mining Innovation Council's Footprints Project (Lesher, et al., 2017). This 5-year program featured coordinated sampling of the region around three distinct types of deposits: disseminated gold at the Canadian Malartic mine in Quebec, unconformity uranium at the Millenium McArthur trend in the Athabasca Basin, Saskatchewan, and porphyry copper at the Highland Valley Mine in British Columbia.

Metadata: Location and Lithology

The samples for the CRPPD were not collected specifically for petrophysical purposes. In contrast, the Finish Geological Survey actually had a devoted petrophysics project to collect a representative samples uniformly around their country (Airo and Säävuori, 2013). While such a strategy is not feasible at present in Canada, the resulting compilation is useful as long as the collection strategies are understood. Samples from regional mapping or samples specifically collected for mineral exploration usually attempt to span the range of lithologies, alterations and mineralizations. Background or country rock sample are almost always included, but not in numbers that are areally or volumetrically representative. The more distinctive or exotic rock types tend to be over-represented. Because of the emphasis on mineral exploration, a notably under-represented class of rocks are unmetamorphosed sedimentary rocks. Note the current lack of samples from the major Canadian basins, and notably the Western Canadian Sedimentary Basin, and the Arctic, Beaufort, Michigan or Hudson Bay basins.

It is important to recognize that the rocks that come to the lab are sufficiently competent to have survived sampling, transport, and the laboratory subsampling procedures. Unconsolidated surficial samples are not usually included, nor are friable samples from structural or altered zones. Shales are highly under-represented.

Note that spatial uncertainties are provided with sample locations. It is not extremely important for this project to have accurate locations, and some sample providers have commercial reasons to guard the specific geological context that location would provide. Thus, for some collections, a single representative point for all the samples within about 10 km of the sampling is used rather the individual locations.

A great deal of effort has gone into producing a useful lithological classification, particularly because field names are often eclectic, inconsistent or biased. Parsons and McGaughey (2007) discuss the issues and difficulties in setting and applying a lithological classification scheme to data coming from a variety of sources. As always in geological mapping and sample classification, the degree of lithological lumping or splitting used by a geologist depends on the way the local geology presents itself, the purpose of the mapping, and importantly on the biases of the geologist. There is the old dictum that geophysicists need only differentiate between “white rocks”, “black rocks” and “dirt” (Roy Hyndman, personal communication, relating wisdom from his mentor Michael Keen).

In the CRPPD, the original information is included as much as possible without editing. Complementary information from the location and geological formation often informs the lithological classification. Each rock is slotted into the three-level scheme proposed (126 categories) by Parsons and McGaughey (2007, and listed completely by Enkin et al., 2012), and the two-level scheme used by the GSC-Field App (490 Categories), which is itself based on a three-level scheme for the previous GSC field data collection system called Ganfeld (Shimamura et al, 2008, and listed completely by Enkin et al., 2012). We also include the classification according to the GSC Sample Management System (840 Categories).

For a broad overview, the lithologies were gathered into a few large groups. First, the rocks were classified as Volcanic, Plutonic, Sedimentary, Metamorphic (further divided, where possible, into Metavolcanic, Metaplutonic, Metasedimentary). For more unusual, veined or monomineralic rocks these were classified using the more vague terms of Structure, and Alteration/Mineralization. All rocks in the Canadian Shield are classified as metamorphic, with the exceptions of kimberlites (late, post metamorphism emplacement) and Athabasca Basin rocks (largely unmetamorphosed Proterozoic quartzites and arkoses). Volcanics, plutonics and their metamorphic equivalents are then classified by the terms Felsic, Intermediate, Mafic and Ultramafic. The set of lithologies included in each of these groups is offered in Table 1.

Summary of Physical Properties Measurements

The methods used in the GSC Paleomagnetism and Petrophysics Laboratory are presented by Enkin et al. (2012) and updated by Enkin (2017). This section outlines some important aspects of the methods and their implications on the compilation.

Table 1: Numbers of samples in CRPPD by lithological category.

