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Critical review
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Abstract: Cross-sectional crustal models of the Late Triassic to Early Jurassic dioritic Iron Mask and Cherry Creek plutons forming the Iron Mask batholith are derived from integrated modelling of correlative prominent gravity and magnetic anomalies. A model for the Iron Mask pluton, comprising two block-like density units (2880 kg/m^3, 2955 kg/m^3), indicates a pluton depth of about 5700 m, and lateral extensions northward and southward below adjacent Nicola Group volcanic cover. The densities are more typical of gabbros than diorites, suggesting compositional changes to gabbroic rocks at depth. Magnetic modelling indicates the density units include several steep and strongly magnetic sheet-like units.

The Cherry Creek pluton is associated with a prominent magnetic high, but lacks a gravity counterpart. A magnetic model, with a maximum depth of 5700 m, indicates marginal areas comprising vertical, relatively deep, and strongly magnetic sheets, with the pluton thinning centrally to less than 1000 m. A similar shallower (maximum depth of 2850 m) model can also reproduce the magnetic signature. In order not to produce a conspicuous gravity high, the density of the pluton must be less than about 2770 kg/m^3, for either deep or shallow model.

North of the Iron Mask pluton, two large dioritic bodies buried mainly within units of Nicola Group rocks are modelled to explain conspicuous gravity highs. To the south, a large gravity low (-33 mGal amplitude) is modelled in terms of a large granitoid body descending to about 9700 m below surface, potentially representing an enlargement of a granodiorite body within the Nicola Horst.

Résumé : Nous avons produit des modèles de coupes transversales de la croûte recoupant les plutons dioritiques d'Iron Mask et de Cherry Creek du Trias tardif-Jurassique précoce, qui forment le batholite d'Iron Mask, par une modélisation intégrée de leurs proéminentes anomalies gravimétriques et magnétiques corrélatives. Un modèle du pluton d'Iron Mask formé de deux unités de blocs de densité (masses volumiques de 2880 kg/m^3 et de 2955 kg/m^3) suggère que le pluton atteint une profondeur de 5700 m et qu'il présente des prolongements latéraux vers le nord et le sud enfouis sous les roches volcaniques de couverture adjacentes du Groupe de Nicola. Les densités modélisées sont plus caractéristiques des gabbros que des diorites, ce qui laisse croire que les roches affichent une transition vers des compositions gabbroïques en profondeur. La modélisation des données magnétiques indique que les unités de densité sont composées de plusieurs unités en feuillets fortement magnétiques, très inclinées.

Au pluton de Cherry Creek est associée une crête magnétique marquée sans contrepartie gravimétrique. Un modèle magnétique, d'une profondeur maximale de 5700 m, indique que les régions marginales du pluton renferment des feuillets fortement magnétiques, verticaux et plutôt profonds et que sa partie centrale s'amincit jusqu'à une épaisseur inférieure à 1000 m. Un modèle semblable, mais moins profond (profondeur maximale de 2850 m), peut aussi reproduire cette signature magnétique. Dans les deux modèles, la masse volumique du pluton ne doit pas dépasser 2770 kg/m^3 si l'on ne veut pas que celui-ci génère une crête gravimétrique notable.

Pour expliquer la présence de crêtes gravimétriques notables au nord du pluton d'Iron Mask, nous avons modélisé deux vastes massifs dioritiques enfouis principalement à l'intérieur d'unités de roches du Groupe de Nicola. Au sud, un large creux gravimétrique (amplitude de -33 mGal) est modélisé sous la forme d'un vaste massif de granitoïde s'enfonçant sous la surface jusqu'à une profondeur d'environ 9700 m et qui pourrait correspondre à un élargissement d'un massif granodioritique présent dans le horst de Nicola.

INTRODUCTION

Cordilleran Cu±Mo±Au porphyry mineralization in space and time is being investigated as part of the Geological Survey of Canada's Targeted Geoscience Initiative Program. One objective is the creation of an integrated 3D model of magmatic-hydrothermal evolution within the Triassic alkalic Iron Mask Batholith (Fig. 1) at the location of the producing New Afton Mine (Schetselaar et al., 2017). The batholith hosts numerous other mineralized occurrences classified by the British Columbia Geological Survey as showings, prospects, developed prospects, producers, or past producers (MINFILE, 2018a). Logan and Mihalynuk (2005) noted that in addition to hosting Cu-Au-Ag produced from porphyry deposits such as Afton, Crescent, Pothook, Ajax West and Ajax East, the batholith contains structurally controlled Cu-magnetite veins (Iron Mask, Makaoo/Python, Grey Mask). The distribution of these and other occurrences in the southeastern portion of the batholith are plotted on a geological map (Fig. 2) after Logan et al. (2006a).

The considerable potential for porphyry-type mineralization within the batholith and its association with strong magnetic signatures has prompted a wider examination of the batholith from a perspective of determining the significance of the signatures for mineral exploration (Thomas, work in progress, 2019). Because information on the large-scale geometry of the batholith is apparently lacking, a supplementary study involving modelling of associated prominent gravity and magnetic anomalies was considered timely and constructive. Results of the study, reported here, provide a regional-scale perspective on the structure of the batholith.

GEOLOGICAL SETTING

The northwest-trending Iron Mask batholith is a Late Triassic to Early Jurassic alkalic intrusive complex in the south-central part of the Cordilleran Quesnel Terrane (Logan and Mihalynuk, 2005) (Fig. 1). It consists of two plutons separated at surface mainly by a broad intervening unit of Eocene Kamloops Group sedimentary rocks (MapPlace, 2018), though the map of Logan et al. (2006a), only partially covering the latter unit, displays volcanic rocks assigned to the group along the margin of the Iron Mask pluton. The plutons were referred to as the Iron Mask and Cherry Creek plutons (Fig. 1) by Kwong (1987), a designation adopted here. Logan and Mihalynuk (2005) referred to both the entire alkalic intrusive complex and to its larger southeastern portion as Iron Mask batholith, and the smaller northwestern body as the Cherry Creek pluton. To avoid confusion, "Iron Mask batholith" will be used when both plutons are the subject of discussion.

The batholith is described as a subvolcanic multiple intrusion, comagmatic and coeval with Upper Triassic rocks of the Nicola Group flanking the southwestern margin of the batholith and much of its northeastern margin (MINFILE, 2018b). These margins, in large part, are in intrusive contact with volcanic and sedimentary rocks of the eastern belt of the Nicola Group (Mortimer, 1987; Preto, 1979) (Fig. 1). Middle Eocene volcanic and sedimentary rocks of the Kamloops Group and Miocene alkaline flood basalts unconformably overlie Nicola Group and Iron Mask pluton rocks (Fig. 2). A 1:25 000 scale geological map of the Iron Mask pluton (Logan et al., 2006a) is displayed in simplified form in Figure 2. Descriptions of geological units forming the pluton, and its porphyry Cu-Au deposits and marginal Triassic and Eocene units are provided by Logan and Mihalynuk (2005).

Iron Mask pluton

The Iron Mask pluton includes three principal intrusions, or phases, which in order of decreasing age are the Pothook diorite, Cherry Creek monzonite, and Sugarloaf diorite (Snyder and Russell, 1993; Logan and Mihalynuk, 2005). A fourth igneous unit, the Iron Mask Hybrid phase, is derived mainly from Pothook diorite and assimilated Nicola Group volcanic rocks. It is a xenolith-rich, heterogeneous unit forming approximately 45% of the batholith. Hybrid rocks mark the contact zones between the three intrusions within the pluton, and between the pluton and volcanic country rock. The xenolith-rich Sugarloaf diorite can also form a hybrid unit. Uranium-lead ages for samples of the Pothook, Hybrid, and Cherry Creek phases are 204 ± 3 Ma, or Upper Triassic (Mortensen et al., 1995). The Sugarloaf diorite is the youngest phase, but had not been dated.

Snyder (1994) suggested that magmatic contamination was important in development of the Iron Mask pluton, believed to have started with intrusion of Pothook diorite magma and its interaction with the Nicola Group that produced the Hybrid unit. Intrusion of the Cherry Creek phase followed closely, possibly partially coeval with hybridization, and finally Sugarloaf diorite intruded along pre-existing structures both within the batholith and Nicola Group country rocks.

The Iron Mask pluton is dominated by the Hybrid and Cherry Creek phases covering areas of approximately similar size (Fig. 2). The Hybrid phase is distributed in a Y-shaped belt running parallel to the length of the pluton and occupying much of its southwestern margin and central portion. A large belt of the Cherry Creek phase flanks the Hybrid phase to the northeast in the southeastern portion of the pluton. A north-northwest-trending unit of Cherry Creek phase lying between the two forks of the Hybrid Y swings west-southwestward around a belt of Pothook diorite at the top of the western fork and continues to the New Afton pit. A very narrow branch of this Pothook diorite unit extends southeast between the western fork and a short belt of the Sugarloaf phase along the southwestern margin of the pluton. Small units of Pothook, Sugarloaf, and Hybrid phases lie

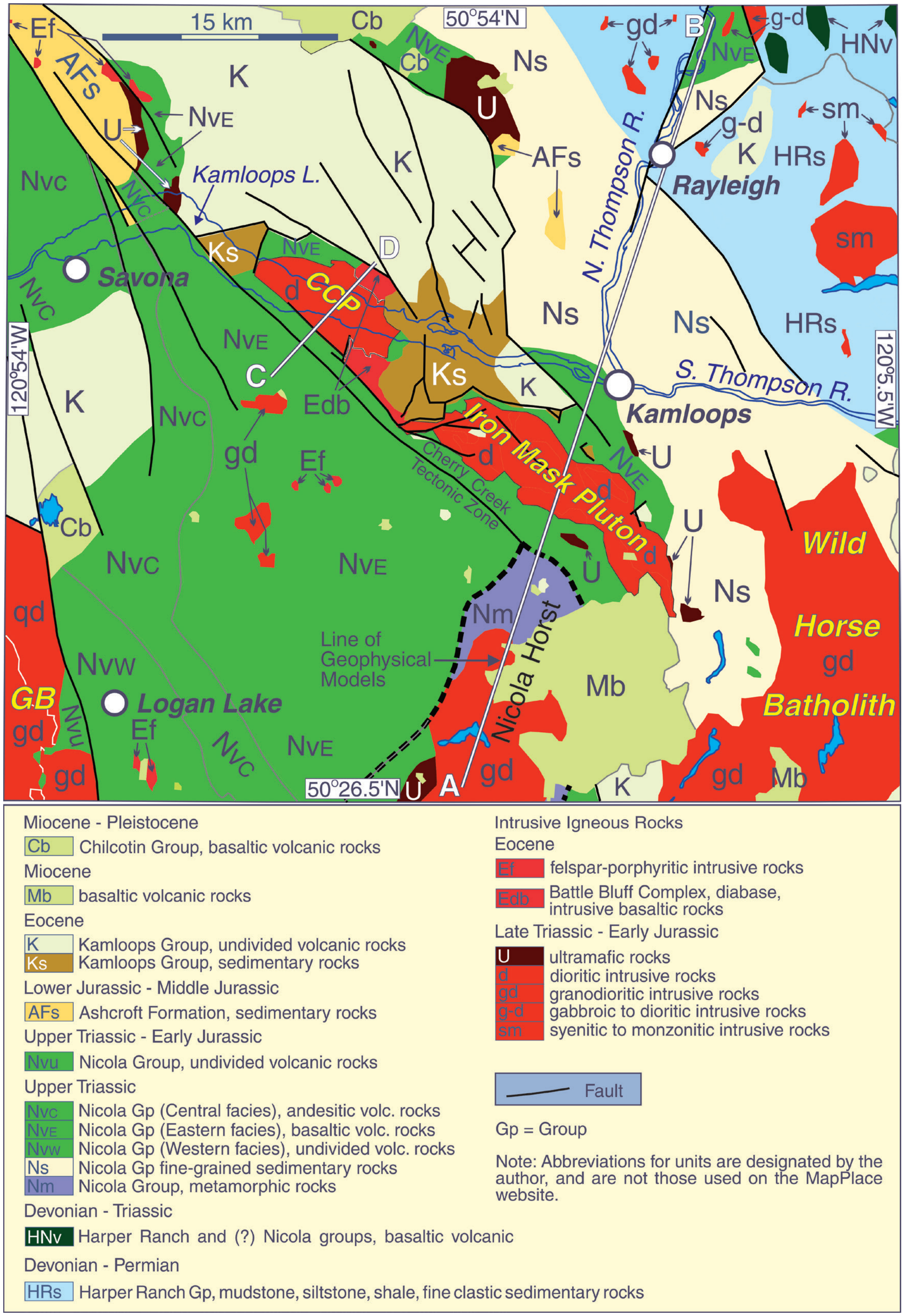

Figure 1. Geological map of region including and surrounding the Iron Mask batholith that includes the Iron Mask pluton and Cherry Creek pluton (CCP), adapted from MapPlace (2018). Lines A-B and C-D are lines along which gravity and magnetic profiles for modelling were derived

