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Three-Dimensional Thickness Model for the Eocene Volcanic Sequence, Chilcotin and Nechako Plateaus, Central British Columbia (NTS 092O, P, 093A, B, C, E, F, G, K, L)

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Introduction

Eocene volcanic rocks in the Chilcotin and Nechako plateaus of central British Columbia are mapped over ~26 400 km^2 (Figure 1; Massey et al., 2005). The original extent of these volcanic rocks, deposited during a short-lived episode of continental magmatism (~55–46 Ma; Bordet et al., in press), is presumed to have been much greater. Regionally included in the Ootsa Lake Group (OLG; Figure 2), these widespread, dominantly felsic sequences display significant lateral thickness variations. In particular, Eocene volcanic successions >3000 m thick are preserved in extensional basins, characterized by north-trending half-grabens in southern BC (Church, 1973, 1985; Ewing, 1981; Thorkelson, 1988; Souther, 1991), with similarly thick sections inferred in central BC (Hayward and Calvert, 2011; Bordet et al., 2013, work in progress).

Eocene OLG strata host low-sulphidation epithermal Au-Ag occurrences (Figure 2; BC Geological Survey, 2013) and also overlie Mesozoic volcanic and sedimentary successions containing mineral and hydrocarbon resources. For example, Late Cretaceous magmatic rocks host the Blackwater Au-Ag epithermal deposit (8.6 million oz. Au; Portmann, 2013; Figure 2a), and a belt of Early Cretaceous Skeena Group sedimentary rocks has hydrocarbon-reservoir potential (Figure 2b; Ferri and Riddell, 2006; Riddell, 2011). Mesozoic hydrocarbon and mineral resources capped by Eocene volcanic sequences may be further obscured by overlying discontinuous Neogene Chilcotin Group flood basalt (CGB; Figure 2; Dohaney et al., 2010) and by a thick and continuous cover of glacial till (Fulton, 1995).

In order to better define the distribution of Eocene volcanic rocks in this region, a three-dimensional (3-D) thickness model for the OLG in the Chilcotin and Nechako plateaus (Figure 1) is developed and presented in this paper. This model is generated from geological constraints, including field maps, cross-sections and stratigraphic columns, and interpreted geophysical-survey data (Figure 2, Table 1). Objectives of this model are to 1) image regional thickness variations of the OLG where it has been mapped previously; 2) identify areas of eroded or covered Eocene volcanic rocks; 3) investigate the spatial and temporal correlation between Eocene volcanic rock accumulations and fault-bounded basins; 4) generate new surface and volume estimates for the Eocene volcanic event; and 5) correlate and extend OLG intervals containing known mineralization into regions covered by CGB and glacial till, with implications for mineral exploration.

Regional Geology

Three main lithostratigraphic packages are represented in the Chilcotin and Nechako plateaus of central BC, a high-standing (~800–1600 m) region with subdued topography (Figures 1, 2a; Holland, 1976). They are Stikine and Cache Creek terrane basement rocks, Ootsa Lake Group (OLG) volcanic rocks, and younger cover rocks that include the Neogene Chilcotin Group basalt (CGB).

Basement rocks include accreted terrane successions of the Stikine (volcanic arc) and Cache Creek terranes (subduction-related accretionary complex; Figure 1; Coney et al., 1980), as well as postaccretion Jurassic to Cretaceous rock packages. In particular, Lower to Middle Jurassic

