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The evolution of Keele Arch, a multiphase feature of the northern mainland, Northwest Territories

B.C. MacLean, K.M. Fallas, and T. Hadlari

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Cover illustration

Cretaceous sandstone of the Martin House Formation resting unconformably on Cambro-Ordovician dolostone of the Franklin Mountain Formation on the east flank of Keele Arch. View is to the north between Mahony Lake and 'St. Charles' Range

Critical review
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Abstract

Keele Arch is a zone of structural, erosional, and depositional features along a corridor between the eastern Colville hills and the Franklin Mountains, Northwest Territories. It has a long history of basin-to-arch reversals.

Paleomaps and sections illustrate the arch's evolution through six phases: 1) uplift as a very early Cambrian pre-rift high, 2) subsidence into a graben chain during Cambrian to mid-Ordovician time, 3) uplift of its southern half into a pre-Devonian arch extending southward from the present day northern Franklin Mountains to beyond Johnson River, 4) renewed uplift into a pre-Cretaceous arch running from north of Lac des Bois to Johnson River, 5) mid-Cretaceous reactivation of the pre-Cretaceous and southern pre-Devonian arches, 6) subsidence of its central zone into Brackett Basin and inversion of the Cambrian McConnell graben into the McConnell Range during late-Campanian to Paleocene time.

Keele Arch consists of four parts: 1) a northern segment extending northeastward from the Northern Franklin Mountains toward Lac des Bois; 2) the north half of Keele Tectonic Zone under the northern Franklin Mountains; 3) between Brackett Lake and Keele River; 4) a fourth and poorly understood segment under Mackenzie Valley, south of Keele River, where the arch axes appear to fall into two sets: an eastern set of Cambrian to mid-Ordovician sag axes and latest Silurian to Eocene uplifts, and a western set of Cambrian to mid-Cretaceous arch axes that tracks across a block of Proterozoic rock directly overlain by Devonian strata.

The arch's economic significance is not fully understood.

Résumé

L'arche de Keele est une zone d'entités structurales, d'érosion et de dépôt le long d'un corridor situé à l'est des collines Colville et des monts Franklin, dans les Territoires du Nord-Ouest. Elle a connu une longue histoire d'inversions bassin-arche.

Les paléocartes et les paléocoupes révèlent une évolution de l'arche en six phases : 1) soulèvement sous forme d'une hauteur antérieure au rifting au tout début du Cambrien précoce; 2) subsidence en une chaîne de grabens du Cambrien à l'Ordovicien moyen; 3) soulèvement de sa moitié sud en une arche pré-dévonienne qui s'étire vers le sud depuis la partie nord des monts Franklin actuels jusqu'au delà de la rivière Johnson; 4) reprise du soulèvement pour produire une arche pré-crétacée s'étirant d'un point situé au nord du lac des Bois jusqu'à la rivière Johnson; 5) réactivation au Crétacé moyen de l'arche pré-crétacée et de la partie sud de l'arche pré-dévonienne; 6) subsidence de sa zone centrale pour former le bassin de Brackett et inversion du graben de McConnell, du Cambrien, pour former le chaînon McConnell dans la période du Campanien tardif au Paléocène.

L'arche de Keele se compose de quatre parties : 1) un segment nord de direction nord-est s'étendant de la partie nord des monts Franklin vers le lac des Bois; 2) la moitié nord de la zone tectonique de Keele sous la partie nord des monts Franklin; 3) un segment s'étendant du lac Brackett à la rivière Keele; 4) un segment encore mal compris sous la vallée du Mackenzie, au sud de la rivière Keele, où les axes d'arche semblent se répartir en deux ensembles : un ensemble oriental d'axes de zone d'affaissement datant du Cambrien à l'Ordovicien moyen et d'axes de zone de soulèvement datant du Silurien terminal à l'Éocène; et un ensemble occidental d'axes d'arche datant du Cambrien au Crétacé moyen qui peuvent être suivis d'un bord à l'autre d'un bloc de roches du Protérozoïque, lesquelles sont surmontées en contact direct par des strates du Dévonien.

L'importance économique de l'arche n'est pas entièrement comprise.

SUMMARY

This report deals with a zone of structural, erosional, and depositional features that spans some 400 km across the mainland Northwest Territories, north of 63 degrees North latitude.

Today, Keele Arch originates in the area east of the Colville hills and trends southward to the Mackenzie River valley where it plunges under Root Basin near Keele River. First identified as a multiphase arch, it has through time been both a positive and a negative feature that rose and fell in a manner similar to that which Eaton et al. (1999) have described for the Peace River Arch of northern Alberta. For much of its length it follows a chain of Cambrian grabens. Its central zone underwent several large-scale tectonic inversions, earning the name Keele Tectonic Zone. The zone coincides with an area of anomalously small gravity values that is the combined product of relatively low density contents of Mackenzie Trough, a particularly deep Cambrian graben, and a superimposed foreland basin that developed during Cordilleran orogenesis.

Paleozoic strata within the study area are part of the sedimentary wedge deposited on the subsiding western margin of the North American continent after the breakup of Rodinia. Mesozoic strata were deposited into a foreland basin that developed in response to tectonic loading imposed by cordilleran uplift. The Phanerozoic stratigraphy can be viewed as having developed in five phases: 1) early extension and rifting, 2) margin subsidence, 3) Ellesmerian foreland subsidence, 4) a period for which we have no record, and 5) regional foreland subsidence, triggered by Cordilleran uplift to the west.

Keele Arch region today consists of four segments: 1) a northern broad arch of Cambro-Ordovician Franklin Mountain Formation that is evidence of Late Silurian and later uplift(s); 2) an arch in the north half of Keele Tectonic Zone, again expressed by exposed Franklin Mountain Formation that provides evidence of Late Silurian (pre-Devonian) uplift; 3) Brackett Basin, a product of Tertiary subsidence of the south half of Keele Tectonic Zone; and 4) a synclinal trend south of Keele River and Keele Tectonic Zone within which Upper Cretaceous strata are preserved.

A series of paleoseismic transects, spanning late Proterozoic to present-day time period, document the arch's evolution.

A Late Proterozoic syncline, filled with Mackenzie/Shaler (M/S) Assemblage strata, was a precursor to Keele Arch. In the earliest Cambrian, Keele Tectonic Zone was established as a pre-extension high, but it soon collapsed to form Mackenzie Trough which

SOMMAIRE

Le présent rapport traite d'une zone d'entités structurales, d'érosion et de dépôt qui s'étend sur quelque 400 km dans la partie continentale des Territoires du Nord-Ouest, au nord de 63 degrés de latitude Nord.

De nos jours, l'arche de Keele s'étend de la région à l'est des collines Colville en s'étirant vers le sud jusqu'à la vallée du Mackenzie, où elle plonge sous le bassin de Root près de la rivière Keele. Tout d'abord identifiée comme une arche polyphasée, elle a alterné au fil du temps entre une entité géologique positive et une entité négative qui s'est soulevée et affaissée d'une manière semblable à ce qui a été décrit dans Eaton et al. (1999) pour l'arche de Peace River, dans le nord de l'Alberta. Sur la majeure partie de sa longueur, elle suit une chaîne de grabens du Cambrien. Sa zone centrale a subi plusieurs inversions tectoniques à grande échelle, ce qui lui a valu l'appellation de «zone tectonique de Keele». La zone coïncide avec un secteur anomal de faibles valeurs gravimétriques, lesquelles sont le produit de l'effet combiné des matériaux de densité relativement faible présents dans la cuvette de Mackenzie, un graben du Cambrien particulièrement profond, et dans le bassin d'avant-pays formé lors de l'orogenèse de la Cordillère qui s'y superpose.

Dans la région d'étude, les strates du Paléozoïque font partie du prisme sédimentaire qui s'est accumulé sur la marge occidentale en subsidence du continent nord-américain, après la rupture de la Rodinie. Les strates du Mésozoïque se sont déposées dans un bassin d'avant-pays qui s'est formé en réponse à la charge tectonique induite par le soulèvement de la Cordillère. La stratigraphie du Phanérozoïque peut être considérée comme le résultat d'une évolution en cinq phases : 1) extension initiale et rifting; 2) subsidence de marge continentale; 3) subsidence de l'avant-pays ellesmérien; 4) période pour laquelle il n'y a aucune enregistrement sédimentaire; et 5) subsidence régionale d'avant-pays, déclenchée par le soulèvement de la Cordillère à l'ouest.

La région de l'arche de Keele se compose de nos jours de quatre segments : 1) au nord, une vaste arche constituée de la Formation de Franklin Montain du Cambrien-Ordovicien, qui témoigne d'un soulèvement au Silurien tardif et de soulèvements ultérieurs; 2) une arche dans la moitié nord de la zone tectonique de Keele, ici aussi soulignée par des affleurements de la Formation de Franklin Mountain, qui rend compte d'un soulèvement au Silurien tardif (pré-Dévonien); 3) le bassin de Brackett, un produit de la subsidence au Tertiaire de la moitié sud de la zone tectonique de Keele; et 4) un alignement synclinal au sud de la rivière Keele et de la zone tectonique de Keele dans lequel les strates du Crétacé supérieur ont été conservées.

Une série de paléotransects sismiques, couvrant la période du Protérozoïque tardif jusqu'à nos jours, documente l'évolution de l'arche.

Un synclinal du Protérozoïque tardif, rempli de strates de l'Assemblage de Mackenzie/Shaler (M/S), a constitué un précurseur de l'arche de Keele. Au Cambrien initial, la zone tectonique de Keele est apparue sous la forme d'une hauteur antérieure à la déformation en extension, mais elle s'est rapidement affaissée pour former la

continued to subside until the Middle Ordovician. South of the trough, McConnell graben formed along the east side of an enigmatic block of Proterozoic rock.

Regional extension gave way to a period of stable continental margin subsidence in the Late Cambrian. Although interrupted by mid-Ordovician and latest Silurian regional uplift and erosional events, this phase lasted until the Late Devonian, when the area subsided rapidly to form a foreland basin to the Ellesmerian Orogeny. By middle Ordovician time, tectonic activity along Keele Arch region had ceased and the Proterozoic block west of McConnell graben may have been emergent. Pillows cored by Saline River Formation (and, at one location, Mount Cap Formation) salt had begun to form within Keele Tectonic Zone. Margin subsidence continued through the Late Ordovician and Silurian with no expression of Keele Arch.

The first manifestation of an arch appeared during the latest Silurian, when Keele Arch region rose to form a well defined pre-Devonian feature. That arch extended southward from north of present day Kelly Lake to Johnson River and possibly further.

During the Devonian to latest Triassic (or possibly Jurassic) time of regional subsidence there was no known expression of Keele Arch region once the arch was onlapped and buried. Root Basin formed in the south where subsidence was more rapid.

The sub-Cretaceous unconformity represents a hiatus extending from latest Devonian to the Late Aptian. Immediately prior to the Late Aptian resumption of deposition, Keele Arch region was a sinuous arch extending southward from possibly as far north as the present day Lac des Bois to perhaps the southern limit of McConnell Range. During the Early Cretaceous, the pre-Cretaceous arch was onlapped and eventually buried after which there was no expression of Keele Arch region until the pre-Cretaceous and southern pre-Devonian arches were reactivated during the Middle Cretaceous.

The mid-Cretaceous arch was subsequently onlapped, but not completely buried, by Turonian to Late Campanian sediment.

Since the Late Campanian, southern Keele Tectonic Zone has subsided to form Brackett Basin. Today's topography is dominated by a foreland basin and many compressional structures, all products of Cordilleran mountain building to the west. Keele Arch region exerted a strong influence on the formation of Campanian to Eocene compressional structures, the most significant of which is the McConnell Range, which rose by inversion of McConnell graben.

cuvette de Mackenzie, dont la subsidence s'est poursuivie jusqu'à l'Ordovicien moyen. Au sud de la cuvette, le graben de McConnell s'est formé le long du flanc est d'un énigmatique bloc de roches du Protérozoïque.

La déformation régionale en extension a cédé la place à une période de subsidence régulière de marge continentale au Cambrien tardif. Bien qu'interrompue par un soulèvement régional et des épisodes d'érosion à l'Ordovicien moyen et au Silurien terminal, cette phase a persisté jusqu'au Dévonien tardif, lorsque le secteur a été soumis à une subsidence rapide pour former un bassin d'avant-pays lié à l'orogenèse ellesmérienne. Dès l'Ordovicien moyen, l'activité tectonique le long de la région de l'arche de Keele avait cessé et le bloc de roches protérozoïques à l'ouest du graben de McConnell a pu atteindre la surface. Des coussins à noyau de sel de la Formation de Saline River (et, à un endroit, de la Formation de Mount Cap) avaient commencé à se former dans la zone tectonique de Keele. La subsidence de marge continentale s'est poursuivie jusqu'à l'Ordovicien tardif et au Silurien sans que l'arche de Keele ne se manifeste.

La première manifestation d'une arche remonte au Silurien terminal, quand la région de l'arche de Keele s'est soulevée pour former une entité pré-dévonienne bien définie. Cette arche s'étendait d'un point situé au nord du lac Kelly actuel en suivant une direction sud jusqu'à la rivière Johnson, et peut-être au-delà.

Pendant la période de subsidence régionale du Dévonien au Trias terminal (ou peut-être le Jurassique), la région de l'arche de Keele n'a pas présenté d'expression affirmée après que l'arche ait été recouverte en avancée (formation d'un biseau d'aggradation) et enfouie. Le bassin de Root s'est formé dans le sud, où la subsidence était plus rapide.

La discordance marquant la base de la succession du Crétacé rend compte d'un hiatus sédimentaire du Dévonien terminal à l'Aptien tardif. Immédiatement avant la reprise de la sédimentation à l'Aptien tardif, la région de l'arche de Keele correspondait à une arche suivant un parcours sinueux vers le sud depuis un point situé aussi loin au nord que l'actuel lac des Bois jusqu'à la limite sud du chaînon McConnell. Au Crétacé précoce, l'arche pré-crétacée a été recouverte en avancée, et éventuellement enfouie, après quoi la région de l'arche de Keele n'a plus présenté d'expression jusqu'à ce que l'arche pré-crétacée et la partie sud de l'arche pré-dévonienne aient été réactivées au Crétacé moyen.

L'arche du Crétacé moyen a plus tard été recouverte en avancée, mais pas complètement enfouie par les sédiments, entre le Turonien et le Campanien tardif.

Depuis le Campanien tardif, la partie sud de la zone tectonique de Keele a subsidé pour former le bassin de Brackett. La topographie observée de nos jours est dominée par un bassin d'avant-pays et de nombreuses structures de compression, tous des produits de l'érection des montagnes de la Cordillère à l'ouest. La région de l'arche de Keele a exercé une forte influence sur la formation des structures de compression du Campanien à l'Éocène, la plus importante étant le chaînon McConnell qui s'est soulevé par inversion du graben de McConnell.

Keele paleo-arch and sag axes fall into four groups that roughly correspond to the present day segments. Within North and South Keele Tectonic Zone all the axes combine to form two central arch segments. Northeast of the zone, the axes consist of Cambrian subsidence and pre-Devonian, pre-Cretaceous, and mid-Cretaceous uplift (arch) phases. South of Keele Tectonic Zone, sag axes range in age from Early Cambrian to mid-Ordovician and are well constrained to the east side of the present day Mackenzie River. Uplift axes in the south fall into two groups. An eastern set coincides with the sag axes and ranges in age from the latest Silurian to the uplift of McConnell Range during the latest Cretaceous to Eocene. A second group, located about 50 km to the west, falls in the Cambrian to mid-Cretaceous age range.