Lithology Group	N	Specific Lithology	N
Volcanic	6785	Rhyolite	805
		Dacite	603
		Andesite	1451
		Basalt	3084
		Unclassified or Other Volcanic	842
Plutonic	4655	Granite	501
		Granodiorite	1263
		Diorite	2319
		Gabbro	122
		Unclassified or Other Plutonic	450
Sedimentary	2982	Siliciclastic	1911
		Volcaniclastic	613
		Carbonate	384
		Unclassified or Other Sedimentary	74
Metamorphic	4714	Metavolcanic	830
		Metaplutonic	1108
		Metasedimentary	2629
		Unclassified or Other Metamorphic	147
Mineralized/Alteration	475		
Structure	42		

The optimal sample size and geometry depend on the goals of a study, the sample lithology, and the requirements of the measurement equipment. In our lab, most work is done on specimens that fit our remanence magnetometer, that is, a cylinder 2.5 cm in diameter and 2.2 cm long. This ~11 cm^3 volume adequately averages mineralogy, sufficient for all but coarse-grained pegmatites and conglomerates with large monominerallic clasts. It is small enough to allow separate sampling from, say, the groundmass of a hand sample and the more unusual mineralogy and texture surrounding a vein. Submitted samples need not be much larger than the specimen cylinder, and reliable measurements have often been made on specimens that are thinner (down to ~1 cm) or from incomplete cylinders such as from split NQ core.

Note that data from other labs has usually been collected on larger samples. Hand samples typically have a volume around 1 litre. Core samples often are 10 to 30 cm long. In the spreadsheet, densities made on paleomagnetism-type samples are noted in the Density Methodology column as "Minicore Archimedes", while larger samples are identified as "Hand sample Archimedes". Measurements of magnetic susceptibility are often averaged from several measurements made over an outcrop of several square metres. In the Magnetic Susceptibility Methodology column, paleomagnetism-type samples have identifiers such as "Minicore Sapphire SI2B", hand-samples like "Hand sample GF Instr. SM-20", and measurements at the outcrop like "Field KT-9 Kappameter".

Three densities (grain, dry bulk, and saturated bulk density, units [g/cm^3]) plus porosity are reported in the CRPPD, following the definitions in Table 2. Grain density, also known as skeletal density, does not include the contribution of the sample porosity, except for the case of blind pores that are not connected to the sample surface (for example in some vesicular volcanics). In contrast, the other densities include porosity, when filled with air (dry bulk density) or with water (saturated bulk density). When only a single density is reported, it is almost always the saturated bulk density.

Table 2: Density and Porosity terms and symbols.

Term	Symbol	Formula
Dry Weight	W_D	
Saturated Weight	W_S	
Immersed Weight	W_I	
Water Density	ρ_W	
Grain Density	ρ_G	$W_D / (W_D - W_I) * \rho_W$
Dry Bulk Density	ρ_B	$W_D / (W_S - W_I) * \rho_W$
Saturated Bulk Density	ρ_S	$W_S / (W_S - W_I) * \rho_W$
Porosity	P	$(W_S - W_D) / (W_S - W_I)$

Magnetic susceptibility and remanence are related through the unitless Koenigsberger ratio (K_N),:

$$K_N = NRM / \chi_0 H_0 , \quad \text{[eq.1]}$$

where NRM is the natural remanent magnetization [A/m], χ_0 is the magnetic susceptibility [SI units = (A/m)/(A/m)], and $H_0 = B_0/\mu_0$, $\mu_0 = 4\pi\times10^{-7}$ (A/m)/T is the strength of the geomagnetic field. For comparing the efficiency of magnetization among different rocks, the Koenigsberger ratio K_N50 is reported using a standard field of B_0 = 50 µT, however for more accurate magnetic anomaly interpretation, it is also reported using the local geomagnetic field strength, which in Canada varies from 51 to 60 µT (~56 µT at the GSC Petrophysics Laboratory). Note that susceptibility measurements that are at the lower measurement limit of the instrument are noted in the spreadsheet with a susceptibility of 9.99E-7 SI.

