TREK Geology Project: Recognizing Endako Group and Chilcotin Group Basalts from Airborne Magnetic Data in the Interior Plateau Region, South-Central British Columbia (NTS 093B, C, F, G)

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Angen, J.J., Westberg, E., Hart, C.J.R., Kim, R. and Raley, C. (2015): TREK geology project: recognizing Endako Group and Chilcotin Group basalts from airborne magnetic data in the Interior Plateau region, south-central British Columbia (NTS 093B, C, F, G); *in* Geoscience BC Summary of Activities 2014, Geoscience BC, Report 2015-1, p. 21–32.

Introduction

The **T**argeting **R**esources through **E**xploration and **K**nowledge (TREK) project is a multidisciplinary Geoscience BC initiative to facilitate more successful mineral exploration in a portion of the Interior Plateau (Figure 1) in south-central BC (Clifford and Hart, 2014). The study area is bounded to the west by Tweedsmuir and Entiako provincial parks, extends easterly to Quesnel, as far north as Vanderhoof and Fraser Lake, and south to include Anahim Lake (Figure 1). This region hosts several significant epithermal and porphyry deposits (Figure 1) including the Blackwater epithermal Au-Ag deposit at approximately 270 million g (9.5 million oz. contained Au, total measured and inferred, Christie et al., 2014) and is therefore considered to have high exploration potential.

However, the Early Jurassic to Eocene stratigraphy and associated intrusions, which are known to host mineralization, have limited exposure at surface. This is partially due to the masking effects of extensive Eocene Endako Group and Neogene Chilcotin Group basalt flows, as well as ubiquitous glacial till cover. This has resulted in uncertain distributions and relationships for the prospective units. Consequently, exploration activity and success is considered to have been muted by this lack of confident geological knowledge. A more detailed understanding of the distribution of these basaltic sequences will aid in future investigations of the controls on mineralization within underlying units.

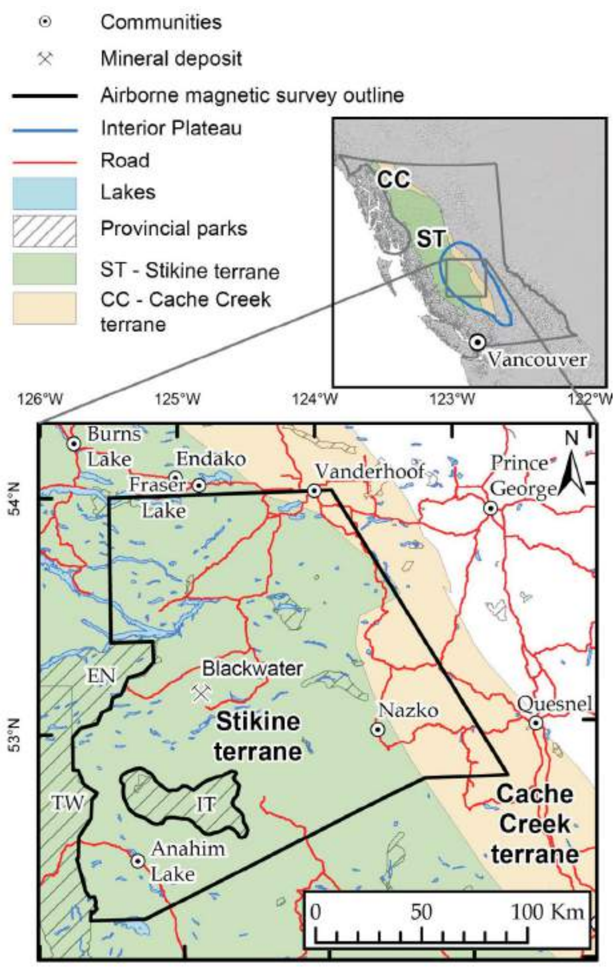

Figure 1. Location of TREK study area outlined in black (south-central British Columbia), excluding the Itcha Ilgachuz Provincial Park (modified after Mihalynuk et al., 2008; Colpron and Nelson, 2011; BC Geological Survey, 2014; DataBC, 2014). Abbreviations: EN, Entiako Provincial Park; IT, Itcha Ilgachuz Provincial Park; TW, Tweedsmuir Provincial Park.