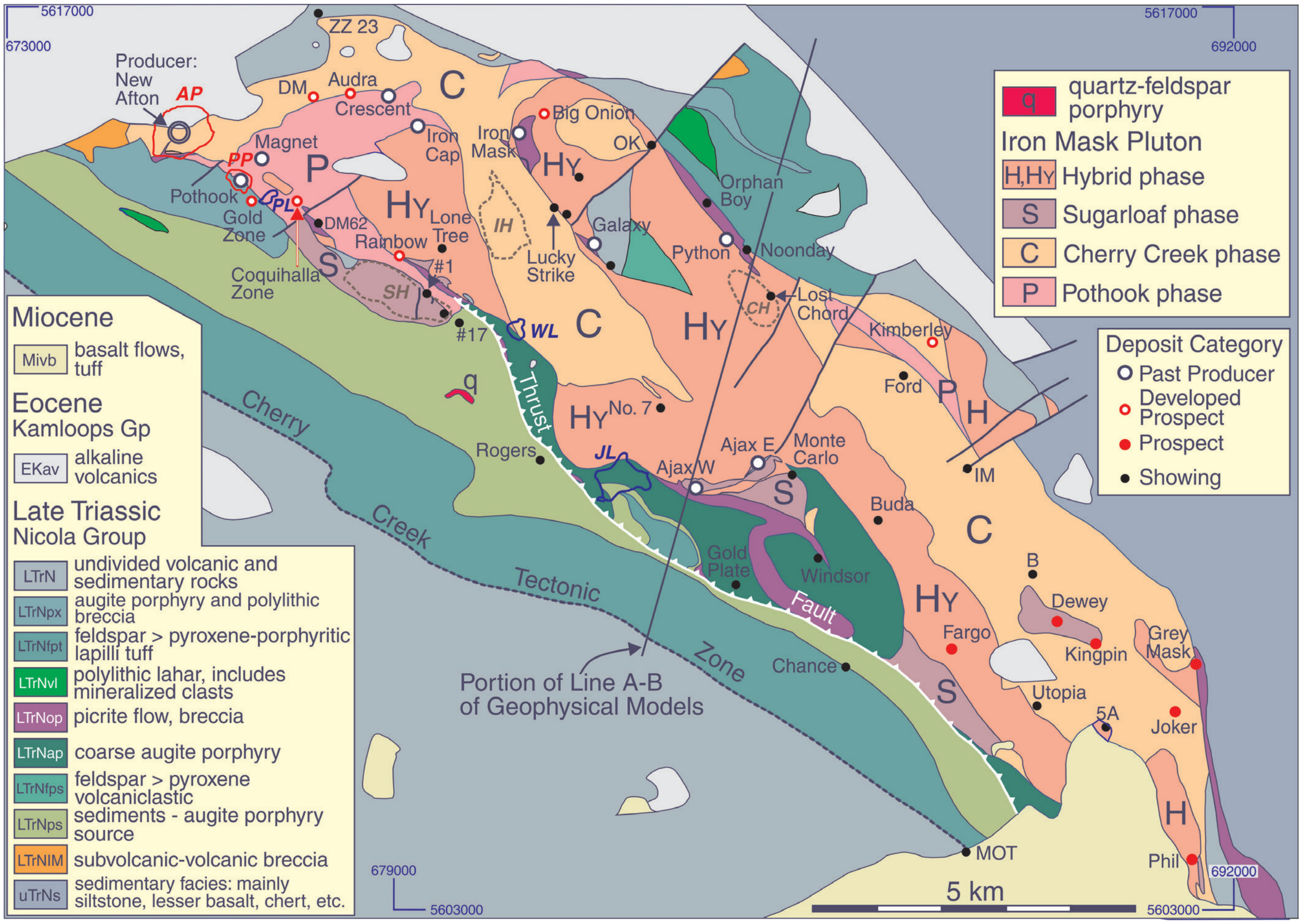

Figure 2. Geological map of the Iron Mask pluton *adapted from* Logan et al. (2006a). Mineralized occurrences as classified by the British Columbia Geological Survey are plotted; some modifications to the category as shown by Logan et al. (2006a) are based on more recent information (MINFILE, 2018a). Irregularly-shaped areas defined by red lines are the New Afton pit (AP) and Pothook pit (PP). Lakes (defined by blue lines) are Jacko Lake (JL), Pothook Lake (PL), and Wallender Lake (WL). Hills (defined by brown dashed lines) are Coal Hill (CH), Ironmask Hill (IH), and Sugarloaf Hill (SH). Portion of line A-B along which geophysical modelling was conducted is plotted. HY, portion of Hybrid Phase distributed in a Y-shaped unit. Abbreviations for units in left-hand legend are after Logan et al. (2006a), those in right-hand legend are designated by the author

within the unit of Cherry Creek phase in the southeastern part of the pluton. Descriptions of phases of the pluton based on Logan and Mihalynuk (2005) follow.

Pothook phase

The Pothook diorite is present mainly near the northwestern margin of the pluton (Fig. 2), emplacement apparently controlled by northwest- and northeast-trending faults. The diorite exhibits gradational contacts with the Hybrid unit, faulted contacts masked by strong potassic alteration with the Cherry Creek phase, and, reportedly, intrusive contacts with the Sugarloaf phase at the Pothook deposit (Stanley, 1994). The Pothook diorite is equigranular, medium- to coarse-grained, and contains 40 to 60% plagioclase, 10 to 25% clinopyroxene, 5 to 7% biotite, up to several percent K-feldspar, apatite, and lesser accessories, and 5 to 10% magnetite. Alteration minerals, including K-feldspar, sericite, epidote, and chlorite, are widespread.

Hybrid phase

The Hybrid phase is a xenolith-rich, heterogeneous igneous component occurring mainly in the extensive Y-shaped belt that traverses most of the Iron Mask pluton (Fig. 2). Hybrid rocks delineate contact zones between phases of the pluton and between the pluton and volcanic country rocks. Logan and Mihalynuk (2005) noted Snyder's (1994) redefinition of the Hybrid phase as a facies-equivalent of the Pothook diorite, considering it to represent outer margins to the Pothook phase that interacted with and incorporated country rock of the Nicola Group. They further noted that matrix of the Hybrid rocks is not necessarily always Pothook diorite, as locally xenolith-rich marginal phases of the Cherry Creek and Sugarloaf phases are hybrid zones, and subdivision of the Hybrid phase into three main types is based on texture and clast abundance (Snyder and Russell, 1995). From the perspective of the study of magnetic signatures of the pluton, the Hybrid phase contains abundant coarse interstitial grains of magnetite in a Pothook dioritic matrix, yielding magnetic susceptibilities typically an order of magnitude higher than most other rock types (Logan and Mihalynuk, 2005).

Cherry Creek phase

The Cherry Creek phase rivals the Hybrid phase in coverage, with extensive pluton-parallel belts in both the northwestern and southeastern halves of the pluton (Fig. 2). Historically, distinguishing between Cherry Creek and Pothook phases was difficult, because of pervasive potassium metasomatism commonly developed adjacent to their contacts (Logan and Mihalynuk, 2005). Textures within the Cherry Creek phase vary from plutonic to hypabyssal and locally volcanic. In the core of the pluton, near Ironmask Hill (Fig. 2), and in the northern part of the southeastern belt, the rocks are leucocratic, fine- to medium-grained equigranular biotite monzonite. Near the margins of the pluton the rocks are characteristically microporphyries ranging in composition from monzodiorite to monzonite. Magnetite is disseminated throughout the groundmass in amounts up to 10%.

Sugarloaf phase

The Sugarloaf phase is represented by a suite of hornblende porphyritic, trachytic rocks of dioritic composition outcropping mainly along the western margin of the pluton as lenticular bodies or as metre-wide dikes in adjacent Nicola Group volcanic rocks. Distribution of the phase was apparently controlled by northwest-trending structures. Dikes of the Sugarloaf phase are oriented radially around Sugarloaf Hill (Fig. 2), interpreted by Snyder and Russell (1993) as a volcanic neck and intrusive centre. Holocrystalline trachytic porphyries of the phase exhibit significant variation in texture, ranging from fine-grained to medium-grained. Rocks of the phase are characterized by hornblende and plagioclase phenocrysts in a fine-grained groundmass of plagioclase, clinopyroxene, magnetite, and K-feldspar.

LARGE-SCALE STRUCTURE OF IRON MASK PLUTON FROM GRAVITY AND MAGNETIC MODELS

The Iron Mask batholith and surrounding area (Fig. 1) are covered by gravity and magnetic data that are modelled to investigate large-scale structure of the batholith.

Regional gravity data and models

A Bouguer gravity anomaly map of the study area is shown in Figure 3. Some gravity data were acquired as part of Canada's National Gravity Mapping Program and have a mean spacing of about 8 km. Supplementary data related to the Lithoprobe Southern Cordillera transect (Thomas et al., 1990), part of Canada's National Lithoprobe program (Clowes, 2010), are more closely spaced. Station spacing along an east-west route of the transect along the southern margin of the area and along two north-northeast-trending routes crossing the Iron Mask pluton (Fig. 3) ranges from about 1 to 3 km (Thomas et al., 1990). Another gravity data set covering the area was acquired by an airborne survey along east-west lines spaced 2000 m apart at a nominal mean terrain clearance of 200 m (Sander Geophysics Limited, 2010). Bouguer anomalies for all data sets were computed using the standard density of 2670 kg/m^3 for the Bouguer correction and related terrain corrections. Although the airborne survey data have a higher spatial resolution (2000 m), the fact that sections of the Lithoprobe transect have stations spaced <1200 m apart in the critical area of the Iron Mask pluton favoured use of the ground gravity data for modelling.

The national and Lithoprobe gravity data were combined and gridded using a cell size of 1 km to produce the Bouguer anomaly map. This relatively small cell size was selected to try to capture higher resolution features that might be present near Lithoprobe stations. Although 1 km might be considered too small to define a reasonable gravity field in areas of wider spaced observations (typically ~8 km), the gravity map does not reveal any apparent problematic noise.

The gravity field of the area (Fig. 3) is dominated by prominent positive anomalies (gravity highs) oriented generally roughly northwest, typically separated by subparallel, narrower, relatively negative anomalies (gravity lows). With the exception of the prominent low south of the Iron Mask pluton, gravity lows are not particularly conspicuous, their minima only a few mGal below the estimated background or "neutral" level of gravity anomalies in the area. Accurate determination of this background level is difficult, because there is no extensive area of relatively flat gravity field. The mean value of the gravity field within the area is −126 mGal, and spot values within a few small

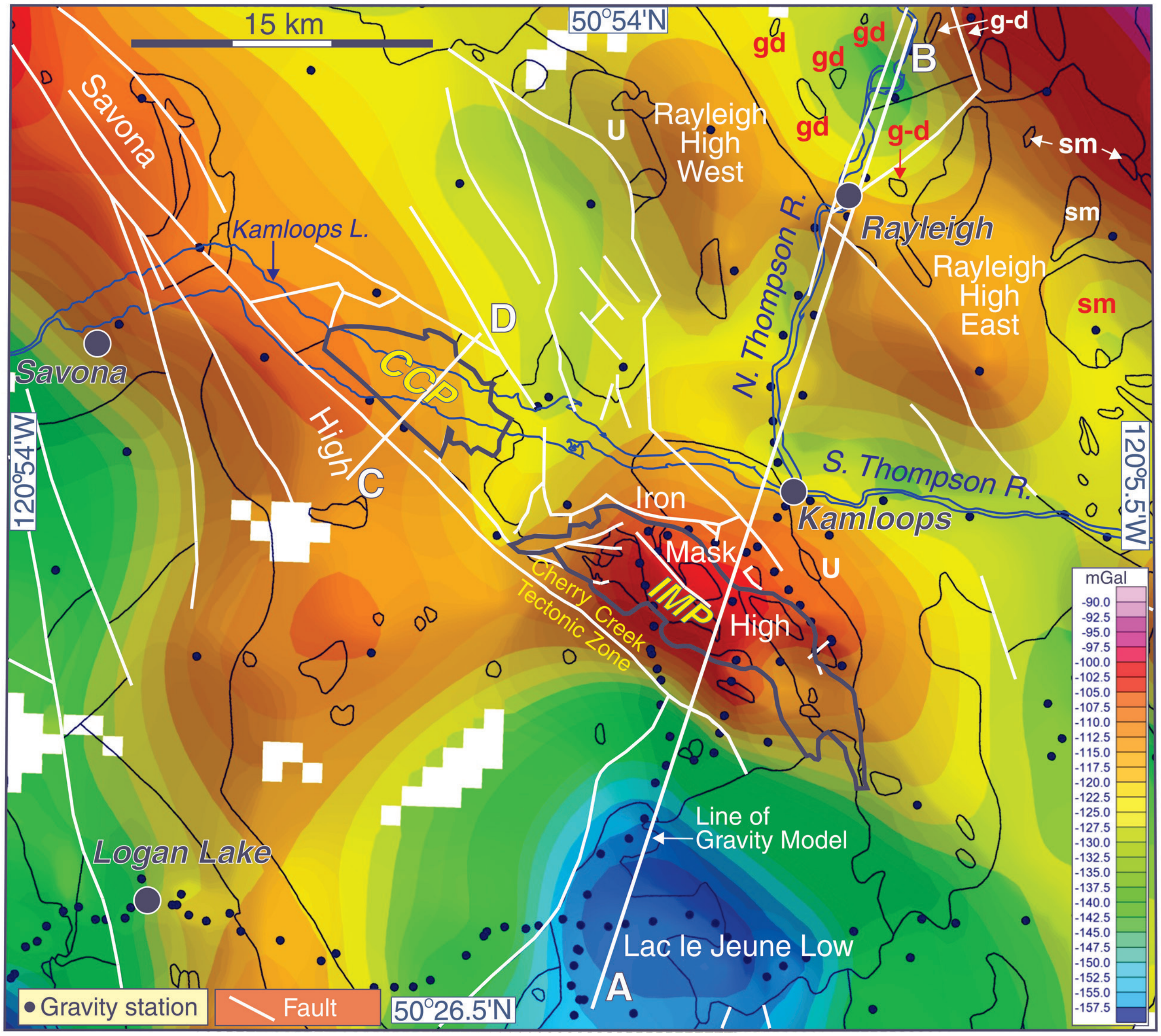

Figure 3. Bouguer gravity anomaly map of region including and surrounding the Iron Mask batholith outlined in Figure 1 based on ground measurements. Geological contacts from Figure 1 are plotted. CCP, Cherry Creek pluton; IMP, Iron Mask pluton. Abbreviations for igneous intrusive rocks: gd, granodioritic; g-d, gabbroic to dioritic; sm, syenitic to monzonitic; U, ultramafic. Line A-B is line along which a gravity model was derived, and C-D is line along which gravity profiles were derived.

areas where the field is relatively flat (pale orange, yellow, pale yellow-green shades in Fig. 3) near the South and North Thompson rivers and western portion of the northern margin yield a mean value of −127 mGal. This latter value is considered a viable estimate of the background field for determining amplitudes of gravity highs and lows, and deriving gravity models.