A number of structural features are unique to the Keele Arch. In particular, the inverted normal faults along the east side of the arch are directly related to the initial formation of the Mackenzie Trough. Salt pillows found across the middle of the arch are concentrated in thick evaporite deposits within Mackenzie Trough, and the northern Franklin Mountains are ridges of resistant lower Paleozoic carbonates raised to the near surface by earlier arch uplift.

Keele Tectonic Zone had a significant influence on the development of the structures that define today's topography. There is a close correspondence between the zone's west bounding faults and the southern Jacques Range, Discovery Ridge and Mackay Range. Its eastern boundary underlies 'St. Charles' Range and the Cambrian McConnell graben underlies McConnell Range. The northern limit of Keele Tectonic Zone coincides with a marked change in the structural trends of the northern Franklin Mountains.

Les axes de la paléo-arche de Keele et des zones d'affaissement se répartissent en quatre groupes, qui correspondent en gros aux segments présents de nos jours. Dans le nord et le sud de la zone tectonique de Keele, tous les axes convergent pour former deux segments d'arche centraux. Au nord-est de la zone tectonique de Keele, les axes témoignent de la phase de subsidence du Cambrien ainsi que des phases de soulèvement (formation d'arche) prédévonienne, pré-crétacée et médio-crétacée. Au sud de la zone tectonique de Keele, les axes de zone d'affaissement datent du Cambrien précoce à l'Ordovicien moyen et sont bien circonscrits à la rive est du cours actuel du fleuve Mackenzie. Les axes de zone de soulèvement au sud sont répartis en deux groupes. Un ensemble oriental coïncide avec les axes de zone d'affaissement et date du Silurien terminal jusqu'à la période de soulèvement du chaînon McConnell du Crétacé terminal à l'Éocène. Un deuxième groupe, situé à environ 50 km à l'ouest, date du Cambrien au Crétacé moyen.

Un certain nombre d'entités structurales sont uniques à l'arche de Keele. En particulier, les failles normales inversées le long du flanc est de l'arche sont directement liées à la formation initiale de la cuvette de Mackenzie. Des coussins de sel présents dans la partie médiane de l'arche sont concentrés dans d'épais dépôts d'évaporites dans la cuvette de Mackenzie, et le nord des monts Franklin est constitué de crêtes formées de roches carbonatées résistantes du Paléozoïque inférieur qui ont été hissées près de la surface lors d'un soulèvement antérieur de l'arche.

La zone tectonique de Keele a exercé une influence considérable sur l'évolution des structures qui définissent la topographie actuelle. Il existe une correspondance étroite entre les failles bordières de la limite ouest de la zone et la partie sud du chaînon Jacques, la crête Discovery et le chaînon Mackay. Sa limite orientale sous-tend le chaînon St. Charles et le graben de McConnell, du Cambrien, sous-tend le chaînon McConnell. La limite nord de la zone tectonique de Keele coïncide avec un changement marqué dans les directions structurales dans le nord des monts Franklin.

INTRODUCTION

A northerly trending arch has been long known to exist west of Great Bear Lake, Northwest Territories (Haimila, 1975). Although long referred to as Keele Arch (Cook, 1975), insights gained during a recent field mapping program and the interpretation of an extensive grid of reflection seismic lines have shown this arch to be but one phase of a multifaceted and tectonically active area that rose and fell in a manner similar to that which Eaton et al. (1999) have described for the Peace River Arch of Alberta.

The study area lies east of the Mackenzie Mountains front and includes Mackenzie Plain, the Franklin Mountains and areas further east as far as the Colville hills and Great Bear Plain (Fig. 1). Much of the ensuing discussion is focused on a 50 km wide swath that begins in the northern Franklin Mountains between Discovery Ridge and the 'St. Charles' Range and runs southward under Mackenzie Valley and McConnell Range to the vicinity of Johnson River.

Density of available borehole and reflection seismic profiles is greatest between Brackett Lake and Keele River, but data are sparse in the northern Franklin Mountains. Seismic-image quality in the core area is rated as very good but, north of Mahony Lake, the data are of much poorer quality, likely due to karst features developed at surface within Mount Kindle Formation carbonates.

PREVIOUS WORK

Keele Arch region was first documented by Haimila (1975) who identified an arch extending northward from the confluence of the Mackenzie and Great Bear rivers to Lac des Bois. He described it as an 'undulating structural high' containing a series of domes that he had identified from a study of drainage patterns on satellite imagery. A suite of residual gravity profiles provided varying levels of support for his thesis.

In the same publication, Cook (1975) named this feature 'Keele Arch' and, from an analysis of unconformable relationships, concluded that the arch had been active in pre-Devonian, pre-Late Cretaceous, and possibly Early Cretaceous time. Evidence for a pre-Devonian uplift and erosional event were found at locations where the Ordovician to Silurian Mount Kindle Formation was absent and Devonian strata lay in direct contact with Cambro-Ordovician Franklin Mountain strata (Fig. 2). Along Mackay Range the Franklin Mountain Formation is variably thinned below the Devonian. Cook (1975) was unsure how far north the pre-Devonian arch extended.

Cook (1975) presented evidence for a pre-Late Cretaceous arch along which Devonian and, in places, Cambro-Ordivician Franklin Mountain strata, were thinned or removed. Upper Cretaceous strata directly overlie Upper Devonian Imperial Formation on the arch's west flank, whereas at the Keele L-04 petroleum exploration well, Upper Cretaceous rocks rest directly on the Middle Cambrian Mount Cap Formation. On the arch's east flank near Kelly and Mahony lakes, Lower Cretaceous strata overlie the Upper (cherty) unit of the Franklin Mountain Formation. Cook (1975) considered this phase of the arch to have extended at least as far north as Lac des Bois. He did not differentiate a pre-Cretaceous from a mid-Cretaceous arch.

Yorath and Cook (1981) outlined on a paleogeology map a pre-Cretaceous Keele Arch that extended some 400 km southward from east of the Colville hills to Keele River in the Mackenzie River valley (Fig. 3). They suggested that the arch may have first developed as early as the Middle Cambrian. They also explored in some detail the mid-Cretaceous arch's effect on Cretaceous stratigraphy, having noted the presence of Late Albian to Turonian conglomeratic sandstones on the crest.

Our understanding of the tectonic elements of Keele Arch region and the development of both it and the adjoining Root Basin were greatly advanced by Williams (1987, 1989a, and 1989b) who, basing his interpretations solely on an analysis of borehole and outcrop data, concluded that the Cambrian Mackenzie Trough had continued to subside during deposition of the Cambro-Ordovician Franklin Mountain Formation before being inverted to form the south portion of the Yorath and Cook arch.

MacLean and Cook (1999), in their analysis of salt tectonism in the Great Bear area, developed a stratigraphic chart summarizing the arch's effect on local stratigraphy. A modified version of their chart is presented in Figure 2. They recognized that a portion of the Keele Arch region between Brackett Lake and Keele River had undergone several tectonic inversions and so named it Keele Tectonic Zone (KTZ) (Fig. 3). They also documented an area south of Keele River where Devonian strata rest directly on Proterozoic rocks.

The work of MacLean (2006) was an early attempt at describing the evolution of Keele Arch region using reflection seismic data. It may be considered a precursor to this report and is consequently somewhat out of date. It does, however, include several reflection seismic images that are pertinent to, but not available for inclusion in, this report. Finally, MacLean (2011) presented a history of the Cambrian basin under the mainland Northwest Territories east of the deformed belt. He described in some detail the early development of the Keele Arch region and identified a Cambrian graben under McConnell Range which he named McConnell graben.

GEOLOGICAL SETTING

Paleozoic strata within the study area are part of the sedimentary wedge deposited on the subsiding western margin of the North American continent after breakup of Rodinia

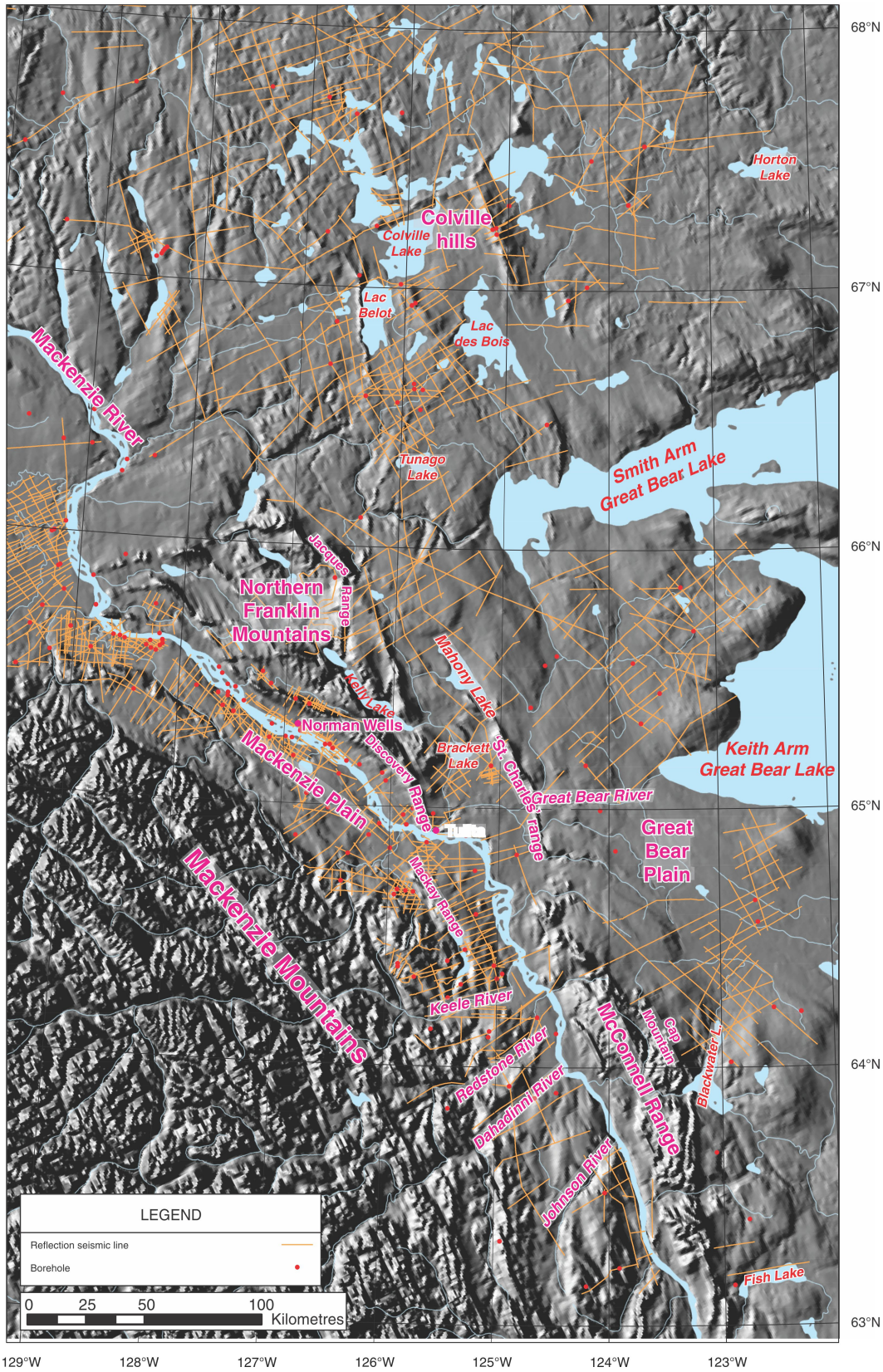

Figure 1. Map showing the locations of reflection seismic lines and boreholes plotted on a digital elevation model. Physiographic elements referred to in the text are identified.

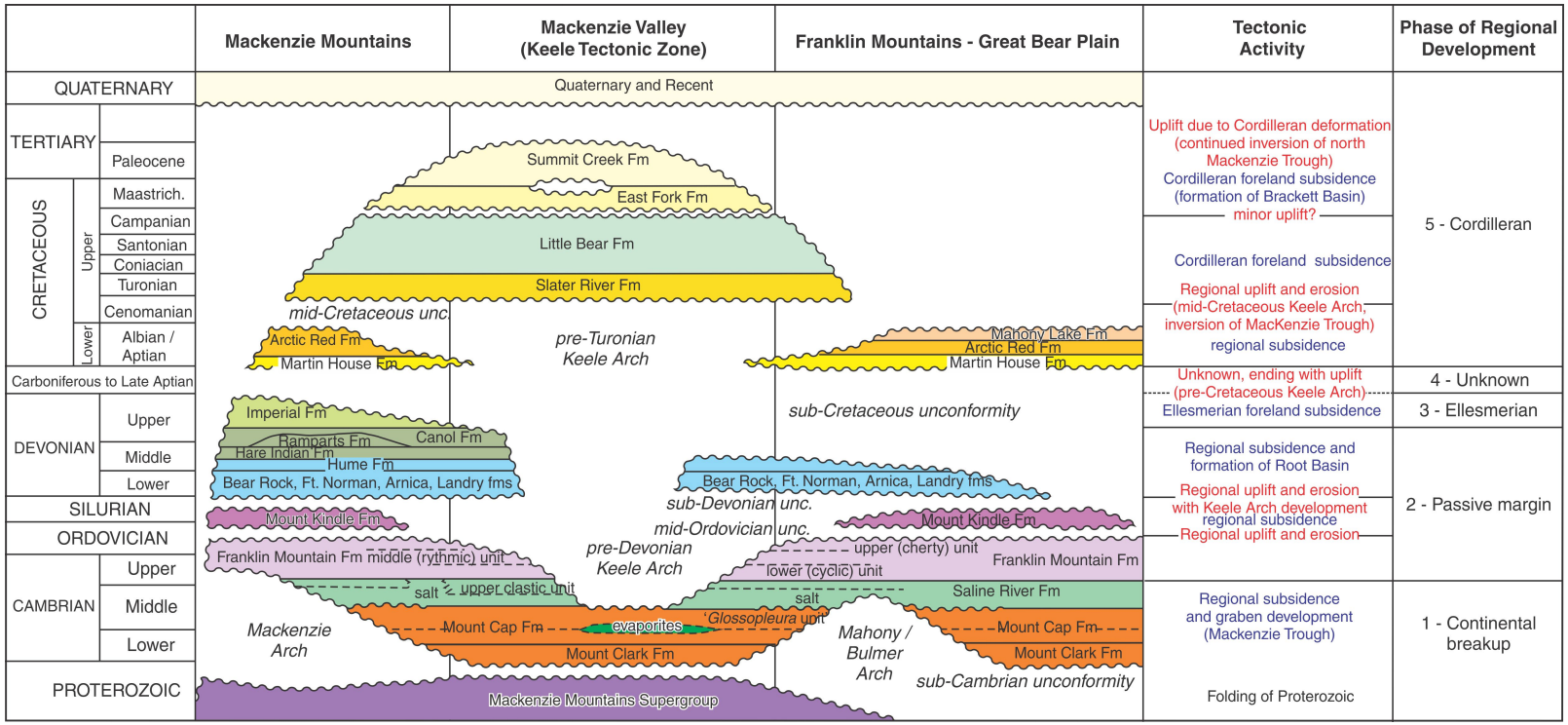

Figure 2. Stratigraphic column *modified from* MacLean and Cook (1999). Colour fills are consistent with those used in this report's maps and cross-sections. The phases of regional development are explained in the body of the text. The old threefold subdivision of the Cambrian Period has been used in order to remain faithful to the referenced literature.