Keywords: *northern Interior Plateau, Endako Group, Chilcotin Group, TREK, magnetic susceptibility*

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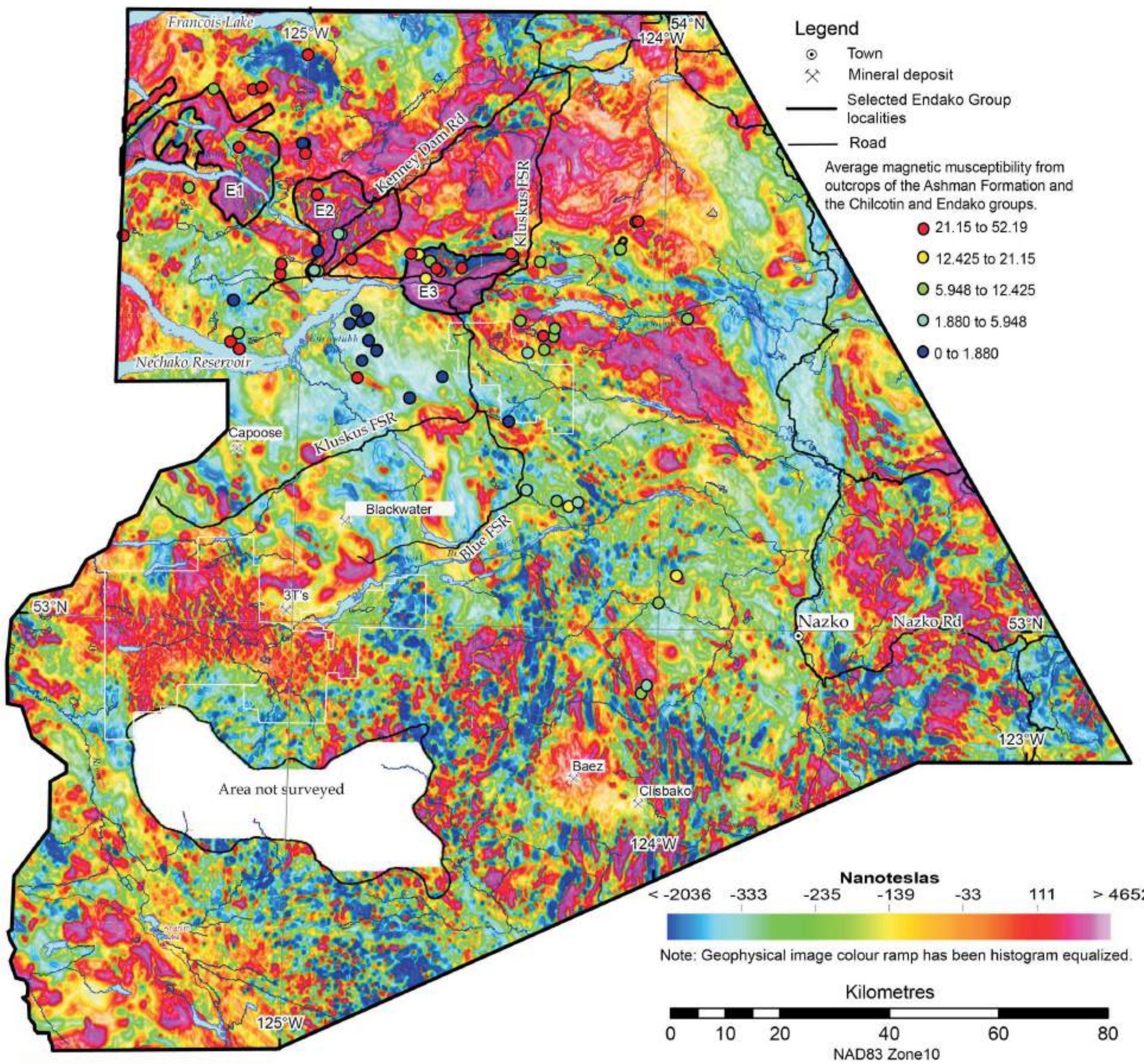

Figure 2. Airborne magnetic data (residual magnetic intensity) for the TREK study area, south-central British Columbia (modified after Geoscience BC, 2014); E1, E2 and E3 indicate three distinct high-magnetic–intensity polygons that correlate to exposures of Endako Group. The average magnetic susceptibilities are plotted for stations in the three units discussed within the text. Selected mineral occurrences are located as well to serve as reference points (BC Geological Survey, 2014).