Correlation of gravity anomalies with geology

Apart from high Bouguer anomaly values in the northeast corner of the area, the most conspicuous gravity high (Iron Mask high), amplitude roughly 25 mGal, is associated with the Iron Mask pluton (Fig. 3). It is roughly oval-shaped, some 25 km long and 12 km wide, and extends from approximately 5 km southeast of the pluton to the pluton's northwestern margin, beyond which, for a few kilometres, it correlates with sedimentary and volcanic units of the Eocene Kamloops Group (Logan and Mihalynuk, 2005). Whereas the sedimentary component of the group probably contributes to the eventual northwestward and northward decrease in the gravity field, the pattern of the Iron Mask gravity high suggests that the higher density, constituent dioritic rocks of the pluton continue for some distance beneath the Kamloops Group. Contours defining the high cut perpendicularly across the pluton near its contact with the Kamloops Group, and continue to trend northeastward within the group. It is conjectured that the pluton is terminated along a northeast-trending fault or intrusive contact beneath the Eocene rocks.

The Iron Mask gravity high extends well to the northeast of the pluton over units of Upper Triassic Nicola Group basaltic rocks (Eastern facies) and fine-grained sedimentary rocks, and Eocene Kamloops Group undivided volcanic rocks and sedimentary rocks. The anomaly also extends a shorter distance southwestward over mainly Nicola Group basaltic rocks (Eastern facies), and smaller areas of Miocene basaltic rocks and Nicola Group metamorphic rocks within the Nicola Horst. Roughly the central third of the gravity anomaly, southeast to northwest sense, coincides most closely with the pluton. These gravity-geology relationships indicate that the pluton extends northeast and southwest for some kilometres beneath the described cover rocks, compatible with its recognition as a subvolcanic intrusion. The peak area of the gravity anomaly coincides essentially with the central portion of the Iron Mask pluton. Contours defining the southeastern flank of the high extend laterally across the intrusion, suggesting probable significant thinning of dioritic phases toward the southeast. The pattern of the Iron Mask gravity high indicates that the intrusion may have an overall elongate basin-like shape, possibly having a central feeder-type geometry. The gravity high is modelled along a regional scale profile derived along the north-northeast-trending line A–B (Fig. 3).

The Cherry Creek pluton in the northwest, in contrast to the Iron Mask pluton, apparently lacks an associated prominent positive gravity signature (Fig. 3; Figure 4a, b). However, no ground-gravity measurements were made directly on the pluton, the closest being only a few observations marginal to the pluton that contribute to definition of the Savona gravity high. The absence of a positive signature is supported by results of the QUEST South airborne gravity survey flown for Geoscience BC at 2000 m line-spacing and a nominal terrain clearance of 200 m (Sander Geophysics Limited, 2010). The derived gravity map shows a weak gravity low running approximately west-northwestward across the central part of the Cherry Creek pluton (Fig. 4b), partially coincident with Kamloops Lake, though the lake effect (water density 1000 kg/m^3) has been integrated into terrain corrections and is not visible in this map. The low is flanked by weak sub-parallel positive signatures (Fig. 4b, c) near the margins of the pluton that swing northwestward becoming part of the Savona gravity high (Fig. 3). These gravity characteristics suggest that the Cherry Creek pluton lacks the thick developments of dioritic rocks predicted at depth within the Iron Mask pluton by gravity modelling.

Northwest of the Cherry Creek pluton the Savona gravity high, amplitude roughly 12 mGal, falls mainly on andesitic and basaltic volcanic rocks of the Nicola Group to the southwest and volcanic rocks of the Kamloops Group to the northeast. Its axial area coincides with a sizable unit of sedimentary rocks of the Lower-Middle Jurassic Ashcroft Formation (Fig. 1). Both groups of volcanic rocks extend beyond the limits of the gravity high, indicating that its principal source is not within the groups themselves. The high extends southeastward from the northwest corner of the area toward the Cherry Creek pluton, near which it swings southward, continuing that trend to the southern margin of the area (Fig. 3). Along this tract, the high passes almost exclusively over Nicola Group mainly andesitic and basaltic volcanic rocks between the Guichon Creek batholith to the west and Iron Mask batholith and Nicola Horst to the east (Fig. 1, 3).

The prominent oval-shaped gravity low south of the Iron Mask gravity high attains a minimum value of about −160 mGal near Lac Le Jeune close to the southern limit of the area, and is named for that lake. Its amplitude, roughly –33 mGal, and spatial dimensions are similar to those of the Guichon Creek batholith to the west. The influence of the Guichon Creek batholith is seen in decrease of the gravity field along the western margin of the area between Logan Lake and Savona (Fig. 3).

The Lac Le Jeune low covers large areas of Nicola Group volcanic rocks on its western flank, smaller areas of Nicola Group volcanic and metamorphic rocks on its northern flank and a moderately large area of Miocene basaltic rocks on its eastern flank. The core of the low coincides principally with a unit of Late Triassic-Early Jurassic granodioritic rocks within the Nicola Horst. The southwestern flank of the Iron Mask gravity high and northeastern flank of the low form a continuous gradient, leading to uncertainty in separation of the two anomalies, which is ultimately based on the estimated background value of −127 mGal for the area, with separation based on the −127 mGal contour.

Rock densities

Rock densities provide a key constraint in modelling gravity anomalies, but in the present case, density data are limited to the immediate area of the New Afton pit. Some of these data, provided by New Gold Inc., are displayed in Table 1. Units BXF, BXFF, and BXFX, assigned to the Nicola Group, were defined by mapping by New Gold Inc. The mean densities of diorites in the Pothook and Sugarloaf phases, and of the Cherry Creek monzonite, are 2760 kg/m^3 and 2750 kg/m^3, respectively. Density determinations by R. Enkin, Pacific Geoscience Centre, on core samples from the New Afton pit area yielded mean densities of 2790 kg/m^3, 2760 kg/m^3, 2720 kg/m^3, and 2800 kg/m^3 for BXF (Nicola Group fragmental and crystalline rocks), diorite, monzonite, and picrite, respectively. The area of the pit has experienced intense hydrothermal alteration, and it is difficult to determine whether the values for diorite and monzonite are representative of these rock types elsewhere in the pluton. From a generic perspective, mean densities for intrusive rocks from the Canadian Shield (Gibb, 1968) and New Zealand (Tenzer et al., 2011) (Table 2), for example, presumably relate to relatively unaltered rocks and offer another perspective in selecting reasonable density values for gravity modelling.

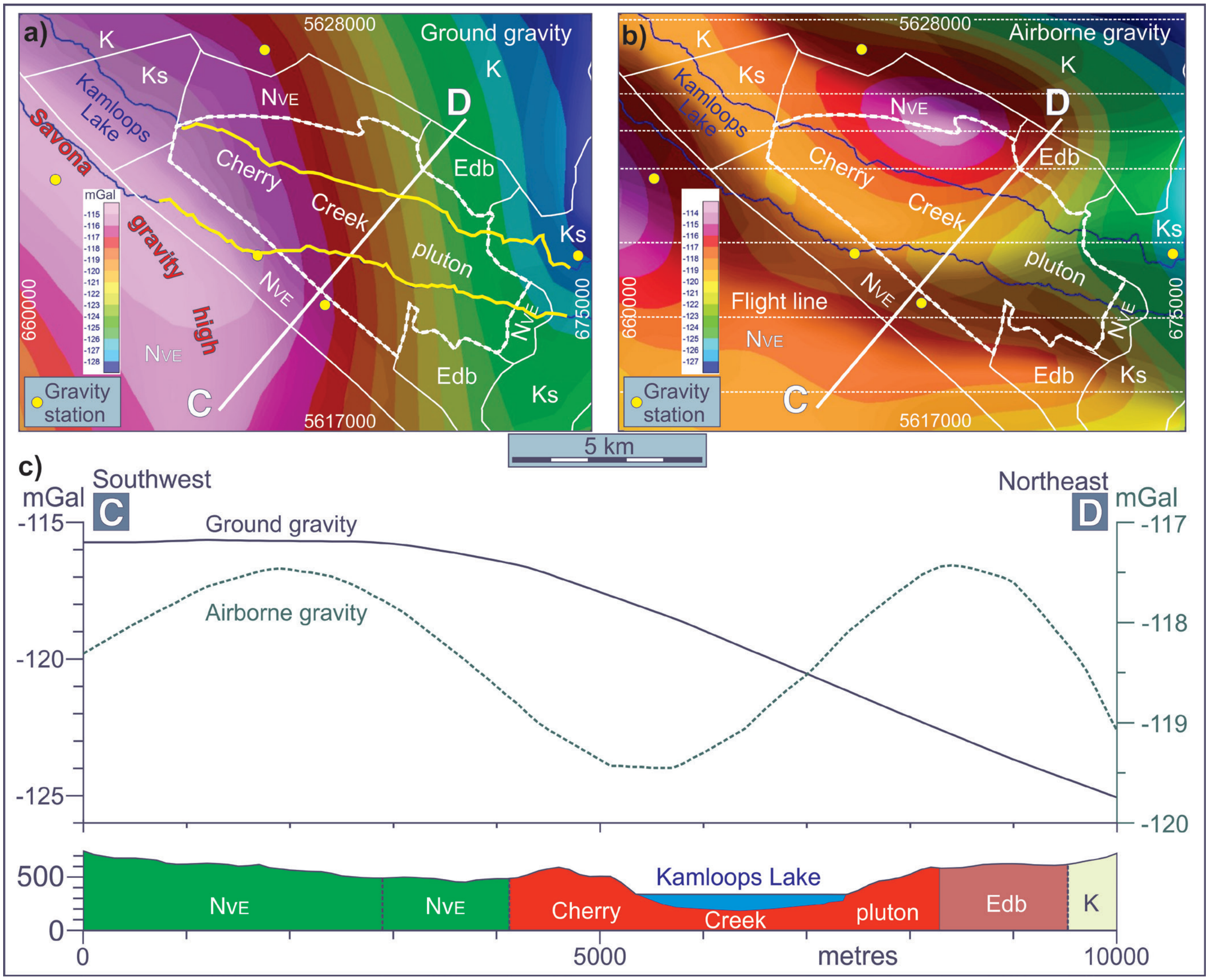

Figure 4. **(a)** Bouguer gravity anomaly map of Cherry Creek pluton based on ground gravity observations at the indicated gravity stations with geological contacts superposed, **(b)** Bouguer gravity anomaly map of the pluton based on QUEST South airborne survey with geological contacts superposed; survey flight lines are plotted, **(c)** Bouguer gravity profiles along line C-D based on ground and airborne data referenced to a schematic geological section. Geological legend for a, b and c: K, Kamloops Group undivided volcanic rocks; Ks, Kamloops Group sedimentary rocks; NVE, Nicola Group Eastern facies, basaltic volcanic rocks; Edb, Eocene Battle Bluff complex, diabase, intrusive basaltic rocks.

Rock density information in the area of the Lac Le Jeune gravity low, predicted to be related to granodioritic rocks, apparently, is lacking. Ager et al. (1973) reported densities of similar intrusive rocks in the nearby Guichon batholith, presenting a density contour map based on more than 1850 measurements within and marginal to the batholith. The contours mimic the roughly oval shape of the batholith. The area enclosed by the innermost contour (2670 kg/m^3) coincides closely with a unit of Bethsaida quartz monzonite (MapPlace, 2018). The slightly larger area enclosed by the 2700 kg/m^3 contour, noticeably extending further east, covers also portions of the Highland Valley and Bethlehem granodiorites (MapPlace, 2018). The 2730 kg/m^3 contour defines a slightly larger area covering the same units, and most of the batholith excluding the border phases. These Guichon batholith densities in the range 2670 – 2730 kg/m^3 relate principally to granodiorite and quartz monzonite. It is proposed that a similar range of densities could characterize the granitoid batholith, partially expressed at surface as a granodiorite, suspected to be the source of the Lac Le Jeune gravity low. In their gravity model of the Guichon Creek batholith, Ager et al. (1973) grouped the Highland Valley, Bethlehem, and Bethsaida phases in a single density unit, and the border phases (mostly quartz diorites ranging up to 2820 kg/m^3 in density) together with the country rocks as a separate composite unit. The density contrast between these units was noted to vary between

Table 1. Mean rock densities and magnetic susceptibilities for rocks in area of New Afton pit.

Rock abbrev.	Rock type	No. samples	Mean dens. kg/m^3	S.D. dens. kg/m^3	Mean suscept. x 10^{-3} SI
BA	Kamloops Group basalt	175	2750	160	29.3
BXF	Consolidation of BXFF and BXFX	2874	2730	150	14.8
BXFF	BXF (fragmental): volcaniclastic sediments (Nicola Group)	4719	2860	160	21.2
BXFX	BXF (crystalline): crystalline tuffs; andesitic flows and pyroxene-plagioclase basalts (Nicola Group)	1494	2850	160	26.8
DI	Diorite (Pothook and Sugarloaf diorites)	467	2760	170	19.5
MO	Monzonite (Cherry Creek monzonite)	170	2750	140	27.8
PI	Picrite, commonly serpentinized; includes peridotite, wehrlite, pyroxenite	183	2810	170	35.7
LA	Latite	53	2750	150	11.4
SH	Shale	4	2680	110	1.1
SS	Sandstone	5	2660	110	2.9
CG	Conglomerate	3	2730	100	4.3
FA	Fault (used if primary lithology completely obscured by deformation and hydrothermal mineralization)	75	2780	170	16.7

Table 2. Mean rock densities for some intrusive rocks in the Canadian Shield and New Zealand.