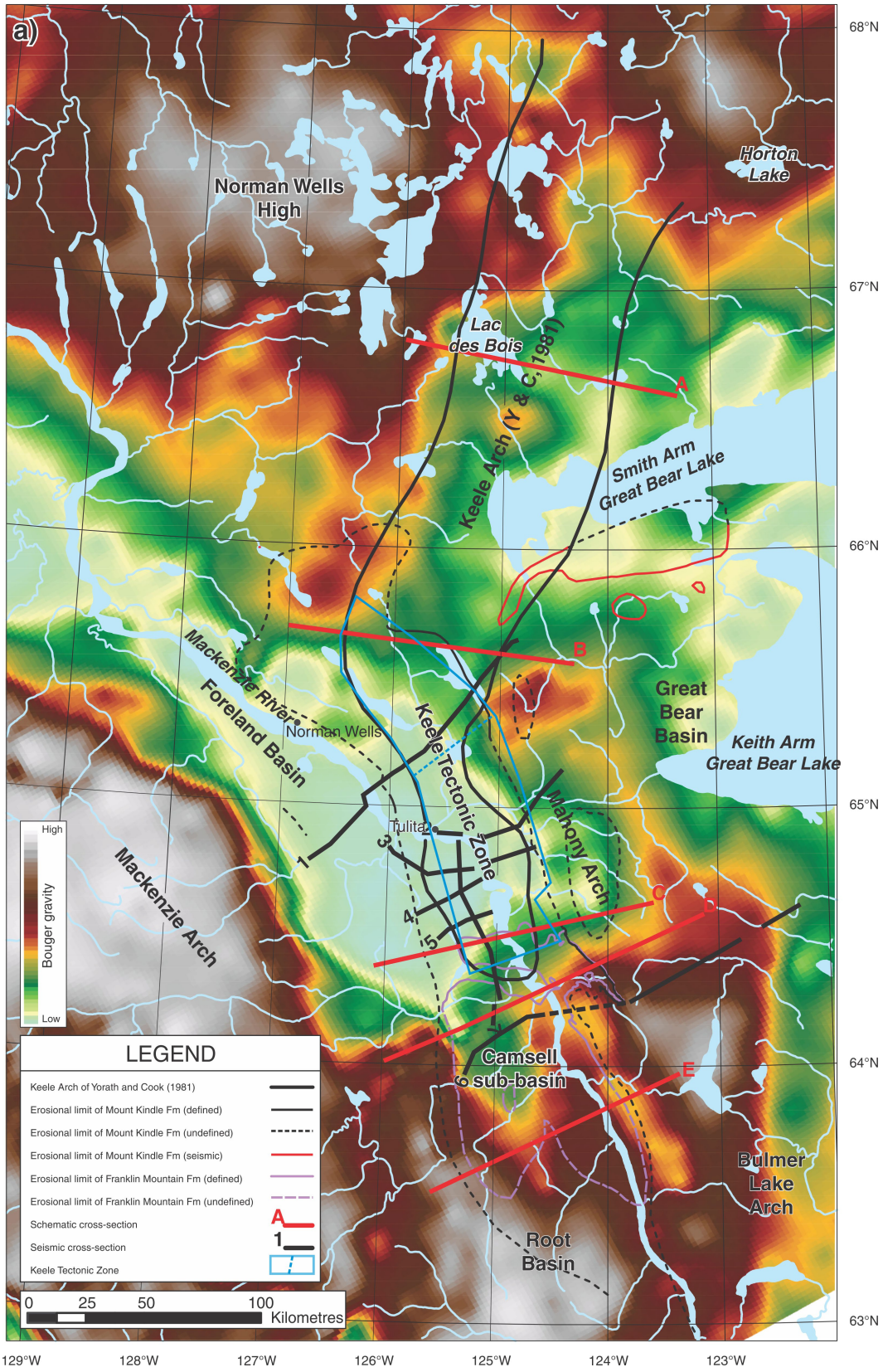

Figure 3. a) Map showing the major Keele Arch region elements plotted on the Bouger Gravity field (Geomatics Canada, 2010).

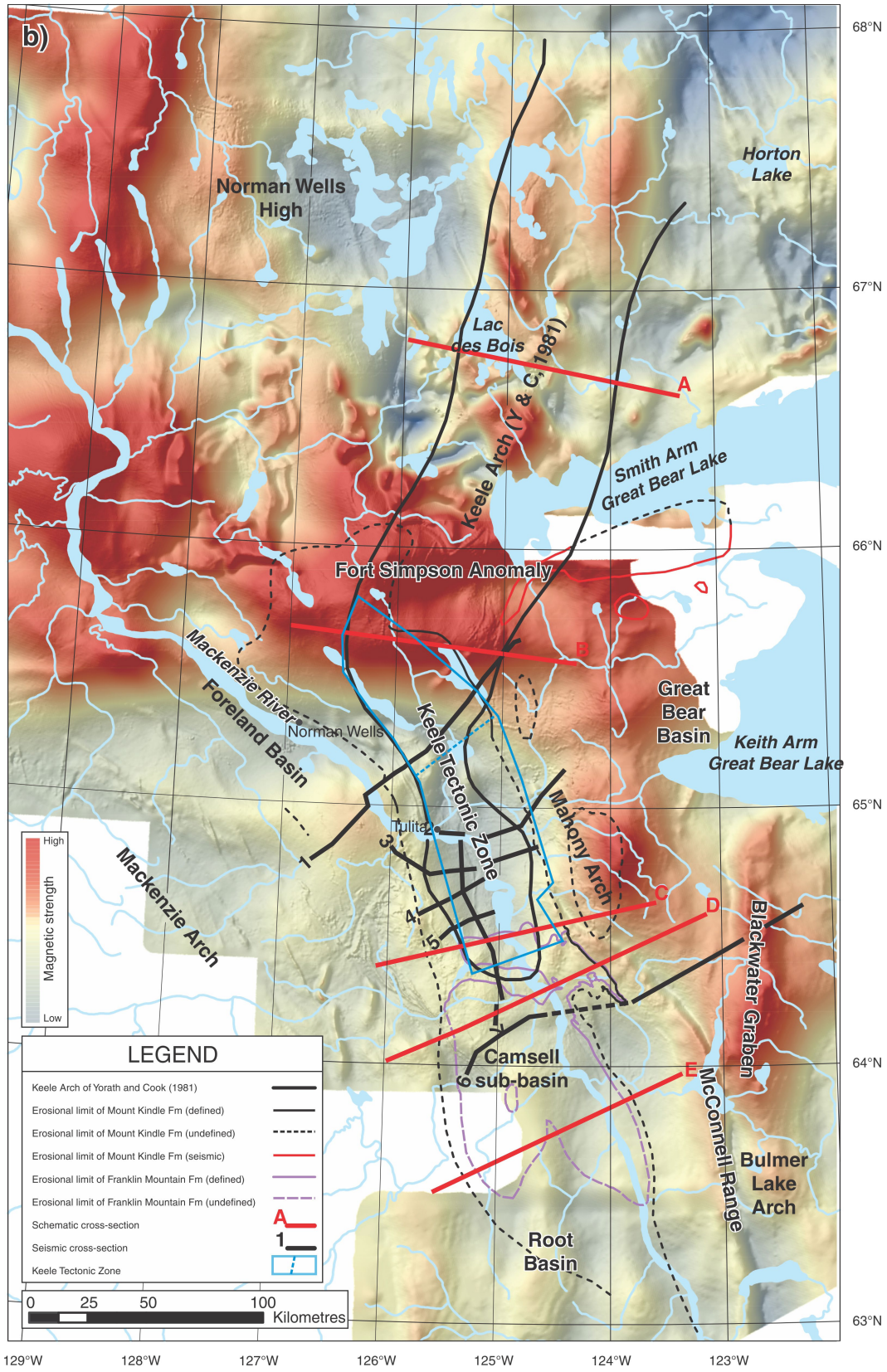

Figure 3. b) Map showing the major Keele Arch region elements posted with the Residual Magnetic field (Geological Survey of Canada, 2010). (Y & C, 1981) refers to Yorath and Cook (1981).

(MacNaughton et al., 2000), whereas Mesozoic strata were deposited into a foreland basin that developed in response to tectonic loading imposed by convergent margin orogenic activity (Stott and Aitken, 1993). The Phanerozoic stratigraphy within the study area can be viewed as having developed in five phases: 1) early extension and rifting, 2) margin subsidence, 3) Ellesmerian foreland subsidence, 4) a period for which we have no record, and 5) regional foreland subsidence triggered by cordilleran uplift to the west (Fig. 2).

Phase 1

The first phase spanned most of the Cambrian and was dominated by continental breakup tectonics (MacLean, 2011). The Mount Clark, Mount Cap, and Saline River formations consist mainly of siliciclastic rocks, derived from the immediately underlying and adjacent tectonic terranes (Hadlari et al., 2012) and evaporites deposited in a trough along the continental margin as the Cambrian sea advanced into an ever-expanding continental basin. During the extension phase a chain of grabens developed along the axis of the trough (MacLean, 2011), portions of which were later to play an important role in the evolution of Keele Arch region (Williams, 1989a).

Phase 2

The second phase was one of thermal, or passive, margin subsidence that commenced in the latest Cambrian with deposition of the Franklin Mountain Formation and ended with the influx of Imperial Formation clastics during the Late Devonian. Two regional unconformities within this sequence document episodes of widespread uplift and erosion that interrupted this subsidence phase. The first lies between the Franklin Mountain and Mount Kindle formations and marks a middle Ordovician hiatus. The second, below the Delorme Group, or where absent, the Bear Rock Formation, is a product of pre-Devonian erosion.

Phase 3

The slowly subsiding platform environment ended and Phase 3 began when, during the Late Devonian, Ellesmerian orogenic activity to the north turned much of the study area into a deep-water foreland basin into which a thick accumulation of Imperial Formation clastics was deposited (Moore, 1993; Hadlari et al., 2009b; Lemieux et al., 2011).

Phase 4

The fourth phase extended from the Carboniferous to the mid-Aptian and is represented by the sub-Cretaceous unconformity. The geological record for this time period has been entirely lost from the study area.

Phase 5

The fifth phase began during the Upper Aptian when much of the western continental margin entered a period of foreland subsidence in response to Cordilleran tectonic loading. Albian strata of the Martin House and lower Arctic Red formations onlapped the Keele Arch under the present day Brackett Basin (Hadlari et al., 2009a). An angular unconformity below the Slater River Formation documents a short-lived middle Cretaceous interruption (Thomson et al., 2011). A second interruption may have occurred during the Late Campanian but the resulting sub-East Fork unconformity is not well documented (Dixon, 1999). Products of compressional tectonism dominate the landscape today (Fig. 1) and that portion of Mackenzie Valley lying within the study area occupies a narrow foreland basin immediately east of the main Cordilleran front.

Potential Field

The regional Bouger gravity field (Fig. 3a) in the study area may be characterized as having wide expanses of high or low values separated by narrow transition zones across which the gravity gradients are steep. Areas of high gravity are, with the exception of Root Basin, associated with areas of shallow Proterozoic ‘basement’ (Norman Wells High, Mackenzie Mountains, and the Bulmer Lake and Mahony arches). The weakest gravitational field underlies the foreland and Brackett basins which are filled with thick, relatively low-density, Cambrian, Cretaceous, and younger strata. Intermediate gravity values are found across Great Bear Basin and along a trend of Cambrian grabens extending from the northern Franklin Mountains to north of Smith Arm (MacLean, 2011).

The residual magnetic field map (Fig. 3b) shows a trend of high values snaking across the map from the southeast to northwest corner. This is part of the Fort Simpson Arch which spans some 1300 km from northeast British Columbia to the Mackenzie Delta (Ross, 1991). Smaller anomalies, attributed to shallower features, include the Blackwater graben arch in Great Bear Plain, which has been attributed to a wedge of Tweed Lake Assemblage basalts preserved under the sub-Cambrian unconformity (MacLean and Miles, 2002), and narrow Cordilleran structures such as the McConnell Range.

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METHODOLOGY

This study of Keele Arch was largely focused on the segment between Brackett Lake and Johnson River. There, surface data were readily available, as the area had been mapped at a 1:125 000 scale and new field mapping was underway. Subsurface data was provided by a fair selection of good-quality reflection seismic lines and numerous boreholes (Fig. 1).

A series of paleoseismic transects covering the time period from the late Proterozoic to the present day was constructed by flattening their constituent seismic lines on the appropriate reflection horizons. The seismic work station provided preliminary images by vertically shifting seismic traces relative to one another. As this process could not make the horizontal shifts necessary for a proper restoration of dipping beds and faults, final adjustments were made by hand.

A cautionary note: The velocity of sound, or 'seismic velocity', through halite is approximately 4550 m/s regardless of its depth of burial. As a salt pillow grows, 4550 m/s material displaces strata whose velocity characteristics are, in most cases, different. A false uplift (velocity pull-up) will appear on a reflection seismic time-section below a salt pillow if the strata displaced by salt had a seismic velocity slower than 4550 m/s. Alternatively, false sags are produced where the displaced strata were of a 'faster material'. Such effects were removed during construction the paleoseismic transects.

Simple paleogeology maps that incorporated surface, borehole, and reflection seismic interpretations were drawn to complement the transects.

The evolution of the feature is presented in Figures 6 through 33, a series of maps and seismic transects that present the geology at a specific moment in time. The arch's development at each of the seven transect locations can be viewed in Appendix B. Before proceeding, it would be prudent to remember that, in the words of Williams (1989a) "Flattened sections discount any topographic relief and are therefore only approximations." Topography is removed and information regarding an arch's elevation relative to a structural datum is lost in the flattening process, with the consequence that lateral differences in vertical movements can be understated.

KEELE ARCH OVERVIEW

Map view

The pre-Cretaceous arch of Yorath and Cook (1981) begins east of the Colville hills, trends south-southwesterly to the northern Franklin Mountains and turns south-southeastward before plunging under Root Basin near Keele River (Williams 1989a) (Fig. 3). Devonian strata used by Yorath and Cook (1981) to define the southern terminus of the arch have since been confirmed by reflection seismic data (MacLean, 2012). The location of the northern portion is not so easily confirmed. This segment was based on the presence of Devonian strata in the area between Smith Arm and Horton Lake. However, Yorath and Cook (1981) included a note on their map acknowledging that these rocks were "interpreted entirely on assumption that a depression exists east of Keele Arch." No subsequent map, borehole, or fossil report that presents evidence for Devonian strata north of Smith Arm has been found to support this assumption.

For much of its length the Yorath and Cook arch lies within areas of low gravity strength (Fig. 3a). The southern portion is associated with the very low gravity field associated with Keele Tectonic Zone that is the product of lower density material within both the Brackett Basin and the underlying Cambrian Mackenzie Tough. The northern portion follows a northeast trend of relatively low gravity that MacLean (2011) attributed to the presence of shallow Cambrian grabens before diverging northward into the area of shallow basement and stronger gravity. The strongest correlation between Keele Arch and the residual magnetic field (Fig. 3b) is where it follows a chain of moderately high values north of Smith Arm.

Keele Arch plunges southward under Root Basin where it crosses the abrupt southern boundary of the low-gravity area associated with Keele Tectonic Zone. MacLean (2011) inferred the presence of a tear fault at this boundary while Williams (1989a) had placed Keele Fault with a down-to-the-south sense of throw. The magnetic field's response to this boundary is much more subtle. The very low magnetic field strength associated with the southern portion of Keele Tectonic Zone gives way southward to intermediate values and long-wavelength north-south-trending 'ridges', possibly related to eastward-directed Cordilleran deformation.

There are areas within which the Cambro-Ordovician Franklin Mountain Formation or the Late Ordovician-Silurian Mount Kindle Formation are absent due to non-deposition or erosion (Fig. 3). The absence of Franklin Mountain Formation under Root Basin is taken as evidence that Keele Arch once extended south of Keele Tectonic Zone. Further evidence of a southern arch is provided by the Mount Kindle Formation outline which defines a paleo-high extending northward from Root Basin into the northern Franklin Mountains.