The TREK geology project utilizes recently acquired airborne magnetic data (Figure 2; Aeroquest Airborne, 2014; Geoscience BC, 2014) to support improved interpretations of the regional geology, geochronology and structure, and to update the regional geological map of this portion of the Interior Plateau. In order to correlate features observed in the airborne magnetic data to rock types and unit distributions, ground-truthing is supported with magnetic susceptibility readings that were routinely carried out in conjunction with 1:50 000 scale regional mapping. Among the most obvious features in the airborne magnetic data and maps are a linear, northwest-trending belt of three regions, each roughly 20 km across, of predominantly high magnetic responses as well as a widespread mottled texture (Figure 2). Field observations indicate that these regions are mostly underlain by rocks of the Endako and Chilcotin groups. To better understand the character and distribution of these rock units, their magnetic and lithological properties were evaluated. This study provides one of many examples where rock petrophysical characteristics can be used to develop a better geological understanding from the newly collected TREK airborne magnetic data, and subsequently improve geological maps to guide mineral exploration efforts.

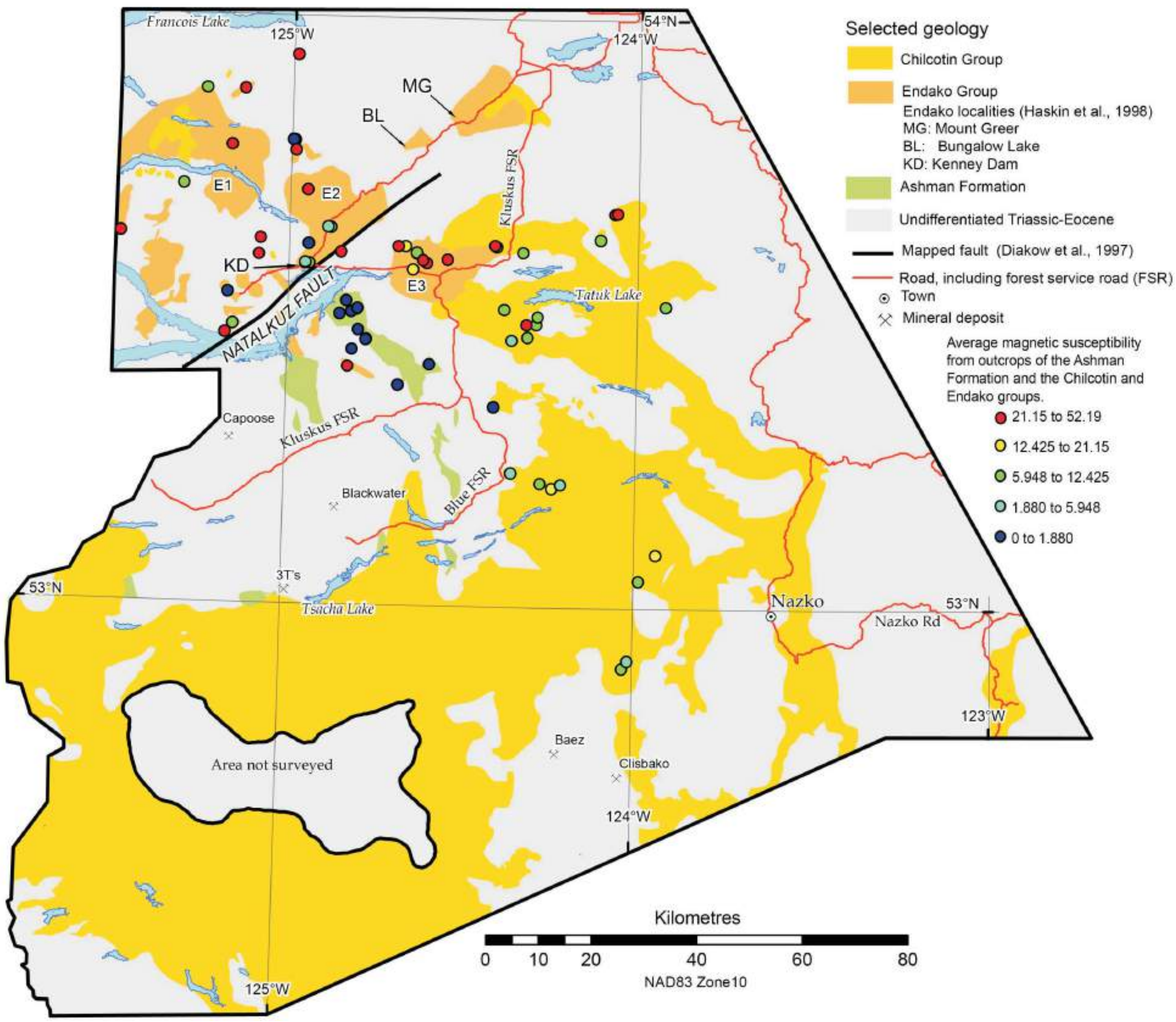

Figure 3. Simplified geological map showing the distribution of the Ashman Formation and the Endako and Chilcotin groups in the TREK study area, south-central British Columbia. Produced from new observations, interpolation of magnetic data, and previous mapping by Diakow and Levson, 1997; Anderson et al., 1998, 1999, 2000; Struik et al., 1999. The average magnetic susceptibilities are plotted for stations in the three units discussed within the text; E1, E2 and E3 indicate three distinct high-magnetic–intensity polygons that correlate to exposures of Endako Group. Selected mineral occurrences are located as well to serve as reference points (BC Geological Survey, 2014).

Geological Setting

The TREK study area is predominantly underlain by rocks of Stikine terrane, with minor exposure of Cache Creek terrane rocks in the east (Figure 1). The Stikine terrane comprises Middle Devonian to Middle Jurassic island-arc volcanic and sedimentary strata with associated plutonic rocks (Gabrielse and Yorath, 1991). In the TREK study area, the oldest Stikine terrane rocks with significant exposure are island arc volcanic rocks of the Lower to Middle Jurassic Hazelton Group (Tipper 1963, 1969; Tipper and Richards, 1976; Diakow and Levson, 1997; Diakow et al., 1997). These are overlain by Middle to Upper Jurassic marine to nonmarine sedimentary