Mapping Quaternary paleovalleys and drift thickness using petrophysical logs, northeast British Columbia, Fontas map sheet, NTS 94I[1]

Adrian S. Hickin, Ben Kerr, Derek G. Turner, and Tom E. Barchyn

Abstract: The relatively subdued topography of British Columbia's northern interior plains does not reflect the irregular, buried bedrock surface. Many areas have been deeply incised by preglacial rivers that have subsequently filled with a succession of Quaternary sediments. In this study, oil and gas petrophysical logs, drill chip samples, water well logs, and surficial and bedrock outcrop maps were used to model the bedrock topography of the Fontas map sheet (NTS 94I). The modelled data produced several depressions that are interpreted to be paleovalleys incised into the soft Cretaceous shale of the Fort St. John Group. Understanding the geometry, thickness, and stratigraphy of the drift has considerable safety and resource management implications as artesian aquifers and natural gas were encountered in the drift during oil and gas well drilling. Four major paleovalleys are suggested. The most dominant paleovalley (Kotcho–Hoffard Paleovalley) is located south of the Etsho Plateau and trends west-southwest across the map area. A second depression occurs within the loop of the Hay River and may be a tributary of the Kotcho–Hoffard Paleovalley that links with the Rainbow Paleovalley in Alberta. A third paleovalley is mapped south of the Sahtaneh River (Kyklo Creek Paleovalley) and is either a tributary to, or crosscuts the Kotcho–Hoffard Paleovalley. The Niteal Creek Paleovalley is located between the Fontas and Sikanni Chief rivers. Its geometry is speculative as there are sparse data, but it may be a tributary of the Kotcho–Hoffard Paleovalley.

Résumé : La topographie relativement douce des plaines intérieures du nord de la Colombie-Britannique ne reflète pas la surface irrégulière du socle enfoui. De nombreux secteurs ont été profondément découpés par des rivières préglaciaires qui ont ultérieurement été remplies par une succession de sédiments durant le Quaternaire. Dans la présente étude, des diagraphies pétrophysiques de gaz et de pétrole, des diagraphies de puits d'eau, des cartes des affleurements et des sédiments superficiels ainsi que des échantillons de déblais de forage ont été utilisés pour modéliser la topographie du socle de la feuille de carte Fontas (SNRC 94I). Les données modélisées ont produit plusieurs dépressions qui sont interprétées comme des paléovallées découpées dans le shale mou du Groupe de Fort St. John (Crétacé). La compréhension de la géométrie, de l'épaisseur et de la stratigraphie des sédiments glaciaires comporte des implications considérables de sécurité et de gestion des ressources en raison du gaz naturel et des aquifères artésiens rencontrés dans les sédiments lors de forages pour le gaz et le pétrole. Quatre grandes paléovallées sont suggérées. La paléovallée principale, Kotcho–Hoffard, est située au sud du plateau Etsho et elle recoupe le secteur de la carte selon une direction ouest-sud-ouest. Une deuxième dépression est située à l'intérieur de la boucle de la rivière Hay et elle pourrait être un tributaire de la paléovallée Kotcho–Hoffard qui rejoint la paléovallée Rainbow en Alberta. Une troisième paléovallée, Kyklo Creek, est cartographiée au sud de la rivière Sahtaneh et elle serait tributaire de la paléovallée Kotcho–Hoffard ou elle recouperait cette dernière. La paléovallée Niteal Creek est située entre les rivières Fontas et Sikanni Chief; sa géométrie est spéculative en raison de la faible quantité de données, mais elle pourrait être un tributaire de la paléovallée Kotcho–Hoffard.

[Traduit par la Rédaction]

Introduction

Bedrock topography is often obscured in glaciated terrain. Sediment accumulates in preexisting valleys, masking bedrock irregularities. Buried valleys are well known throughout Canada's Interior Plains (e.g., Stalker 1960, 1967; Christiansen 1961; Andriashek and Fenton 1989; Horne and Seve 1991; Pawlowicz et al. 2005). However, with the exception of Mathews (1978) work on the Paleo-Peace River valley near Fort St. John, little bedrock topography and drift thickness information has been published for northeast British Columbia (NEBC). This study provides regional bedrock topography and drift thickness for the Fontas map sheet (National Topographic System (NTS) map sheet 94I). The mer-

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A.S. Hickin,[2] B. Kerr, and T.E. Barchyn. Ministry of Energy, Mines and Petroleum Resources, P.O. Box 9323 Stn Prov Govt, Victoria, BC V8W 9N3, Canada.
D.G. Turner. Department of Earth Science, Simon Fraser University, 8888 University Drive, Burnaby, BC V5A 1S6, Canada.

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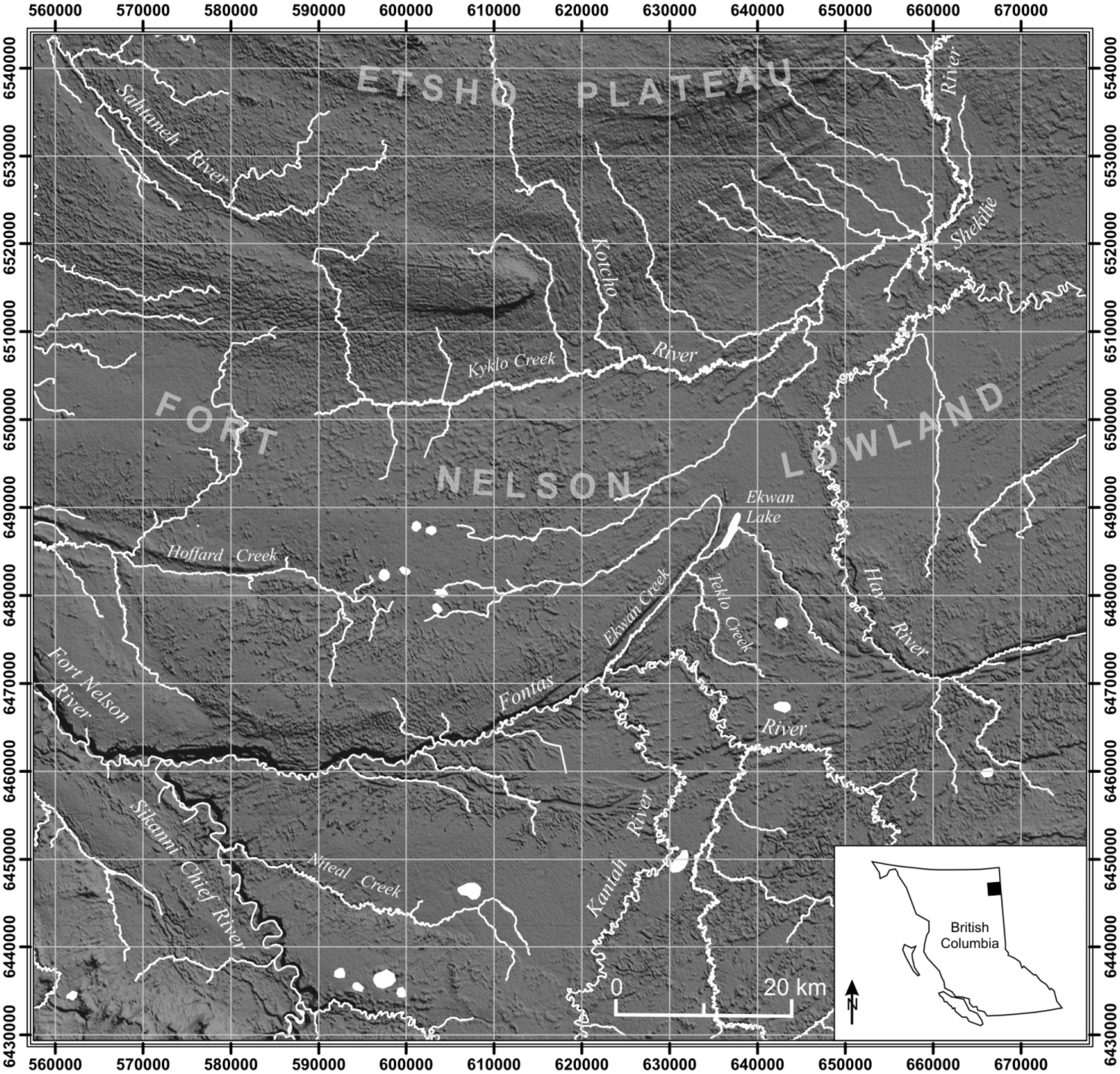
[2]Corresponding author (e-mail: adrian.hickin@gov.bc.ca).