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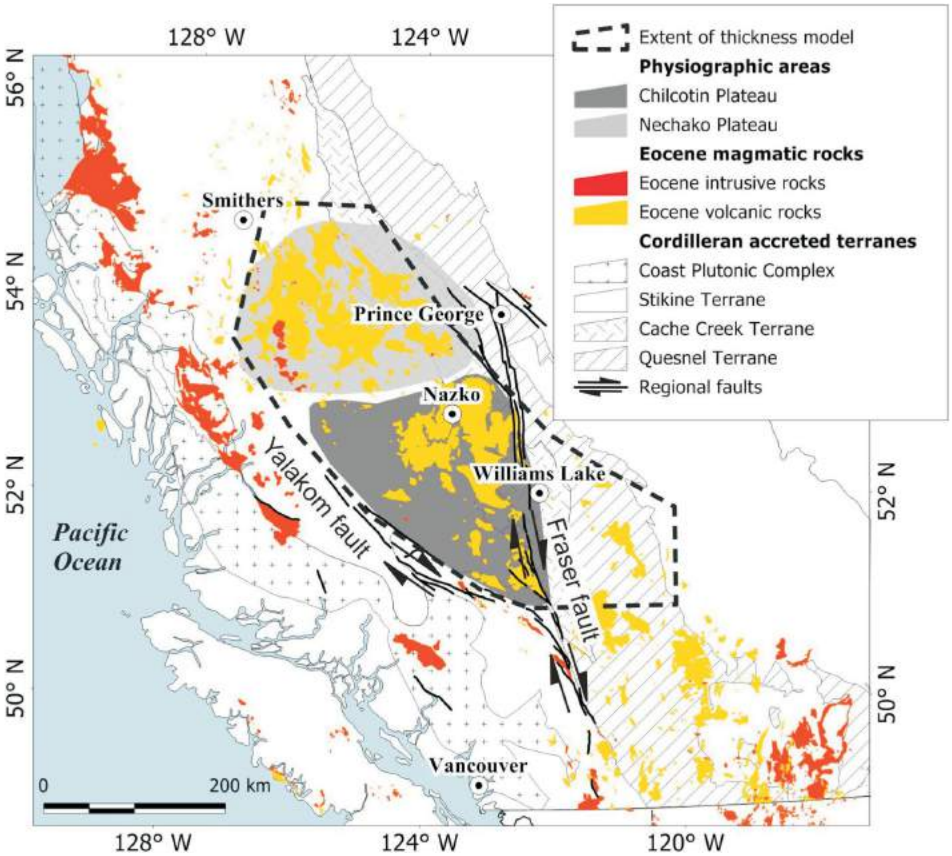

Figure 1. Distribution of Eocene volcanic and intrusive rocks in the Chilcotin and Nechako plateaus of central British Columbia with respect to Cordilleran accreted terranes and major faults. The thickness model covers the Chilcotin and Nechako plateaus, as well as the Williams Lake area east of the Fraser fault. Geology polygons, faults and terranes are after Massey et al. (2005). Map projection UTM Zone 10, NAD 83.

strata of the Hazelton Group (Stikine terrane) occur in the Chilcotin Plateau west of Nazko (Figure 2b; Tipper, 1959), whereas thick beds of Cretaceous chert-pebble conglomerate and sandstone of the Aptian to Albian Skeena Group are exposed for ~150 km along the Nazko River (Figure 2b; Riddell, 2011).

Eocene volcanic rocks of the OLG (Figure 2; Duffell, 1959) comprise mainly rhyolite and dacite lavas, and minor pyroclastic and reworked volcaniclastic deposits, locally capped by andesitic lavas (Bordet et al., work in progress). New isotopic dates indicate a range of 55–46 Ma (Bordet et al., in press). A Paleocene volcaniclastic sequence that was identified in a hydrocarbon-exploration well (B-16-J; Figure 2b) is inferred to overlie Cretaceous basement rocks (Riddell, 2011) and is combined with the OLG for the purpose of this study.

Cover rocks of the Neogene CGB (Figure 2; Bevier, 1983; Mathews, 1989) unconformably overlie the OLG and are of variable thickness but mostly less than 25 m (Mihalynuk, 2007; Andrews et al., 2011). Holocene volcanoes of the Anahim belt (Souther, 1986) occur to the west of the study area (Figure 2).

Eocene Structure

The Cretaceous to Early Cenozoic structural architecture of the study area is characterized by a series of north-trending horsts and grabens that occupy a region between two regional-scale northwest- and north-trending dextral strike-slip faults, the Yalakom and Fraser faults, respectively (Figures 1, 3). The thickest OLG sections are preserved mainly within Eocene grabens, while Mesozoic rocks are exposed along exhumed horst blocks, as established from stratigraphic investigations (Bordet et al., work in progress), hydrocarbon-exploration drilling (Riddell, 2011) and geophysical surveys (e.g., Hayward and Calvert, 2011; Talinga and Calvert, work in progress).