stratigraphy of the Bowser Lake Group, including the Ashman Formation (Tipper and Richards, 1976; Diakow et al., 1997; Riddell, 2011). A significant unconformity, interpreted as a period of uplift and deformation, marks the Late Jurassic to Early Cretaceous (Tipper and Richards, 1976). This unconformity is overlain by similar marine to nonmarine strata of the Lower Cretaceous Skeena Group (Tipper and Richards, 1976; Riddell, 2011). The Skeena Group is in turn overlain by felsic to intermediate continental-arc–related volcanic rocks of the Late Cretaceous Kasalka Group (Diakow et al., 1997; Kim et al., 2015).

Eocene volcanic strata in central BC include the Ootsa Lake Group and Endako Group. The Ootsa Lake Group is composed predominantly of rhyolite to dacite flows and minor associated volcaniclastic rocks (Duffel, 1959) and is geochronologically constrained from 55 to 46 Ma (Grainger et al., 2001; Bordet et al., 2014). The Endako Group was originally defined north of Francois Lake (Figure 3) by Armstrong (1949) as a 600 m thick sequence of Oligocene basalt flows. It comprises andesitic to basaltic flows that conformably overlie the Ootsa Lake Group at Bungalow Lake and Mount Greer (Figure 2; Haskin et al., 1998). It has yielded K-Ar whole rock ages ranging from 50 to 31 Ma (Mathews 1964; Stevens et al., 1982; Diakow and Koyanagi, 1988; Rouse and Mathews 1988), but the more reliable Ar-Ar dates constrain it to between 51 and 45 Ma (M.E. Villeneuve, unpublished data, reported in Grainger et al., 2001). This indicates that the Endako Group is, at least in part, coeval with the Ootsa Lake Group (Grainger et al., 2001; Bordet, 2014). In the southeastern portion of the map area, basalt and basaltic andesite are observed interfingered with felsic volcanic rocks of the Ootsa Lake Group leading to the conclusion that they should be included in the Ootsa Lake Group in this area (Bordet, 2014). The tectonic setting for Eocene volcanism in this region is northwest-directed extension associated with movement on faults with dextral transtensional offsets (Struik, 1993; Struik and MacIntyre, 2001).

The Chilcotin Group is a sequence of Neogene flood basalts that cover much of south-central BC (Bevier, 1983). They are estimated to cover roughly 30 000 km^2 of south-central BC and unconformably overlie Eocene and older rocks (Andrews and Russell, 2007, 2008). Exposures of the Chilcotin Group generally occur in areas of low topography, with older units occupying adjacent higher topography, suggesting that it was deposited within paleovalleys (Mihalynuk, 2007). Analysis of well data supports this, and also indicates that the flood basalts rarely exceed 50 m in thickness (Andrews and Russell, 2008).