Fig. 1. The study area is located in northeastern British Columbia in NTS map sheet 94I (Shuttle Radar Topography Mission (SRTM) digital elevation model; 10× vertical exaggeration).



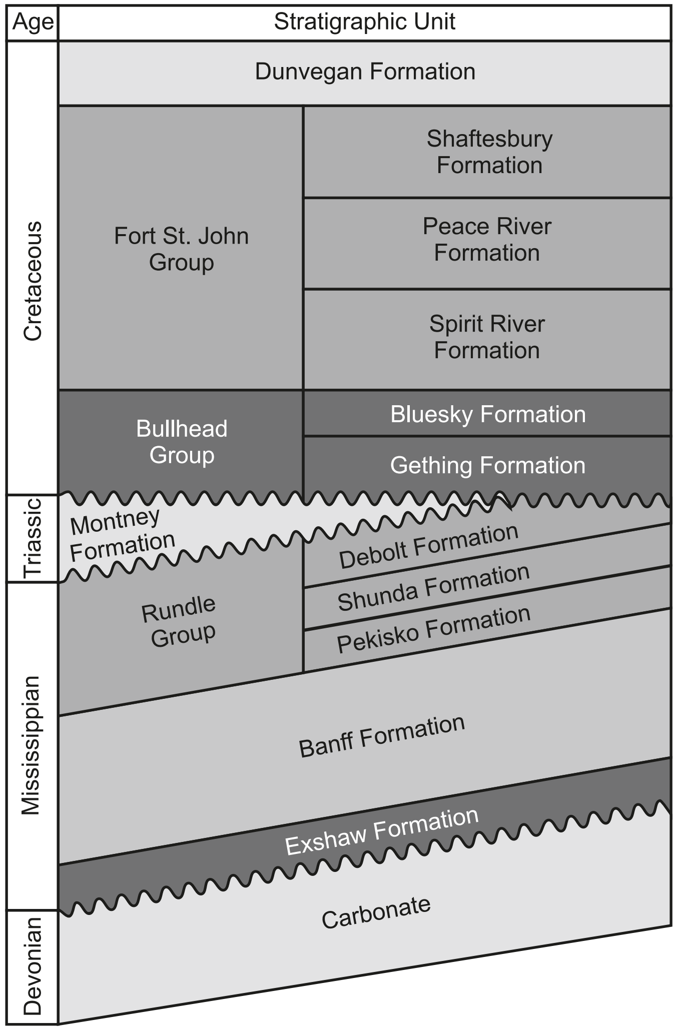
its and limitations of the mapping methods are discussed, and the major trends of paleovalleys in the study area are identified. Understanding the geometry and depth of these paleovalleys is becoming increasingly important for shallow gas exploration, drilling safety, casing depth estimates, aquifer management, and seismic processing and interpretation (Levson et al. 2006).

The study area is located in the British Columbian portion of Canada's Interior Plains (Holland 1976; Fig. 1). Much of the surface topography occurs at <610 m (2000 ft) above sea level (asl) and is part of the Fort Nelson Lowland physiographic region. Areas with elevations >610 m (2000 ft) asl, such as the Etsho Plateau, are arbitrarily assigned to the Alberta Plateau physiographic region (Holland 1976).

Much of the map area is underlain by Cretaceous age shale of the Fort St. John Group (late Albian to Cenomanian; Fig. 2). The Fort St. John Group is exposed along incised portions of the Sikanni Chief, Fontas, Kotcho, and Fort Nelson rivers and along portions of the Etsho Plateau escarpment. It consists of soft shale and siltstone with thin beds of fine-grained sandstone. In areas with elevation >610 m, Thompson (1977) mapped Upper Cretaceous Dunvegan Formation. Thompson (1977) did not encounter Dunvegan Formation in outcrop but inferred its presence based on topographic expression. Three areas are mapped as Dunvegan Formation in the map area, including the Etsho Plateau in the north, the uplands of the upper Fontas River in the southeast, and several prominent knobs in the southwest. Where exposed, west of the study area, the Dunvegan Formation is typically a cliff-forming succession of deltaic and pro-deltaic sandstone, conglomerate, and carbonaceous mudstones (Stott 1967).

In this study, major subsurface stratigraphic boundaries were picked from well logs, which include the Shaftesbury

Fig. 2. Generalized bedrock stratigraphy for the study area (after Stott 1982 and Thompson 1977).



and Spirit River formations of the Fort St. John Group (Cretaceous), Bullhead Group (Cretaceous), Diaber Group (Triassic), and Rundle Group (Mississippian; Fig. 2). Fort St. John Group, in the study area, is difficult to divide into its members as this succession represents distal basin facies, dominated by shale and siltstone, and minimal sandstone. Despite this, the Fort St. John Group can be separated into the Shaftesbury Formation and the Spirit River Formation. The lower Shaftesbury Formation contains a highly radioactive interval (condensed section), the base of which is marked by a sharp gamma drop separating the Shaftesbury from the underlying Spirit River Formation (W. Walsh, personal communication, 2007).

Where present, Bullhead Group strata underlie Fort St. John Group sediments. The Bullhead Group in 94I is represented by a thin wedge of siltstone and sandstone that thins to the northeast and pinches out to the west (Stott 1973). The base of the Bullhead Group in the area is coincident with the sub-Cretaceous unconformity.

The base of the Cretaceous is marked by a regionally extensive unconformity that eroded southwest dipping pre-Cretaceous sediments, forming erosional edges of the older Triassic and Mississippian units. The Triassic Diaber Group, represented by the Montney Formation, occurs in the southwest of the map area with an eastern margin near Kantah River. The Montney Formation consists of siltstone, shale, and sandstone and is an important gas-bearing unit (Glass 1997; British Columbia Ministry of Energy, Mines and Petroleum Resources 2006). Where the Triassic succession is absent, the Cretaceous package occurs directly above the Mississippian Rundle Group. The Rundle Group consists of crinoidal limestone (Pekisko Formation), interbedded limestone, dolostone, siltstone, sandstone, shale and breccia (Shunda Formation), and limestone with minor dolomite and shale (Debolt Formation). The Rundle Group also contains important gas-bearing units with several play styles including subcrop margin, distal ramp, and regional platform (Glass 1997; British Columbia Ministry of Energy, Mines and Petroleum Resources 2006).

The surficial geology of NEBC and northern Alberta is the result of Tertiary and Quaternary events. During the Tertiary, the Laramide Orogeny resulted in the uplift and subsequent erosion of the Rocky Mountains and adjacent areas. Erosion was the dominant geomorphic process through to the early Quaternary (Edwards and Scafe 1996). Paleodrainage during this time was likely eastward, down the regional slope towards Hudson Bay. Quartzite-rich gravels were transported from the Rocky Mountains, onto the Alberta Plateau as far east as central Alberta. These gravels armoured the relatively soft Cretaceous sediments and assisted in the formation of tablelands. Some of the major valleys (and paleovalleys) in NEBC are likely remnants of Tertiary drainage systems. Climatic deterioration began at the end of the Tertiary culminated by the glacial–interglacial cycles synonymous with the Quaternary. Much of the landscape of NEBC is attributed to the most recent cycle during the Late Wisconsinan (ca. 25–10 ka). In British Columbia, this glaciation is referred to as the Fraser Glaciation (Clague and Ryder 1989).

The Wisconsinan glacial history in NEBC has been described by Mathews (1963, 1978, 1980), Bobrowsky and Rutter (1992), Catto et al. (1996), Bednarski and Smith (2007), and Bednarski (2008). NEBC was first glaciated prior to the Late Wisconsinan but only a limited, controversial record of these events exists (Mathews 1978, 1980; Reichmen 1980; Hartman 2005; Trommelen 2006). During the Late Wisconsinan, valley glaciers (montane), the Cordilleran Ice Sheet (CIS), and the Laurentide Ice Sheet (LIS) all interacted. The relationship of these glaciers is complex, with coalescence and nonsynchronous advances occurring along the ice margins (Bednarski and Smith 2007). In general, the LIS advanced from east to west up the regional slope, blocking drainage and developing large pro-glacial lakes along the margin (Mathews 1980). During this same interval, ice accumulated in the mountains and thickened to form large valley glaciers, which eventually combined to form the CIS that flowed east onto the plains from the Rocky Mountains (Rutter 1977; Clague 1989; Catto et al. 1996; Bednarski 2001; Bednarski and Smith 2007). The CIS and LIS likely coalesced for a period before receding (Jackson et al. 1997). As the CIS thinned to form valley glaciers, the LIS retreated, again forming large pro-glacial lakes along its margin (Mathews 1980; Dyke et al. 2003). Evidence for the advance and retreat of ice and the presence of glacial lakes is recorded in the thick sediment sequences and surface landforms that mask the underlying bedrock topography.