Electric resistivity and chargeability measurements in the CRPPD currently are only compiled from measurements made in our laboratory. All measurements have been made using copper – copper sulfate electrodes on two parallel sample faces. The resistivity [ohm.m] is measured at 1 or 0.1 Hz, while the chargeability is determined from the impedance spectrum in frequency domain converted to time domain decay from a step by Inverse Fourier Transform. The reported chargeability uses the Newmont Standard [ms], that is, the time integral of the voltage decay from 430 to 1100 ms normalized by the voltage step.

Canadian Rock Physical Property Database

The CRPPD database now contains sufficient data to allow useful cross-plots of all the compiled properties (Table 3), along with differentiation by lithology (Table 1). In this section, the data are summarized to provide some understanding of typical and exotic distributions of physical property data. First density and porosity data are summarized, then electrical properties, finishing with magnetic properties.

The grain density (Fig. 2) lies between 2.6 and 2.8 g/cm^3 for 70% of the samples. It is rarely is lower than 2.6 g/cm^3 (3.5%), as expected because so few minerals have density below 2.6 g/cm^3 (Fig. 3). The exceptions are vesicular volcanics. The more dense rocks with high concentrations of ferromagnesian minerals, sulfides, or oxides, are particularly evident in the histogram of Mineralized/Alteration samples in Fig. 2. There are over three times as many entries of saturated bulk density (Fig. 4) as grain density, and similar observations are evident. The main difference is that 20% of the samples have saturated bulk density <2.6 g/cm^3, because of the effect of porosity. Figure 5 shows that 29% of the samples have porosity above 1%, especially within the volcanic and sedimentary classes. The cross-plot of porosity to density (Fig. 6) demonstrates their expected anticorrelation for rocks with porosity >1% (Log(porosity)>0). The anticorrelation is particularly evident among the sedimentary rocks which are dominated by density = 2.6 g/cm^3 minerals, quartz and feldspar, and density = 1 g/cm^3 water in the porosity. Below porosity=1%, the relationship between

Table 3: Numbers of rows in the CRPPD with specific properties compiled. Bold marks number of compiled measurements for each property, otherwise number of samples with both properties available for cross-plots.

	Grain/Dry Density & Porosity	Sat Bulk Density	Mag Susceptibility	Nat Rem Mag & Koenigsberger	Resistivity	Chargeability
Grain/Dry Density& Porosity	**3845**	3845	3771	3547	3188	3174
Sat Bulk Density		**12514**	11146	3417	4003	3755
Mag Susceptibility			**18276**	6010	3993	3742
Nat Rem Mag & Koenigsberger				**6021**	3803	3631
Resistivity					**4051**	3800
Chargeability						**3800**

porosity and density is much less clear, as the density variations are dominated by mineralogy rather than porosity.

Figure 6b employs a useful transformed density scale, introduced by Enkin et al. (2016), to spread out the cross-plot in the 2.6-3.0 g/cm^3 range while allowing points with high density on the same diagram. The value 2.5 g/cm^3 is subtracted from each density, and the result is plotted on a log-scale. Densities below 2.5 g/cm^3 cannot be plotted, and practically it is best to start the scale at 2.53 g/cm^3, allowing 90% of the data to be plotted.

Electric resistivity (Fig. 7) has a mode around 3000 Ω·m. Note, however, that laboratory measurements are consistently observed to be about 1 order of magnitude higher than those observed from in situ measurements, for instance using magnetotellurics (e.g., Bancroft et al., 2014). Mineralized/Alteration rocks feature the lowest resistivities, however porous Volcanics and Sedimentary rocks also have large populations of low resistivity rocks. Figure 8, the cross-plot of resistivity to density, provides a rough explanation of the two main resistivity trends. The conduction pathway through low density rocks is controlled by ionic conductivity through the porosity and permeability, while in high density rocks galvanic conductivity is related to the presence of conductive ore minerals. Both of these conductivity mechanisms are texture-controlled. The small sizes of the samples do not represent well the conductivity pathways seen at survey scales. The cross-plot of resistivity to porosity (Fig. 9) provides part of the explanation in terms of Archie's law (Archie, 1942), which expresses rock resistivity as power relationships to the porosity and the pore-water resistivity. Ignoring the variations in pore water resistivity (which are certainly large), we see that the resistivity is proportional to the porosity to the -0.8 power. Typically, Archie-law porosity exponents are around -2 for porosity > 10%, and down to -1 for porosity around 1% (e.g., Shahi et al., 2017). To date, there is little work on applying Archie's law to non-sedimentary rocks with very low porosity. If the true Archie-law porosity exponent should be larger than -1, then the pore water resistivity must be systematically higher in high-porosity samples, which is an unexpected implication.