Methodology

Airborne magnetic data were collected for the TREK study area during the summer of 2013 (Aeroquest Airborne, 2014). The residual magnetic-intensity (RMI) map is reproduced as Figure 2 (Geoscience BC, 2014). The RMI is the remaining signal after primary data have been modified to remove the Earth's current magnetic field and large scale trends. Features of interest were identified from the airborne data and evaluated during regional ground-truthing and geological mapping between July and September of 2014.

Magnetic susceptibility measurements were collected using either a KT-9 (Exploranium Radiation Detection Systems, 1997) or KT-10 (Terraplus Inc., 2013) Kappameter. These hand-held field meters are designed for measurements on outcrops, and drillcore and rock samples, but the large induction coil on these instruments makes them most appropriate for collecting data at the outcrop scale (Lee and Morris 2013). They both have an inductive coil diameter of 65 mm and utilize an operating frequency of 10 kHz. The KT-9 has a reported sensitivity of 1 x 10^{-5} SI units (Exploranium Radiation Detection Systems, 1997) while the KT-10 has a sensitivity of 1 x 10^{-6} SI units (Terraplus Inc., 2013). However, these values are for when the Kappameters are used in standard mode on a flat surface. All measurements were collected in pin mode, where a pin holds the measuring coil a fixed distance above the surface of the rock, and a correction factor is applied for this separation. This is deemed to provide the most accurate value for rough surfaces if a minimum of five measurements are averaged (Exploranium Radiation Detection Systems, 1997). A typical accuracy of ±10% compared to laboratory measured values is estimated for the KT-9 when operating in pin mode (Exploranium Radiation Detection Systems, 1997). Given that this is predominantly a result of surface roughness, not the measurement capability of the Kappameter, the same accuracy is implied for the KT-10 model as well. Periodically, a single rock was measured using both models to check for consistency. These measurements were well within the cumulative measurement error.

A total of ten measurements were collected within a single rock type at each outcrop. These data can be used to indicate within-site variability, as well as to determine an average value for each station. The average value for each station is interpreted as the most likely value to correlate with readings obtained from the airborne data, and is therefore the value chosen for presentation within the simplified geological map (Figure 3).

Field Observations

Endako Group

Outcrops of Endako Group are resistant to weathering, often forming steep cliffs composed of distinct flows (1–5 m) that are rarely columnar jointed. These vary from subhorizontal to dipping as much as 20° (Figure 4a). Flow tops frequently exhibit pahoehoe textures (Figure 4b). They have variable hematization ranging from a thin veneer on otherwise dark grey basalt (Figure 4b) to pervasively oxidized and red to orange throughout (Figure 4c). They weather dark grey to dark reddish-brown. Fresh surfaces are dark green-grey to black, aphanitic to porphyritic with 1 to 3% (and rarely up to 20%) plagioclase phenocrysts that range in size from 1 to 5 mm. The size and abundance of plagioclase phenocrysts helps to distinguish it from the Chilcotin Group. Several localities were observed to contain from 1 to 2% olivine and pyroxene phenocrysts up to 2 mm. Amygdules are often filled with opalescent silica (Figure 4d), and less commonly with quartz, calcite, chlorite and/or limonite. These range in size and shape from 3 mm and spherical to 10 cm and elongate. The abundant vesicle infill, particularly with opalescent silica, aids in distinguishing the Endako Group from the Chilcotin Group.

Figure 4. Distinctive features of Endako Group volcanic rocks, south-central British Columbia: **a)** Endako Group basalt flows dipping 10° to the east, photograph taken looking downdip; **b)** weakly hematized flow top exhibiting pahoehoe texture; **c)** strongly hematized flow top; **d)** opaline silica and clay minerals filling vesicles.

Haskin et al. (1998) report pillow lava and hyaloclastite within the Endako Group.

Chilcotin Group

The Chilcotin Group generally forms dun brown weathering outcrops in low topography. At some localities, it produces a distinctive bright red soil (Figure 5a). Where cliff exposures were observed, they exhibit subhorizontal flows with both colonnade and entablature (Figure 5b) style columnar jointing, as well as minor pillow basalt. They are characteristically olivine-phyric, with as much as 20% olivine up to 2 mm. Sparse plagioclase (up to 3%) and pyroxene (up to 10%) phenocrysts up to 2 mm were also observed. Flow tops are vesicular with little to no infill of vesicles (Figure 5c). Bevier et al. (1983) report rare chabazite amygdules. Dark green, coarse-grained, dunite to lherzolite xenoliths are far from ubiquitous, but where they are observed they are an excellent diagnostic feature when trying to distinguish the Chilcotin Group from the Endako Group (Figure 5d). Resnick et al. (1999) report these xenoliths as containing olivine, chromian diopside, orthopyroxene and magnetite. Rare hyaloclastite and felsic tephra have been documented previously but were not observed during this study (Bevier et al., 1983; Andrews and Russell, 2007; Farrell et al., 2007; Gordee et al., 2007).