Methods

Bedrock topography mapping follows methods outlined by Hickin and Kerr (2005). The process can be summarized into four steps: (1) compile all available data sources, (2) standardize the data in a database, (3) spatially analyze the data and model subsurface horizons, and (4) add geological interpretation.

Several data sources were used to determine the base of the drift as well as the top of the Spirit River Formation, Bullhead Group, Diaber Group, and Rundle Group. These sources include oil and gas petrophysical well logs, drill cuttings, water well logs, and available surficial and bedrock maps.

The most important and reliable source of data was from oil and gas petrophysical logs available from the British Columbia Ministry of Energy, Mines and Petroleum Resources. These contacts, or picks, are termed "hard picks." The majority of the drift–bedrock contacts and all of the bedrock stratigraphy were complied from these data. Gamma logs were the most common log used as they provided lithologic information for both cased and uncased portions of the wells. The drift contact was typically identified by a sharp upward shift from a uniform, relatively high gamma signal in the bedrock to a relatively low, fluctuating signal in the drift (Fig. 3). The uniform gamma signal is associated with thick sequences of dark, organic-rich shale and siltstone of the Fort St. John Group (Shaftesbury Formation). The fluctuating gamma signal is attributed to unconsolidated drift, containing a relatively low organic content and consisting of a variety of units including gravel, sand, diamict, silt, and clay (Fig. 3). Resistivity and conductivity logs were also used where the drift contact occurred below casing. Unfortunately, not all contacts were obvious. In some cases, the contrast between weathered shale and till was subtle and more speculative. In addition, not all wells were logged to surface so that only maximum depth to bedrock could be ascertained.

Drill cuttings were also used to provide an estimate of the depth to bedrock. All available drill cuttings with tops within 300 m of surface were examined and logged (Fig. 4). Glacial sediments have an abundance of exotic clasts that can be transported a considerable distance. In NEBC, these allochthonous lithologies include Canadian Shield granites and Omineca Belt phyllites (Mathews 1980), which presence in drill cuttings suggests glacial sediments.

In most wells where both a petrophysical log and drill cuttings were available, the contacts correlate within 10–15 m. However, there were some wells where the contact determined from the petrophysical log differed greatly from that determined from the drill cuttings. In some cases, granitic fragments were mixed with shale and siltstone over a lengthy interval (>100 m) or cuttings showed an inversion of glacial sediments under shale. Contamination must be considered. In addition, loss of circulating drilling fluids, gradational contacts, and the lag time for a sample to reach the surface all contribute to the ambiguity of the precise depth to the contact. Wherever possible, the cuttings contacts were verified with petrophysical data. The contacts determined solely from drill cutting were only used in the model where no other data were available. In some cases, driller's logs and tour sheets provided supplementary information regarding lithologic units encountered, drilling conditions, or problems associated with the penetration of aquifer- or gas-bearing units in both bedrock and drift. These noted intervals were incorporated into the model as "soft picks" where applicable.

The Province of British Columbia requests drill logs to be submitted to the British Columbia Ministry of Environment for all water wells drilled. The lithologic data from logs within the study area were compiled and incorporated into the model as soft picks. Unfortunately, many of the descriptions were colloquial and provide only limited information.

The final data set incorporated bedrock and surficial geological maps. Outcrop locations and elevations from Thompson (1977) were included as known depth to bedrock. In addition, bedrock and veneer (depth to bedrock <1 m) polygons from surficial maps were also digitized and included as known depths to bedrock (Trommelen 2006; Smith 2008*a*, 2008*b*, 2008*c*, 2008*d*). Data points were generated within the polygons in 100 m grid cells. Bedrock picks in bedrock polygons were coincident with surface elevations from a

Fig. 3. The major stratigraphic units can be identified from gamma logs. The base of drift is marked by an upward shift from a relatively high, uniform gamma response to a more varied, generally reduced signal.

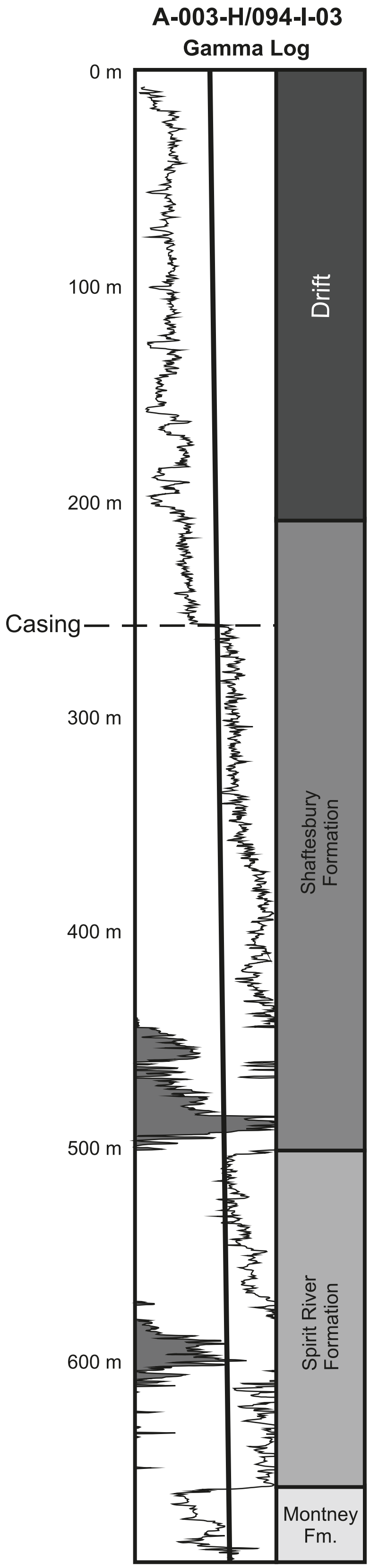
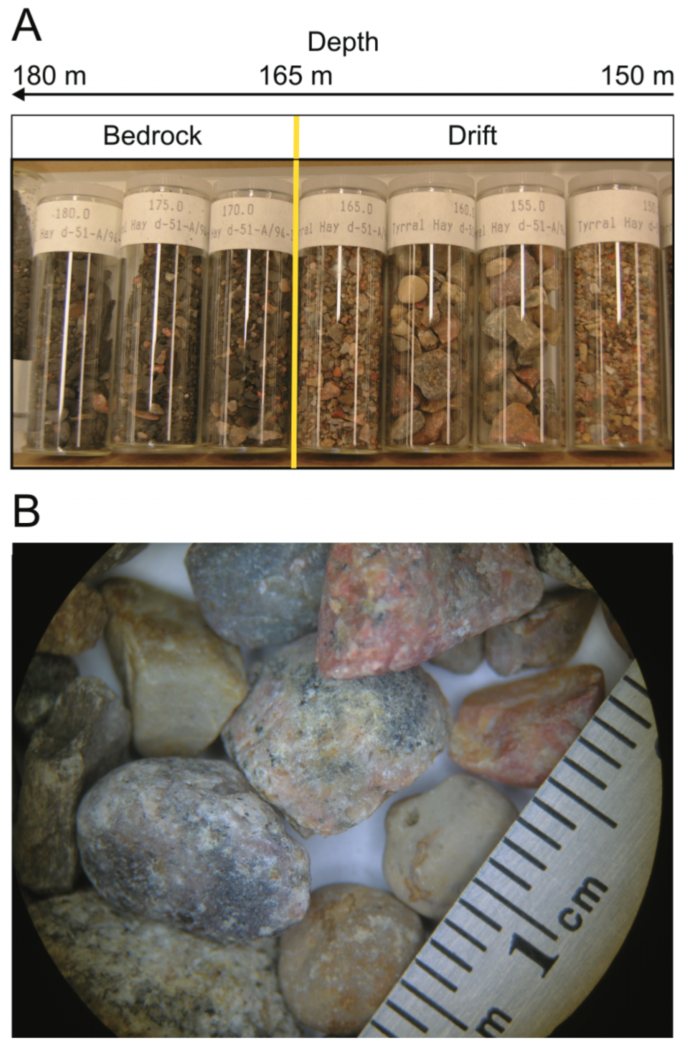


Fig. 4. (A) Drill chip samples are washed and collected during oil and gas well drilling. The recovered chips show a clear distinction between shale bedrock (left) and glacial sediments (right).
(B) Closeup of glacial sediments from the chip sample archived (tick marks in mm).