Province-wide transtensional deformation in the Eocene was concentrated along north- and northwest-trending dextral strike-slip fault systems, in some cases reactivating crustal-scale faults such as the Fraser and Yalakom faults (Figure 3; Souther, 1970; Ewing, 1980; Struik, 1993), along which several tens to hundreds of kilometres of displacement are inferred (Eisebacher, 1977; Ewing, 1980; Umhoefer and Schiarizza, 1996). Early Eocene, steeply dipping northwest-trending faults (e.g., Yalakom fault) accommodated dextral transtension. This fault motion was kinematically linked to secondary, northeast-trending, synvolcanic extensional faults (Figure 3, inset map; Struik, 1993) that formed pull-apart basins in which OLG strata accumulated and were preserved. Late Eocene to Early Oligocene, north-trending, en échelon dextral faults (e.g., Fraser fault) are inferred to be coeval with northwest-directed extension (Struik, 1993). The exhumation of metamorphic core complexes (Figure 3, inset map) in central and southern BC occurred coevally with regional extensional deformation and Eocene volcanism (e.g., Struik, 1993).

Methods and Model Constraints

Thickness Model

An Eocene thickness model was computed for the region of Eocene OLG distribution in the Chilcotin and Nechako plateaus (Figures 1, 2) using Manifold ™ GIS software. Methodologies used here are adapted from Mihalynuk (2007) and detailed in Bordet et al. (2011). The modelling workflow includes the following steps:

1) **Generate input points from surface, section and point datasets** (Table 1): Eocene and Neogene cover thickness and elevation information attributed to each point is either obtained from direct measurements or calculated.
2) **Organize input data points into two datasets**: a) post-Eocene cover sequence (Chilcotin Group basalts and