Section view

Schematic cross-sections illustrate the fundamentals of Keele Arch region and how they differ from north to south and from the Middle Aptian to the present day (Fig. 4 and 5).

Section A is based solely on surface mapping as reflection seismic images were of too poor a quality. Strata that might have recorded a post-Devonian arch are absent. The Devonian strata assumed to lie north of Great Bear Lake by Yorath and Cook (1981) have not been included with the

result that the feature more resembles a west-facing hinge than an arch. Had these strata been present, the arch would have been wide and subtle to the point of being barely discernible.

Section B tracks from the Northern Franklin Mountains eastward across the north end of Mahony Lake and a low, unnamed ridge into Great Bear Plain. A central zone of thick Cambrian to Ordovician strata is evidence of enhanced subsidence of north Keele Tectonic Zone. The steep reverse fault must, therefore, once have defined the east boundary of an extensional graben (Fig. 4b, 5b). The western limits of the Mount Kindle, Lower, and Upper Cretaceous strata are attributed to one or more episodes of uplift and erosion as will be discussed below. Two narrow topographic ridges and the last phase of uplift on the deep-rooted fault are products of eastward-directed compressional forces generated during Cordilleran mountain building.

Section C tracks from the deformational front of the Mackenzie Mountains across Mackenzie Plain and McConnell Range into Great Bear Plain. Under Mackenzie Plain, a very thick accumulation of Cambrian strata is in marked contrast with the thin Cambrian section that lies under Great Bear Plain. The thicker section was deposited in the Mackenzie Trough graben of Keele Tectonic Zone. As was the case in Section B, the reverse fault, now under McConnell range, must once have defined the eastern boundary of an extensional Cambrian graben (Fig. 4c, 5c). The absence of Franklin Mountain, Mount Kindle, Devonian, and Lower Cretaceous strata in the centre of Section C (and D) are the result of erosion across different phases of Keele Arch. McConnell Range and the foreland basin are both products of Cordilleran mountain building. Upper Cretaceous strata are thick in the foreland basin, absent across McConnell Range, and very thin in Great Bear Basin.

A key feature of Section D is that Devonian strata rest directly on a block of Proterozoic strata under the foreland basin. As will be discussed later, the geological history of this zone is poorly understood as the data necessary to determine whether pre-Devonian Phanerozoic strata had ever been deposited across the block is not available. Also of note is that the wide Mackenzie Trough of Section B has narrowed into McConnell graben (MacLean, 2011). While there is no evidence of a pre-Cretaceous arch (Fig. 5d), a central gap in the distribution of Lower Cretaceous strata (Fig. 4d) is evidence of a mid-Cretaceous one. A thick accumulation of Devonian strata fills Camsell sub-basin of Root Basin. The frontal thrust to the Mackenzie Mountains (Fig. 3) lies further east than in Section C with the result that the preserved foreland basin is narrower and more sharply folded.

Section E displays an even deeper Root Basin whose eastern boundary is defined by a hinge zone. When compared with Section D, it is apparent that the zone across which Devonian rocks rest directly on Proterozoic has broadened. A small erosional inlier of unknown material, preserved between the Proterozoic and Devonian rocks, is evidence of pre-Devonian deposition. Although coloured as Franklin Mountain on the section, the inlier could consist of any pre-Devonian Phanerozoic unit. There is no evidence of a pre-Cretaceous arch (Fig. 5e). Whether the absence of Lower Cretaceous strata is due to non-deposition or erosion is unresolved. The frontal thrust of Sections C and D is not present and the foreland basin is consequently wider and shallower.

In summary, it is observed that:

- The arch is weakly developed north of Great Bear Lake (Section A).
- Subsidence of Keele Tectonic Zone may have continued uninterrupted from Early Cambrian to Middle Ordovician time (Section B).
- Subsidence and uplift phases of Keele Arch region are best defined within Keele Tectonic Zone (Sections B and C).
- South of Keele Tectonic Zone there is an area from which virtually all pre-Devonian Phanerozoic strata are missing (Sections D and E).
- A Late Silurian high is evident on all but Section A.
- Nowhere do Lower Cretaceous strata extend across the arch. It is difficult to ascertain from these sections if this is solely due to mid-Cretaceous uplift and erosion or to a combination of pre- and mid-Cretaceous events.

KEELE ARCH DEVELOPMENT

Discussion begins with a review of the present-day geology map and seismic images, steps back in time to immediately prior to deposition of Cambrian strata, and then returns by steps to the present.

Present day

Today's geology map (Fig. 6) shows Keele Arch region consisting of four segments. 1) A northern, northeast-striking, broad arch (1a) of Cambro-Ordovician Franklin Mountain Formation flanked by Silurian and Devonian strata is evidence of Late Silurian and later uplift(s). Parallel to it is a second, narrower, feature (1b) that has been interpreted as a late product of Cordilleran deformation and not a true Keele Arch feature. 2) In the north half of KTZ a northwest-striking arch of Cambro-Ordovician Franklin Mountain Formation, flanked by Silurian and Devonian strata, is again evidence of Late Silurian and later uplift(s). That a mid-Cretaceous arch existed here is confirmed by the two areas of Upper Cretaceous strata directly overlying Cambro-Ordovician strata of the Franklin Mountain Formation. 3) Brackett Basin, in the south half of KTZ, is evidence of Tertiary subsidence. 4) A synclinal trend exists south of Keele River and KTZ within which Upper Cretaceous strata are preserved.

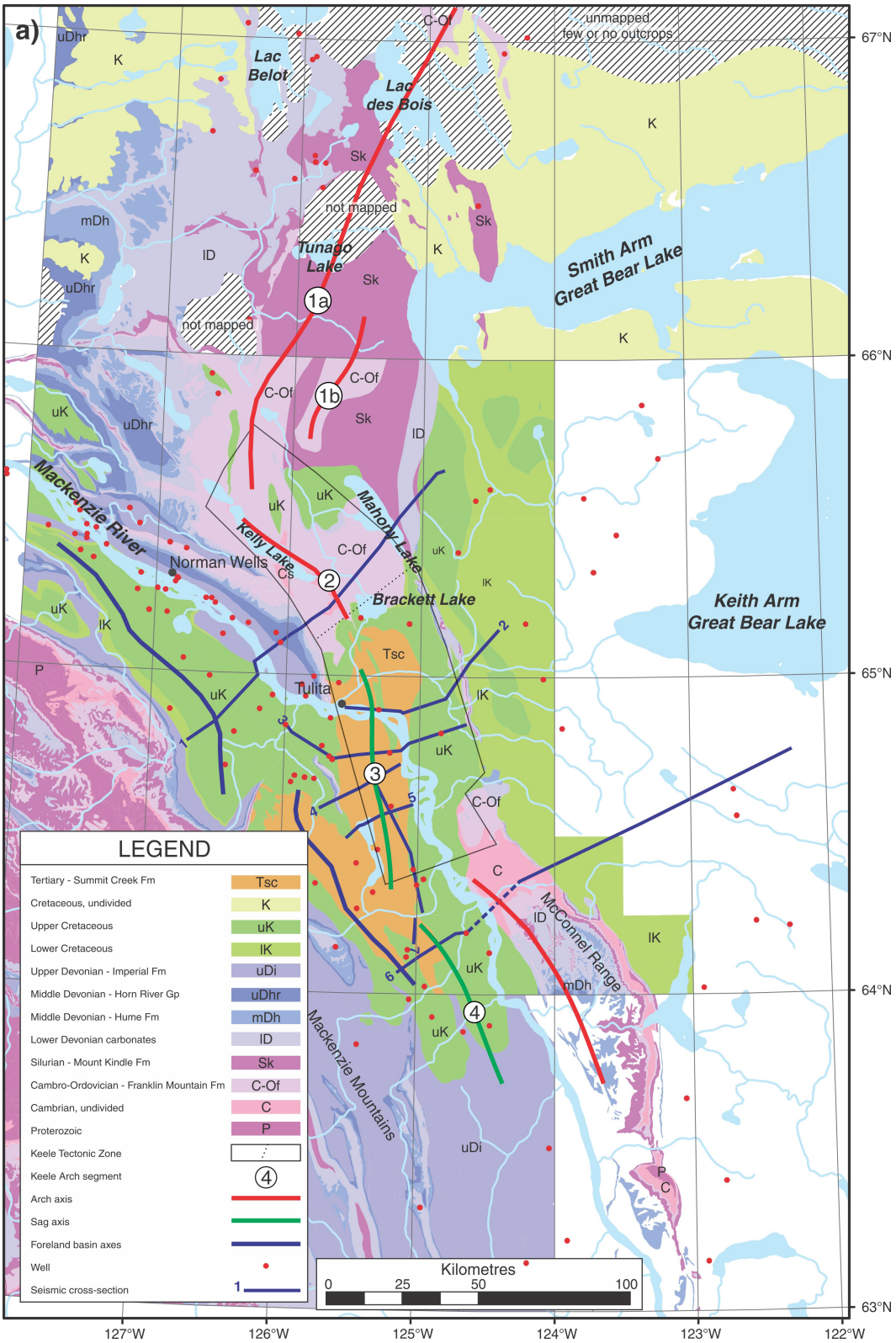

Figure 6. a) Simplified map of the present day geology, *modified from* Aitken and Cook (1970), Cook et al. (2010), Douglas (1974), Douglas and Norris (1974), Fallas (2013a, b, c, d), Fallas and MacLean (2013a, b), Fallas and MacNaughton (2013, 2014), and Fallas et al. (2013a, b, c, d).

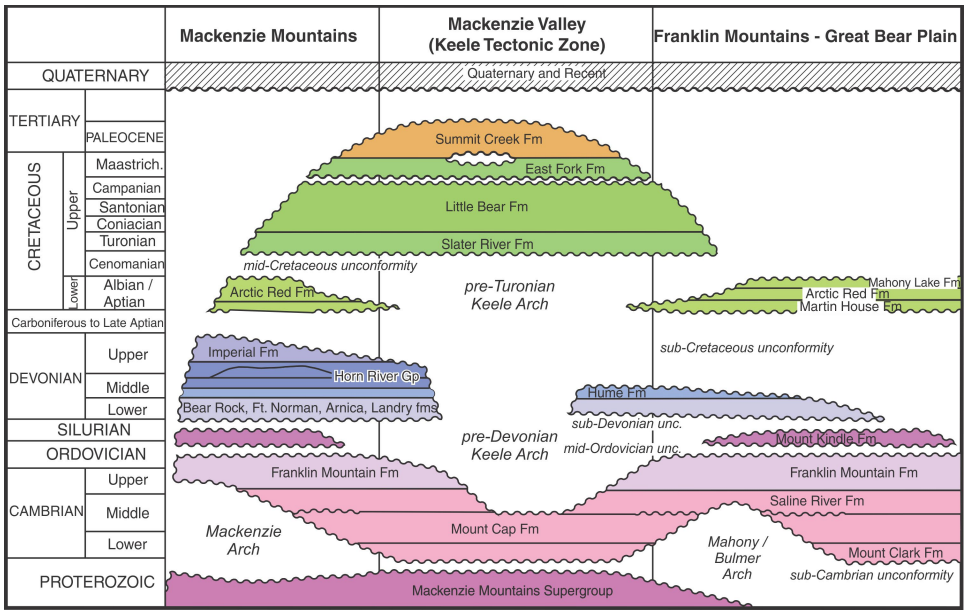

Figure 6. b) Stratigraphic column (*modified from* MacLean and Cook, 1999).

Section views (Fig. 7) show large-scale tectonic elements, including the Devonian Root Basin (Fig. 7, Transect 6) and a large Proterozoic syncline. To the east is Great Bear Basin which is bounded on the west by deep, large-scale vertical faults which underlie the McConnell and 'St. Charles' ranges. The foreland basin and numerous folds and thrust faults involving Paleozoic and Cretaceous strata are late products of Cordilleran deformation.

That portion of Transect 6 (Fig. 7) across the large data gap is based on the extrapolation of seismic horizons into the gap and the surface mapping of Cook et al. (2010). Paleosections through this zone that will be discussed below were based on this interpretation.

Large-scale stratigraphic elements include a thick sequence of Mackenzie/Shaler Assemblage (M/S Assemblage) strata in the Proterozoic syncline. This assemblage was so named by Cook and MacLean (2004) for they interpreted it to be the subsurface equivalent of the Late Proterozoic Mackenzie Mountains Supergroup which is exposed in the Cordillera, as well as the Shaler Supergroup exposed in Brock Inlier to the northeast. Above it lie Cambrian strata (orange and green units) that attained considerable thicknesses within grabens, the largest of which is Mackenzie Trough. The Cambrian Saline River Formation includes the Evaporite Member (Dixon and Stasiuk, 1998) that provided a detachment layer for Late Cretaceous and Tertiary thrust faults and folds as well as sufficient ductile material for the development of numerous pillows such as those found on Transect 3 (Fig. 7).

A distinctive seismic reflection within the Mount Cap interval marks the base of what MacLean and Cook (1999) called the '*Glossopleura* unit' because of its general correspondence to a shale interval found, by Fritz (1970), to contain *Glossopleura* in the Shell Keele River L-04 well (Fig. 7, Transect 7). The marker serves as an informal boundary between an upper and lower Mount Cap Formation. A salt pillow (MacLean and Cook, 1999) lies immediately below the '*Glossopleura* unit' at the L-04 location and is the single known occurrence of Mount Cap salt in the mainland Northwest Territories.

Note the velocity pull-up under the Old Fort Point structure (Fig. 7, Transect 3) where pillow growth displaced 'slow velocity' strata of the Upper Cretaceous East Fork Formation.

Above the Saline River Formation lies a thick carbonate sequence (purple and blue), capped by the clastic and carbonate rocks of the Horn River Group. The carbonate sequence was deposited during a period of continental-margin subsidence that lasted from Late Cambrian until middle-Late Devonian time. Mid-Ordovician and sub-Devonian unconformities and lateral thickness changes within this sequence are products of regional and local uplift episodes. The sub-Devonian unconformity cuts sharply down-section in the southern portion of Transect 7 (Fig. 7) until it merges with the sub-Cambrian unconformity.

Overlying the Horn River Group are the clastic rocks of the Imperial Formation, deposited into an Ellesmerian foreland basin (light green in Transects 1, 6, and 7 of Fig. 7). The Imperial Formation is capped by the sub-Cretaceous unconformity which represents a Carboniferous to mid-Albian hiatus.

The thick Cretaceous succession was deposited as the Cordillera developed to the west. The mid-Cretaceous (sub-Slater River) unconformity is the result of regional uplift and erosion. Local enhancement of that uplift is documented by the absence of Lower Cretaceous strata and thinning of Upper Cretaceous beds across the Keele Arch region (Fig. 7,

Transects 1 to 6). The upper strata preserved in Brackett Basin consist of East Fork Formation and the non-marine clastic rocks of Summit Creek Formation.

Structures preserved across the Keele Arch region include normal faults related to Cambrian extension, folding associated with salt pillows, Cordilleran thrust and reverse faults detached within Saline River evaporites, and reverse faults formed by Cordilleran inversion of Cambrian normal faults. Each of these structure types is linked to features that developed during the earlier history of the Keele Arch.

pre-Cambrian

Prior to the breakup of Rodinia and the ensuing encroachment of the Cambrian sea, the sub-Cambrian unconformity (top of Proterozoic) was part of a continental peneplain. The paleomap of the unconformity surface (Fig. 8) shows an arm of Late Proterozoic M/S Assemblage under the Mackenzie River valley south of Tulita (Cook and MacLean, 2004).