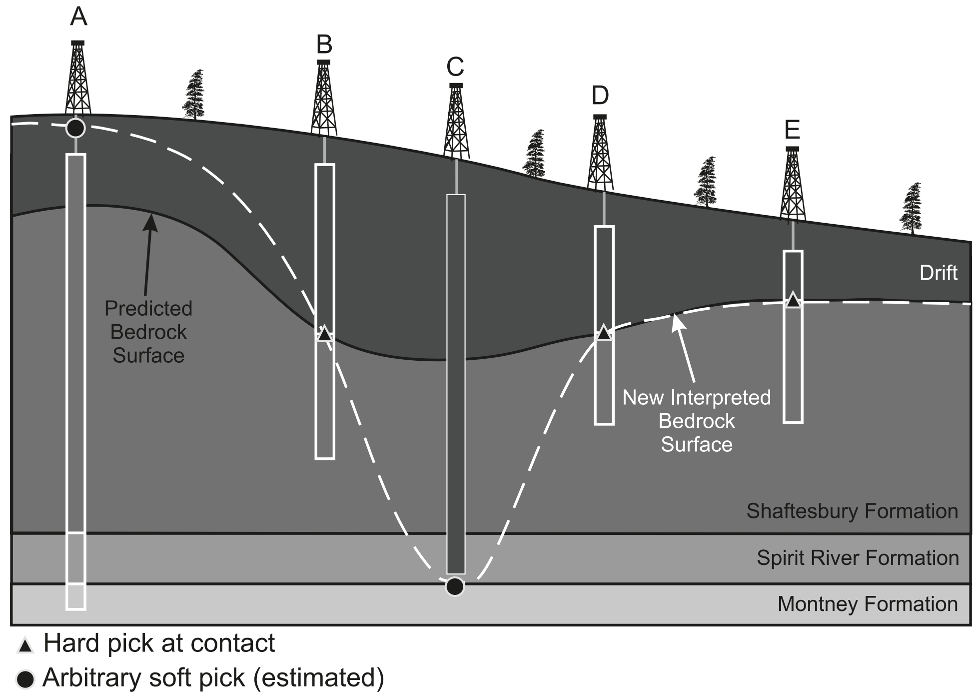


30 m Shuttle Radar Topographic Mission (SRTM) digital elevation model (DEM). Data points for veneer polygons were generated by subtracting 1 m from the DEM. These data are also considered soft picks.

All data were standardized and entered into a Microsoft Access database. Two classifications of data were established, lithologic and stratigraphic. Lithologic data refer to sediment types encountered (e.g, sand, gravel, shale, siltstone, etc.) but do not imply age or assignment of the sediment to a formation or group. These data were typically from oil and gas driller's logs and tour sheets, water well data, and drill cuttings. Stratigraphic data were derived from the petrophysical logs, and units were assigned to formations and groups implying an age relationship (e.g., Drift, Shaftesbury, Spirit River, etc.). All data were then available for query and display as logs in cross sections during the modelling and interpretation phase.

Once the data were compiled and sorted, point location and elevation below the surface data were extracted from

Fig. 5. The predicted surface was an interpolated surface that honoured only the "hard" data point (those that contain *x*,*y*,*z* information) and used spatial analysis to estimate the depth to bedrock between data points. However, in some cases, known information is available but can not be represented as point data (e.g., the bedrock surface is known to be less than or greater than some depth below surface). To incorporate this additional information, estimated soft picks were established. In this example, there were no hard drift picks at well sites A and C because no contacts were present. Consequently, the predicted surface violated known information displayed in the well logs. At well site A, bedrock was observed to the top of the logged section of the well; therefore, the *z* value for the bedrock surface must pass above the logged portion of the well. The predicted surface over estimated the depth to bedrock because there was no contact to pull the predicted bedrock surface towards the ground elevation. A arbitrary soft pick (interpreted) was added between the top of the logged portion of the well and the ground surface forcing the new interpreted surface above the top of the well. At well site C, drift was logged to the base of the well, but the contact occurred below the logged section. Here, the depth of the predicted bedrock surface was under estimated. A soft pick was established below the logged section of the well, forcing the new interpreted surface below the well. Because there is no hard data at wells A and C, when the new surface is interpolated from both the hard and the soft picks, it must be considered an interpretation.



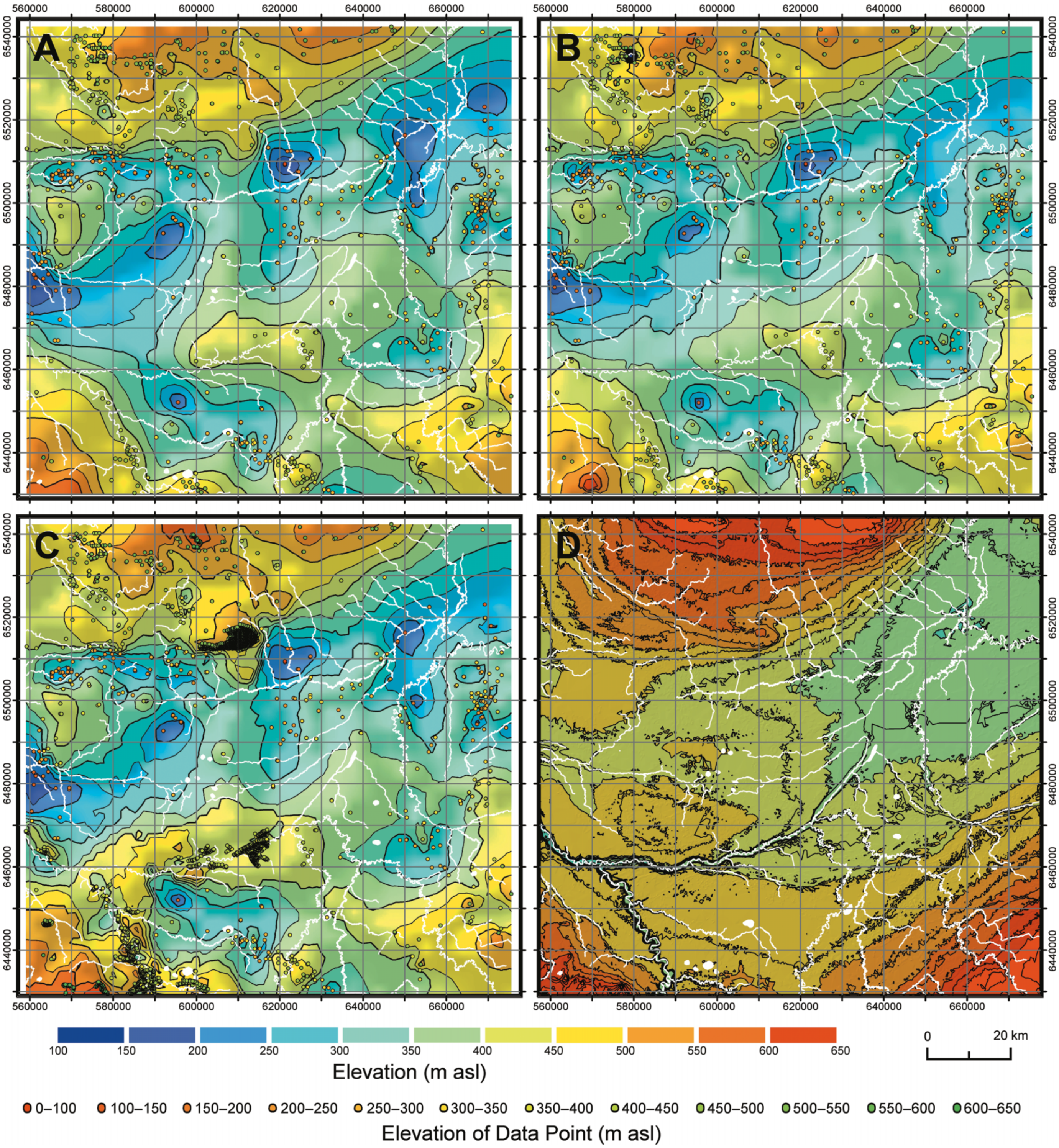
the database for the major stratigraphic boundaries. These data provided the basis for generating interpolated surfaces that correspond to the major stratigraphic boundaries. The quality of a predicted surface is closely linked to the quantity, reliability, and spatial distribution of inputs. The data distributions were spatially analyzed using histograms and semivariogram-covariance clouds in ArcMap and the Geostatistical Analyst extension. These characteristics provided insight into the most suitable interpolation method for predicting values between points (cf. Bailey and Gatrell 1995). The interpolation parameters were then fine-tuned through an iterative process in an attempt to minimize the root mean square error (i.e., the difference between the predicted value for the surface and the known data points).