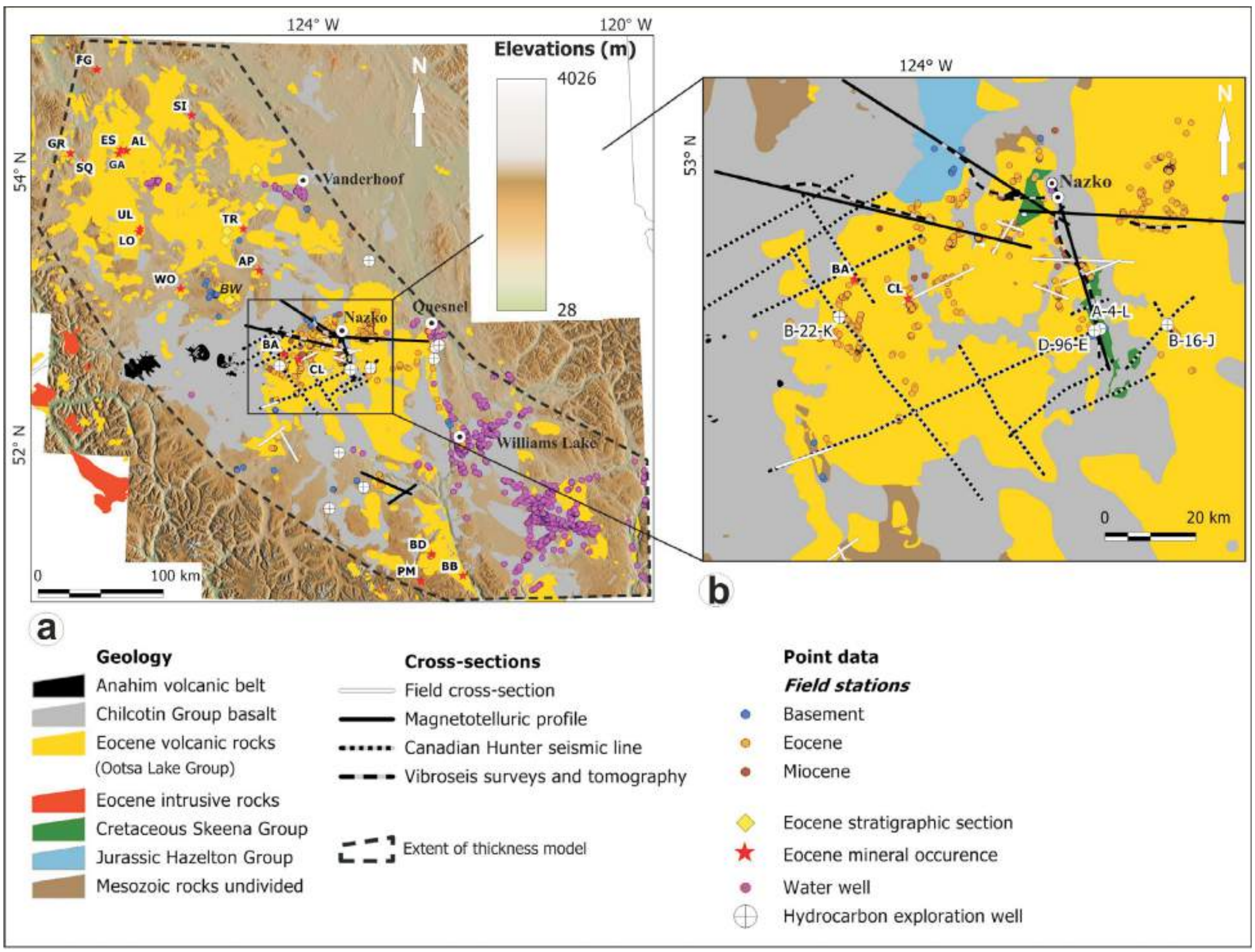

Figure 2. Datasets used to constrain the thickness model: **a)** simplified geology of the study area, showing Cenozoic volcanic rocks superimposed on a digital elevation model (Centre for Topographic Information, 1997); **b)** extent of the detailed interpretation. Eocene volcanic rock distribution after Massey et al. (2005), and updated from recent mapping by Dohaney et al. (2010) for the Chilcotin Group basalt, Mihalynuk et al. (2008, 2009) and this study. Eocene mineral occurrences (compiled from BC Geological Survey, 2013): AL, Allin; AP, April; BA, Baez; BB, Big Bar; BD, Blackdome; CL, Clisbako; ES, Equity Silver; FG, Free Gold; GA, Gaul; GR, Grubstake; LO, Loon; PM, Poison Mountain; SI, Silver Island; SQ, Silver Queen; TR, Trout; UL, Uduk Lake; WO, Wolf. Other: *BW*, Blackwater deposit. Map projection UTM Zone 10, NAD 83.

Table 1. Datasets and sources used for building the thickness model of the Eocene volcanic sequence, Chilcotin and Nechako plateaus.

	Input data	Sources
Polygons	Eocene geology polygons	Massey et al. (2005) Mihalynuk et al. (2008, 2009)
	CGB polygons	Interactive Chilcotin Database (Dohaney et al., 2010)
	Digital Elevation Model	Centre for Topographic Information (1997)
Sections	Geological cross-sections	Mihalynuk et al. (2008, 2009), field sections (this study)
	Magnetotelluric profiles A, B, C, D, G, H	Spratt and Craven (2011), Spratt et al. (2012)
	Tomography models lines 5, 10, 15 and 6	Smithyman (2013), Smithyman et al. (2014) Talinga and Calvert (2014)
	Canadian Hunter seismic lines	Interpreted lines by Hayward and Calvert (2011) after reprocessing by Arcis Corporation
	Geoscience BC vibroseis	Reprocessed lines by WesternGeco MDIC (2010)
Points	Oil and gas wells	Compiled thicknesses from Bordet et al. (2011), after Riddell (2011) and previous drilling reports
	Water wells	Interactive Chilcotin Database (Dohaney et al., 2010)
	Stratigraphic sections	Bordet et al. (in press)
	Mineral occurences	Mineral exploration drill hole logs as recorded in ARIS (BC Ministry of Energy and Mines, 2013) and linked to MINFILE (BC Geological Survey, 2013). Drilling depths at Eocene prospects rarely exceed 150 m and represent minimum thicknesses. Maximum drilled thicknesses of Eocene are reported for Blackdome (400 m; Faulkner, 1986) and Equity Silver (460 m; Cyr et al., 1984).
	Field stations	Field mapping (this study)

Holocene volcanoes); and b) Eocene sequence (generally anything between the basement and cover).

3) Generate a **base elevation model for the cover sequence and for the Eocene + cover sequence**. All elevation surfaces are generated using 1 by 1 km cell size, 10 neighbours and the Kriging interpolation method.
4) Generate a **thickness model for the cover sequence and for the Eocene + cover sequence** by subtracting the corresponding base elevation models from a digital elevation model (DEM).
5) Generate an **Eocene thickness model** by subtracting the thickness model of the cover sequence from the thickness model of the Eocene + cover sequence.

The resulting model was tested by comparison with a surface directly generated from thicknesses assigned to individual points, and by interpolating these thicknesses over the model area. Results obtained from the two methods are similar, with only minor differences occurring in areas with fewer constraints, such as the Nechako Plateau.