	Tenzer et al. (2011) – New Zealand					Gibb (1968) – Canadian Shield				
Rock type	No. samples	Mean density kg/m^3	S.D. kg/m^3	Min. density kg/m^3	Max. density kg/m^3	No. samples	Mean density kg/m^3	S.D. kg/m^3	Min. density kg/m^3	Max. density kg/m^3
Granite	288	2640	80	2330	2940	*944	2640	40	2500	2780
Granodiorite	53	2680	70	2530	2940	*944	2640	40	2500	2780
Syenite	15	2720	150	2440	2860	9	2700	40	2620	2780
Diorite	186	2800	120	2430	3160	50	2770	60	2640	2890
Gabbro	236	2880	150	2260	3340	60	3000	70	2800	3130

*Massive and foliated granite and granodiorite, granitic gneiss, and quartz-feldspar biotite gneiss are included.

−100 kg/m^3 and −150 kg/m^3, with contrasts of −130 and −150 kg/m^3 providing a good match to the observed gravity data.

Modelling the gravity field – Iron Mask pluton

Besides a knowledge of rock densities, a critical criterion for modelling gravity data is determination of the background field for comparison with anomalous features of the field. The level of background field is estimated to be −127 mGal, but information on rock densities is limited. Another limitation in modelling is insensitivity of a modelled signature to changes in depth to the bottom of a modelled unit. This is particularly true for steep narrow units. In Figure 5, gravity and magnetic signatures of a rectangular geological unit with its top at surface are computed for bottom depths ranging from 500 to 5000 m below surface at 500 m intervals. At greater depths the difference in amplitudes for successive depths become smaller and smaller. A discernible change in depth may not therefore radically change the perceived goodness of fit (visual) between an observed and calculated (= model) profile. The goodness of fit can be numerically evaluated in terms of the root mean square error (RMSE), but often smaller perturbations along a profile that are not modelled contribute to the RMSE, diminishing its utility. Visual goodness of fit is adopted here, and hence uncertainty in positions of bottoms of units is an inherent weakness of derived models.

The 52 km long, north-northeast-trending gravity profile along line A-B (Fig. 3) selected for modelling is displayed in Figure 6a. The line is positioned to take advantage of detailed gravity stations related to nearby Lithoprobe seismic traverses (Thomas et al., 1990). In the south the profile commences on the Nicola Horst, then crosses the Cherry Creek Tectonic Zone along the northeast boundary of the horst, continuing across the Iron Mask pluton before traversing variously mainly volcanic and sedimentary units of the Nicola Group and terminating just north of Rayleigh (Fig. 1, 3).

The profile is dominated by the −33 mGal amplitude Lac Le Jeune Low and +25 mGal amplitude Iron Mask high, with the small +8 mGal amplitude Rayleigh East high present as a noticeable perturbation in the northern half of the profile. The Lac Le Jeune low correlates closely with a Late Triassic-Early Jurassic granodiorite intrusion occupying a significant part of the Nicola Horst (Fig. 1, 6b, 6c). This intrusion and adjacent buried portions are considered the probable source of the gravity low. Comparison of its amplitude and spatial dimensions with those of the low linked to the Guichon batholith (Ager et al., 1973) has been noted. The source of the Rayleigh East high is more difficult to explain, given its correlation principally with sedimentary rocks of the Nicola and Harper Ranch groups.

A gravity model derived assuming a background gravity field at a level of −127 mGal, using rock densities based on previous discussion for intrusive units, and constrained by geological contacts (Fig. 6b, c) is shown in Figure 6d. The nature and densities of country rocks potentially hosting the Iron Mask pluton and proposed Lac Le Jeune granitoid unit are unknown. Sedimentary and volcanic units of the Nicola Group and sedimentary rocks of the Harper Ranch Group of unknown thickness cover most of the area near the gravity profile. Vaca's (2012) multidisciplinary studies at several alkalic Cu-Au porphyry deposits within the Quesnel Terrane yielded densities for the mainly basalts of hosting Nicola Group volcanic rocks ranging typically between 2750 kg/m^3 and 3050 kg/m^3 and having a mean value of 2900 kg/m^3. Such high densities imply that any basaltic rocks within the Nicola Group northeast of the Iron Mask pluton must be thinly developed, otherwise the large density contrast required to produce the prominent gravity high over the pluton might not exist. Furthermore, the volcanic facies of the Nicola Group in this area is not necessarily composed exclusively of basaltic rocks. Schiarizza (2016) recognized four assemblages within the group in a study north of Kamloops, with only one dominated by basaltic rocks. The others are heterogeneous and include a variety of sedimentary, volcanic, and volcaniclastic rock types. Even near Kamloops, polylithic conglomerates have been observed in a unit mapped as Eastern volcanic facies (Paul Schiarizza, pers. comm., 2018). Ultimately, a density for background country rocks evolved during the modelling process, its value of 2730 kg/m^3 allowing reasonable contrasts with the densities used for modelling the Lac Le Jeune granitoid intrusion and mainly dioritic Iron Mask pluton.

The Lac Le Jeune low is modelled as a large granitoid body. It is slightly over 14 000 m wide near surface, tapering very slightly downward and descending to a depth of about 9700 m below surface (local) (Fig. 6d). It represents an enlargement of the granodiorite body within the Nicola Horst and extends some 3500 m north-northeastward at shallow depth from the mapped contact between the granodiorite and Nicola Group metamorphic rocks within the horst. It has a modelled density of 2650 kg/m^3, which is about as low a density as permissible, based on the densities of the Guichon batholith (Ager et al., 1973). The density could be increased, but would require a complementary increase in the density of the background crust, in turn requiring an increase in density of modelled units representing the Iron Mask pluton.

The initial model of the Iron Mask pluton consists of two juxtaposed units having densities of 2925 kg/m^3 and 2850 kg/m^3, descending to about 9300 m below surface. The higher 2925 kg/m^3 density is significantly higher than the measured mean (2760 kg/m^3 (Table 1)) of dioritic rocks in the pluton, and is more typical of the density of gabbroic rocks measured elsewhere (Table 2). At surface, the dominant Hybrid Phase is derived mainly from Pothook diorite and assimilated volcanic rocks of the Nicola Group (Logan and Mihalynuk, 2005) that possibly include unit

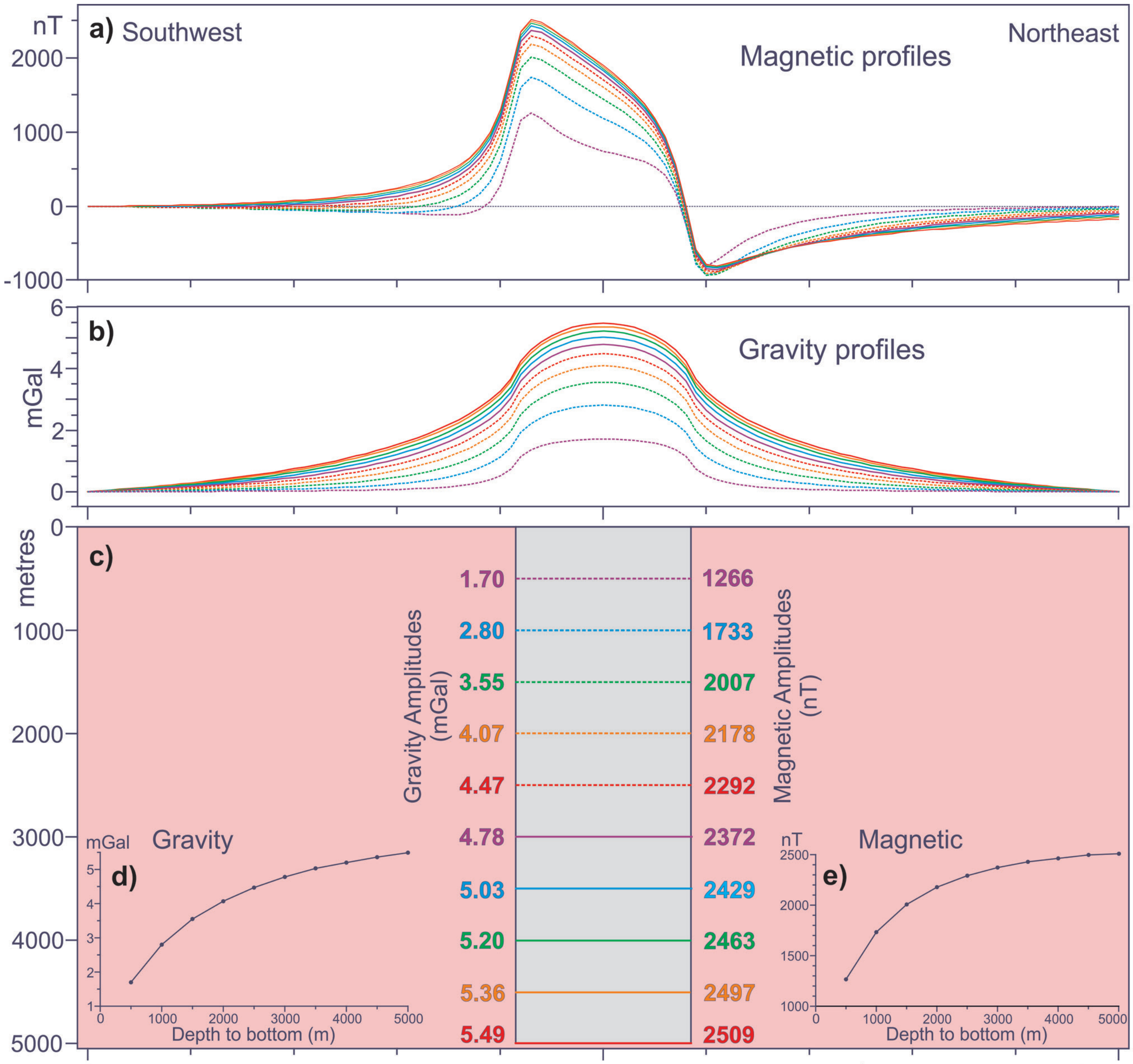

Figure 5. a) Series of magnetic profiles for a geological unit (grey body in (c)) having various depths to its bottom, calculated using the parameters (inclination (72°), declination (18°), field strength (44.7 A/m)) for the magnetic field in the area of the Cherry Creek pluton and a magnetic susceptibility of 100 × 10^{-3} SI; profiles are colour-coded (both solid and dashed lines) to match the various bottom contacts, **b)** corresponding gravity profiles based on a density contrast between the body and host rocks of 100 kg/m^3, **c)** the geological unit with various depths to its bottom contact; graphs showing depth to bottom versus **d)** gravity and **e)** magnetic anomalies illustrate how the amplitude of anomalies increases less rapidly for incremental increases in depth to the bottom at successively greater depths.