To generate the bedrock topography map, two interpolation methods were used, a predicted and a fitted surface. The predicted (kriged) surface involved only the hard picks and was used as a working model into which the soft picks were incorporated (fitted). These were generated on cumulative combinations of samples from the three data sources in addition to geological interpretation.

Ordinary kriging was performed on the hard pick data, assuming general isotropy and using parameters generated from a semivariogram of elevation values. This provided statistically predicted bedrock topography in which to estimate soft picks. The next step in the process was to add nonpoint data (soft picks). All surfaces were imported into Viewlog software so that the data could be viewed and modified in cross section. The soft pick data were incorporated into the model by propagating a north–south cross section at 250 m intervals from the east side of the map sheet to the west, providing slices across the map area. This was repeated with an east–west cross section propagated from the north to the south. Posted on each cross section were the lithology and stratigraphy logs and the predicted surface. New points were added where the predicted surface violated some known information (Fig. 5).

The new combination of hard and soft elevation values were then interpolated using a radial basis function. This function honours the data at known points (now the hard and soft picks) and uses proximal points in a user-defined neighbourhood to predict values between known points. Points representing bedrock outcrop or surficial veneer were subsequently incorporated, and the interpolation was performed again. Density of elevation values from outcrop and veneer was much higher than from the other data sources. This affected the parameters used for modelling, but the results of the prediction were visually similar.

Fig. 6. The modelling process generated three working surfaces: (A) a predicted (kriged) bedrock topography surface incorporating only hard picks (similar to the predicted surface in Fig. 5); (B) a fitted interpolated surface based on hard picks, well cuttings, and water well data; (C) a fitted interpolated surface base on all hard and soft data; this model is the basis for combining isolated depressions into valleys by introducing paleovalley thalwegs (see Fig. 7); and (D) modern topography (Shuttle Radar Topographic Mission (SRTM) digital elevation model (DEM)).



The final process involved applying the radial basis function to the hard, soft, and outcrop–veneer points, as well as incorporating a geologic interpretation. Points were added along cross section between depressions representing possible paleovalley thalwegs. The radial basis function was applied for a final time to include the thalweg data, resulting in a model of linear depressions considered more plausible as representing bedrock topography.

Fig. 7. The final model is achieved by linking the depressions in Fig. 5C to form paleovalleys (left). Additional data points were added to the working model (Fig. 5C) along proposed thalwegs interpreting the base of the valley between wells. The entire dataset was then reinterpolated using the software to produce a geological interpretation of the paleovalleys (includes hard, soft, and thalweg picks). Drift thickness was established by subtracting the geologically interpreted model from ground elevation (right). (A) Depressions are connected into four paleovalleys. (B) Because the thalwegs are established based on interpretation of the data, more than one bedrock topographic model is possible. For example an alternative interpretation can be generated if the single chip sample east of the Sikanni Chief River is eliminated and the thalwegs removed, resulting in a model with three paleovalleys. KCP, Kyklo Creek Paleovalley; KHP, Kotcho–Hoffard Paleovalley; NCP, Niteal Creek Paleovalley; RPV, Rainbow Paleovalley.

Results

Data

The data collection resulted in a total of 660 bedrock picks (hard picks), mainly from petrophysical logs. Picks from water wells and drill cuttings resulted in 130 data points. An additional 2984 points were generated from outcrop locations mapped by Thompson (1977) and from the grid cell points within mapped veneer and outcrop polygons from Trommelen (2006) and Smith (2008*a*, 2008*b*, 2008*c*, 2008*d*).

Model

Three working models were generated to illustrate the bedrock surface: (1) a predicted (kriged) bedrock topography surface incorporating only hard picks (Fig. 6A); (2) a fitted interpolated surface based on hard picks, drill cuttings, and water well data (Fig. 6B); and (3) a fitted interpolated surface base on all hard and soft data (Fig. 6C).

The predicted surface produces several significant depressions within the map area (Fig. 6A). The most prominent of these depressions form a northeast trend along the base of the Etsho Plateau. Several smaller depressions occur southwest of the Sahtaneh River, west of the Sikanni Chief River, and under the headwaters of Teklo Creek. An additional depression occurs within the loop of the Hay River along the British Columbia – Alberta border. The fitted surfaces reinforce these trends, partially constraining the topographic geometry (Figs. 6B, 6C).

The most significant relief in the map area occurred along the southern base of the Etsho Plateau. Here, three isolated lows (Fig. 6A) were present, with the lowest bedrock surface pick at an elevation of 90 m asl. In all of these depressions, multiple wells contained deep bedrock picks validating the depressions as real subsurface topographic lows.

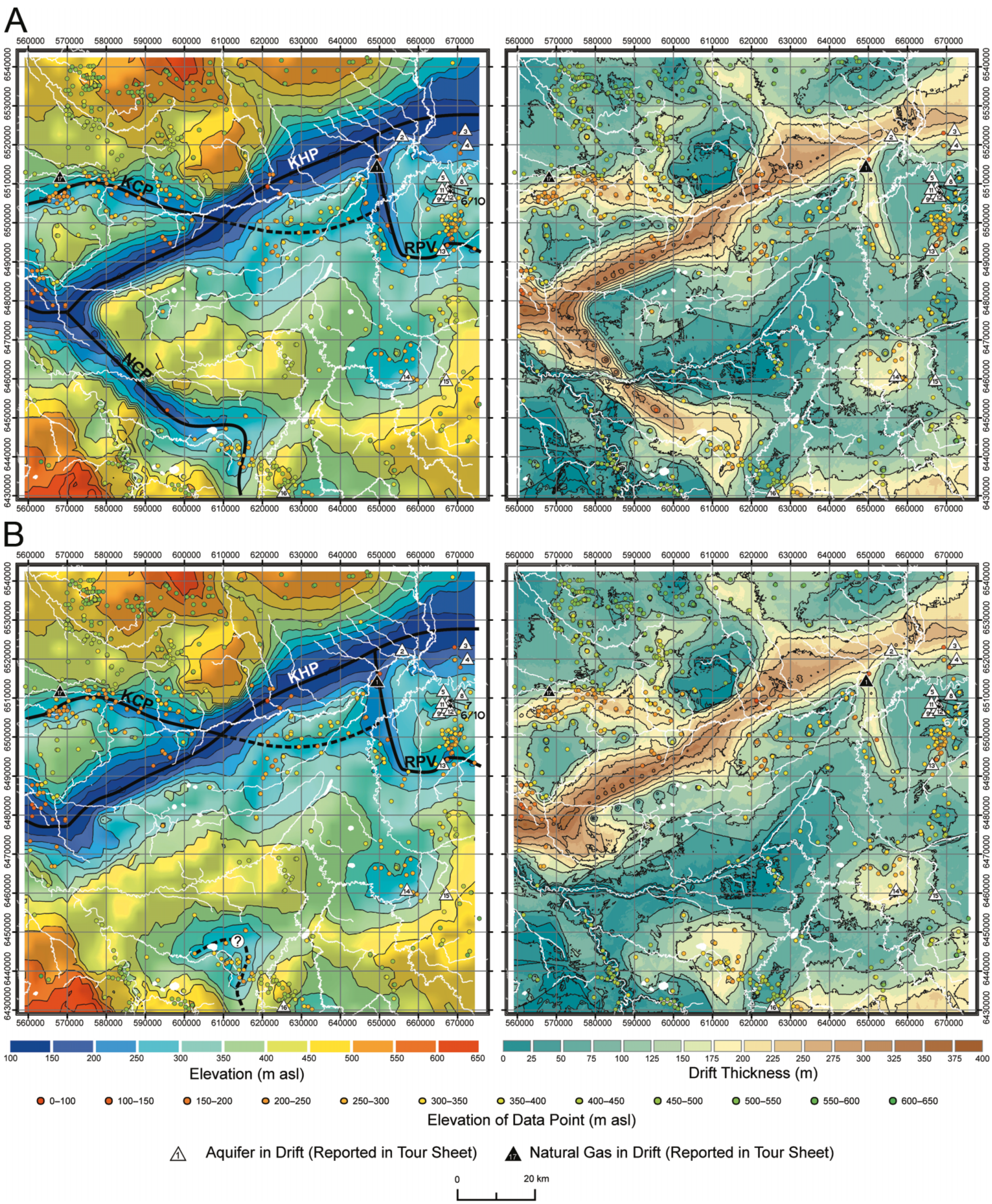
Other significant depressions were present. A linear depression, consisting of >25 hard picks, occurred southwest of the Sahtaneh River. The depression trended to the east with a minimum elevation of 230 m asl. The depression east of the Sikanni Chief River had the bedrock surface at 250 m asl and a single data point at 130 m asl, based on logged chip samples (the petrophysical logs are inconclusive). This point occurred in isolation and lacked corroborating data; consequently, the certainty of the bedrock surface at this location is provisional. Another depression occurred along the British Columbia – Alberta border within the loop of the Hay River. This depression had a minimum elevation of 170 m asl. The last of the major depressions occurred under the headwaters of Teklo Creek with a minimum elevation of 265 m asl, corroborated by 11 other wells in the vicinity.