Induced polarization (IP) chargeability has a wide variety of measurement methods and definitions. Furthermore, no standards have been proposed that can provide inter-laboratory comparisons. The CRPPD reports Newmont Standard chargeability, that is the integration of voltage from 430 to 1100 ms after the current is removed normalized to peak voltage. For the current compilation (Fig. 10), it is most interesting to note that the mode of the measurements is 5 ms, and only 13% have a chargeability value above 10 ms. Above this limit the IP is probably detectable in an IP survey. Note that mineralized samples are far more likely to have high chargeabilities than any other lithology class due to increased sulfide content. The high concentration of sulfides in many mineralized rocks also leads to high density. The cross-plot of chargeability with density (Fig. 11) displays a weak positive correlation while there appears to be very little relationship between resistivity and chargeability (Fig. 12).

The analysis of magnetic properties is particularly important for mineral exploration and more generally for geological mapping, as magnetic surveys surveys are the most commonly employed geophysical mapping tool. To the first order, magnetic susceptibility is a measure of magnetite (Fe_3O_4) concentration, as magnetite is the only common strongly magnetic mineral. Unfortunately, magnetite is only an accessory mineral and its formation and destruction in geological processes remains poorly studied and quantified.

Magnetic susceptibility, the magnetization [A/m] acquired in a unit magnetic field [A/m], is unitless. Unfortunately the standard equation for magnetic susceptibility in cgs units uses a geometric factor of 4π differently such that 1 SI = 4π cgs, or about a factor 10 different. Also authors often publish magnetic susceptibilities without stating the power of 10 that was used. Fortunately, the bimodal histogram of magnetic susceptibilities (Fig. 13) is surprisingly robust in a huge variety of geological settings and regions, such that it is usually possible to work out the units and power of 10. Remarkably, there is almost always a mode around 3×10^{-4} and one around 3×10^{-2} SI. Sedimentary and Metamorphic rocks have many more around 3×10^{-4} while igneous rocks have more around 3×10^{-2} SI. Mineralized and Altered rocks do not follow the bimodal distribution rule.

The cross-plot of the logarithm of magnetic susceptibility to density (Figs 14–19) is particularly important for geophysical interpretation and for lithological analysis. This plot has been emphasized in a series of papers by Herbert Henkel (1976, 1991, 1994) so it now called the Henkel Plot (Dentith, et al., 2017). In all these plots, contours of point density based on the whole collection are plotted to help identify the similarities and variations of the various rock classes selections which are plotted. The Henkel plot using the Grain Density is displayed in Figure 14. Note how there are very few samples with density below 2.6 g/cm^3. This should not be surprising since quartz has a density of 2.62 g/ cm^3. An increase in ferromagnesian minerals will lead to an increase in density. Grain densities of less than 2.6 g/cm^3 are associated with rocks having moderate porosity and low permeability. That is, density measurements where water cannot connect to the interior pores of a sample; typically vesicular volcanics exhibit this type of effect.

We see that the points mostly fall on two curves which start from a vertical at density $\approx$ 2.65 g/cm^3 and increasing in density and susceptibility. The same pattern is apparent when plotting Saturated Bulk Density (Fig.s 15-19), but with three times as many available points. The main difference is a bit more scatter and particularly many more low density (<2.6 g/cm^3) points, mostly from volcanic and sedimentary rocks.

The principal rock classifications are separated in Figures 16a-e and repeated using the log(Density-2.5) scale in Figures 16f-i. Volcanic rocks (Fig. 16a, f) tend to sit in the upper mode. Enkin (2014) showed that the large number of Volcanics with susceptibility around 3×10^{-3} SI are mostly from the Neogene Chilcotin Volcanics of British Columbia. These rocks are notable for being anhydrous, deep, intracratonic basalts, which leads to the iron being partitioned atypically among oxides and silicates. Plutonic rocks (Fig. 16b, g) are dominated by measurements within the upper mode. In contrast sedimentary rock (Fig. 16c, h) and metamorphic rocks (Fig. 16d, i) are dominated by the lower mode. Note how the sedimentary rocks have more points with slightly lower density and higher susceptibility than the metamorphic rocks. Finally, note how the Mineralized and Alteration group of rocks (Fig. 16e, j) follow completely separate rules.