Paleotransects (Fig. 9), constructed by flattening the reflection from the top of the Proterozoic, show the arm of M/S Assemblage to have been a large syncline preserved under the sub-Cambrian unconformity surface. Transects 1 and 3 (Fig. 9) provide the clearest evidence of the syncline's width and shape. The folded nature of the strata is indicative of post-deposition compression.

pre-*Glossopleura* Cambrian

Two maps (Fig. 10) chart the arch's development prior to deposition of the *Glossopleura* unit of the Mount Cap Formation. Map a is an adaptation of Figure 11 of MacLean (2011) and shows the pre-extension configuration as the Cambrian sea advanced into the area and deposited the basal siliciclastic rocks of the Mount Clark Formation. Keele Arch region was expressed as a pre-extension high in Keele Tectonic Zone. Further south, McConnell graben developed along the east side of an enigmatic block of Proterozoic rock. The presence of a thick accumulation of Mount Clark Formation in McConnell graben has been confirmed in measured sections at Mount Cap (Aitken et al., 1973).

The hachured map polygon represents the aforementioned block of Proterozoic rock upon which Early Devonian strata lie in direct contact. It overlaps the east side of the outlier of pre-M/S Assemblage strata shown in Figure 7, but it remains unclear what, if any, role that outlier played in the arch's development. The absence of pre-Devonian Phanerozoic strata across the zone precludes a confident analysis of the block's early Paleozoic history. It is a matter of speculation as to whether the block was emergent during the entire Cambrian to Silurian time interval or just during portion(s) of it. One consequence is that the original western limit of McConnell graben may have been located further west than it is today.

Map b (Fig. 10) portrays the early extension phase during which time a significant thickness of pre-*Glossopleur*a unit Mount Cap Formation strata was deposited into Mackenzie Trough and McConnell graben. The pre-extension high of KTZ has been inverted into Mackenzie Trough which, as illustrated, may have been contiguous with McConnell graben. The presence of pre-*Glossopleura* unit strata in McConnell graben is inferred from the identification of *Ollenellus* in strata exposed on Cap Mountain (Aitken et. al., 1973). A separate area of subsidence and deposition developed east of Mahony Arch in the hanging wall of Blackwater Fault.

Paleotransects (Fig. 11), constructed by flattening the reflection from the base of the *Glossopleura* unit, illustrate the role of extensional faults in the development of Mackenzie Trough. The west side of the graben is well imaged on the seismic data (Transects 1, 3 and 4 of Fig. 11), but its eastern boundary, except on Transect 1 (Fig. 11), is more interpretive for it lies under a chain of mountain ranges where reflection seismic images are generally of poor quality. As previously stated, the presence of thick Cambrian strata immediately west of the Bulmer Lake and Mahony arches in McConnell graben is confirmed in outcrop on Cap Mountain.

In summary, Keele Arch region was initially a pre-extension high but soon subsided into Mackenzie Trough (in KTZ) which may have been contiguous with McConnell graben.

Mid-Cambrian*

* Rather than risk misinterpreting their intent, the earlier workers' threefold subdivision of the Cambrian is used throughout this report.

The map (Fig. 12) is an adaptation of Figure 12 of MacLean (2011) and shows the Cambrian basin to have expanded and its central graben core to have extended northeastward toward the present day Smith Arm of Great Bear Lake. The graben zone's abrupt change of direction at the north end of KTZ is reminiscent of a 'triple junction', a common feature of rifted margins. During this later part of the Middle Cambrian, upper strata (*Glossopleura* unit) of the Mount Cap Formation were deposited across the basin with the thickest accumulations within the central grabens (MacLean, 2011). The situation of the Proterozoic block, represented by the hachured area, remains unknown but the small area of exposed Proterozoic lying just north of it suggests that at least a portion of the block may have been emergent also.

Paleotransects (Fig. 13), constructed by flattening on the reflection from the top of the Mount Cap Formation, show the Cambrian grabens to have continued their subsidence and expansion. The thickest Early Cambrian strata in Mackenzie Trough were deposited in the region of Transects 2 to 5 of Figure 13. Transect 7 (Fig. 13) is unique in that

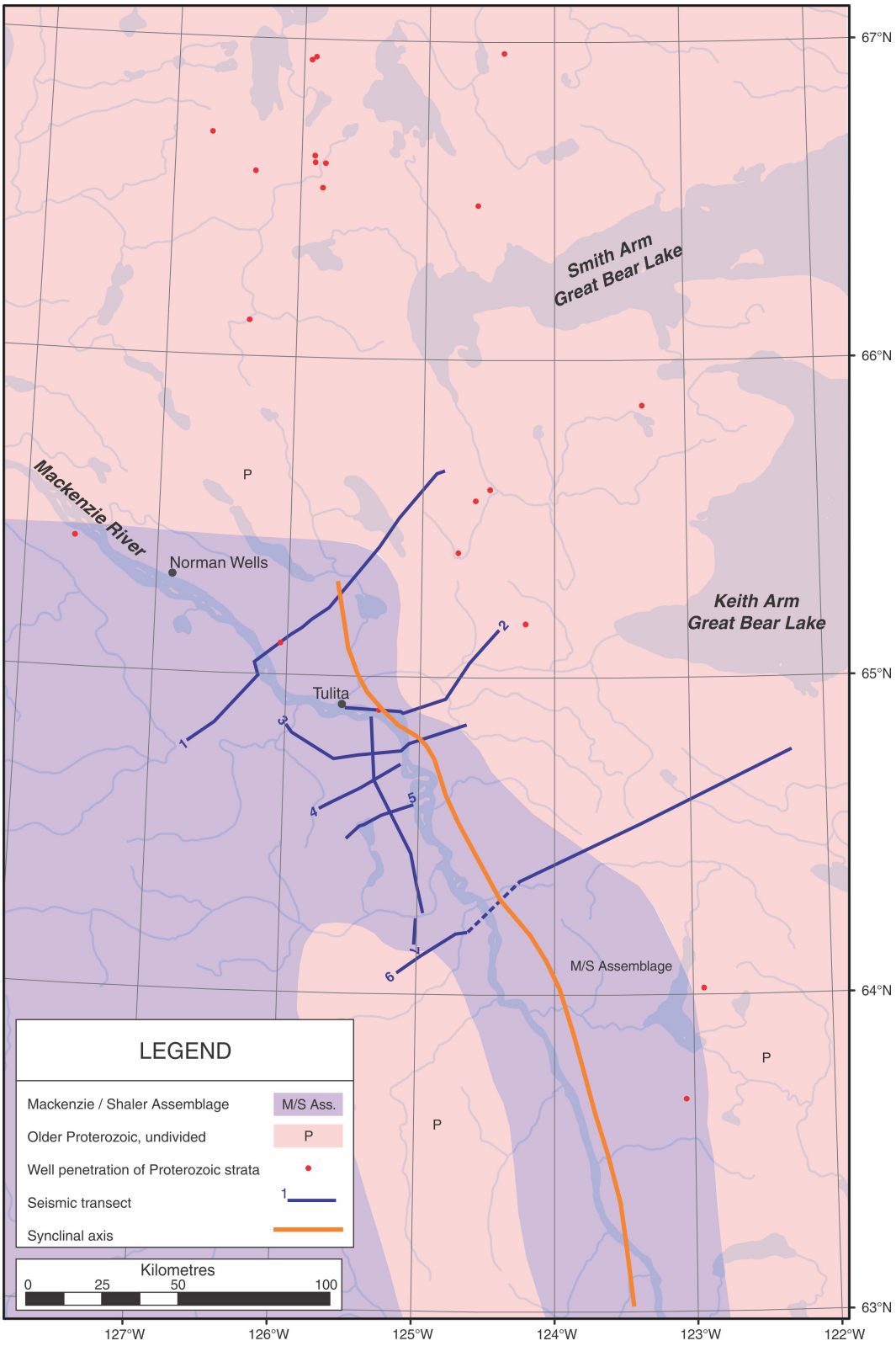

Figure 8. Pre-Cambrian paleogeology map, immediately prior to deposition of Cambrian strata. Datum is the sub-Cambrian unconformity.

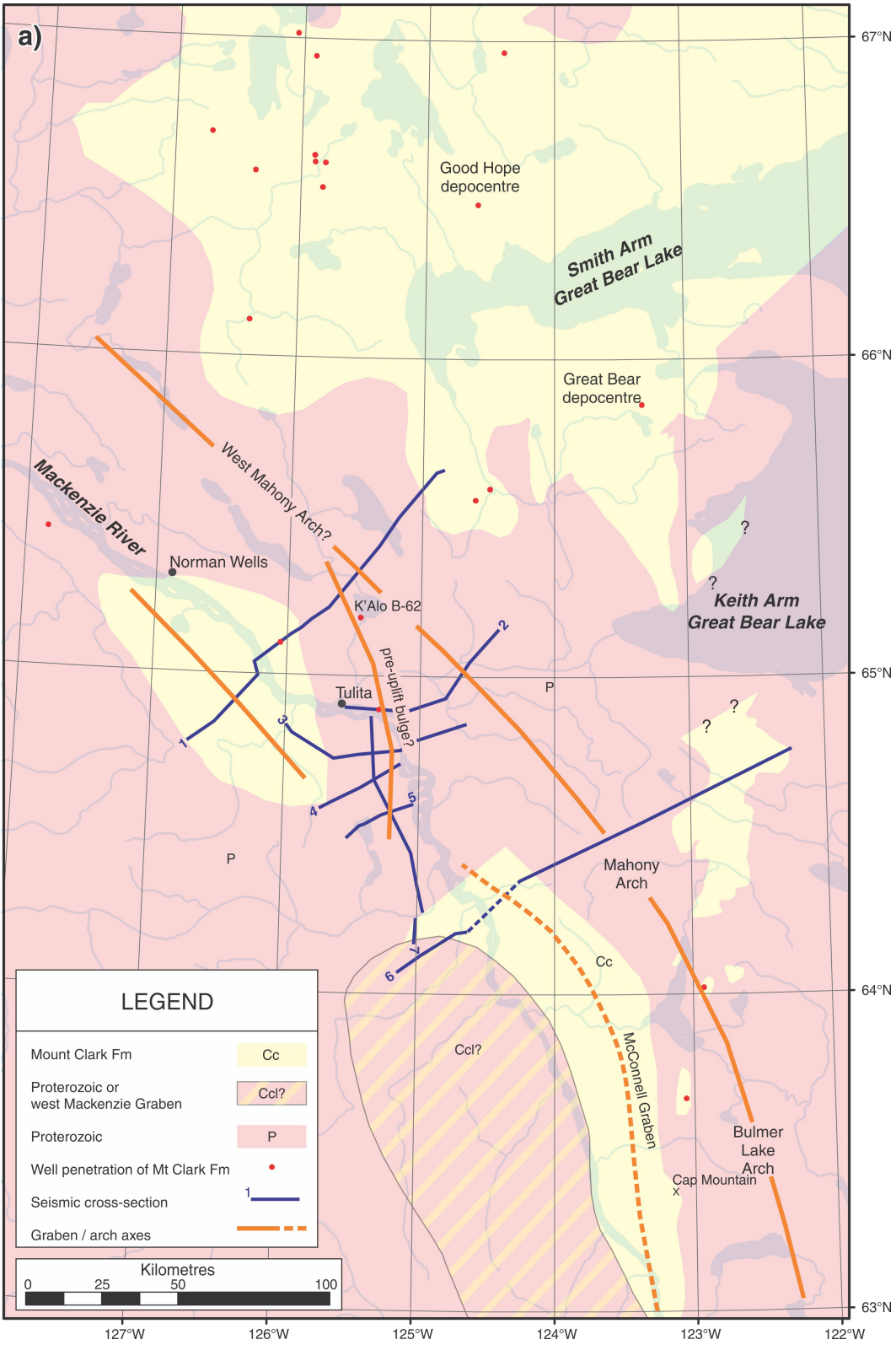

Figure 10. Early Cambrian paleogeology maps. **a)** Earliest Cambrian, immediately prior to the development of Mackenzie Trough (*adapted from* Figure 11 of MacLean (2011)).

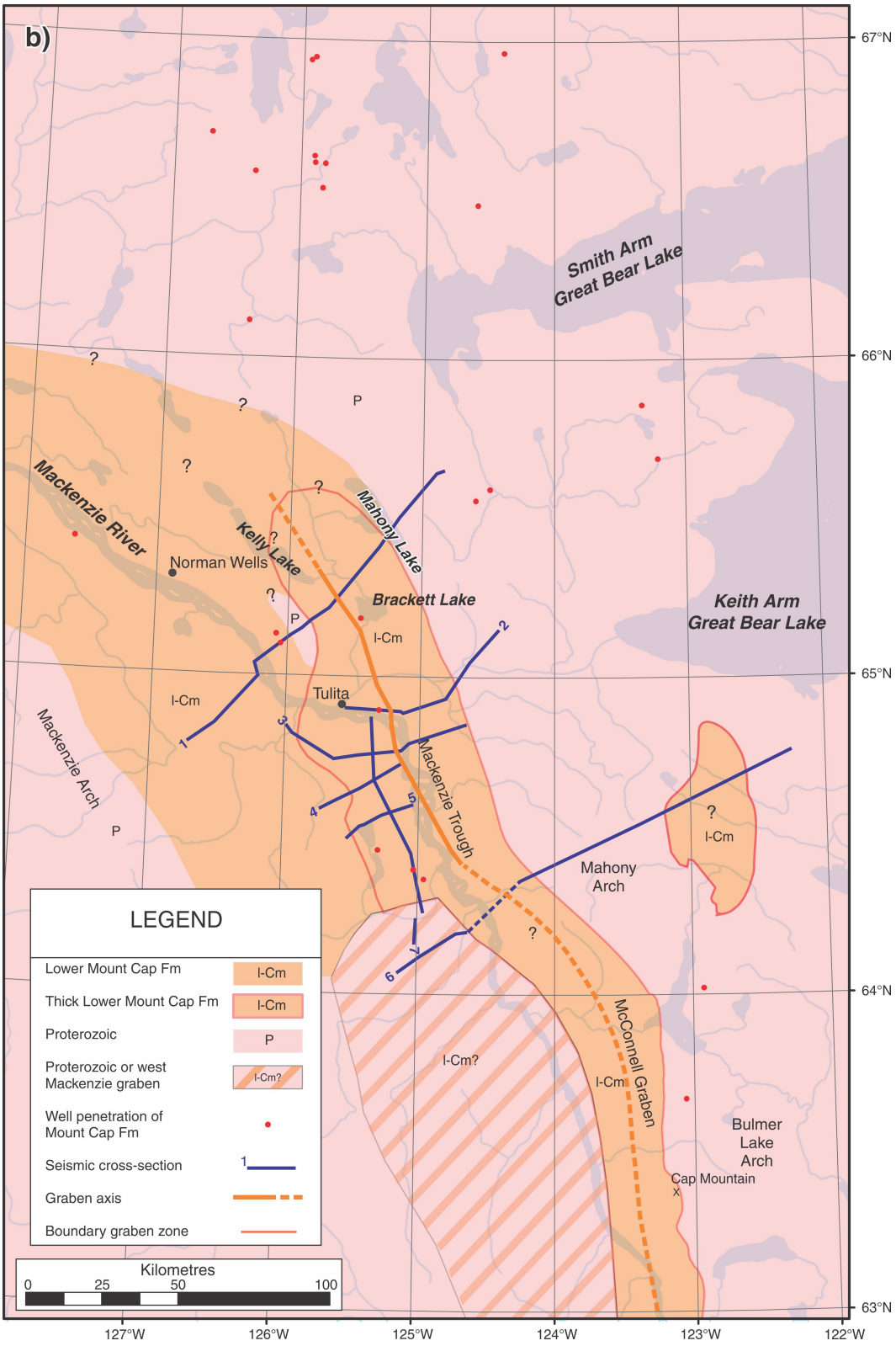

Figure 10. Early Cambrian paleogeology maps. **b)** Early Cambrian, immediately prior to deposition of the Glossopleura unit.