Structural Interpretations

Structures and lineaments for the Chilcotin and Nechako plateaus were interpreted (Bordet et al., 2013) from processed aeromagnetic data (Geological Survey of Canada, 1994) and digital topographic data (Centre for Topographic Information, 1997; Figure 3, inset map). These interpretations were refined (Figure 4) using seismic-reflection data (WesternGeco MDIC, 2010; Hayward and Calvert, 2011), tomographic models (Smithyman, 2013; Smithyman et al., work in progress; Talinga and Calvert, work in progress) and magnetotelluric inversion models (e.g., Spratt and Craven, 2011; Spratt et al., 2012), which utilize contrasting electromagnetic properties at depth to illustrate the lateral continuity of lithological packages.

Results

A model of OLG thickness in central BC is presented in Figure 3 (regional model) and Figure 4 (focused model). The OLG volcanic successions are generally 100–500 m thick within the previously mapped boundaries of Eocene rocks. The thickest accumulations of OLG rocks range from ≥1000 to ≥2000 m and are imaged in the Chilcotin Plateau southwest of Nazko (Figure 3), where numerous geophysical, field and well data are available to constrain and validate the model (Figure 2b). To the north, in the Nechako Plateau, thickness variations are only constrained by the previously mapped Eocene boundaries, by a few stratigraphic sections and by shallow-drilling information from mineral prospects distributed within these boundaries (Figure 2a, Table 1). Notably, the model extrapolates OLG thicknesses below the expected base of the CGB (Figure 3).