The major volcanic classifications from felsic to mafic are plotted on the Henkel plot in Figure 17, and the corresponding plutonic rocks in Figure 18. Note the progression in increasing density from Rhyolite/Granite, through Dacite/Granodiorite and Andesite/Diorite, to Basalt/Gabbro. The main classifications of sedimentary rocks are displayed on the Henkel plot in Figure 19. Siliciclastic rocks (Fig. 19a) plot dominantly in the lower mode, but a significant proportion sit in the low susceptibility tail. Such rocks are dominated by quartz and feldspar. Volcaniclastic rocks (Fig. 19b) also mostly plot in the lower mode, but a significant proportion also sit in the upper mode, as expected due to their more magnetic source rocks. Carbonate rocks (Fig. 19c) have very low magnetic susceptibility.

Natural Remanent Magnetization (NRM) (Fig. 20) has a similar bimodal distribution, with modes around 2×10^{-3} A/m and 0.5 A/m, with similar variations among rock classifications as the magnetic susceptibility (Fig. 13). The remanent magnetization does not track proportionately with the susceptibility for all rock classifications, as demonstrated with the histograms of the Koenigsberger ratio (K_N) (Fig. 21). While most rocks have K_N between 0.1 and 1 (53%), the large proportion with K_N>1 (34%) shows that aeromagnetic interpretation should pay far more attention to the effects of magnetic remanence. Volcanic rocks much more commonly have K_N above 1 than plutonic rocks. A high proportion of sedimentary rocks also have high K_N, with red-beds of the Athabasca Supergroup containing remanently magnetized hematite among the rocks with the highest values. Note, however, that even though the remanence of the Athabasca red beds dominates the induced magnetization, their effect on the aeromagnetic anomaly maps is almost invisible because of high susceptibility and remanence values of the basement rocks underlying near surface basin sedimentary rocks. A further complication in the Athabasca magnetic interpretation is introduced by the strong magnetic properties associated with Quaternary overburden related to the presence of Canadian shield erratics in drumlins.

The cross-plot of NRM to density (Fig. 22) is similar to the susceptibility to density cross-plot (Fig. 14). The cross-plot of Koenigsberger Ratio to density (Fig. 23) displays an interesting negative correlation (subtle but apparent in Fig. 23b), probably because the denser rocks contain larger grains of magnetite which are less paleomagnetically stable.

Henkel (1976, 1991, 1994) recommends that the K_N-susceptibility cross-plot be used along with the susceptibility-density cross-plot to characterize rocks. The NRM-susceptibility cross-plot (Fig. 24) is possibly clearer, but note that the lines of equal K_N assume a single chosen field (50 nT) rather than the local field, which in Canada means the Koenigsberger ratios are a bit more variable and about 10% lower. Here the separation of the volcanic rocks from the metamorphic and plutonic, and then the sedimentary rocks is made clear.

To close this exposition of the CRPPD, consider the mineral mixing lines which explain much of the distribution of the Henkel plot (Figs 25 and 26), closely following the analysis presented by Henkel (1991) and expanded here in discussions with Tark Hamilton and Bill Morris. For explaining density and magnetic susceptibility, almost all rocks can be considered to be combinations of three groups of minerals: Quartz-Feldspar-Calcite (QFC), FerroMagnesian (FM) silicates, and Magnetite (M).

When working with the grain density (Fig. 25), all but 2-3% of the measurements are well described by the model. Since the saturation bulk density (Fig. 26) also includes the contribution of water in the pore space, water must be added as a 4th component, especially for sedimentary rocks and vesicular volcanics. This is not an issue Henkel (1991) needed to consider as his entire collection consists of samples from the Fennoscandian Shield which are metamorphosed rocks which have negligible porosity.