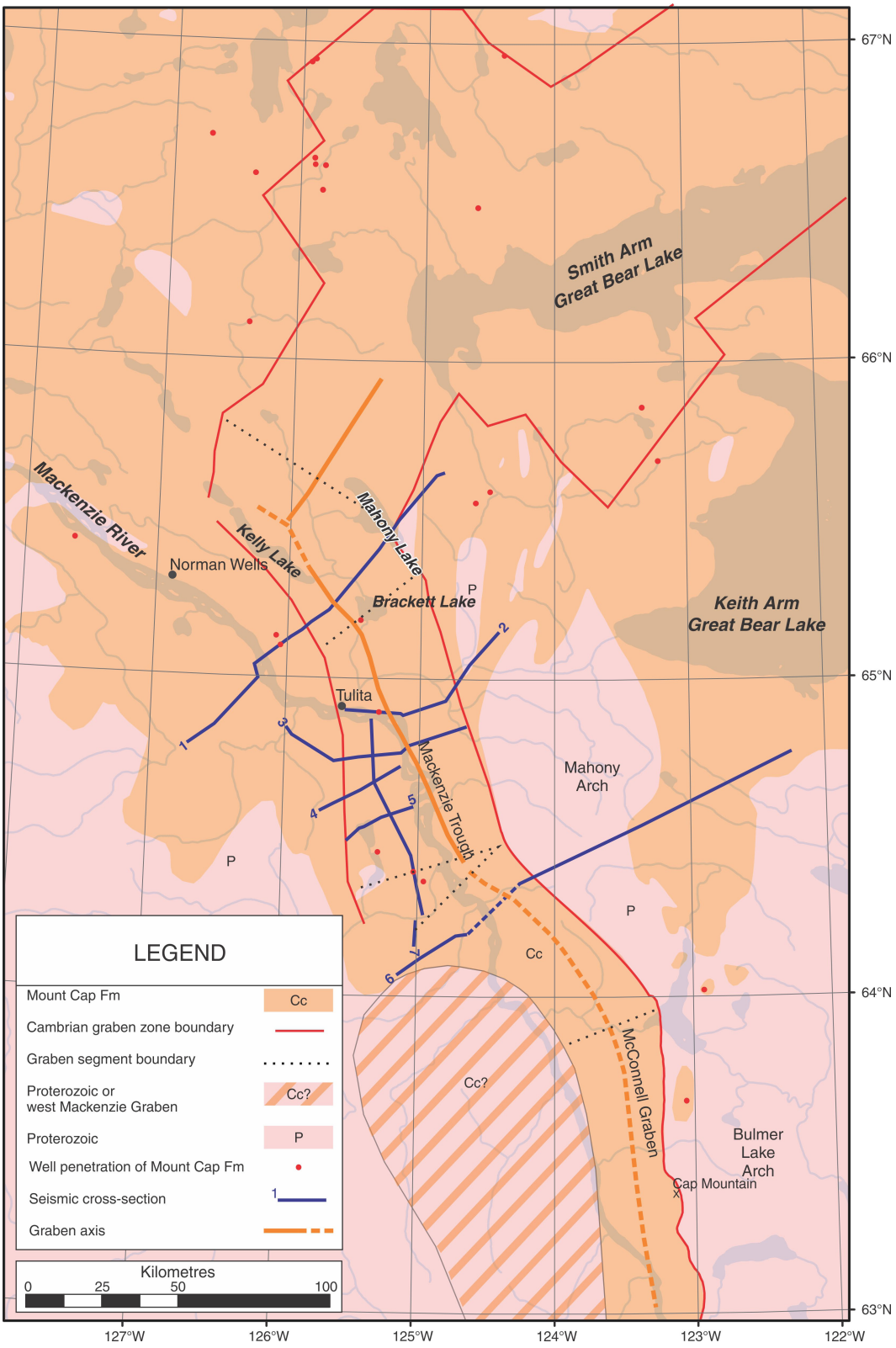

Figure 12. Middle Cambrian paleogeology map at the close of Mount Cap Formation deposition (*adapted from* Figure 12 of MacLean (2011)).

it contains an areally restricted salt accumulation at the sub-*Glossopleura* unit boundary. Mount Cap and Mount Clark, formations are shown possibly extending beyond the south end of the transect and into the west end of Transect 6 (Fig. 13) to acknowledge that its present day absence there is, to some extent, likely due to erosion. The presence of a thick accumulation of Mount Cap Formation in McConnell Graben has been confirmed in measured sections at Cap Mountain (Aitken et al., 1973).

In summary, Keele Arch region remained a chain of extensional grabens. Both this chain and the arch extended northeastward beyond KTZ. An enigmatic high lay to the west, south of the present day Keele River.

Late Cambrian

During the Middle to Late Cambrian, Saline River Formation was deposited across most of the study area and onlapped, but did not completely cover, the Mackenzie and Mahony arches. The enigmatic hachured zone (Fig. 14), with an adjoining area of emergent Mount Cap Formation, took on the character of a north-plunging arch. This arch may have been a product of post-depositional uplift, in which case the Saline River edge was erosional. Alternatively, the edge was depositional if the Saline River Formation was deposited around a pre-existing uplift.

Paleotransects (Fig. 15), constructed by flattening on the reflection from the top of the Saline River Formation, show continued graben subsidence and the accumulation of thick sediments within them. The focus of Late Cambrian subsidence, while remaining in Mackenzie Trough (KTZ), shifted northward to the vicinity of Transect 1 (Fig. 15), or possibly further north under the northern Franklin Mountains where data are lacking.

Thicknesses of Saline River Formation shown in Transects 4 and 5 (Fig. 15) are rather more interpretive as construction of the paleosections involved returning material from within the pillows' cores to their original location.

In summary, the graben character of Keele Arch region was unchanged. An arch may have developed west of, and parallel to, McConnell graben but its timing is unclear.

Mid-Ordovician

Deposition of Saline River siliciclastic and evaporate rocks gave way to Franklin Mountain Formation carbonates during the Late Cambrian, as the tectonic environment changed from Phase 1 extension to Phase 2 margin subsidence (Fig. 2). The change was transitional as reflected by the conformable and gradational nature of the Saline River to Franklin Mountain contact (Pugh, 1983). Subsidence continued until interrupted during the Middle Ordovician by uplift and consequent regression and erosion. The maps and sections portray the geology immediately prior to a return to margin subsidence conditions and the deposition of the Late Ordovician-Silurian Mount Kindle Formation.

The hachured zone on the map (Fig. 16) shows the Late Cambrian emergent area of Figure 10 to have shrunk dramatically. Two possible explanations are offered for the absence of Franklin Mountain Formation on the crest of the high. If the Franklin Mountain edge was depositional, then the area was an emergent island within the Early Ordovician sea. However, if the edge was erosional then Franklin Mountain Formation was deposited further onto, or completely across, the high only to be removed during mid-Ordovician regression. Until the material preserved within the small inlier is identified, this question must remain unanswered.

Paleotransects (Fig. 17) were constructed by flattening the top of the Franklin Mountain Formation. The sections are somewhat speculative given that the original thickness of the Franklin Mountain Formation is unknown due to widespread erosion at the mid-Ordovician unconformity. The considerably greater thickness of the formation within KTZ (Fig. 17, Transect 1) supports the interpretation of Williams (1989a) that Mackenzie Trough continued to subside faster than did the surrounding region. The focus of Mackenzie Trough subsidence remained near, or north of, Transect 1 (Fig. 17).

Pillows cored by Saline River Formation halite began to develop (e.g. Fig. 17, Transect 4).

In summary, Keele Arch region continued to develop as a submerged subsiding graben trend, with an exposed enigmatic high on its west flank, south of the present day Keele River.

Mid-Silurian

Margin subsidence resumed in the Late Ordovician and continued through the Early Silurian during which time the Mount Kindle Formation was deposited (Fig. 18). Later erosion removed any direct evidence regarding depositional thicknesses (hence the 'speculative' label on (Fig. 19). However, Williams (1989a) estimated that the formation was only about 100 m thick across the Keele Arch region but provided no supporting evidence for his estimate. If correct, it would suggest a degree of depositional thinning as the unit thickened away from the area to almost 200 m.

In summary, Keele Arch region had no surface expression but seafloor topography may have been in the order of 100 m.

Latest Silurian

The paleomap of the sub-Devonian unconformity (Fig. 20) and transects constructed by the flattening of its seismic reflection (Fig. 21) capture the situation immediately prior to deposition of Devonian strata. They offer

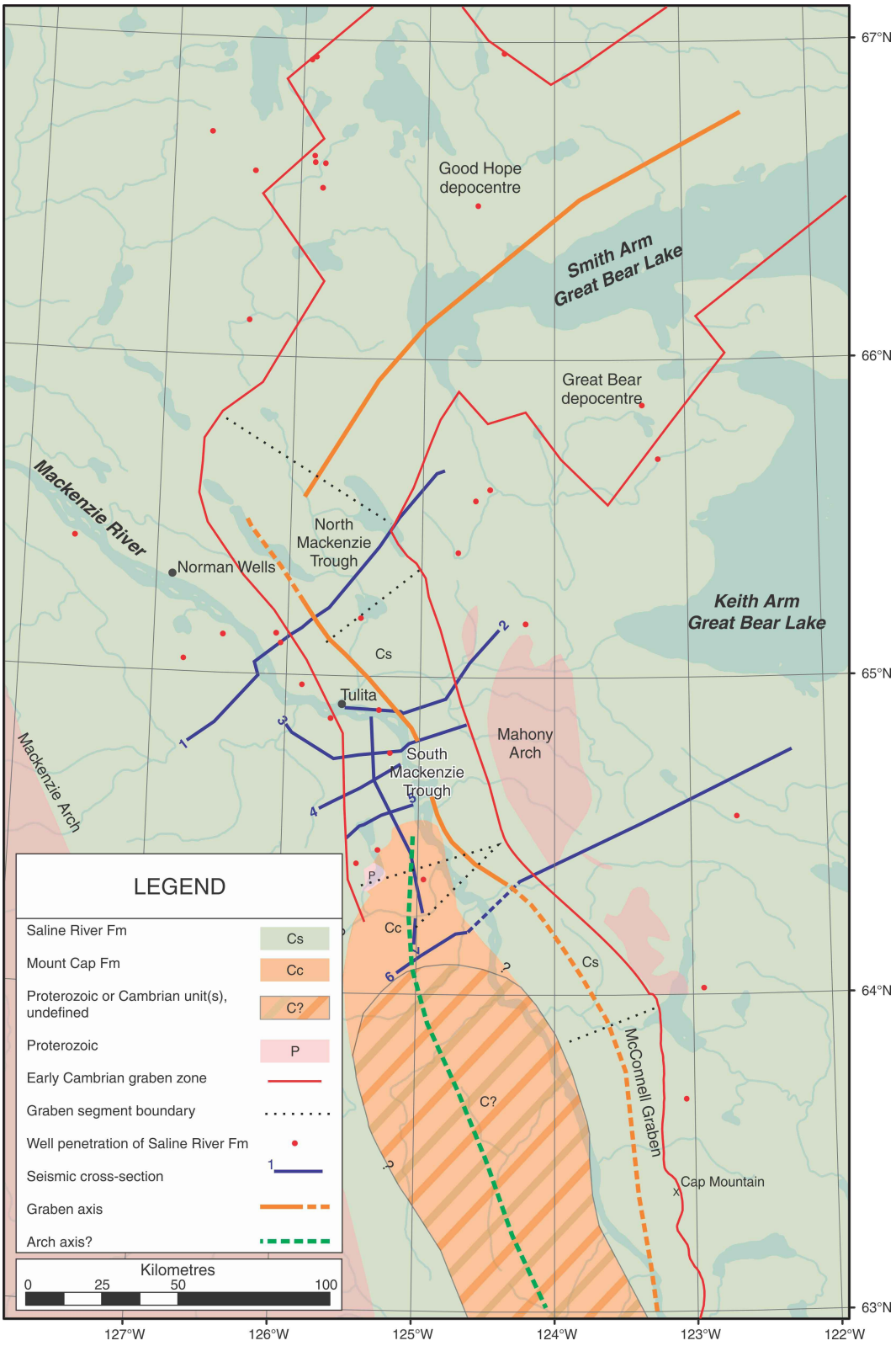

Figure 14. Late Cambrian paleogeology map at the close of Saline River Formation deposition (*adapted from* Figure 12 of MacLean (2011)).

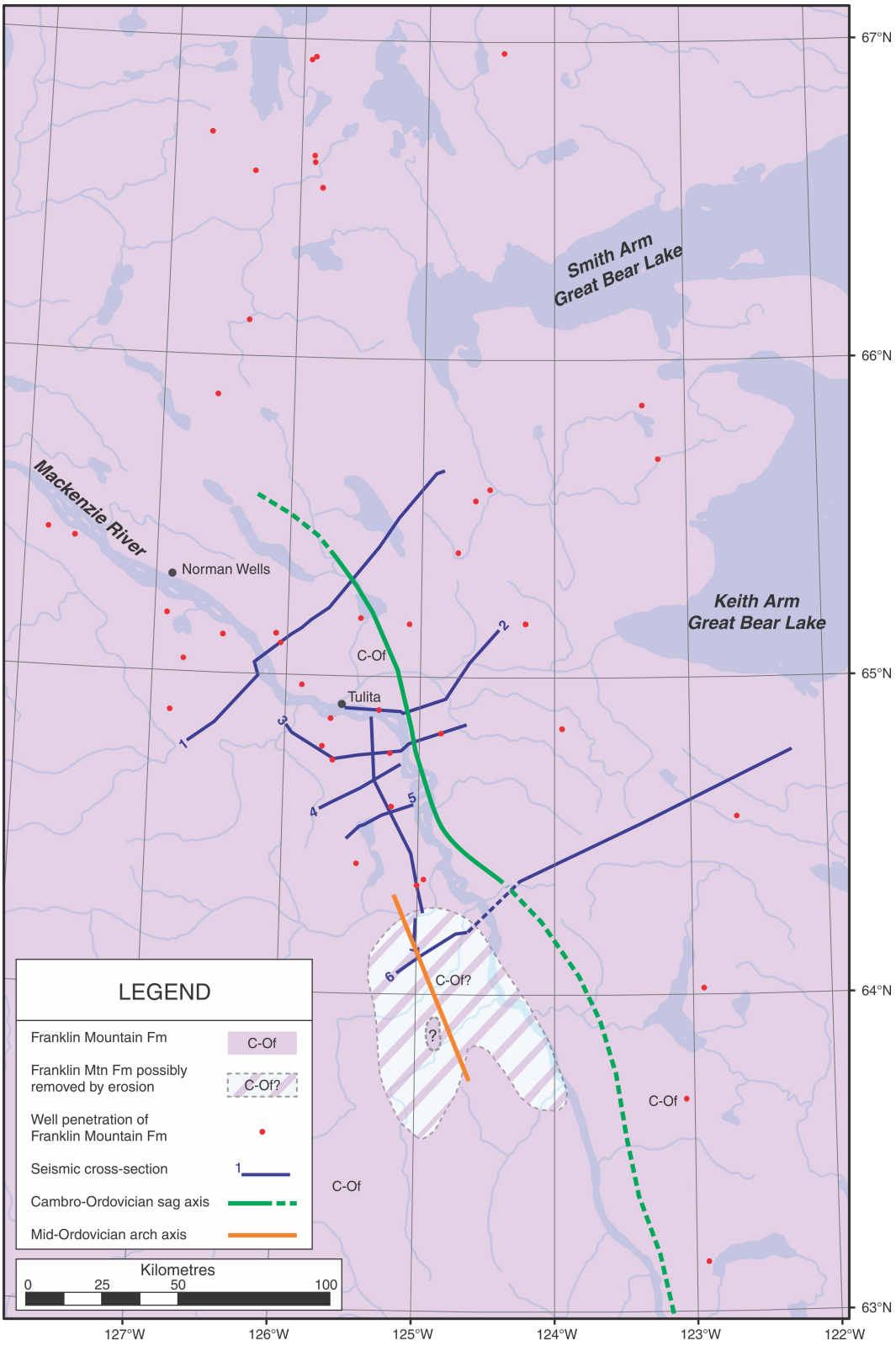

Figure 16. Middle Ordovician paleogeology map at the time of regional uplift and erosion.