As noted, the soft picks were generated from subsidiary data such as drill chip samples, water well data, and mapped outcrops and drift veneers, which were used in conjunction with the predicted surface to estimate a new bedrock surface in some areas. Two fitted surfaces were generated, incorporating all known, predicted, and estimated data (i.e., hard and soft picks): (1) only the hard data, the logged chip samples, and water well data (Fig. 6B); and (2) all data (Fig. 6C). The first of these surfaces (Fig. 6B) did little to change the orientation of the depressions, which suggests that the subsidiary data are consistent with the predicted surface. However, two areas of the model were significantly affected by the outcrop and veneer data. A cluster of points in the northern portion of the map (Fig. 6C) pulled the bedrock surface closer to the current ground elevation and created a topographic high. The second area affected was near the Fort Nelson – Fontas River confluence, where bedrock outcrop was mapped. This added complexity to the bedrock topography and pulled the modelled surface closer to present ground elevation. The resulting surface closed the northern extent of the depression east of the Sikanni Chief River. There were no data at this location to confirm the true geometry of this topographic low.

Aquifers and natural gas occurrences in drift

During data compilation, oil and gas drilling records (tour sheets) were inspected for any indication of artesian flow or natural gas (location shown in Fig. 7). Fifteen records indicate wells that intersected artesian aquifers within the drift and two wells that encountered natural gas (Table 1). Location 1 (Table 1; Fig. 7) is an important site that encountered both natural gas and artesian water within the drift succession. The site is located over a depression that is interpreted to be at the confluence of two paleovalleys, Rainbow Paleovalley (RPV) and Kotcho–Hoffard Paleovalley (KHP; see discussion section). Coarse-grained sediments were penetrated at 140 m with a gas show reported at 170 m below surface. Following the gas, water began to flow at a rate of 1–4 m^3/min. This eventually led to the abandonment of the well.

Three locations were noted within the eastern portion of KHP to have intersected aquifers (locations 2–4). A 32 m thick gravel to boulder deposit was encountered at 89 m below surface at location 2. The coarse-grained sediment hosted an artesian aquifer with an initial flow rate of 21 m^3/min. This high flow rate resulted in the abandonment of the original well, which was later redrilled with equipment capable of controlling water flow. Drill records at location 4 indicate artesian aquifer at 80–86 m below surface. Flowing water de-



layed the drilling of the surface casing. No artesian flow was encountered at location 3. However, sloughing sand and gravel were reported to 140 m with an aquifer flow rate of 0.001–0.002 m^3/min. These wells suggest a portion of the KHP contains aquifers within coarse-grained units interpreted to be fluvial or glaciofluvial valley fill.

Table 1. Gas well with tour sheets that report intersecting artesian aquifers or natural gas in the drift.

Location (Fig. 7)	Well name	Easting*	Northing*	Well authorization No.	Depth (m)	Encountered
1	A-094-L/094-I-09	649399	6514608	15130	45–170	Gas–Water
2	D-075-C/094-I-16	655804	6522540	6162	92–121	Water
3	C-082-A/094-I-16	672024	652092	19164	49	Water
4	A-042-A/094-I-16	672533	6520216	7618	80	Water
5	D-051-J/094-I-09	666139	6512034	6188	91–105	Water
6	B-019-I/094-I-09	667604	6507717	10253	91	Water
7	C-029-I/094-I-09	667542	6509192	11820	110	Water
8	C-044-I/094-I-09	671061	6511075	12426	95	Water
9	B-002-J/094-I-09	665293	6506577	12648	97	Water
10	B-019-I/094-I-09	667502	6507738	12649	8–97	Water
11	C-021-J/094-I-09	666101	6508916	12663	110–123	Water
12	C-008-I/094-I-09	668196	6507136	12664	78–91	Water
13	D-052-B/094-I-09	666259	6493237	12749	100	Water
14	B-016-C/094-I-08	657046	6461030	9810	173–198	Water
15	D-093-J/094-I-01	667116	6459843	3934	0–163	Water
16	D-001-D/094-I-02	625490	6431230	8964	170–200	Water
17	D-085-K/094-I-12	569600	6511673	19810	203	Gas

*Universal Transverse Mercator (UTM) coordinates in North American Datum (NAD) 83, Zone 10.

Eight other wells, located between RPV and the eastern portion of KHP (locations 5–12) encountered an aquifer between 70 and 110 m below surface, though typically around 100 m. This aquifer does not appear to be related to any deeply incised paleovalley, though the model would suggest drift thickness between 50–100 m with local variability.

The well at location 13 occurs within RPV where the model suggests bedrock to be 100–150 m below surface. This well encountered strong artesian flow at 100 m below surface (5 m^3/min) that caused abandonment of the first surface hole. The well was later redrilled with a diverter to control the water.

Locations 14 and 15 are near the depression that is situated at the headwaters of Teklo Creek. Records at location 14 document gravel between 173 and 198 m with limited water flow. However, there was sufficient flow to reduce the drilling mud viscosity, preventing proper well bore cleaning. Location 15 was abandoned after intersecting a sandy artesian aquifer at 115 m. Water flowed from the well at approximately 17 m^3/min, flooding the lease and flushing sand and silt into the surrounding forest.

Location 16 is in the southern area of the map sheet near the Kantah River. Water was encountered in gravel from 193 to 197 m below surface with a flow rate of approximately 1 m^3/min. This well is located on the edge of a depression that projects to the south or may join with Niteal Creek Paleovalley (NCP).

The final well of note in this study is location 17, situated along the edge of Kyklo Creek Paleovalley (KCP). This location is significant as natural gas was encountered between 80 and 203 m during surface hole drilling (i.e., a surface hole is drilled to set surface casing before drilling of the main gas well). The drill string was tripped at 200 m (brought to surface), and on the way out of the well, high gas levels were detected. The maximum reading was 6710 gas units (background for this well was 20–22 units)[3] that persisted for 12 min. The gas subsided before increasing a second time to a maximum of 348 gas units. The initial high reading may have been elevated owing to the vacuum caused by raising the drill stem with a mud ring seal. Nonetheless, this clearly indicates the presence of natural gas in the valley-fill sediments of KCP.

Discussion

Data

The spatial distribution of data in the study area does not exhibit stationarity (i.e., the distribution is not random). Wells are drilled based on geologic potential and proximity to infrastructure (pipelines, roads), and as such, first-order effects influence the distribution. Second-order effects are also present as there are clusters of development wells drilled around exploration wells that successfully identified gas reservoirs.

Comparison of the predicted and fitted surfaces shows similar trends. Given the present distribution of available data, the predicted and interpreted bedrock topography is only an approximation. Users of these data must be aware that the quality of prediction decreases as a function of distance from known elevation points used in the interpolation. Unfortunately, as the final model was created using an exact interpolator and included soft picks, no estimates of accuracy with any real meaning can be claimed from the final result.

Model

The working models indicate that the bedrock surface differs significantly from the current topography of the map area. The isolated depressions are likely part of linear trends reflecting paleovalleys that have incised into the soft Creta-

[3] Gas unit: relative gas content of drilling mud reported from gas detectors at the mud tank. Typically 100 units equal ~1% equivalent methane in air (EMA).

ceous shale of the Fort St. John Group and subsequently buried. The final model results from the modification of the working models so that the final bedrock topographic surface represents both the point data as well as an imposed geological interpretation and, therefore, better represents a plausible surface. The data suggest several viable interpretations can be developed from these models, of which two examples are presented in Fig. 7.

In all interpretations, the three main depressions along the southern margin of the Etsho Plateau are combined to form a single paleovalley extending across the map sheet. This depression, referred to as KHP, extends to the west of the map area under Hoffard Creek and to the east into Alberta where it links with the Zama Paleovalley mapped by Pawlowicz et al. (2005). The small depression that occurs along the British Columbia – Alberta border within the loop of the Hay River may link to the RPV also mapped by Pawlowicz et al. (2005).