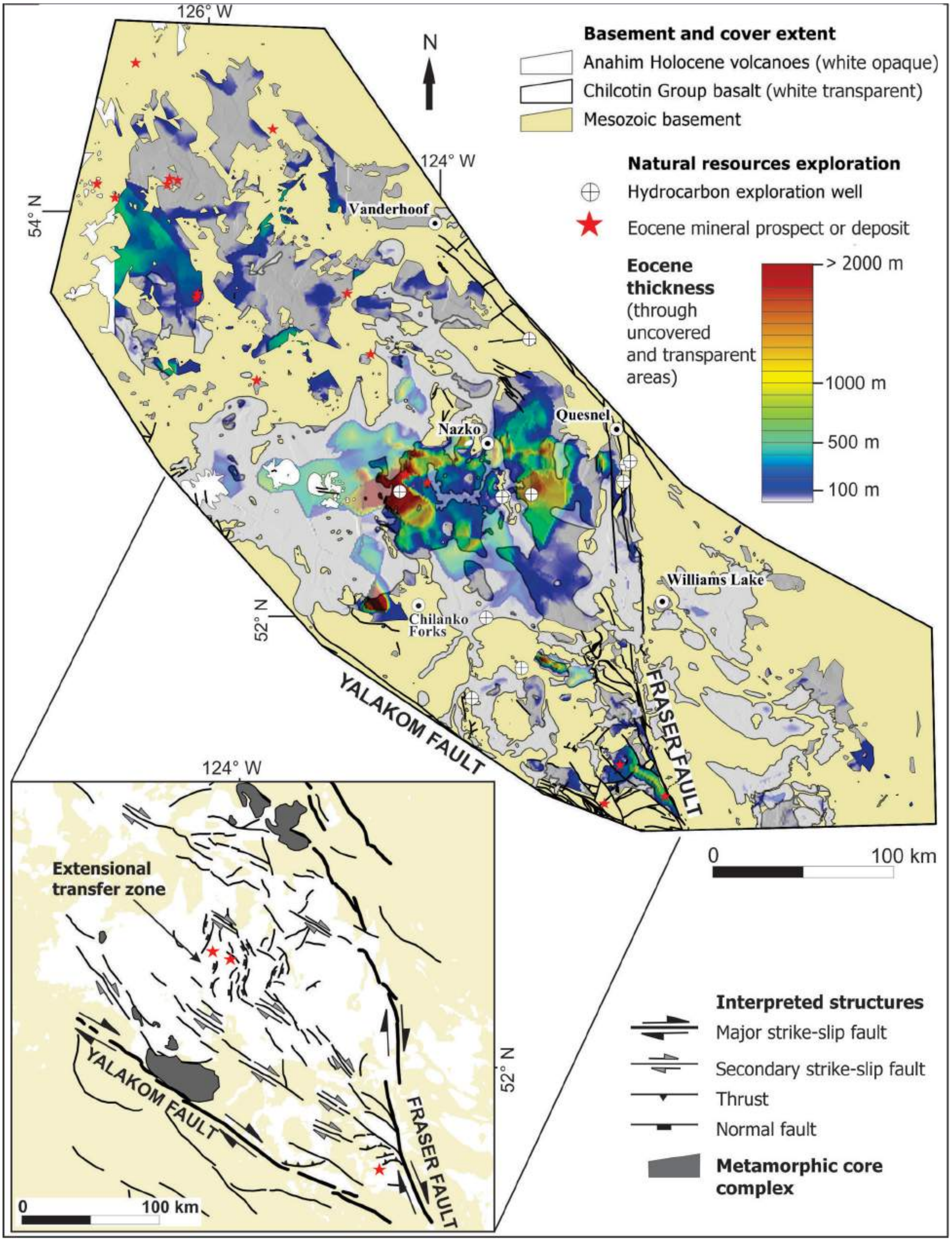

Figure 3. Thickness model of the Eocene volcanic sequence for the Chilcotin and Nechako plateaus, and interpreted structural lineaments in a selected area of the Chilcotin Plateau (inset map; after Bordet et al., 2013). Map projection UTM Zone 10, NAD 83.

The focused model area (Figure 4a) displays rectangular domains with OLG thicknesses of greater than ~1000 m separated by areas of 100–500 m thickness. Areas of thinner OLG are typically proximal to, and include, mapped basement exposures (e.g., Cretaceous conglomerate of the Nazko River valley and Jurassic exposures west of Nazko; Figure 2b), or occur where field constraints or geophysical sections were not available (e.g., ~20 km south of Nazko; Figure 2b). The OLG can attain thicknesses of >3000 m in the better constrained areas, such as at hydrocarbon-exploration well sites B-22-K and B-16-J (Figure 4a), along magnetotelluric and tomographic sections, and along seismic lines reprocessed from the 1980s Canadian Hunter data (Hayward and Calvert, 2011) and 2008 Geoscience BC vibroseis surveys (WesternGeco MDIC, 2010).

Discussion

Limitations of the Model

Data sources at variable scales of observation were integrated to evaluate the thickness and structural patterns for the Eocene volcanic rocks in the Chilcotin and Nechako plateaus. Considering the heterogeneity in the distribution of the available datasets and variable confidence levels of thickness estimates made from these disparate data, the following limitations of the resultant thickness model should be considered:

- The basal contact of Eocene rocks is exposed only at a few locations. Therefore, for most areas, the basal contact depth is inferred from interpretation of geophysical data.
- Ambiguities exist in the age determinations made on cuttings from hydrocarbon well B-22-K (Bordet et al., in press, work in progress). These potentially large errors are amplified when propagated to interpreted seismic and tomographic sections, which rely on thickness constraints from the well.