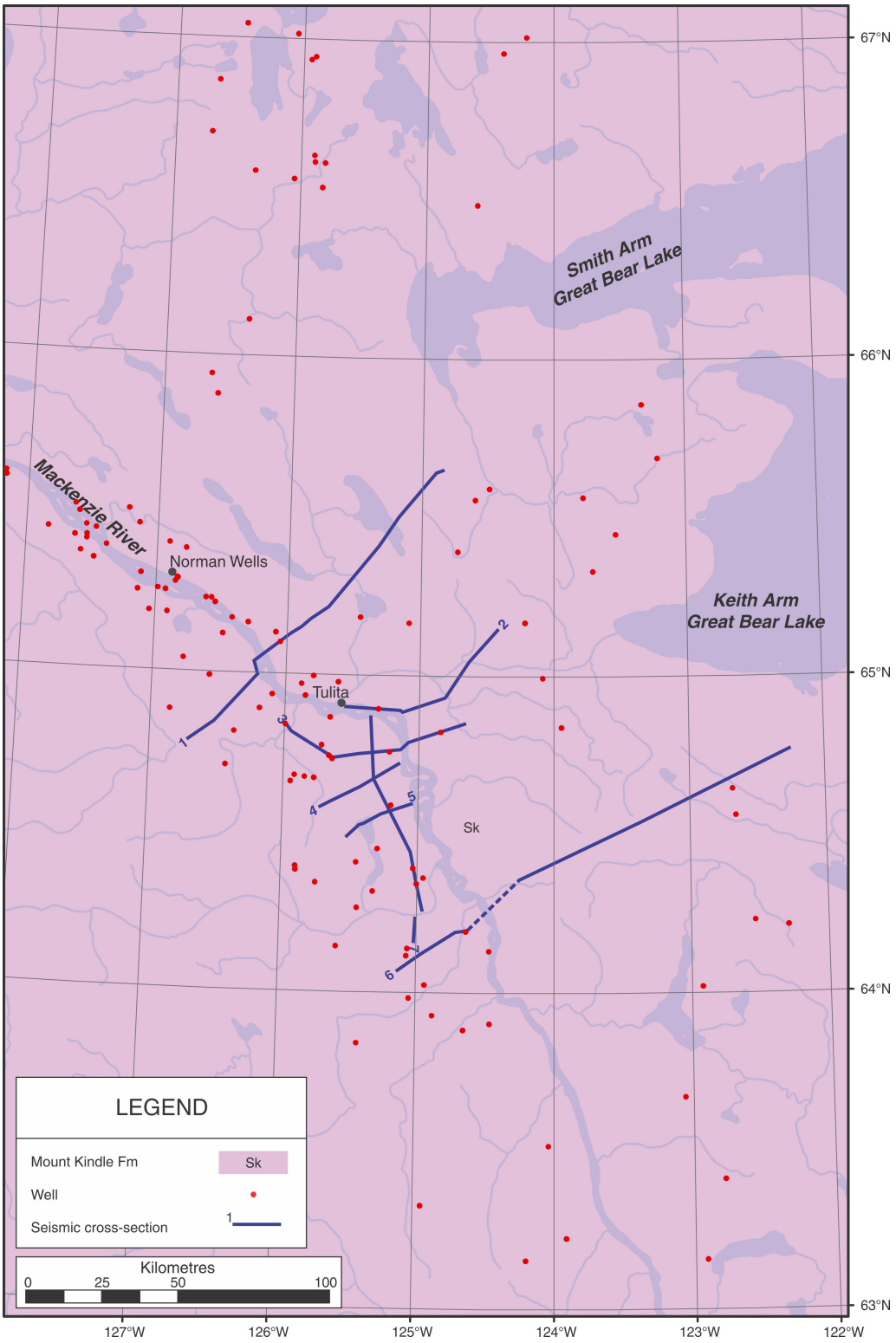

Figure 18. Mid-Silurian paleogeology map immediately prior to pre-Devonian erosion.

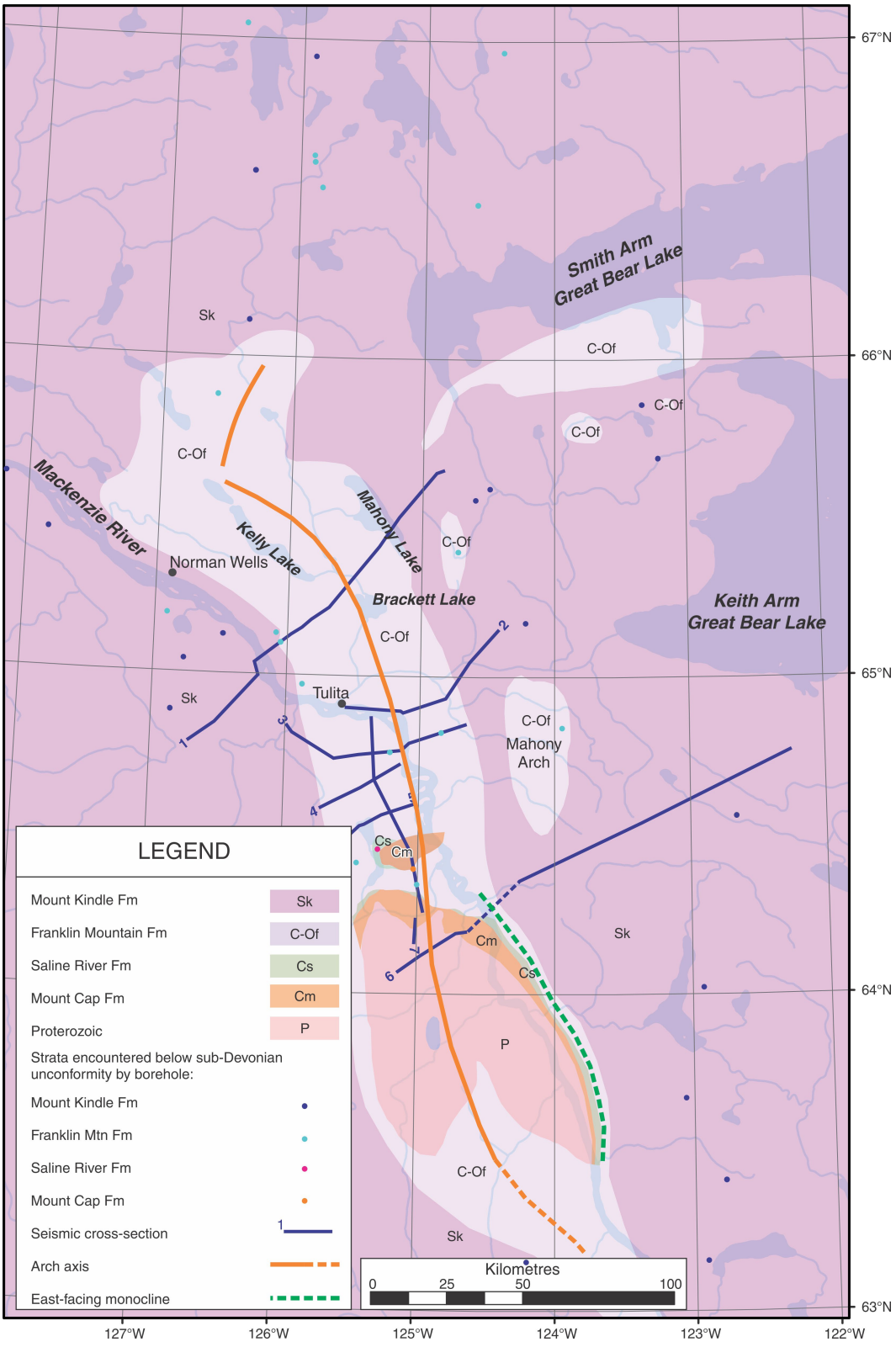

Figure 20. Latest Silurian paleogeology map after pre-Devonian erosion.

the first evidence of an extensive arch. Regional uplift and subsequent erosion removed much of the Late Ordovician-Silurian Mount Kindle Formation and locally, the entire formation as well as some or all of the underlying Franklin Mountain Formation. The largest of the areas of exposed Franklin Mountain on the map outlines the Late Silurian (pre-Devonian) Keele Arch (Fig. 20). The arch followed a sinuous trend that extended for over 400 km from the northern Franklin Mountains to the southern map boundary and, for the first time consisted of all four of the segments identified on Figure 6. Williams (1989a) estimated that uplift resulted in up to 1 km of strata being eroded from along the axis.

North of Brackett Lake, the mapped arch is less well constrained than first appears. Here, the Mount Kindle edge is derived from outcrop and is consequently the product of not only pre-Devonian erosion but of all subsequent erosional episodes as well, including any during the long pre-Cretaceous hiatus.

In the south, Proterozoic strata were exposed to surface erosion and flanked on the north and east by Cambrian strata of Mackenzie Trough and McConnell graben, respectively. Mahony Arch has re-appeared suggesting that it too may have undergone locally enhanced uplift.

The isolated area of exposed Mount Cap and Saline River strata located north of the Proterozoic exposure was a product of uplift and erosion above a pillow of Mount Cap salt (Fig. 21, Transect 7).

Saline River salt pillows continued to grow, particularly in the central trough area (Fig. 21, Transects 2 through 5).

In summary, Keele Arch was, for the first time, well defined, the product of a broad warping of the Franklin Mountain and Mount Kindle formations above the Mackenzie Trough. It included, and may have extended well south of, the enigmatic Proterozoic high.

Latest Jurassic

When subsidence resumed after the late Silurian hiatus, a succession of Devonian carbonates was deposited across the continental shelf. Later erosion removed any direct evidence regarding total depositional thicknesses. Subsidence began in the south where the Proterozoic block subsided rapidly under Root Basin (Fig. 22, Transect 6). Pugh (1993) presented evidence that the rest of the arch initially remained above sea level while shedding material into the surrounding sea and described how quartzose sands of the Tsetso Formation (Delorme Group) on the flanks the arch give way laterally to the more evaporitic Camsell Formation. Williams (1989a) related how Delorme Formation in north Root Basin (Camsell sub-basin of Morrow (1991)) contained abundant siliciclastic rocks that graded southward into siltstones. Both authors attributed the clastic content to erosion of the nearby Keele Arch. Williams (1989a) also found chert clasts in Delorme strata on the southeast side of the arch which he interpreted as being derived from the Cherty (upper) unit of the Franklin Mountain Formation.

The long period of carbonate deposition ended in the Middle Devonian when Horn River Group shale eventually buried the shelf carbonates. Horn River Group deposition ended when the region, according to Moore (1993), became a foreland basin to the Ellesmerian Orogeny and received the predominately clastic material of the Late Devonian Imperial Formation. A large hiatus in the geological record spans the Late Devonian to Late Aptian interval, but Issler et al. (2005) calculated from fission-track analysis of Imperial Formation samples taken at the East Mackay I-77 exploration well, that Carboniferous to Triassic (and possibly Jurassic) rocks once attained a combined thickness of 2.5 to 3.5 km. These Phase 4 strata are represented on the transects by the uppermost grey layer. There was insufficient information to construct a map.

In summary, while still emergent, Keele Arch region influenced nearby stratigraphy but was tectonically quiescent until at least the end of the Devonian. There is no information available regarding its evolution during the pre-Cretaceous hiatus.

Pre-Cretaceous

The sub-Cretaceous unconformity represents a hiatus extending from latest Devonian to the Late Aptian (Fig. 2). Consequently the map and transects in Figures 23 and 24 reflect the end product of a long and largely undocumented history.

A cautionary note: While the following text and figures describe a pre-Cretaceous arch, direct evidence for it is sparse, and separating its effects from those of the later mid-Cretaceous arch difficult. Seismic evidence for a pre-Cretaceous feature is the onlap and thinning of Lower Cretaceous Martin House and Arctic Red formations on the east flank of a large salt pillow located in south KTZ (Fig. 6, Transect 2) and apparent onlap onto the arch's west flank in the Summit Creek area (Fig. 9.4.2 *in* Hadlari et al., 2009a). The stratigraphic relationships observed beyond the limits of south Keele Tectonic Zone, both at surface and on seismic, could be attributed to the mid-Cretaceous event alone.

The map (Fig. 23) shows the arch to have consisted of all four segments identified in Figure 6, except that Segment 4 was shifted east of the Mackenzie River. Arching would have involved renewed uplift of KTZ and, for the first time, of a broad area north of Great Bear Lake as well as the west side of McConnell graben. The former area lay north of the Cambrian graben trend. Removed from the grabens' confining influence, warping at the level of the Franklin Mountain and Mount Kindle formations produced a wider and more subtle uplift than was the case in KTZ.

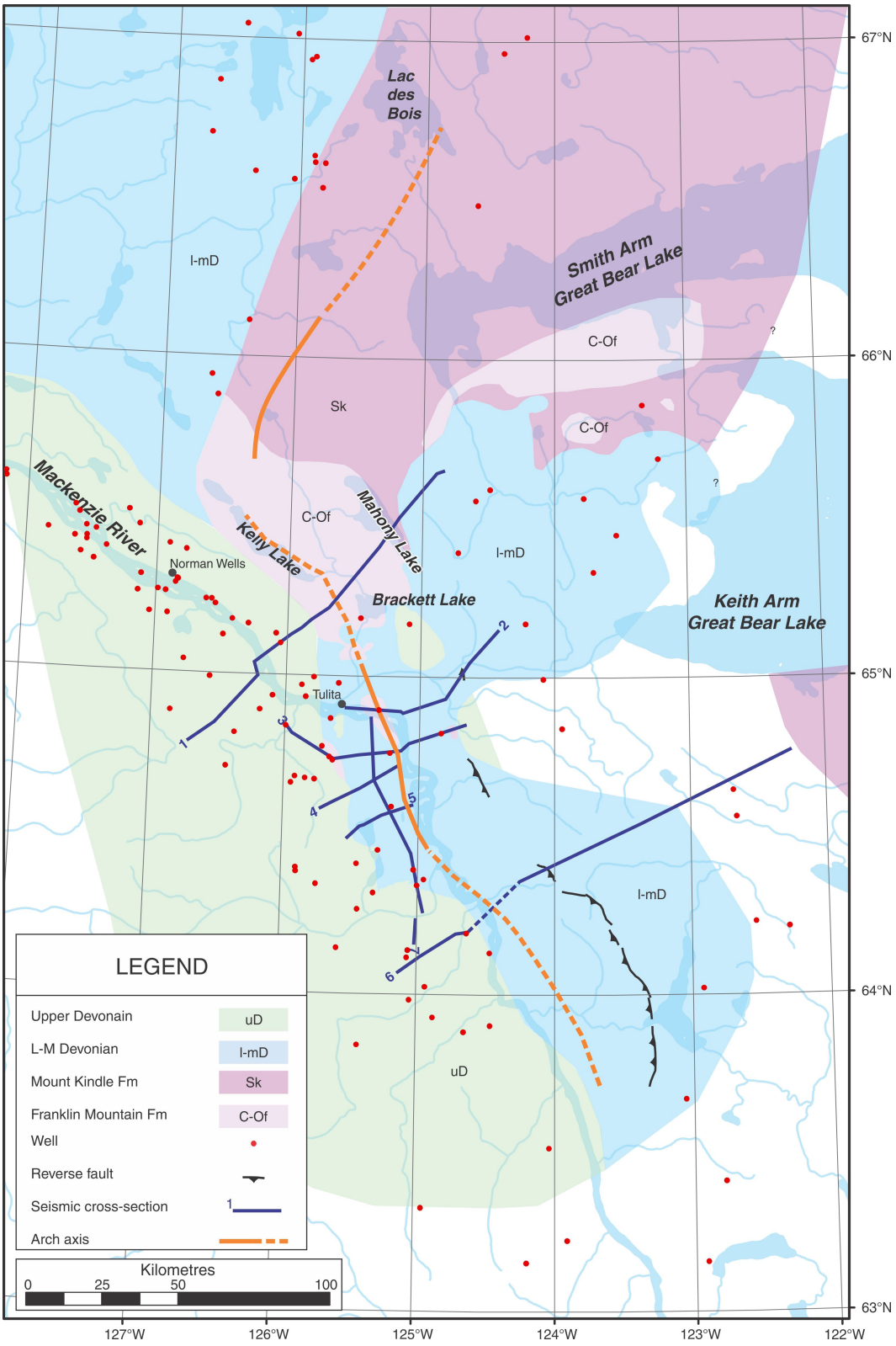

Figure 23. Late Aptian paleogeology map immediately prior to deposition of Lower Cretaceous strata.