First are Quartz-Feldspar-Calcite (QFC), which Henkel (1991) calls the diamagnetic component. For the purpose of modelling, there is no advantage to assigning these minerals a negative or zero susceptibility, since the other components have magnetic susceptibilities orders of magnitude higher and the model is insensitive to the actual value of the QFC component. We use 10^{-6} SI, the lowest value on our Log Susceptibility scale. For density, the QFC component is assigned 2.62 g/cm3, the density of quartz.

Second are the FerroMagnesian (FM) silicate minerals, which Henkel (1991) calls the paramagnetic component, or one could use the term mafic minerals. These predominantly ferrous (Fe^{+2} bearing) minerals have a large range of densities and susceptibilities, but the observation is that the lower branch on the Henkel plot very neatly defines what would be a straight line on a linear-linear plot, with the endpoint around typical values of biotite (density 3.1 g/cm^3, susceptibility 9×10^{-4} SI). The analysis is only weakly dependent on the precise choice of the FM endpoint. Note that the mode of the lower branch of the measurements is very near 75% QFC and 25% FM.

The final component is simply Magnetite (M). Henkel (1991) provides equal discussion to pyrrhotite and magnetite, but to start it is advantageous to simplify the system as magnetite likely dominates the samples in the collection. Pure magnetite, with density 5.2 g/cm^3 and susceptibility 3.0 SI plots well off the scales as presented in Fig. 25 and 26. The mixing line of QFC minerals and M provides an upper envelope for almost the whole collection. The curve which best fits the upper branch on the Henkel plot is QFC minerals mixed with a 20:1 combination of FM minerals and M. The upper mode lies near 90% QFC, 9.5% FM and 0.5% M.

The QFC minerals are light coloured, while the FM minerals and magnetite are dark, so the proportion of FM+M is analogous to the Colour Index often used as a simple felsic-mafic index in igneous rock classification. Henkel (1991) uses the similar concept of "silicate density", which is the density of a rock if all the magnetite is removed. Do note that there is a simple typographical error on page 4 of Henkel (1991) in the denominator of the equation for silicate density. It should read

$$d_S = (d - d_M\, s / s_M) / (1 - s / s_M), \qquad \text{[eq.2]}$$

where d_S is the silicate density, d is the observed or total density, s is the observed susceptibility, d_M is the density of magnetite and s_M is the susceptibility of magnetite. The equation reasonably assumes that the susceptibilities of the QFC and FM components are negligible. The important point is that colour index or the silicate density provides a ratio of the QFC to FM minerals, and in igneous rocks this corresponds to the felsic to mafic level.

The surprizing feature on most magnetic susceptibility histograms is that it they are bimodal. With the QFC, FM, and M mixing model, we can be more precise about the mineralogy of the whole rock which leads to these distributions. Iron in the chemical analyses typically makes up a few percent of a rock, so the question is how the iron is partitioned between silicates, oxides and sulfides. It depends not only on primary minerals but on subsequent geochemical processes. This is a topic that will be presented in a forthcoming publication.

Summary

This first public release of the Canadian Rock Physical Property Database provides a useful compilation of measurements on 20,000 rocks or outcrops along with locations and lithologies. The current focus is on mineral exploration, so the physical properties concern those probed using the principle mineral exploration tools of gravity, magnetic, electric and electromagnetic surveys. The database demonstrates the typical distributions of physical properties of typical rock types, and helps practitioners identify exotic physical properties of rocks that result from rocks with atypical mineralogies and unusual (ore forming) geological histories. The database provides the initial step in developing an understanding of physical properties changes with alteration.

The data is available as a spreadsheet, and is presented graphically as a series of histograms and cross-plots. Where possible, the general explanations of these distributions is explained in terms of the lithologies. In particular the Henkel plot (Log magnetic susceptibility against density) is shown to be diagnostic for the range of lithologies because of the direct link to the major and accessory mineralogy of rocks.

There is a great deal of petrophysical data which has been collected by colleagues in government, academe, and industry which can and should be included in the Canadian Rock Physical Property Database. The requirement is that lithologies and locations in Canada must be included with the measurements. The compilation will directly improve understanding of the link between geophysics and geology in general, and improve specific geological interpretations by providing well-defined petrophysical constraints on geophysical inversion analyses.