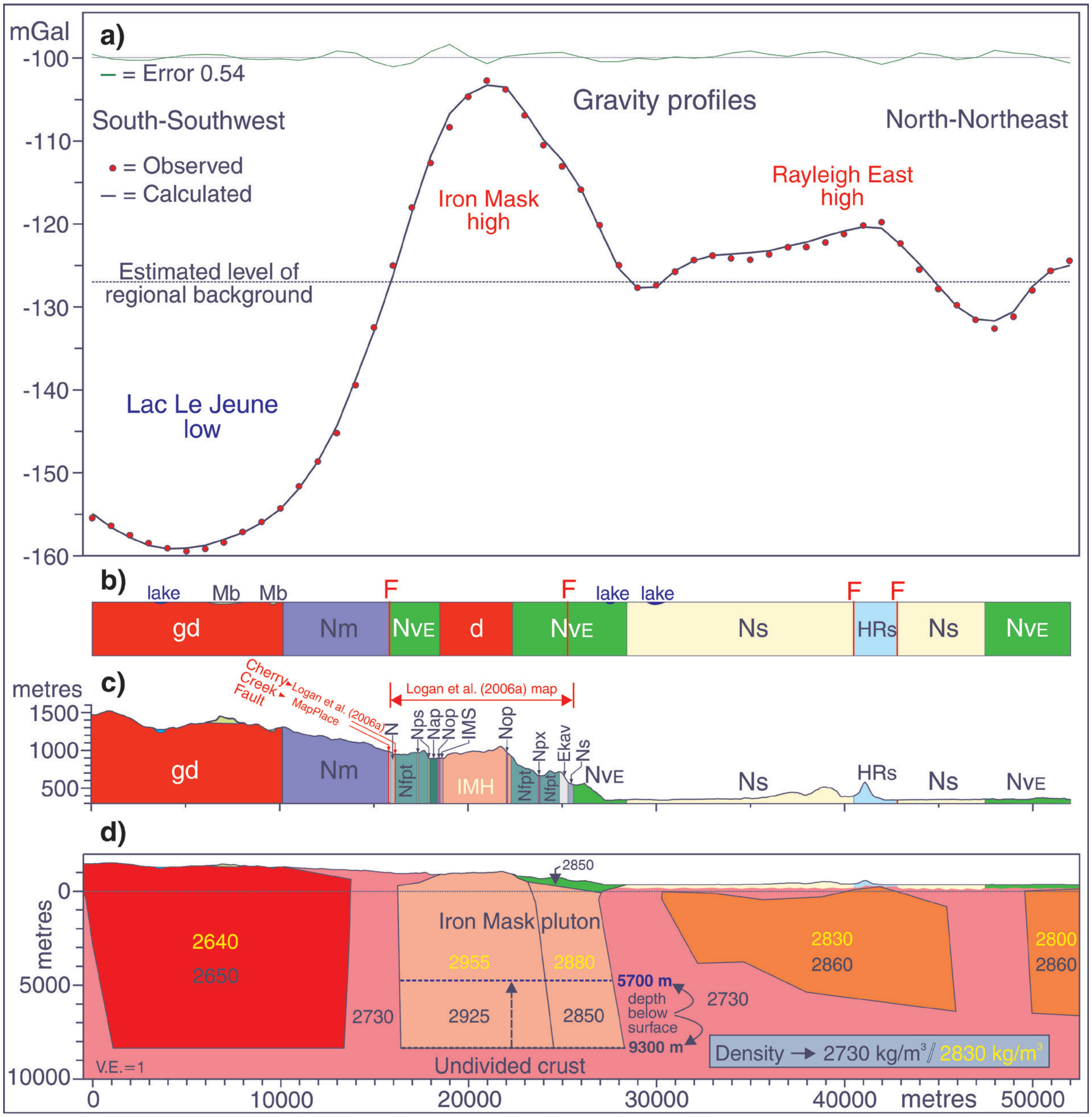

Figure 6. **a)** Observed and calculated (= model) gravity profiles, and error profile along Line A-B (see Figures 1, 3 for location), **b)** schematic geological section (arbitrary vertical contacts) illustrating surface geology (from MapPlace, 2018) with abbreviations keyed to Figure 1: gd, Late Triassic-Early Jurassic granodioritic rocks; d, dioritic rocks of Iron Mask pluton; Nm, Nicola Group metamorphic rocks; NvE, Nicola Group Eastern facies, basaltic volcanic rocks; Ns, Nicola Group fine-grained sedimentary rocks; HRs, Harper Ranch Group, various sedimentary rocks; Mb, Miocene basaltic volcanic rocks. F, fault, **c)** geological section (arbitrary vertical contacts) incorporating MapPlace (2018), and Logan et al. (2006a) information (most abbreviations for Logan et al. (2006a) are missing LTr (Late Triassic) at beginning in the interest of space; in one case (before Ns), uTr (also Late Triassic) is missing, and EKav is complete). Late Triassic Nicola Group: N, undivided volcanic and sedimentary rocks; Nps, sediments having augite porphyry source; Nap, coarse augite porphyry; Nop, picrite flow, breccia; Npx, augite porphyry and polylithic breccia; Ns, Nicola sedimentary facies; Nfpt, feldspar>pyroxene-porphyritic tuff. Latest Triassic Iron Mask Pluton: IMS, Sugarloaf – porphyritic hornblende diorite; and IMH, Hybrid – xenolith-rich Pothook or Sugarloaf phase. Eocene Kamloops Group: EKav, undivided alkaline volcanic rocks. **d)** Gravity model; densities in units of kg/m³. Densities for models with deep and shallow base for Iron Mask pluton, 9300 m and 5700 m below surface, respectively, are shown in navy and yellow. Minor changes in contact positions for the shallow model are not indicated.

BXFF fragmental and unit BXFX crystalline varieties having mean densities of 2860 kg/m^3 and 2850 kg/m^3 (Table 1), respectively, that could contribute to the higher 2925 kg/m^3 value, and explain the 2850 kg/m^3 value of the less-dense modelled unit. The modelled units have near-vertical sides, descend to the same depth below sea level as the Lac Le Jeune granitoid, and underlie rocks of the Nicola Group southward and northward along the modelled section. The upper contacts in these areas dip very gently over distances of about 2300 m and 4700 m, respectively. The southern boundary of the southern unit is near coincident with the Cherry Creek fault.

Uncertainty in depth to the bottom of modelled units has been discussed (Fig. 5). In the present case the match between the model and observed gravity profiles is excellent (Fig. 6a) and the displayed model seems geologically plausible. Models with other depths and slightly different unit densities could also be plausible. And indeed, subsequent to magnetic modelling of the pluton, to be discussed, the depth of the pluton was revised to a much shallower 5700 m below surface (Fig. 6d).

Mapped geology offers no clues relating to a likely source of the Rayleigh East High that correlates mainly with sedimentary rocks of the Nicola and Harper Ranch groups (Fig. 1, 3), though several small gabbroic-dioritic intrusions punctuating Harper Ranch sedimentary rocks, seemingly, are reasonable candidates. However, with the exception of one small intrusion in the northeast corner coinciding with a gravity high, the other intrusions fall within a conspicuous gravity low north of Rayleigh, suggesting that they are relatively thin. In spite of this observation, gravity modelling indicates the source of the Rayleigh East high is probably a large unit of rocks of possibly dioritic composition based on its modelled density of 2860 kg/m^3. The unit is roughly 15 500 m wide, extending from a depth as shallow as 100 m to a maximum depth of about 6700 m below surface. A separate, presumed dioritic body having a similar vertical extent and the same density is modelled under the north end of the profile.

Modelling the gravity field – Cherry Creek pluton:

The lack of definition of the ground gravity field over the pluton prohibits modelling of ground data. In similar vein, the airborne gravity map (Fig. 4b) does not reveal correlative anomalies that could help define the deep structure of the pluton. However, the map does outline a small gravity high that peaks on the northern margin of the pluton at its contact with Nicola Group volcanic rocks. This has an amplitude of about 4 mGal relative to "neutral" values within the pluton along Kamloops Lake. It is partly expressed in a gravity profile along line C-D (Fig. 4c), positioned to provide a magnetic profile for modelling. The airborne gravity data have a noise level better than 0.5 mGal with a half sine wave ground resolution of 1.8 to 2 km (Sander Geophysics Limited, 2010). Considering the maximum width of the pluton is 4.5 km, a resolution of 2 km means that only three gravity determinations at most have been made across the width of the pluton. This, and positioning of the aforementioned high, suggest that modelling of these data would be unproductive. Modelling is, therefore, focused on the magnetic signature of the pluton.

Regional magnetic data and models

Aeromagnetic coverage of the Iron Mask and Cherry Creek plutons (Fig. 7) is provided by a combined airborne magnetic-radiometric survey "Kamloops survey" centred approximately on Kamloops. It was flown in 2008 as a contribution to the Geological Survey of Canada's Mountain Pine Beetle Program (Thomas, 2010). Line-spacing was 400 m and mean terrain clearance 125 m. A higher resolution combined helicopter-borne magnetic-electromagnetic-radiometric survey "Fugro survey" was flown over the northwestern two-thirds of the Iron Mask batholith in 2011 by Fugro Airborne Surveys for New Gold Inc. The nominal terrain clearances for the respective instruments were 35 m, 35 m, and 60 m. Flight lines were oriented northeast and spaced 100 m apart.

The Earth's magnetic field includes significant contributions from the Earth's core and crust, and minor contributions from atmospheric electrical currents. Magnetic surveys measure this "total magnetic field," but because the data are typically used in investigations of the crust, the core component is eliminated by removing a reference field, such as the International Geomagnetic Reference Field (IGRF). Atmospheric-induced contributions may be eliminated by monitoring a magnetic base station during a survey. The resulting "corrected" data represent the residual total magnetic (RTM) field, related principally to magnetizations within the crust, which is characterized by both negative and positive values, instead of positive absolute total field values. Data collected in all aforementioned surveys have been corrected in the described manner.

Correlation of magnetic anomalies with geology

A brief description of the magnetic field defined by the Kamloops survey follows. A more comprehensive discussion of the magnetic field as it relates to the geology and mineral occurrences in the Iron Mask batholith is provided by Thomas (work in progress, 2019).

A prominent belt of strong magnetic highs extends northwest successively across the Iron Mask pluton, Cherry Creek pluton, and a broad area of undivided volcanic rocks of the Kamloops Group (Fig. 7). It is flanked either side by a generally relatively subdued magnetic field correlating mainly with sedimentary rocks of the Nicola and Harper Ranch groups to the northeast, and volcanic rocks of the

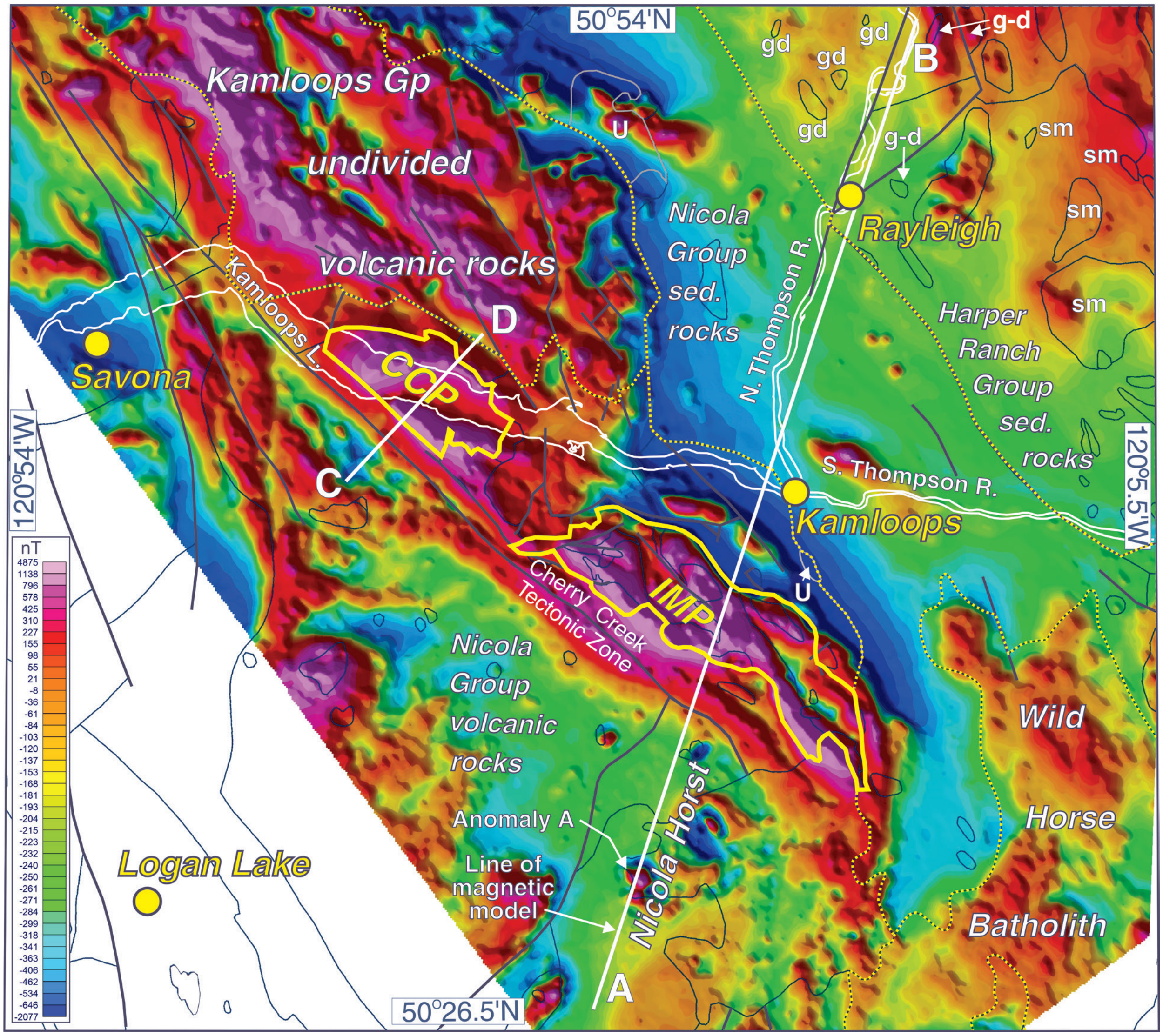

Figure 7. Residual total magnetic field map of region including and surrounding Iron Mask batholith based on data from the Kamloops survey. Geological contacts from map in Figure 1 are superposed. The small, roughly oval to circular contacts in the northeast corner define igneous units; gd, granodioritic; g-d, gabbroic to dioritic; sm, syenitic to monzonitic; U, ultramafic. CCP, Cherry Creek pluton; an IMP, Iron Mask pluton. Lines A-B and C-D are lines along which magnetic models were derived.

Nicola Group to the southwest. The belt of highs includes three principal areas of magnetic high, each including a number of individual magnetic elements. One area coincides with the Cherry Creek pluton and another with the Iron Mask pluton. These are separated by an area of relatively suppressed magnetic field coinciding with a unit of Kamloops Group sedimentary rocks. The third, and largest, area is north of Kamloops Lake, where it coincides with an extensive unit of volcanic rocks of the Kamloops Group.

The largest peak values (>4000 nT) in the survey area are associated with the Iron Mask pluton, and a few other peak values are >3000 nT. This strong expression is not unexpected given that all rock varieties in the Hybrid unit, underlying roughly 40% of the pluton, contain magnetite that often constitutes more than 10% by volume (MINFILE, 2018c). Stanley et al. (1994) reported magnetite concentrations ranging from 10 to 15% in various phases of the pluton, and magnetite is commonly associated with mineralization (Logan, 2003; Logan et al., 2006b).

The quietest area of magnetic field coincides principally with sedimentary rocks of the Nicola and Harper Ranch groups northeast of the Iron Mask batholith, though it is perturbed locally by spatially small and generally weak to moderately strong magnetic highs, some associated with small granodiorite-diorite or syenite-monzonite intrusions. The Wild Horse batholith east of the Iron Mask pluton correlates closely with a moderately strong positive magnetic signature. The magnetic field is fairly quiet immediately south of the Iron Mask pluton over mainly Nicola Group Eastern facies basaltic volcanic rocks, but is disturbed locally by moderately strong highs, a few attributable to relatively spatially small Late Triassic-Early Jurassic granodioritic intrusions. It is speculated that more extensive positive magnetic signatures over basaltic rocks between Savona and the Cherry Creek pluton (Fig. 7) relate to similar intrusions buried at shallow depth. The Nicola Horst lacks a discernible magnetic signature, the magnetic field being relatively weak and featureless, apart from some spatially small, yet distinct magnetic highs.