The depression southwest of Sahtaneh River is relatively well constrained and is interpreted to be a paleovalley that trends to the east. This depression is referred to as KCP. This depression either crosses or is a tributary to KHP. Because a depression of similar elevation and dimension occurs on the east side of KHP, it is possible this is the eastern extension of KCP and is of a different age than KHP. If this is the case, two scenarios are possible: (1) KCP is an older paleovalley that was incised by KHP to a lower base level, or (2) KCP is younger than KHP and developed subsequent to the infilling of KHP.

The remaining depressions are more problematic for interpretation. The depression below the headwaters of Teklo Creek has no obvious connection with the other topographic lows in the area. Consequently, there is insufficient data to link this depression with any of the paleovalleys.

Another depression located east of the Sikannni Chief River is referred to as the NCP. This paleovalley consists of several bedrock surface picks toward the southern edge of the map area between 250 and 270 m asl and a deep pick at 130 m asl (between Niteal Creek and the Fontas River). This suggests a northwest sloping valley, perhaps a tributary to KHP (Fig. 7A). This deep well occurs in isolation and the pick is based mainly on the drill cuttings. If this pick is in incorrect, the interpretation of NCP will be altered significantly (Fig. 7B). For the purposes of further discussion, the data are assumed correct and the former interpretation (Fig. 7A) is adopted, although the geometry of the NCP remains tentative.

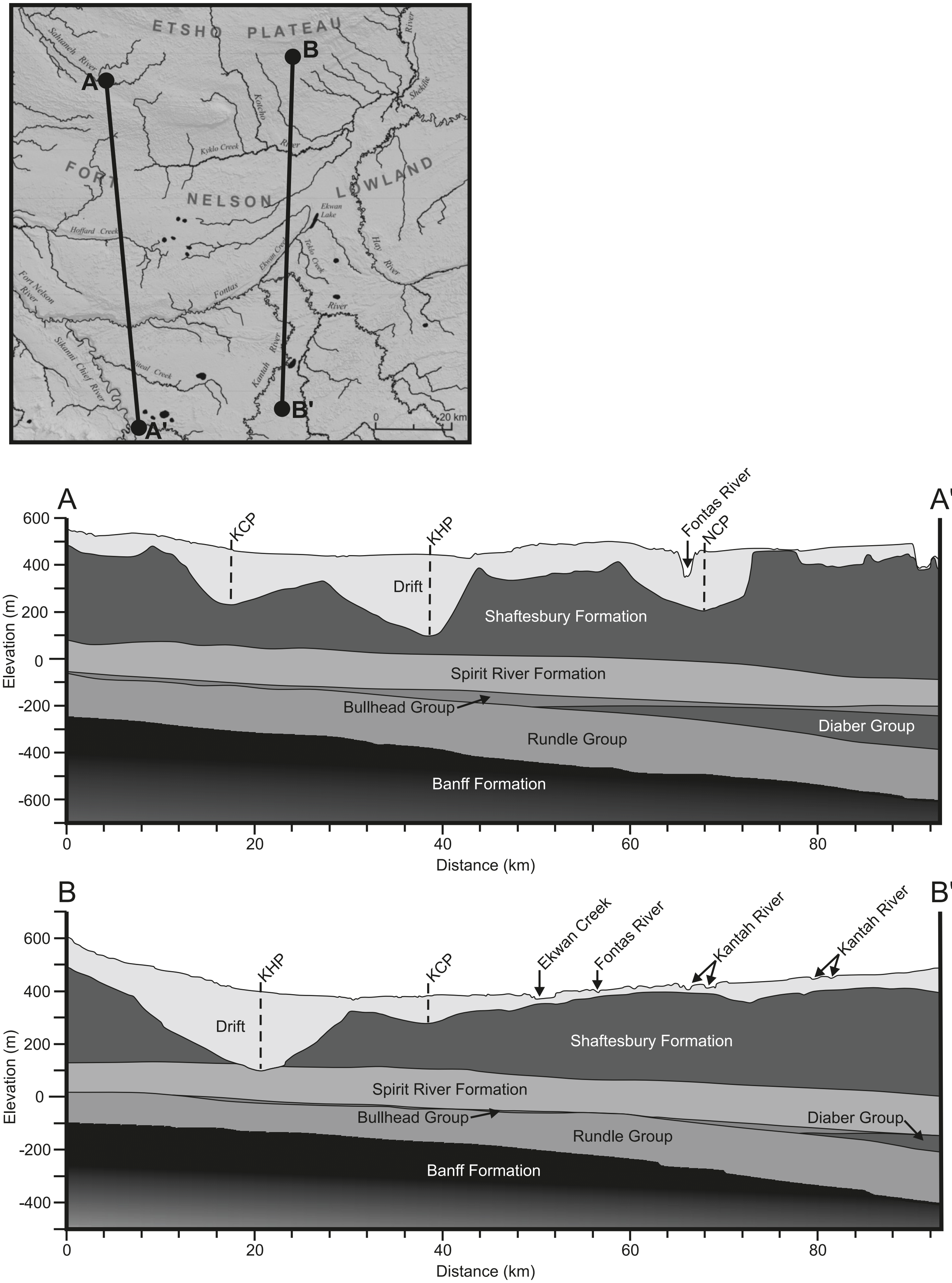
Implications

The paleovalleys described in this study suggest that the present landscape masks a network of previously unreported buried valleys. The relief and the dimensions of the valleys are much larger than any contemporary fluvial systems in the area. The scale of these valleys, particularly KHP, suggests a lengthy duration of evolution, although the dimensions may, in part, be attributed to the limitations of the model. The modelled paleovalleys are wider, deeper, and have broader concave-up cross sections than contemporary river valleys in NEBC (Fig. 8). The morphology of modern valleys reflects two different origins: (1) occupation of incised meltwater channels (e.g., Fort Nelson River), or (2) post glacial incision through unconsolidated sediment or bedrock (e.g., Sikanni Chief River). Regardless of origin, modern valleys tend to be smaller, steep walled, and are narrow relative to the paleovalleys. Those valleys with a meltwater origin formed during deglaciation likely from short catastrophic events with very high discharges and velocity. The meltwater valleys tend to be wide (though narrower than the paleovalleys) with flat bottoms and are occupied by under fit rivers. Postglacially incised valleys tend to form relatively narrow canyons. The modern valleys have developed since deglaciation (ca. 10–13 ka), a relatively short time; and it is conceivable that, over a longer timescale, modern valley may evolve to similar dimensions as the paleovalleys. Therefore, it is suggested that the paleovalleys may reflect Tertiary or Early Quaternary drainage systems. The paleovalleys may have been repeatedly excavated by cyclical glaciations throughout the Quaternary; and the paleovalleys reflect a complex origin of repeated incision and glacial over-deepening and widening associated with interglacial–glacial cycle, respectively. Therefore, paleovalleys may represent the culmination of geomorphic work. However, at any given time in the past, drainage geometries and dimensions may have been more comparable with modern systems. Stratigraphic control or exposure dates from the bedrock surface in the base of the valleys may elucidate the timing of incision; presently no definitive age(s) can be assigned. The crosscutting relationship between KCP and KHP suggests that drainage patterns may have changed through time and that some valleys are super-imposed, stacked, or incised through one another.

There is evidence that many modern valleys in NEBC are coincident with older paleovalleys that existed prior to the last glaciation. For example, the Profit, Peace, Murray, and Kiskatinaw river valleys have pre-Late or Late Wisconsinan age sediments on the valley floor (J.M. Bednarski, personnel communication, 2007; Trommelen et al. 2008). The modern drainages may have become established where preexisting valleys occur because the paleovalleys represent regional depressions, despite being masked by the valley-fill. The origin of the paleovalleys remains unclear. There is no obvious relationship between paleovalley orientation and major structural trends or stress fields (Bell and Babcock 1986). In fact, the trend of KHP is oblique to the major structural trend of the Rocky Mountain Fold and Thrust Belt, west of the study area. The Cretaceous sediments in the study area are generally flat lying to slightly inclined, gently dipping to the southwest (Thompson 1977). There are two major fault systems that occur in northeast British Columbia and northwest Alberta, the Bovie Lake and Hay River faults (Great Slave Lake Shear Zone; Wright et al. 1994; Maclean and Morrow 2004). These structures occur several hundred kilometres from the study area and have no direct influence on the orientation of the paleovalleys. It is possible that subordinate structures associated with these major structural features have not been detected and could play a roll in paleovalley development, particularly if the structures were active or present through the Tertiary and Quaternary.