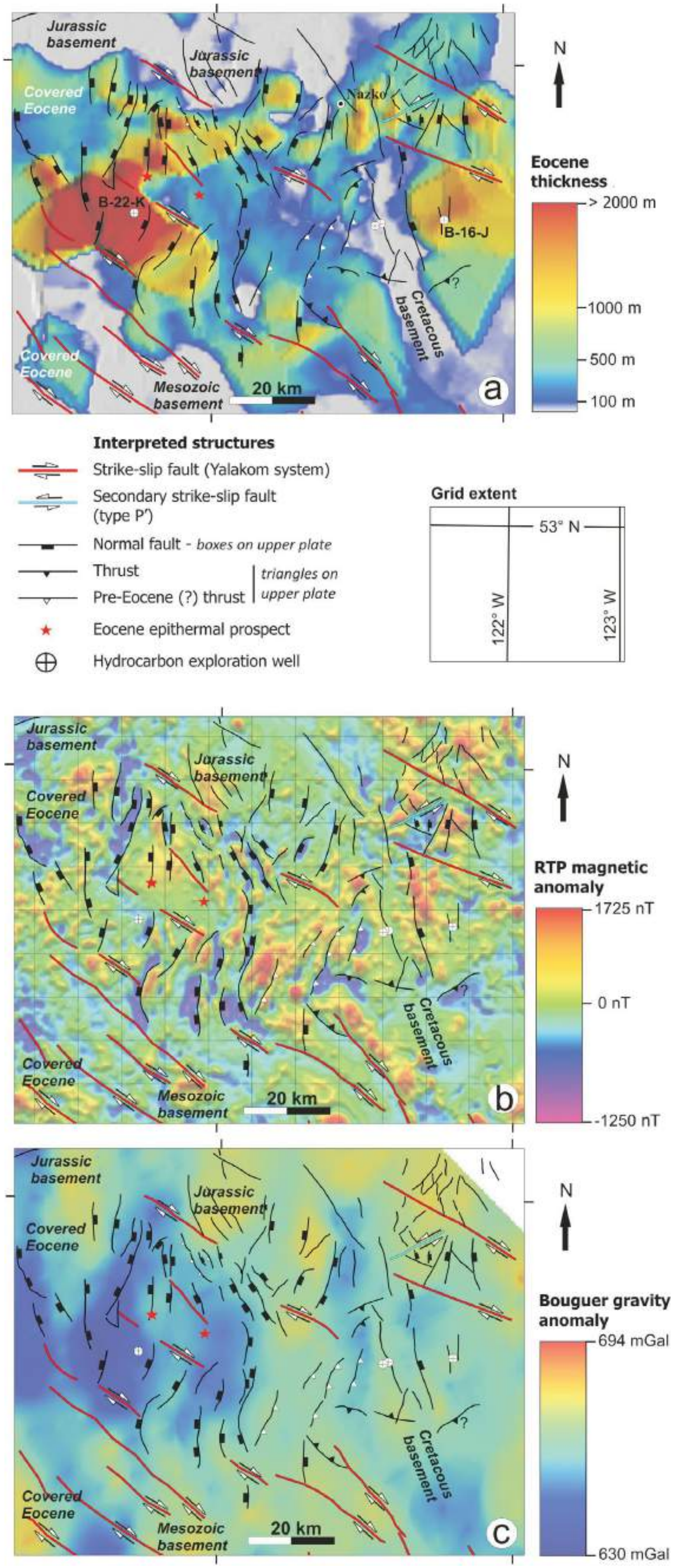

Figure 4. Interpreted structural lineaments in the focused model area draped over **a)** Eocene thickness model, **b)** reduced-to-the-pole (RTP) magnetic anomaly (Geological Survey of Canada, 1994), and **c)** gravity anomaly (Ferri and Riddell, 2006). Interpretations are developed from integration of magnetic and topographic lineaments (from the RTP and DEM), seismic reflectors (after Hayward and Calvert, 2011) and tomographic models (Smithyman, 2013; Smithyman et al., work in progress). Two Eocene epithermal prospects are within the transfer zone located on Figure 3. Map projection UTM Zone 10, NAD 83.

- The distribution of water wells used to constrain the thickness of Chilcotin Group basalt is of sufficient density only in the southeast corner of the study area (NTS 092P, 093A, B; Figure 1). Basalt layers are confirmed to cap sections in two other areas where intersected by oil and gas wells, but isotopic dates to confirm correlation with Neogene Chilcotin Group are lacking. Such uncertainties are compounded during Eocene thickness calculation, because the calculation involves subtraction of post-Eocene unit thicknesses from the depth to the base of the Eocene.
- The sharp gradients of modelled Eocene accumulations (Figure 4a) may be a visual bias of the model due to the uneven distribution of input constraints that produce artifacts in the Kriging method employed. However, some of these boundaries may be real and are interpreted as faults (see below).

Distribution and Volume of the Eocene Volcanic Sequence

Eocene igneous rock units are currently interpreted to extend over ~26 400 km^2 within the area modelled and over 60 700 km^2 in total in BC (33 400 km^2 of volcanic rocks, 27 300 km^2 of intrusive rocks; Table 2; Massey et al., 2005). However, these are erosional relicts of originally more areally extensive deposits, and any volume calculations are conservative on this basis.

Isolated Eocene erosional remnants occur locally in areas dominated by Mesozoic basement (Figure 3), and are emphasized by the distribution of mineralized prospects, such as in the Nechako Plateau. Using a buffer of 10 km around these Eocene remnants (corresponding to half the average distance between isolated polygons) and generating a new surface corresponding to merged buffered polygons, an 'eroded Eocene surface' of ~26 500 km^2 is generated (Table 2).

A partly transparent fill is applied to the extensive CGB cover to reveal significant thickness of Eocene under cover, such as to the west of well B-22-K and northwest of Chilanko Forks (Figure 3). This 'covered Eocene surface' is estimated at ~5 200 km^2 (Table 2).