Magnetic susceptibilities

In the absence of information on remanent magnetization within the Iron Mask pluton, modelling has been completed assuming that all magnetization within the pluton is induced. Hence, measurements of magnetic susceptibility provide a vital constraint for modelling. As for density data, measurements of magnetic susceptibility are limited to the vicinity of the New Afton pit, some results of which listed in Table 1 indicate strong mean values ranging from 14.8 to 35.7 × 10^{-3} SI for several units, including BXF, BXFF, BXFX, and Pothook and Sugarloaf diorites; Cherry Creek monzonite; and the unit of picrite. Separate determinations by R. Enkin, Pacific Geoscience Centre yielded mean susceptibilities of 17.6, 13.6, 7.4, and 26.8 × 10^{-3} SI for rocks within units of BXF, diorite, monzonite, and picrite, respectively. The intense hydrothermal alteration that has affected the area of the pit may result in the values for diorite and monzonite being unrepresentative for these rock types in other parts of the pluton.

Modelling the magnetic field – Iron Mask pluton

A magnetic profile for modelling was selected along the same path (A-B, Fig. 7) as that for the gravity model. The profile (Fig. 8, 9a) was derived from magnetic data recorded by the Kamloops survey, since this provides uniformity along the length of the profile. Data from the Fugro survey offers higher resolution, but coverage is limited to the Iron Mask pluton and narrow marginal areas of Nicola Group volcanic rocks (Fig. 8). Because of this limited extent, the profile does not display the background magnetic field against which prominent magnetic highs can be compared for modelling purposes. The profile, geological sections, and a derived magnetic model are shown in Figure 9.

The profile (Fig. 9a) is dominated by a central high, roughly 3100 nT amplitude, located over the Iron Mask pluton (Fig. 9b, c), that includes three principal peaks. A smaller amplitude, albeit prominent, high lies approximately 4.5 km north-northeast of the primary peak of the central high, falling on the Eastern volcanic facies of the Nicola Group, but within and above the buried Iron Mask pluton as modelled from gravity data (Fig. 6). Flanking lows result in difficulty in estimation of its amplitude, which is at least 800 nT. Near the south-southeast end of the profile a distinct, narrow magnetic high (Anomaly A in Fig. 7) about 1100 nT amplitude coincides with a small area of Miocene basaltic volcanic rocks protruding westward from a larger unit. Although there are small perturbations of the magnetic field over these Miocene rocks, it is concluded that the more distinct signatures are related to various underlying rocks within the Nicola Horst. A strongly magnetic igneous plug approximately 480 m wide and 1350 m vertical extent, top surface at the base of the Miocene volcanic layer just 60 m below surface, is modelled to explain Anomaly A (Fig. 9d).

Modelling of the principal, central magnetic high was guided by the gravity model, base 9300 m below surface (Fig. 6d), of the Iron Mask pluton, and assuming the source of the high is within the pluton. In the magnetic model the pluton is subdivided into several narrow, vertical to near-vertical sheets having generally moderately high to high magnetic susceptibilities. The sheets are colour-coded with deeper shades of pink representing relatively stronger susceptibilities for the 9300 m deep model; susceptibilities range from 7.5 to 120 × 10^{-3} SI. Compared to the mean susceptibilities (Table 1) determined on rocks within the Afton pit that range from 19.5 × 10^{-3} SI for dioritic rocks to 35.7 × 10^{-3} SI for picritic rocks, these modelled susceptibilities are surprisingly large, but not out of the question. Ludwig (2016) derived an inverted model from a strong magnetic anomaly running southeastward from the New Afton pit, the edge of which passed over the past producer (magnetite) Magnet deposit. The model included a narrow zone of strong susceptibilities extending from surface to about 1500 m depth, dipping at approximately 75° and increasing in width downward from about 250 m to some 700 to 800 m in its lower half. Susceptibility values attain maxima of about 630 × 10^{-3} SI and 550 × 10^{-3} SI within the core at depths of roughly 100 m and 500 m, respectively. Although the inverted anomaly was proximal to a magnetite deposit, this model demonstrates the potential for high susceptibilities within the pluton.

The case for steep units is supported by structural measurements displayed on the 1: 25 000 scale geological map of Logan et al. (2006a). Dips of bedding, veins, igneous flow layering, foliations, and brittle shears within a 5 km wide belt centred on the model line A-B (Fig. 2) were examined. The measurements are not uniformly distributed, tending to occur in widely separated clusters, but eighty measurements within the belt have a mean dip of 60.5° ± 19°, and 53% of these have a dip greater than 60°. Very widely distributed clusters of measurements elsewhere in the pluton are characterized by similar populations of dips. Although a variety of structures are steep throughout the pluton, strike directions are extremely variable, and by no means universally aligned with the overall trend of the pluton, but their general steepness provides a measure of accord with the modelled magnetic units.

Steep magnetic units with strongly contrasting magnetic susceptibilities facilitate reproduction of the individual peaks on the high. It was initially assumed that magnetic units

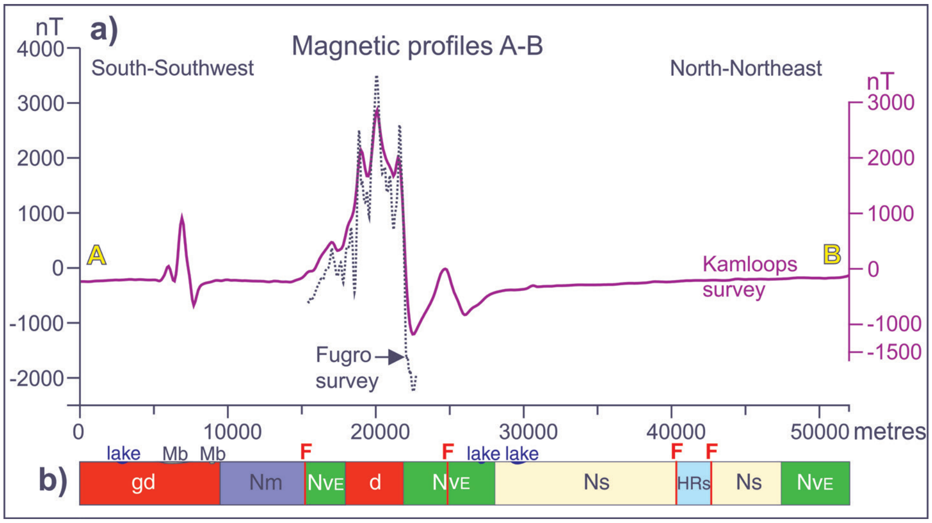

Figure 8. a) Magnetic profiles derived from Kamloops and Fugro survey data along line A-B (Fig. 7); **b)** schematic geological section (arbitrary vertical contacts) illustrating surface geology (from MapPlace, 2018): gd, Late Triassic-Early Jurassic granodioritic rocks; Nm, Nicola Group metamorphic rocks; NVE, Nicola Group Eastern facies, basaltic volcanic rocks; Ns, Nicola Group fine-grained sedimentary rocks; HRs, Harper Ranch Group, various sedimentary rocks; Mb, Miocene basaltic volcanic rocks; F, fault.

extended to the same depth as the two units representing the Iron Mask pluton derived in the gravity model, and the bottoms of all magnetic units were positioned at a depth of about 9300 m below surface. The match between the observed and calculated profiles is reasonable (RMS error = 64.55 nT), but the lower part of the calculated south-southwestern flank of the central magnetic high is noticeably displaced upward by as much as roughly 165 nT from the observed profile. This relates to the vertical component of the magnetic attraction of deeper portions of modelled units significantly influencing the magnetic field for a considerable horizontal distance from their locations. This effect can be compensated by placing the bases of units at shallower depth.

Accordingly, experimentation of models having bases of magnetic units at shallower depth ensued. Repositioning bases at 5700 m below surface produces much improved agreement between observed and calculated profiles along the south-southwestern flank of the Iron Mask magnetic high (Fig. 9a), with curvatures of relevant parts of the profiles closely matching. Because former lower portions of magnetic units no longer contribute to the magnetic high, the susceptibilities of the new model units were increased to compensate. Generally, the increase in units within the central part of the Iron Mask pluton, where the top of the pluton coincides with the ground surface, is less than 11%, one exception being 22%. The relatively small increase is a consequence of the magnetic response of deeper parts of steep, narrow magnetic units below a critical depth being relatively insignificant (Fig. 5). Significantly larger percentage increases in susceptibility are required for units of the pluton buried under younger cover rocks.

Potential field modelling is ambiguous and several geologically reasonable models may be consistent with a particular gravity or magnetic profile. In the present case a gravity model suggests a thicker pluton (base at 9300 m below surface) than a magnetic model (5700 m below surface) (Fig. 9d). Discussion of uncertainty in the depth to bases of modelled units in the gravity model (Fig. 6d) noted that a satisfactory match of observed and modelled profiles could be achieved for shallower bases for the two units modelled for the Iron Mask pluton, by marginally increasing the unit densities. Given that the magnetic model with shallower bases results in a much better match of the south-southwestern flank of the Iron Mask magnetic high, it is conceivable that the base of the pluton may be as shallow as about 5700 m below surface. In this case densities of each of the two pluton units needed to be increased by 30 kg/m^3 and the density of the Lac Le Jeune granitoid decreased by 10 kg/m^3 in the gravity model (Fig. 6d). Relatively minor changes in densities of the two interpreted intrusive bodies in the northern half of the profile were also required, as were minor changes in positions of portions of some of the modelled units (not displayed in Fig. 6d). If the evidence of magnetic modelling is favoured, a shallower depth of approximately 5700 m for the base of the pluton is proposed.

The modelled magnetic units are vertical or near-vertical, but could they possibly be dipping at relatively gentle angles? In a model in which they dip south-southwest, even at a relatively steep 60°, the problem of matching the lower part of the south-southwest flank of the Iron Mask high is exacerbated. It is, therefore, considered unlikely that they dip in that direction, and certainly not at a relatively low angle. If they dip north-northeast at 60°, the calculated profile falls well below the observed profile, where the pluton is buried beneath

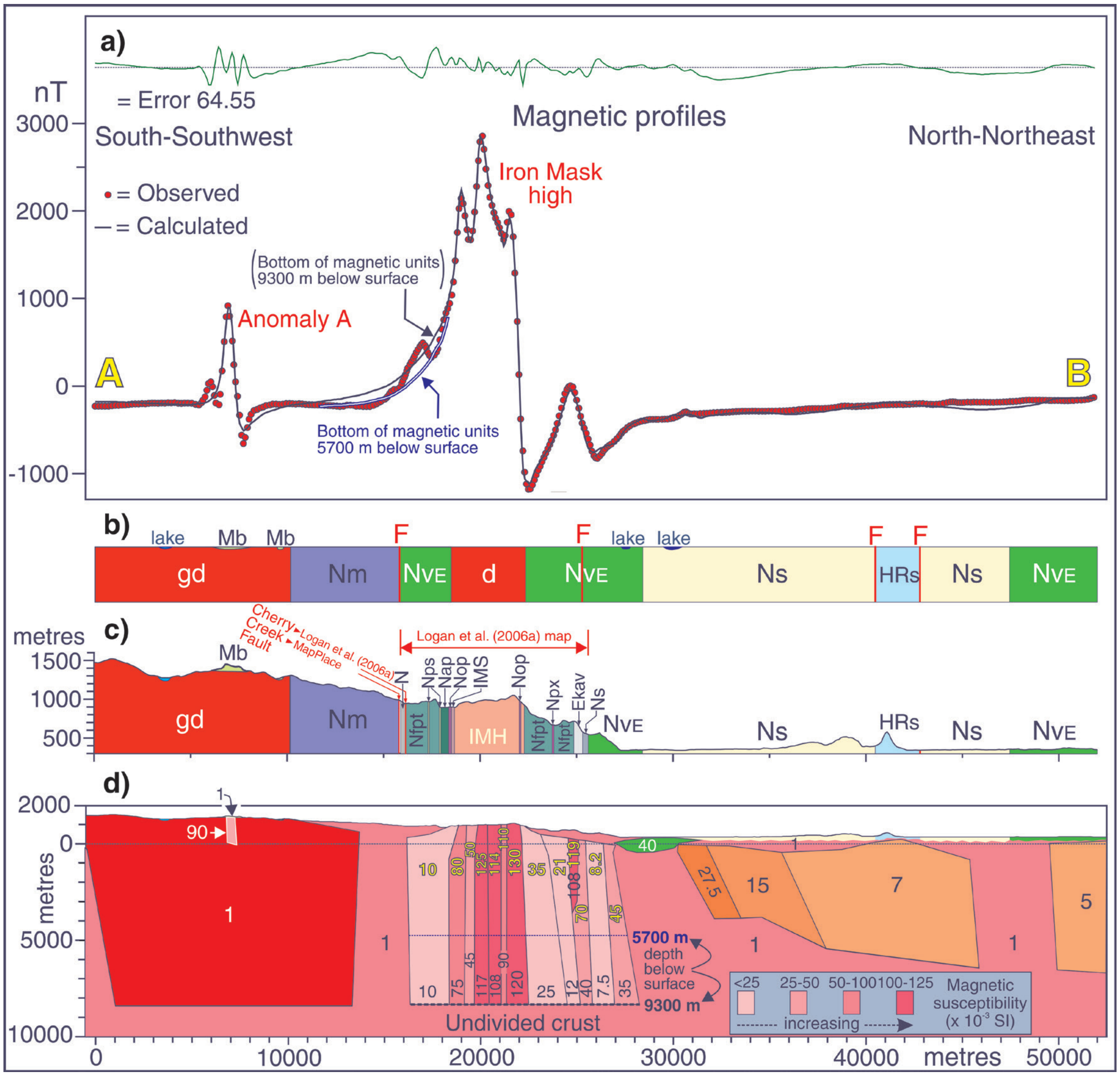

Figure 9. a) Observed and calculated (= model) magnetic profiles and error profile along Line A-B (see Figures 1, 7 for location); **b)** schematic geological section (arbitrary vertical contacts) illustrating surface geology (from MapPlace, 2018) – *see* Figure 6b caption for explanation of abbreviations, **c)** geological section (arbitrary vertical contacts) incorporating MapPlace (2018) and Logan et al. (2006a) information – *see* Figure 6c caption for explanation of abbreviations, **d)** magnetic model; susceptibilities for magnetic units within the Iron Mask pluton when they extend to depths of 9300 m and 5700 m below surface are shown in navy and yellow, respectively. Units within modelled Cherry Creek pluton are colour-coded according to size of their magnetic susceptibility; the pink of the undivided crust unit (susceptibility = 1 x 10^{-3} SI) is not part of this coding.

younger formations along its northeastern margin. Although such a misfit can be compensated by increasing magnetic susceptibilities of relevant units, steeply dipping units can more easily reproduce the observed magnetic signature and are a favoured explanation. There are insufficient structural measurements to favour a dip in any particular direction.