Two of these paleovalleys link with buried valleys in Alberta, RPV and KHP (Pawlowicz et al. 2005). RPV is well constrained in Alberta and is narrower than the modelled

Fig. 8. North-to-south cross sections show the modeled tops of the major stratigraphic boundaries, paleovalleys, and modern rivers (25× vertical exaggeration). KCP, Kyklo Creek Paleovalley; KHP, Kotcho–Hoffard Paleovalley; NCP, Niteal Creek Paleovalley.



RPV in British Columbia with a canyon like morphology. The canyon morphology suggests this valley may be younger than KHP and perhaps forming during the Quaternary. The direction of paleo-drainage is inconclusive.

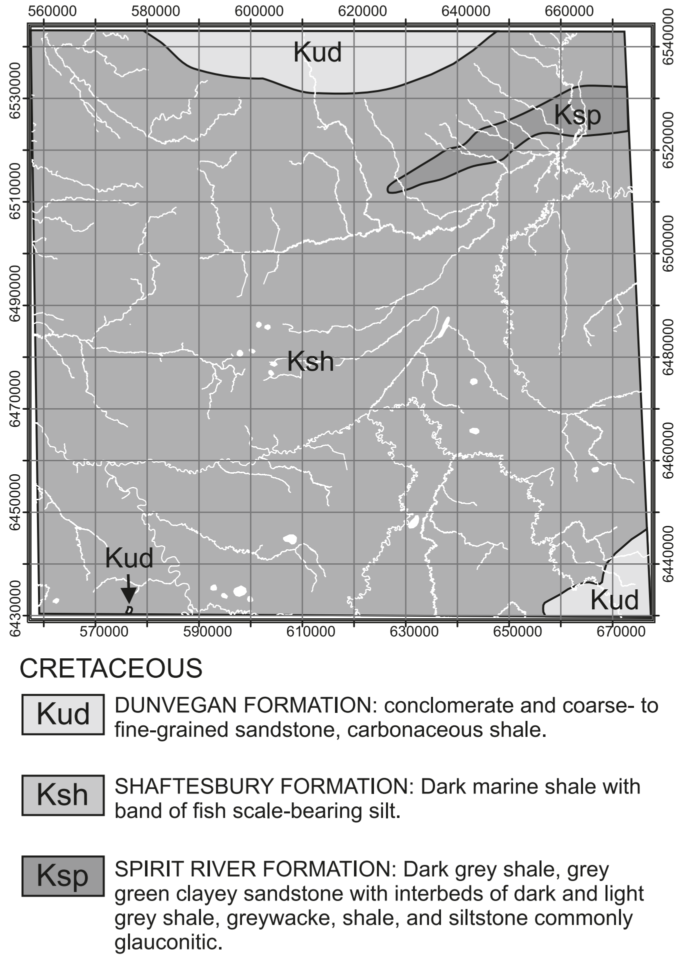
KHP links with the Zama Valley and is less well constrained in Alberta. Pawlowicz et al. (2005) suggested it can be traced east, under Zama and Hay lakes to the Chinchaga River. The slope of KHP is speculative as the paleovalley floor shows little appreciable dip beyond the error associated with the model. But, if this paleovalley is indeed the western extension of the Zama Valley, then the paleo-slope of Zama–KHP from west of Zama Lake, Alberta, to the western edge of this study is approximately 0.05%, which tentatively suggests paleo-drainage to the west and eventually to the north into the artic basin. The Zama–KHP has economic significance as shallow gas was discovered within its valley-fill sediments in Alberta in 1988 (Clare 1988) and has since been the target of natural gas exploration around the discovery (Sousa and Rainbow gas fields). Gas has been in production from shallow wells with Quaternary age reservoirs in the Zama–KHP valley-fill since 1993 (Levson et al. 2006). Although, there is no production of natural gas from Quaternary reservoirs in British Columbia, gas was noted in tour sheets in valley-fill sediments in both KHP and KCP.

The stratigraphy of valley-fills cannot be correlated from one well to the next. However, paleovalleys contain sequences of unconsolidated coarse-grained sediments (fluvial or glaciofluvial aquifers) interbedded within fine-grain sediments (diamict, lacustrine, or glaciolacustrine). These sequences are capped by Late Wisconsinan glacial and deglacial sediment at surface, which implies the paleovalleys, at least, predate the Late Wisconsinan. The valley-fills likely contain lengthy Quaternary stratigraphic records as other smaller preglacial valleys in NEBC contain records that extend to the Middle Wisconsinan and possibly older (Mathews 1978; Trommelen et al. 2008). Since the paleovalleys identified in this study are significantly deeper and perhaps older than others in NEBC, they may represent excellent sites for Quaternary age terrestrial records in western Canada.

Surface bedrock mapping relies on exposed outcrop, which is rare in the Fort Nelson Lowland, commonly restricted to incised river valleys. Bedrock topography mapping through petrophysical logs provides insight into the subcrop geology. In this study, the models show that the paleovalley network has incised up to 300 m into the Fort St. John Group shale (Fig. 8). The model also suggests the eastern portion of KHP has incised through the Shaftesbury Formation into the Spirit River Formation. Consequently, a wedge of the Spirit River Formation should appear on the bedrock subcrop geology map of 94I, reflecting the erosion of the upper Fort St. John Group sediments (Fig. 9).

As the oil and gas industry expands in NEBC, drilling practices and water and land management issues are becoming major concerns (Levson et al. 2006). Thick inhomogeneous Quaternary sediments associate with the deep paleovalleys have proven to be a safety issue for oil and gas, as well as the water well industry. Incidents have cost these industries millions of dollars in lost time, abandonment of wells, destruction of equipment, as well as injuries and in extreme cases fatalities (i.e., British Columbia Oil and Gas Commission 2005). Drilling within paleovalleys requires the use of mitigative measures (e.g., blowout preventers or heavy mud) to reduce the impact of intersecting either artesian water or natural gas. In addition, protecting sources of potable water should be considered when drilling in the paleovalleys. In accordance with the British Columbia Petroleum and Natural Gas Act, surface casing is to be set into bedrock, which may be in excess of 300 m within the paleovalleys.

Fig. 9. Bedrock subcrop map based on the bedrock topography model (Fig. 7A).



Conclusions

The objective of this study was to model the bedrock topography of the NTS map sheet 94I using oil and gas petrophysical logs, drill chip samples, water well logs, and surficial and bedrock geology maps. The models suggest bedrock topography has much more reflief than modern topography because the bedrock topography is masked by thick accumulations of Quaternary drift. Several conclusions can be drawn from the results:

- The modeled data produced several depressions that likely represent paleovalleys when combined. These depressions are interpreted to be previously undocumented paleovalleys. The most prominent of these is KHP, which spans the map sheet along a west-southwest trend. The base of the valley is over 250 m below the modern surface and likely links with the Zama Paleovalley in Alberta (Pawlowicz et al. 2005). A tributary valley of KHP is mapped on the eastern side of the map sheet and is referred to as RPV. It can be traced into Alberta where it links with Rainbow Valley of Pawlowicz et al. (2005). The third paleovalley, KCP, trends east–west and may be a tributary to or crosscut the KHP. KCP is well constrained on the northwest side of the KHP but is less well defined southeast of KHP. The fourth paleovalley, NCP, is considered speculative as its depth and geometry rely heavily on an isolated drill chip sample. If the chip sample is valid, NCP trends to the northeast and may be a tributary to KHP. Alternatively, the depression may be part of a paleovalley that extends to the south.

- There may be other geologically plausible ways to link the depressions. The geometry of the paleovalleys is limited by the quality, density, and distribution of the data. Data such as drill chip samples are less reliable than the petrophysical logs. Areas with a high density of wells provide the best confirmation of bedrock tops and verify less precise data such as drill chip samples. Some areas have many wells and the geometry of paleovalleys can be constrained (e.g., western portion of KCP). Other areas have only a single data point and rely more on interpretation. The models generated here provide a regional–scale interpretation. The current density of wells is insufficient for high resolution interpretation, and new models should be developed as more wells are drilled or other techniques are developed that can better constrain the subsurface paleovalley geometry (e.g., geophysics such as shallow seismic or electromagnetic surveys).
- Understanding the geometry, thickness and stratigraphy of the drift has implications for the oil and gas industry. The presence of artesian aquifers or potential natural gas reservoirs poses a significant hazard to drilling. Subsurface modelling of the Quaternary succession and hydrogeology in NEBC should be a focus of further work.

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