Mapped, eroded and covered extents of Eocene volcanic rocks for the modelled area total ~58 000 km^2 (Table 2). This is more than double the original estimate, and increases the total Eocene volcanic extent for BC to 65 100 km^2. The corresponding volume of Eocene volcanic rocks for the modelled area is calculated at ~12 000 km^3, an estimate that does not consider vertical erosion of the original volume.

Structural Controls on Regional Variations in Thickness

The focused OLG thickness model (Figure 4a) highlights the spatial correlation between areas of significant Eocene

Table 2. Surface-area calculations for the Eocene volcanic sequence, for British Columbia and the thickness model area. Calculations are based on summation of polygon areas using Manifold™.

Area	Name	Surface area estimate (km^2)	Polygon source
British Columbia	Eocene - volcanic	**33 412**	Massey et al. (2005)
	Eocene - intrusive	27 316	
	Eocene - volcanic + intrusive	60 728	
Modelled area (total surface 100 000 km^2)	Existing Eocene - volcanic	**26 355**	Massey et al. (2005)
	Eroded + existing Eocene - volcanic	52 822	Massey et al. (2005). Buffer around Eocene polygons that display surface area less than or equal to 200 km^2 within the basement surface extent. Union of buffer polygons defines surface of eroded Eocene
	Eroded Eocene - volcanic	26 467	Calculated
	Covered Eocene - Volcanic	5 237	Thickness model. 100 m thickness contour defines polygon of Eocene extent. Covered Eocene corresponds to intersection of this polygon with the Chilcotin Group basalt
	Combined existing + eroded + covered Eocene - volcanic	**58 059**	Calculated
British Columbia	Combined existing + new estimate for Eocene volcanic rocks only	**65 116**	Calculated

accumulation and large structures interpreted from magnetic anomalies (Figure 4b). The orientation and kinematics of the interpreted structures are in agreement with a transtensional regime (Struik, 1993). In this context, northwest-trending thickness discontinuities are interpreted as dextral strike-slip faults, and north-trending lineaments are cospatial with normal faults interpreted from seismic-reflection data and from tomographic and seismic-velocity models (Figure 4). Within this strain system, east-trending lineaments may correspond to thrusts (Figure 4). West of a north-trending ridge of Cretaceous basement in the central part of the detailed study area, a series of north- to northeast-trending lineaments correlates with shallow-angle reflectors that are interpreted as thrust faults on the seismic reflection profiles (Figure 4). These structures are interpreted to result from pre-Eocene tectonic shortening and were possibly reactivated as extension faults during the Eocene.

The thickest Eocene accumulation in the vicinity of well B-22-K is inferred to have developed in an extensional transfer zone, where the deformation is accommodated mainly by extensional displacements between large dextral faults. This transfer zone also correlates with areas of low gravity that replicate the shape and orientation of north-trending extensional basins (Figure 4c). Interestingly, this area also hosts two of the known Eocene epithermal prospects within the region investigated here (Figure 4).

These structural interpretations are consistent with coeval eruption of Eocene volcanic rocks during extensional deformation and with the preservation of remnant Eocene sequences within extensional basins.

Implications for Exploration

Eocene mineral prospects and deposits occur within areas of known rock exposure (e.g., Wolf, Free Gold; Figures 2a, 3, Table 1). This OLG thickness model provides a new perspective on areas where Eocene rocks may be present beneath cover. Stratigraphic investigations by Bordet et al. (2013, work in progress) suggest that Eocene mineralization is hosted in rhyolite lavas and breccias that form the lowest OLG stratigraphic levels. The identified structural domains seem to strategically control the distribution of known mineralization. The spatial correlation of a fault transfer zone, which links the Yalakom and Fraser faults, and the occurrence of epithermal-style Au mineralization at the Blackdome mine (Figure 3) suggest a local structural control on Eocene mineralization. Similarly, the Baez and Clisbako epithermal Au prospects (Figure 2b) are located in a domain interpreted as an extensional transfer zone between large dextral faults (Figures 3, 4). Finally, the new Eocene thickness and structural framework provides insights into areas where hydrocarbon-rich Cretaceous basins may have been deformed or thermally affected by a thick Eocene volcanic cover.

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British Columbia Geological Survey contribution 2013-2.

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