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Appendix 1: The Canadian Rock Physical Properties Database

The spreadsheet "of_8460_database.xlsx" contains sample identifiers (columns A to F), location (columns G to W), sample information and description (columns X to AB), lab information (columns AC to AG), sample lithology (columns AH to AZ), density and porosity (columns BA to BJ), magnetic properties (columns BK to BX), and electric properties (columns BY to CF). Enjoy!

Appendix 2: Henkel Plots in the literature

The file "of_8460_appendix.pdf" displays all the Henkel plots (Log magnetic susceptibility against density) known to have been published. The plots have been stretched to the same scale for comparison. Superimposed on the plots are the contours of point density from the Canadian Rock Physical Property Database, as in Figure 15. The plots are ordered chronologically by publication date, and the reference is placed on each page.

Note the variety of units that are employed for magnetic susceptibility: cgs, 10^{-6} cgs, SI, 10^{-5} SI, 10^{-6} SI or μSI. Also note the wide variety of limits on the density and susceptibility scales. By placing all the plots on a common scale, it is much easier to compare the data sets and recognize what is typical and what is exotic.

The main observation is that the various collections are consistent with the CRPPD, thus validating the current work. Compare, for example, the contours from the CRPPD with the large collection from Finland (Fig. A21) compiled by Airo (2015) or the collection from Mongolia (Fig. A53) compiled by Yang et al. (2013). In contrast, recognize the large number of low density rocks from Uganda (Fig. A56) described as "possibly sedimentary and altered rocks" (Ruotoistenmäki and Birungi, 2015), or the very high density gabbros and peridotites from Sweden (Fig. A59) collected by McEnroe et al. (2018).

Figure Captions

(The file "of_8460_figures.pdf" displays the figures referenced in this document.)

Figure 1. Locations of the samples and sites compiled in the Canadian Rock Physical Properties Database (CRPPD). Red: volcanic rocks, Dark Red: plutonic rocks, Yellow: sedimentary rocks, Blue: metamorphic rocks, Green: mineralized/alteration rocks. Base map from a) Google Earth, b) the geological provinces of Canada.

Figure 2: Histograms of Grain Density. The black index line at 2.62 g/cm^3 marks the density of quartz.

Figure 3: Black dots plot the ranked Saturated Bulk Density, along with the densities of common rock-forming minerals. Red: FerroMagnesian (FM) minerals; Blue: Quartz-Feldspar-Calcite (QFC) and associated non-FerroMagnesian minerals; Green: sulfides; Black: Magnetite; Grey: other oxides. Note how most rock densities coincide with the QFC mineral densities.

Figure 4: Histograms of Saturated Bulk Density. The black index line at 2.62 g/cm^3 marks the density of quartz. There are over three times as many Saturated Bulk Densities compiled than Grain Densities because of the added laboratory procedures required for Grain Density determinations. Note the overall similarity of the two set of histograms, after consideration of the role of porosity especially in Volcanic and Sedimentary rocks.

Figure 5: Histograms of Porosity. The uncertainties using the weighing method is typically around 0.2% porosity, implying that the lower shoulders of these distributions are approximate. Note the mode of porosity in sedimentary rocks around 10% (i.e., LOG Porosity $\approx$ 1).

Figure 6: Cross-plots of Porosity against Density demonstrating the near perfect anticorrelation of in high porosity sedimentary rocks. The correlation is not as strong in the other rock types because of the wider variety of mineralogy and the greater uncertainty in very low porosity rocks. a) Linear density scale. b) Densities plotted on a displaced Log scale such that the density = 2.6 to 3.0 g/cm^3 range is conveniently spread out. The light blue numbers with arrows indicate the number of measurements which plot outside the scale. Red: volcanic rocks, Dark Red: plutonic rocks, Yellow: sedimentary rocks, Blue: metamorphic rocks, Green: mineralized/alteration rocks.