Magnetic Data

Endako Group

In the study area, three domains identified from the RMI data, each covering >100 km^2 with exceptionally high magnetic responses, predominantly >400 nanoteslas (nT) and as high as 1500 nT, correlate with large mapped exposures of Endako Group basalt (Figures 2, 3). These domains also contain local (5–25 km^2) subdomains with magnetic responses as low as –1000 nT, see discussion below. Outcrop magnetic susceptibilities for Endako Group outcrops exhibit a wide range of values, as low as 0.309×10^{-3} and as high as 52.2×10^{-3}, with a mean of 19.2×10^{-3} (Figure 6). The lowest magnetic susceptibility value for the Endako Group (Figure 6) corresponds to an intensely hematized flow top such as the one represented in Figure 4c. The high

Figure 5. Distinctive features of Chilcotin Group volcanic rocks, south-central British Columbia: **a)** red soil and weathering colour; **b)** road outcrop exhibiting entablature columnar jointing; **c)** flow top without infill of vesicles; **d)** dunite xenolith.

magnetic response recorded for Endako Group rocks, generally >400 nT, in the RMI data (Figure 2) corresponds well with the predominantly high magnetic susceptibilities, with a mean value of 19.2×10^{-3} recorded for Endako Group outcrops (Figure 6).

Chilcotin Group

Extensive exposures of Chilcotin Group basalts generally correspond to regions in the airborne magnetic data with a distinctive mottled appearance including relatively small (approximately 1 km in diameter) highs in the range of 400 to 800 nT and lows in the range of –400 to –800 nT (Figures 2, 3). This texture has been observed elsewhere for the Chilcotin Group including in the Bonaparte Lake region to the southeast of the current study area (Thomas and Pilkington, 2008; Thomas et al., 2011). Magnetic susceptibilities recorded for rocks of the Chilcotin Group during this study exhibit values with a range from 2.82×10^{-3} to 39.1×10^{-3}, and an average of 10.9×10^{-3} (Figure 6).

Ashman Formation

The Ashman Formation is included as a reference to compare the basaltic sequences to. Within the study area it is composed predominantly of chert pebble conglomerate with lesser siltstone and sandstone. Ashman Formation outcrops identified in the field correspond to regions in the airborne magnetic data with limited variability, exhibiting magnetic intensities consistently between –300 nT and –200 nT. Magnetic susceptibilities measurements record similarly limited variability, from 0.00×10^{-3} to 0.249×10^{-3}, with a mean value of 0.102×10^{-3} (Figure 6).

Data Comparison

The magnetic susceptibility data for the Endako Group (Figure 6) would fall along the ‘magnetite trend’ of Henkel (1991). The highest density of data that define this trend are centred around 30×10^{-3} (Enkin, 2014). In contrast, the magnetic susceptibility for the Ashman Formation (Figure 6) falls near the ‘paramagnetic trend’ of Henkel (1991), centred around 0.3×10^{-3} (Enkin, 2014). This suggests that the magnetic intensity for the Endako Group is controlled