The susceptibilities in the shallow model of the Iron Mask pluton range up to 130 × 10^{-3} SI, which, based on a formula cited by McCafferty et al. (2004), is equivalent to a magnetite content of 4.14%. Many susceptibilities are greater than or equal to 50 × 10^{-3} SI, equivalent to 1.6% magnetite content.

Modelling the magnetic field – Cherry Creek pluton

The Cherry Creek pluton is associated with two belts of magnetic highs. One runs along the southeastern margin of the pluton, apparently partially extending southeastward into a unit of Eocene Battle Bluff complex (Fig. 10a, b). The strongest peak values range from roughly 1675 nT to 4375 nT, while many others fall between roughly 200 nT and 1000 nT. Estimation of a background level for the magnetic field is made difficult by the presence of many closely spaced magnetic highs in the area, but it is speculated to lie between −200 nT and −300 nT.

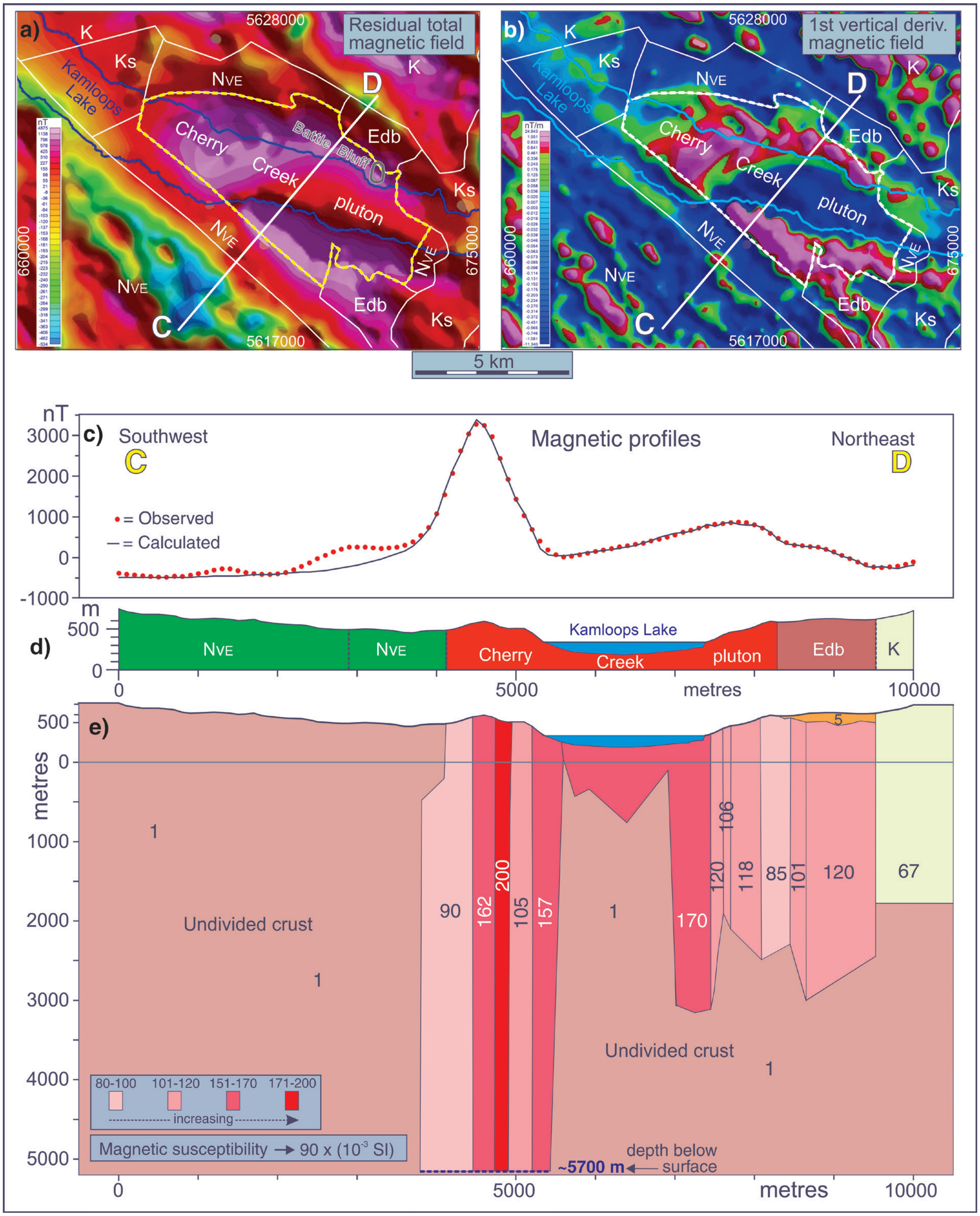

Figure 10. **a)** Residual total magnetic field map of Cherry Creek pluton with geological contacts superposed; C-D is line of modelled magnetic profile, **b)** Map of first vertical derivative of magnetic field of the pluton with geological contacts superposed, **c)** observed and calculated magnetic profiles along line C-D for model in (e), **d)** geological section (arbitrary vertical contacts) along C-D illustrating surface geology (from MapPlace, 2018); geological legend for (a), (b) and (d): K, Kamloops Group undivided volcanic rocks; Ks, Kamloops Group sedimentary rocks; NVE, Nicola Group Eastern facies, basaltic volcanic rocks; and Edb, Eocene Battle Bluff complex, diabase, intrusive basaltic rocks, **e)** magnetic model derived from observed profile along C-D with units in red-pink shades representing the Cherry Creek pluton; these units are colour-coded according to size of their magnetic susceptibility; the pink of the undivided crust unit (susceptibility = 1 x 10^{-3} SI) is not part of this coding.

The second magnetic high covers roughly the western half and northern marginal area of the pluton. It extends northeast from within Kamloops Lake, curving east-southeastward on land to lie between the lake and a unit of Battle Bluff complex. Peak values are weaker, but three are in the range 1585 nT to 1920 nT. Strong, linear northeast-trending gradients associated with the broad western portion of the high expressed in the map of the first vertical derivative of the magnetic field (Fig. 10b) hint at the presence of faults. In the southeastern half of the pluton, the two highs are separated by a parallel low that is essentially coincident with Kamloops Lake.

Kwong (1987) reported that the Cherry Creek pluton is composed entirely of the Cherry Creek unit (= Cherry Creek phase). In the Iron Mask pluton the unit includes biotite monzonite and microporphyries ranging in composition from monzodiorite to monzonite, and contains up to 10% disseminated magnetite (Logan and Mihalynuk, 2005). Although the magnetite content is substantial, the Cherry Creek phase within the Iron Mask pluton produces the weakest magnetic response of the component units (Thomas, in press).

A northeast-oriented magnetic profile (C-D, Figure 10c) crossing the central part of the Cherry Creek pluton was selected to model the two belts of magnetic high and intervening low along Kamloops Lake. The low, as predicted from the derived model (Fig. 10e), apparently is related primarily to a much thinner section of the pluton, though the waters of Kamloops Lake, effectively locally increasing the flight elevation, suppress somewhat the magnetic signal. The north end of the profile crosses a unit of Battle Bluff complex (Ewing, 1981) essentially lacking a closely correlative magnetic high, though the magnetic field is slightly elevated. This is attributed to the underlying Cherry Creek pluton, rather than to the complex. The complex comprises three diabase sills, cumulative thickness about 120 m, the lowest of which follows the contact between the basal formation of the Eocene Kamloops Group in this area, the Tranquille Formation, and basement rocks (Ewing, 1981). A map and stratigraphic column presented by Ewing (1981, Figure 12) indicates that the basement is Nicola Group, though MapPlace (2018) shows the Battle Bluff complex in contact with the Cherry Creek pluton (Fig. 10).

The magnetic profile is dominated by a central high, approximately 3800 nT in amplitude, spanning the Cherry Creek pluton south of Kamloops Lake (Fig. 10c). This is flanked to the northeast by a much less intense and broader high, ~1350 nT amplitude, extending from the south shore of the lake to the northeast end of the profile, peaking on the pluton, before decreasing gradually northeastward over the Battle Bluff complex. Amplitudes are relative to the background field at the southwest end of the profile. Modelling was guided by the magnetic model derived along line A-B crossing the Iron Mask pluton that indicated a maximum depth of the pluton of about 5700 m below surface (Fig. 9d). The amplitudes of the principal magnetic highs for the Cherry Creek pluton and Iron Mask pluton are fairly similar, about 3800 nT and 3100 nT, respectively. Accordingly, bases of modelled magnetic units related to the central high were arbitrarily positioned ~5700 m below surface (Fig. 10e).

The portion of the pluton south of Kamloops Lake is modelled as five contiguous vertical sheets having a cumulative width of about 1700 m and susceptibilities ranging from 90 to 200 × 10^{-3} SI, and are the main source of the central magnetic high. Susceptibility values for six similar vertical sheets terminating at roughly 5700 m below surface, modelled to explain the principal magnetic high associated with the Iron Mask pluton, are noticeably lower, ranging from 50 to 130 × 10^{-3} SI, but their cumulative width is a much wider 4000 m (Fig. 9d). The thinner portion of the Cherry Creek pluton beneath the lake has a high susceptibility of 170 × 10^{-3} SI.

Under the southern and central portions of Kamloops Lake the thickness of the pluton decreases dramatically to a maximum of about 950 m, before increasing rapidly under the northern part of the lake, where its base descends to a depth of about 3400 m below the lake bottom. The base can be shallowed by 1000 m without significant change to the root mean square fit of the observed and calculated profiles, and the misfit could be easily rectified by small modifications to susceptibility and/or contacts. Further shallowing, probably, would also not produce large changes. The inherent problem of positioning the bases of narrow, steep units has been discussed, and considering that the displayed geometries were based on progressive modelling, this model is considered acceptable, but naturally not unique.

From Kamloops Lake to the northeast end of the profile the Cherry Creek pluton is modelled to be between about 2300 m and 3500 m thick, and partially buried beneath Battle Bluff volcanic and sedimentary rocks (Fig. 10e). Several narrow vertical units are modelled within the northern margin of the pluton, susceptibilities ranging from 85 to 120 × 10^{-3} SI. An arbitrary susceptibility value of 1 x 10^{-3} SI has been assigned to country rocks, thought to be represented mainly by Nicola Group volcanic rocks. The contact between the Battle Bluff complex and Kamloops Group volcanic rocks to the northeast is marked by a west-northwest-trending linear fault (Ewing, 1981), and this is interpreted to be vertical and to truncate the Battle Bluff complex and underlying Cherry Creek pluton in the model.

To maintain the level of the magnetic field at the northeast end of Profile C-D, controlled mainly by magnetizations within the pluton, a high susceptibility and significant thickness are required for volcanic rocks of the Kamloops Group in this locality. Thomas (2010) determined a mean susceptibility value of 11.56 ± 12.11 × 10^{-3} SI (range 0.27 – 40.40 × 10^{-3} SI) from more than 100 in situ measurements on seven outcrops of such volcanic rocks located some 70 to 120 km north of Kamloops Lake. Their distant locations mean the values provide only a general idea of the susceptibilities of these rocks. Mean susceptibilities for massive volcanic rocks at three outcrops range from 22.34 to 25.16×10^{-3} SI, with a much lower value of 4.54×10^{-3} SI obtained at another outcrop. Massive amygdaloidal volcanic rocks at an outcrop produced a low mean value of 2.39×10^{-3} SI, and even lower susceptibilities of 0.37 to 2.51×10^{-3} SI were associated with apparently fragmental volcaniclastic varieties. In the model a thickness of 2500 m was assigned to the Kamloops Group north of the Battle Bluff complex based on stratigraphic thicknesses described by Ewing (1981). This thickness, in turn, determined the susceptibility required to reproduce the observed magnetic field, which is a large 67×10^{-3} SI, that compares with the largest single value of about 40×10^{-3} measured to the north. However, the magnetic field over the large expanse of Kamloops Group volcanic rocks north of Kamloops Lake is characterized by strong magnetic anomalies, some of which rival the positive magnetic signatures over the Cherry Creek pluton in peak values. Given the large susceptibilities modelled for pluton magnetic units, a value of 67×10^{-3} SI apparently is reasonable. The local suppression of the magnetic field over the Battle Bluff complex and its inclusion of sedimentary rocks led to assignment of a low, and arbitrary, susceptibility value of 5×10^{-3} SI to the complex.

The Iron Mask and Cherry Creek plutons both include significant portions of dioritic rocks and both are modelled with steep composite units having high magnetic susceptibilities. The maximum depth of units in both plutons is the same at roughly 5700 m below surface, because the modelled depth of the Cherry Creek pluton was purposely made the same as that of the Iron Mask pluton. The exposed maximum surface widths of the two plutons are both approximately 4.5 km, but the Iron Mask pluton may be significantly wider at depth. A width of about 11.3 km is modelled from the large correlative gravity high (Fig. 6d), whereas modelling the magnetic signature of the Cherry Creek pluton indicates it to be roughly 5.7 km wide (Fig. 10e).