Figure 7: Histograms of Resistivity. The index line is plotted at the modal resistivity = 3200 ohm.m (LOG Resistivity = 3.5) also indicates the resistivity above which most geophysical surveys can not differentiate from infinite resistivity.

Figure 8: Cross-plots of Resistivity against Density. a) Linear scale. b) Displaced Log scale. Same density scales and symbology as Fig. 6. The grey markup indicates the broad trends of the process interpretations.

Figure 9: Cross-plots of Resistivity against Porosity, indicating their broad anticorrelation. The power-law least-squares fit line is marked in grey. The slope of this fit is much shallower than expected based on typical Archie cementation exponents measured in sedimentary rocks, but it is robust to ~±10% regardless of what outlier criterion is applied.

Figure 10: Histograms of Chargeability. The index line at chargeability = 6 ms marks a level below which an IP survey is not expected to observe any significant chargeability.

Figure 11: Cross-plots of Chargeability against Density. a) Linear scale. b) Displaced Log scale. Same density scales and symbology as Fig. 6. There is poorly developed positive correlation, likely due to the enhanced chargeability in dense mineralized samples.

Figure 12: Cross-plots of Chargeability against Resistivity. There is no significant correlation. It is worthwhile noting however that lines of electric current will be concentrated along low resistivity pathways, so high chargeability in high resistivity rocks are unlikely to be observed in geophysical surveys.

Figure 13: Histograms of magnetic susceptibility. Note the bimodal distribution, with modes indicated along the index lines.

Figure 14:Cross-plot of Magnetic Susceptibility against Grain Density. Same symbols as Fig. 6. The light blue contours indicate equal point density at levels 1, 2, and 5 times the outside contour.

Figure 15: Cross-plots of Magnetic Susceptibility against Saturated Bulk Density (Henkel Plot). a) Linear scale. b) Displaced Log scale. Same density scales and symbols as Fig. 6. The light blue contours indicate equal point density at levels 1, 2, and 5 times the outside contour.

Figure 16: Cross-plots of Magnetic Susceptibility against Saturated Bulk Density (Henkel Plot) separated by lithological class. a) to e) Linear scale. f) to j) Displaced Log scale. Same density scales and symbology as Fig. 6. The light blue contours indicate equal point density at levels 1, 2, and 5 times the outside contour.

Figure 17: Cross-plots of Magnetic Susceptibility against Saturated Bulk Density (Henkel Plot) separated by volcanic lithology. a) to d) Linear density scale. Same blue contours as in Figure 15a.

Figure 18: Cross-plots of Magnetic Susceptibility against Saturated Bulk Density (Henkel Plot) separated by plutonic lithology. a) to d) Linear density scale. Same blue contours as in Figure 15a.

Figure 19: Cross-plots of Magnetic Susceptibility against Saturated Bulk Density (Henkel Plot) separated by sedimentary lithology. a) to d) Linear density scale. Same blue contours as in Figure 15a.

Figure 20: Histograms of Natural Remanent Magnetization intensity. Note the bimodal distribution, with modes indicated along the index lines.

Figure 21: Histograms of Koenigsberger Ratio, assuming a common magnetic field of 50 nT. Note that 34% of the measured samples have Koenigsberger Ratio greater than 1, implying that remanence will dominate over induced magnetization about 1/3 if the cases studied.

Figure 22:Cross-plots of Natural Remanent Magnetization against Density. a) Linear scale. b) Displaced Log scale. Same density scales and symbols as Fig. 6.

Figure 23: Cross-plots of Koenigsberger Ratio against Density. a) Linear scale. b) Displaced Log scale. Same density scales and symbols as Fig. 6.

Figure 24: Cross-plots of Magnetic Susceptibility against Natural Remanent. Lines of equal Koenigsberger Ratio (assuming 50 nT) are drawn. The percentages are the proportion of sample within each Koenigsberger Ratio range.

Figure 25: Henkel Plot (Log Magnetic Susceptibility against Saturated Bulk Density) identical to Figure 15a, with superimposed mixing curves based on Quartz, Biotite and Magnetite mixing end-member properties.

Figure 26: Log Magnetic Susceptibility against Grain Density identical to Figure 14, with superimposed mixing curves based on Quartz, Biotite and Magnetite properties.