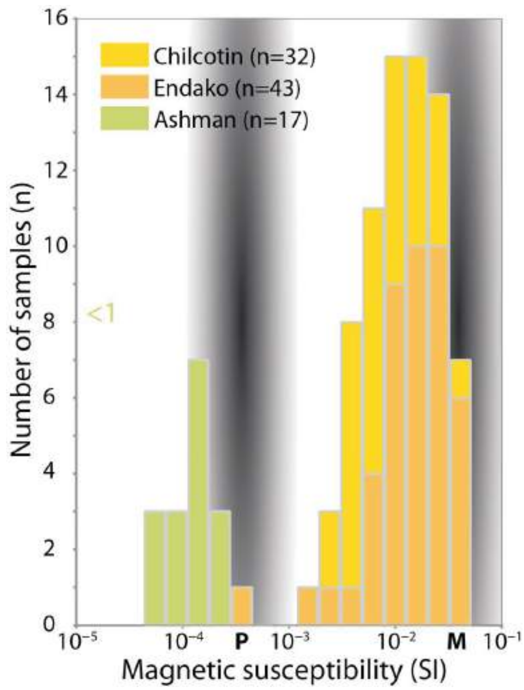

Figure 6. Magnetic susceptibility data: histogram plot of mean magnetic susceptibilities from confidently identified outcrops of Chilcotin Group, Endako Group and Ashman Formation, south-central British Columbia. The <1 indicates a single data point for Ashman Formation that plots below the limit of this diagram. The approximate location of the magnetite (M) and paramagnetic (P) trends of Henkel (1991) as reported by Enkin (2014) are indicated by shading. The Endako Group data best fit the magnetite trend, the Ashman Formation data best fit the paramagnetic trend, and the Chilcotin Group data largely fit between them.

by magnetite, whereas the magnetic intensity for the Ashman Formation is controlled by paramagnetic minerals (e.g., biotite, clays). Magnetic susceptibilities recorded for rocks of the Chilcotin Group during this study exhibit similar variability to those of the Endako Group, but tend toward slightly lower values (Figure 6). This is in agreement with previous observations by Enkin (2014) who noted that magnetic susceptibilities for Chilcotin Group samples generally fall in the gap between the magnetite and paramagnetic trends.

Discussion

Distribution of Endako Group and Eocene Extension

The high magnetic signature of the Endako Group was combined with field observations to reinterpret some of the map boundaries for this unit (Figure 3). These new map patterns provide additional insight into adjacent structures within the region. The linear southeastern boundary of the E2 Endako Group polygon in the vicinity of Kenney Dam suggests a fault contact (Figures 2, 3). Furthermore, the Endako Group outcrops to the west of this feature are exposed to the bottom of the Nechako River canyon below Kenney Dam, approximately 100 m below adjacent older volcanic rocks (Figure 3). This supports the inferred northwest-side-down movement along the Natalkuz normal fault (Figure 3; Diakow et al., 1997). It also fits the currently accepted model where Eocene volcanism in central BC is coeval with normal faulting related to extensional tectonics, leading to the deposition of these rocks in extensional basins (Struik, 1993; Struik and MacIntyre, 2001; Grainger et al., 2001; Bordet, 2014). The up to 20° dip of Endako Group basalts reported by Haskin et al. (1998) supports syn- to postdepositional faulting as opposed to pre-existing faults that controlled deposition of Eocene volcanic strata as previously proposed (Diakow et al., 1997; Anderson et al., 1999).

The E1 and E2 polygons exhibit some high (1500 nT) to low (–1000 nT) magnetic response striping whereas the E3 polygon exhibits only one zone of low magnetic intensity to the north (Figure 2). It may be that the high-low magnetic striping observed for E1 and E2 is the result of faulting and associated fluid flow that destroys magnetic minerals. If this is the case, the more uniform high magnetic signature of E3 (Figure 2) could reflect a slightly younger age than the Endako domains with striping.

Mottled Texture of Chilcotin Group

The extremely low magnetic responses recorded within the airborne magnetic data for the Chilcotin Group (–800 nT) are lower than those recorded for regions of known sedimentary rocks (–300 nT to –200 nT) belonging to the Ashman Formation (Figures 2, 3). Magnetic susceptibilities for the Ashman Formation are consistently at least an order of magnitude lower than those of the Chilcotin Group (Figure 6). This indicates that there is not a direct correlation between magnetic response in airborne data and magnetic susceptibility. Enkin (2014) reported exceptionally high Koenigsberger ratios (K_N = remnant magnetism/induced magnetization in a 50 000 nT field) for Chilcotin Group samples, with 96% of samples having K_N >1 and 45% having K_N >10. Therefore, the remnant component will dominate the RMI signature for Chilcotin Group rocks (Enkin, 2014).