Curiously, no prominent gravity high is associated with the Cherry Creek pluton (Fig. 3, 4a, b, c). Given the high densities (2955 and 2880 kg/m^3) modelled for the two density units (depth 5700 m) in the Iron Mask pluton, characteristic of dioritic rocks, and the similar depth of part of the Cherry Creek pluton, it is puzzling why the latter is not associated with a prominent gravity anomaly. Possibly, dioritic rocks observed at surface grade downwards into lower density, yet reasonably strongly magnetic rocks having a more granitic or granodioritic composition. Or perhaps the Cherry Creek pluton is relatively thin. These options are examined by determining the gravity response of the magnetic model, assigning different densities and/or modifying depths and unit contacts.

If a density of 2880 kg/m^3 is applied to all units in the magnetic model (Fig. 10e), peak gravity responses of about 8.3 mGal and 8.9 mGal are calculated at the flight elevation (200 m) of the airborne survey above the pluton south and north of Kamloops Lake, respectively; the gravity field attains roughly 7.1 mGal between the peaks. These values are significantly more than the roughly 2 mGal gravity highs measured along profile C-D (Fig. 4c), although neither are located within the area of the pluton. That to the south correlates with the Nicola Group, whereas that to the north displays partial coincidence with the pluton, peaking just northwest of the profile with an amplitude of roughly 5 mGal.

Clearly the density of 2880 kg/m^3 is too high, and/or modelled units extend too deep. Tables 1 and 2 of rock densities indicate that diorites may have lower densities. The mean densities of Pothook and Sugarloaf diorites within the Iron Mask pluton, within the Canadian Shield and in New Zealand are 2760 kg/m^3, 2770 kg/m^3 (Gibb, 1968,) and 2800 kg/m^3 (Tenzer et al., 2011), respectively. The dilemma is that the Cherry Creek pluton supposedly has compositional similarities to the dioritic rocks of the Iron Mask pluton, and would be presumed to have similar densities. A choice arises of accepting a Cherry Creek pluton model having deep units with densities much lower than those of equivalent rocks in the Iron Mask pluton, or favouring a model in which magnetic units are less deep, and have densities close to 2880 kg/m^3, thus maintaining a degree of compatibility with the gravity model for the Iron Mask pluton (Fig. 6d). The concept of such a model was examined by creating a model in which units defining the pluton extend only to about 2850 m below surface (Fig. 11d), approximately half the depth of units in Figure 10e. A series of various densities was applied to the units (same density for all units each time), and even though the depth of the units is much smaller, a density of 2880 kg/m^3 produces anomalies south and north of Kamloops Lake, respectively, having amplitudes of roughly 7.2 mGal and 8.2 mGal. The density must be decreased to 2770 kg/m^3 before the amplitudes (roughly 1.6 and 1.95 mGal) are more consistent with the observed amplitudes (Fig. 11b). Remarkably, when a uniform density of 2770 kg/m^3 is applied to the units of the pluton in the deep-pluton model (Fig. 10e), the gravity effect differs little from that of the shallow model (Fig. 11d), with amplitudes of gravity highs south and north of Kamloops Lake being 1.75 and 1.96 mGal, respectively. This relates to the minor contribution of deep parts of geological bodies to potential field anomalies. Seemingly, for either a deep or shallow model of the Cherry Creek pluton, the densities of the plutonic rocks are significantly less than those of presumed counterparts in the Iron Mask pluton.

The apparent significant difference in density is intriguing and raises the question as to whether it is accompanied by complementary differences in the petrology, petrogenesis, and geochemistry of the two plutons that may have a bearing on the development of mineralization. It is noted that the Iron Mask pluton is significantly richer in mineral occurrences than the Cherry Creek pluton.

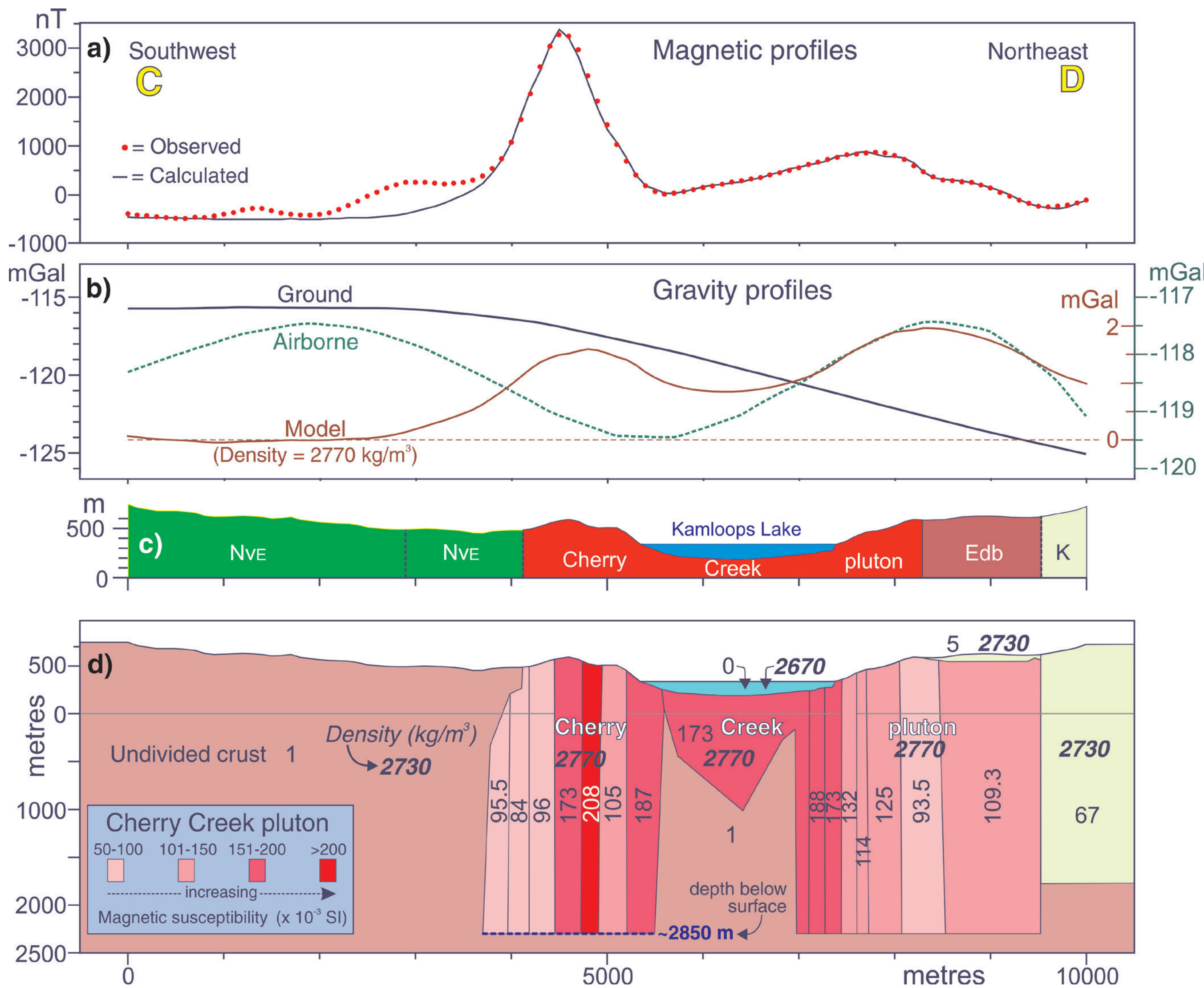

Figure 11. a) observed and calculated magnetic profiles along line C-D for model in (d), **b)** gravity profiles along C-D derived from the ground and airborne gravity surveys and produced from the model in (d) when a density of 2770 kg/m³ is applied to all units of the Cherry Creek pluton and a density of 2730 kg/m³ is applied to the country rocks that may be dominated by Nicola Group volcanic rocks, and to the Kamloops Group; the density of 2670 kg/m³ indicated for Kamloops Lake represents the density of the lake after application of gravity terrain corrections, **c)** geological section (arbitrary vertical contacts) along C-D illustrating surface geology (from MapPlace, 2018); K, Kamloops Group undivided volcanic rocks; NVE, Nicola Group Eastern facies, basaltic volcanic rocks; Edb, Eocene Battle Bluff complex, diabase, intrusive basaltic rocks, **d)** magnetic model derived from observed profile along C-D with units in red shades representing the Cherry Creek pluton, colour-coded according to the size of their magnetic susceptibility; the pink of the undivided crust unit (susceptibility = 1 x 10^{-3} SI) is not part of this coding.

DISCUSSION AND CONCLUSIONS

Prominent gravity and magnetic anomalies associated with the Iron Mask batholith have provided a means for modelling its size and shape. Two-dimensional cross-sectional models across the centres (longitudinal sense) of the two component plutons, the Iron Mask and Cherry Creek plutons, are derived. Both plutons are characterized by strong magnetic fields that include component magnetic highs having amplitudes greater than 3000 nT, but the gravity signatures are quite different. Gravity data from a ground survey define a very strong 25 mGal amplitude high peaking within the central portion of the Iron Mask pluton, but the gravity field associated with the Cherry Creek pluton lacks a noticeable positive signature and simply decreases uniformly eastward across the pluton. The lack of a signature undoubtedly relates to a local paucity of stations defining the field. A gravity map produced from airborne data likewise reveals a lack of a noteworthy gravity high, but does outline a small, approximately 5 mGal amplitude high centred on the northern margin of the pluton (Fig. 4b). Considering that both plutons are largely of dioritic composition, this difference in gravity expression suggests a major difference in thickness and/or density of the intrusions.

An initial gravity model for the Iron Mask pluton predicted a body extending to roughly 9300 m below surface, and consisting of two units separated by a vertical contact having densities of 2850 kg/m^3 and 2925 kg/m^3. These densities are noticeably higher than densities measured on dioritic rocks near the New Afton deposit, and general values obtained in other areas; they are more typical of gabbroic rocks. Given the reasonable possibility for a presence of gabbroic rocks, the model was considered acceptable. The shape of the pluton defined by gravity modelling was retained in magnetic modelling that indicated the pluton includes 13 steep, sheet-like units having strong magnetic susceptibilities, several in the range 75 to 120 × 10^{-3} SI. The steep, narrow geometries of the units facilitated reproduction of individual peaks on the principal magnetic high associated with the pluton. However, difficulty in achieving a close fit to the south-southwestern flank of this magnetic high was remedied by reducing the depth of the bottom of the modelled pluton to approximately 5700 m below surface. This revision led to development of a second, preferred gravity model having the same depth. Minor modifications to some contacts in the initial model and slight increases in densities of the two component units were required.

Two large bodies are modelled to explain less prominent gravity highs north of the Iron Mask pluton, buried mainly within units of Nicola Group sedimentary and volcanic rocks. Except for slight differences in density, the bodies are identical in both the deep and shallow models for the Iron Mask pluton. The top surfaces are at relatively shallow depths ranging generally from about 100 to 800 m, whereas bottom surfaces attain a maximum depth ranging from 4000 to 7000 m. Based on modelled densities of 2800 kg/m^3 and 2830 kg/m^3 (shallow model), the bodies are interpreted to represent dioritic intrusions.

The large Lac Le Jeune gravity low is interpreted in terms of a large granitoid batholith, whose surface is reflected in Late Triassic-Early Jurassic granodioritic rocks exposed within the Nicola Horst. The batholith extends to a depth of approximately 9700 m below surface.

In the absence of an associated gravity anomaly, the subsurface shape of the Cherry Creek pluton was modelled from magnetic data, initially assigning a depth of 5700 m below surface to units directly correlating with the principal magnetic high. This depth was chosen because the amplitude of the high is similar to that associated with the Iron Mask pluton. Density considerations vis-à-vis the lack of a noteworthy positive gravity signature over the pluton prompted creation of a second, shallower model having a general depth of about 2850 m below surface. This model comprises several near-vertical, narrow sheet-like units, all with strong magnetic susceptibilities (84 – 208 × 10^{-3} SI). In order not to produce a gravity high where none has been defined, the density of the pluton has been assigned a relatively low value of 2770 kg/m^3. This density is reasonable and consistent with measured densities for dioritic rocks in the Iron Mask pluton (Table 1). Unexpectedly, the deeper magnetic model when assigned the same density also does not produce a significant gravity high. Gravity data does not therefore help in determining which of the two magnetic models is a more reasonable representation of the shape of the pluton with respect to depth.

Magnetic modelling suggests horizontal zoning across both plutons with steep sheet-like units displaying significant variation in magnetic susceptibility. This large-scale horizontal magnetic zoning with steep contacts between zones may have relevance for structural studies and fluid pathways. Some contacts may be represented by faults, as Logan and Mihalynuk (2005) have noted a significant presence of high- and moderate-angle faults considered to be major deep-seated structures that may have controlled development of the Nicola Group and intrusion of various phases of the Iron Mask pluton.

The difference between the gravity expression of the Cherry Creek and Iron Mask plutons, and apparent differences in modelled depths and densities of the plutons is intriguing. The density difference infers that diorites within the Iron Mask pluton, for whatever reason, are significantly more dense, and/or the presence of a large component of gabbroic rocks. Mineral occurrences are much more abundant and widespread in the Iron Mask pluton, raising the question as to whether there are petrogenetic differences between the diorites that influence mineralization within the plutons. The modelled extension of the Iron Mask pluton along both flanks below adjacent volcanic rocks enlarges the area of potential mineralization, although the volcanic cover is an impediment to exploration, and the depth to any mineralization may deter any mining venture. The potential presence of a large granitoid batholith rivalling the economic Guichon batholith also offers thought for exploration, though once again Nicola Group cover rocks may pose difficult challenges.

Potential field models are inherently ambiguous, and confidence in models is enhanced when independent constrains are available. The models presented suffer from a lack of such constraints, and particularly with respect to rock properties. Available density and magnetic susceptibility information is restricted to the vicinity of the New Afton deposit. More reliable models could be achieved given the availability of a more comprehensive rock-property database and detailed ground gravity profiles across both plutons. The problem relating to precise definition of depths to the bottom of modelled units would, however, remain.

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