Bevier et al. (1983) reported normal and reverse polarity for differing flows within the Chilcotin Group. Locally, two reversals were documented in a single cliff exposure. If each flow has varying magnetic susceptibility, the combined inputs from a series of normal polarity flows overlain by a series of reverse polarity flows will have a different value at each location. Regions dominated by normal polarity flows will exhibit extremely high magnetic responses while those dominated by reverse polarity flows will exhibit extremely low magnetic responses in airborne data as the magnetic intensity of the flows either adds to or

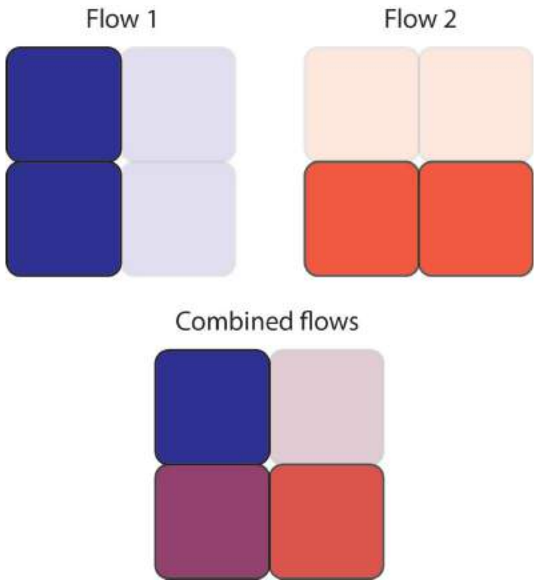

Figure 7. Schematic showing possible cause of mottled aeromagnetic signature of Chilcotin Group basalts, south-central British Columbia. The blue solid fill in flow one indicates strong reverse polarity remnant magnetization, while the translucent fill indicates weak remnant magnetization. Similarly, the solid and translucent red fill in flow two indicates strong and weak normal polarity remnant magnetization. When flow two is overlain on flow one, a variable signature is recorded where red indicates strong normal polarity, blue indicates strong reverse polarity, and purple indicates zones where equal and opposite remnant magnetizations have cancelled one another out.

subtracts from the overall field (Enkin, 2014). In outcrop, many of the high magnetic susceptibility Chilcotin Group stations contained dunite to lherzolite xenoliths. Resnick et al. (1999) reported that such xenoliths are proximal to eruptive centres. Analogous studies documented lateral variations in magnetic intensity associated with variable cooling rates, with the region in close proximity to the eruptive centre exhibiting a magnetic susceptibility twice that of distal regions of the same flow (Kolofíková, 1976).

Consider a simple model with only two flows; a lower flow of reverse polarity that has high magnetic susceptibility in the west and low in the east (flow 1, Figure 7), while an upper flow of normal polarity has high magnetic intensity in the south and low in the north (flow 2, Figure 7). The southwest quadrant will be neutral, the southeast quadrant will have strong normal polarity, the northeast quadrant will be neutral, and the northwest quadrant will have strong reversed polarity (Figure 7). If this model was extended to include flows of various shapes, each with varying magnetic intensity, a mottled texture with extreme highs and lows (or rather, inverse polarity highs) as observed in the airborne dataset would be conceivable.

Limitations

The magnetic datasets have limitations with respect to bedrock mapping. There are several localities where exposures of both Endako and Chilcotin group basalts outcrop but do not correspond to their distinctive magnetic signatures (Figures 2, 3). This may result from the basaltic strata being relatively thin in these locations. Airborne magnetic surveys represent an averaged value in the uppermost part of the crust. Therefore, thin exposures of Chilcotin basalt will not yield the distinctive magnetic signature since the data will more accurately reflect the underlying or surrounding rock type. This will prove valuable in future efforts to develop thickness models. There are also regions that exhibit magnetic intensities up to 1500 nT that were underlain by rocks not belonging to the Endako Group. This emphasizes the need to ground-truth airborne magnetic data.

Conclusion

Regional geological mapping during the summer of 2014 revealed that several large regions of high magnetic response that cumulatively form a northwesterly trend on the TREK airborne magnetic survey RMI (Geoscience BC, 2014) correspond to thick successions of Eocene Endako Group basalts. Outcrops of these rocks yield high magnetic susceptibilities, averaging 19.2×10^{-3}. The Neogene Chilcotin Group basalts exhibit a distinctive mottled signature on airborne magnetic maps reflecting exceptionally strong remnant magnetism with normal and reversed polarity variations between flows. The evaluation and recognition of magnetic signatures for thick sequences of these two basaltic units will aid in developing improved geological and structural maps as well as three dimensional models for the TREK region. Now that these distinct magnetic signatures are identified, future efforts to interpret the TREK airborne magnetic data can be focused on more subtle features that may provide insight into the controls on mineralization.

Acknowledgments

This research was made possible by a grant from Geoscience BC. The authors thank E. Bordet for a thoughtful review of an earlier draft of this manuscript.

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