Arch uplift was greatest in KTZ. North KTZ rose by at least the combined thickness of the Bear Rock and Imperial formations and removed all post middle Franklin Mountain (post-Late Cambrian) subsidence (Fig. 24, Transect 1). This was accomplished in the west by inversion of a pre-existing normal fault. Information as to how the east side rose is lost in the data gap under Mahony Lake.

The location of the crest of the arch is best constrained in both map and section view where it is crossed by Transect 2 (Fig. 24). South of Transect 2 (Fig. 24) the arch was less well defined for it is wider and salt pillowing has only served to make locating the axis more difficult.

South of KTZ, a southern arch might have developed within the large data gap in the manner illustrated in Transect 6 (Fig. 24).

Transect 7 is not perfectly parallel to the arch axis (Fig. 23). Consequently, the apparent uplift located to the right of centre in the transect (Fig. 24) is simply where the transect-to-arch separation is at a minimum.

In summary, the Keele Arch reappeared as a broad feature across which Devonian strata depositionally thinned and/or was removed by erosion. Structural inversion of Cambrian normal faults produced uplifts along its margins. A sinuous arch, it extended southward from as far north as Lac des Bois to possibly south of Keele River. Its effects are today largely indistinguishable from those of the later mid-Cretaceous arch.

Latest Early Cretaceous

A Lower Cretaceous siliciclastic succession, beginning with the late-Aptian / early Albian Martin House Formation, was deposited across the region. Direct evidence regarding depositional thicknesses was removed by later erosion, but fission-track analysis has provided an estimated value of about 1 km (Issler et al., 2005). As relative sea level rose, Martin House and younger strata onlapped the pre-existing high (Fig. 25, Transect 2) and chert-rich debris, sourced from weathered Franklin Mountain Formation, was shed from the still-emergent arch (Yorath and Cook, 1981).

The section views reflect the inference of Dixon (1999, Fig. 16) that the Sans Sault member of the Arctic Red Formation is a lateral equivalent of the Mahony Lake Formation.

In summary, the pre-Cretaceous arch was onlapped by the Early Cretaceous sea as recorded by the Martin House to Arctic Red deposition. By the end of Mahony Lake/Sans Sault deposition the Keele Arch region was not active and had no surface expression.

Mid-Cretaceous (late Albian to late Cenomanian)

Cretaceous deposition was interrupted during late Albian to late Cenomanian time by the regional uplift and erosion that produced the mid-Cretaceous (sub-Slater River) unconformity (Fig. 2).

In the south the arch axis differed from the pre-Cretaceous one. There, a second trend developed to the west (Fig. 26 and Fig. 27, Transect 6), roughly coincident with the latest Silurian arch (Fig. 20). Williams (1989a) estimated that the mid-Cretaceous arch had a topographic expression of several hundred metres.

Inversion of the east bounding fault of McConnell graben during the pre-Cretaceous hiatus (Fig. 24, Transect 6) had been suspected, but supporting evidence was lacking. However, by the middle Cretaceous, inversion clearly affected the full length of McConnell graben and Mackenzie Trough (Fig. 27, Transects 1, 2, and 6).

The westernmost portion of Transect 3 (Fig. 27) was constructed by restoring the hanging-wall blocks of the present-day shallow detachment thrusts seen on Figure 7 to their original positions. Preservation of bed thicknesses during this restoration process has revealed two very large pre-Cretaceous salt pillows.

In summary, the mid-Cretaceous Keele Arch was similar to its pre-Devonian and pre-Cretaceous ancestors.

Turonian

During the late Cenomanian (Thomson et al., 2011), sediment making up the Slater River Formation buried the mid-Cretaceous arch, except for a small island near the intersection of Transects 4 and 7 (Fig. 28). Possible basal sands on the arch have been found to contain abundant chert clasts weathered from the underlying cherty unit of the Franklin Mountain Formation (Yorath and Cook, 1981).

The thinning of Slater River Formation across the arch (e.g. Fig. 29, Transect 2) is attributed to onlap onto a topographic high rather than to erosion. Inclusion of Slater River Formation in Transect 1 (Fig. 29) is supported by its presence today in four outliers of Upper Cretaceous (Slater River Formation) rock in the northern Franklin Mountains (Fig. 6).

In summary, in map view Keele Arch consisted of a small emergent remnant of the pre-Cretaceous and mid-Cretaceous arches.

Late Campanian

Little Bear Formation was deposited as a wedge on the east flank of the rising Mackenzie Mountains (Yorath and Cook, 1981). Although Dixon (1999) suggested that Little Bear equivalents may have extended into Great Bear Basin,

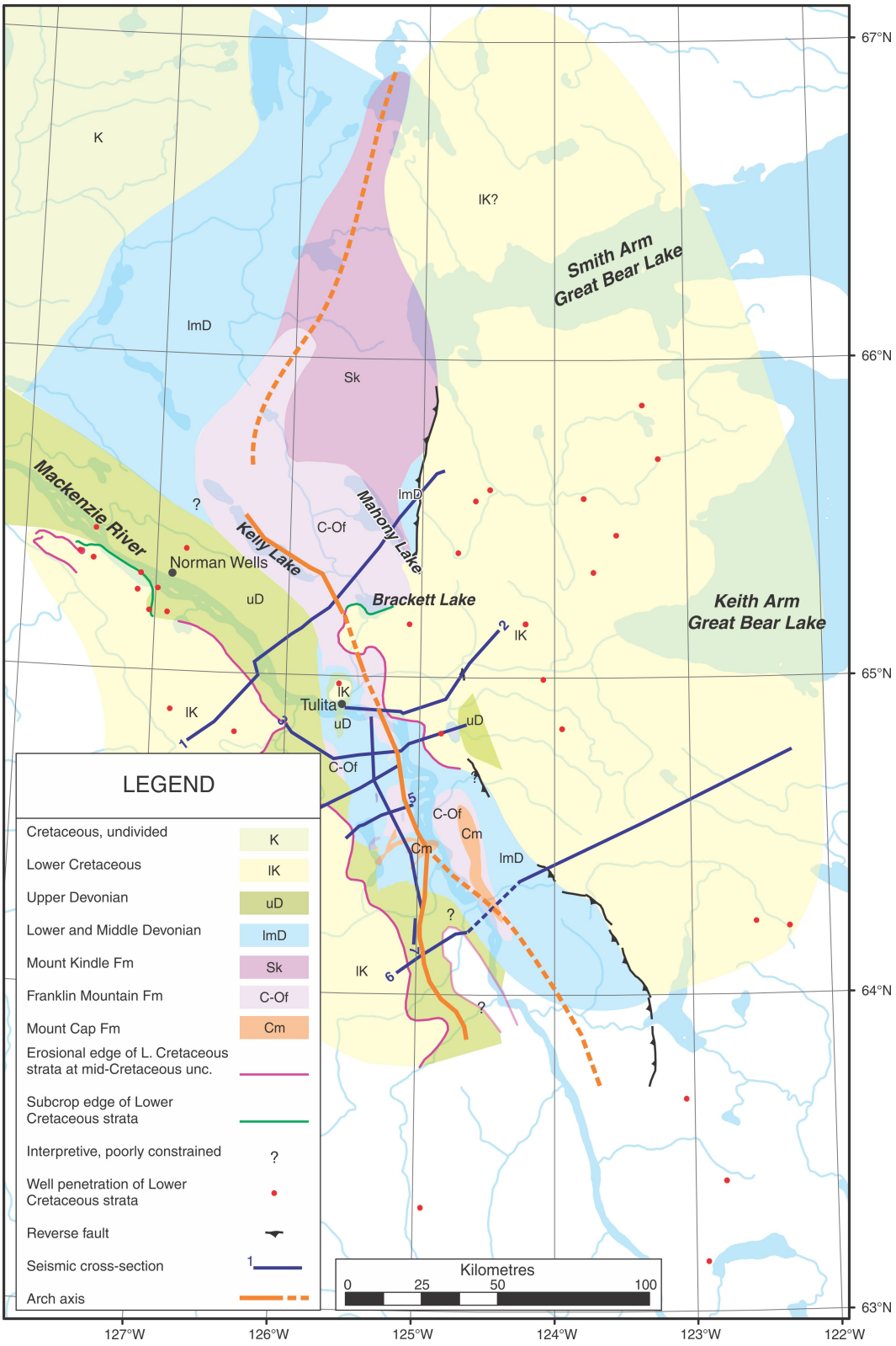

Figure 26. Mid-Cretaceous paleogeology map immediately after regional erosion.

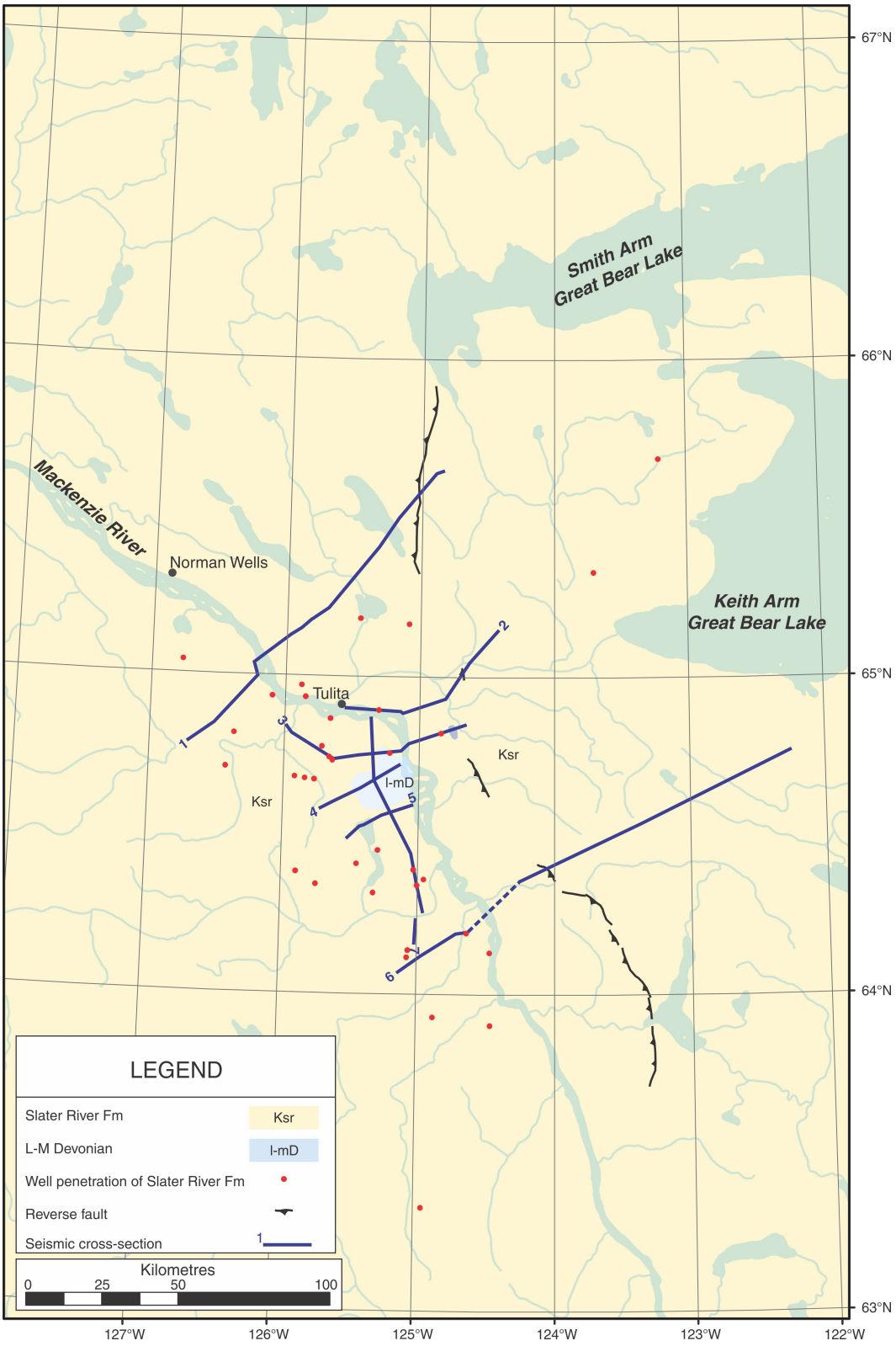

Figure 28. Turonian paleogeology map after close of Slater River Formation deposition.

only to be removed later by erosion, the map (Fig. 30) restricts it to west of 'St. Charles' range where it's presence has been confirmed (Fallas, 2013b).

The small exposure of Slater River Formation (Fig. 30) is attributed to erosion over a pillow of Saline River salt (Fig. 31, Transect 2).

Section views show Little Bear Formation to be thickest in the foreland basin (Fig. 31, west end of Transects 2, 3, and 4) and thinnest or perhaps non-existent in the north (Fig. 31, Transects 2 and 7) and to the east (Fig. 31, Transect 3). Note that, with the top of the east-dipping wedge of Little Bear strata forced flat, depths displayed in the western portions of the transects may be exaggerated.

Opinions vary as to the nature of the contact between Little Bear Formation and the overlying East Fork Formation. The boundary was considered to be transitional by Yorath and Cook (1981) and Sweet et al. (1989), but Yorath and Cook (1981) noted that it was disconformable at its type section. Dixon (1993) considered the boundary to be equivalent to the sub-Smoking Hills unconformity in Anderson Plain but later described it as a maximum flooding surface which developed locally into an unconformity across Keele Arch (Dixon, 1999). Transect 2 (Fig. 31) provides evidence of an unconformity, at least locally, and of topographic relief at the end of Little Bear time.

In summary, Keele Arch region was predominantly a locus of deposition with local topographic uplift related to salt movement. Non-deposition and/or erosion created local unconformities on these uplifts.

Late Maastrichtian

The full extent of East Fork Formation deposition is unknown for today it is only preserved in Mackenzie Valley, south of Tulita, and there is no surviving evidence of East Fork deposition east of Mackenzie River, south of 64° 40′ (Fig. 32).

Where both the top and base of the formation are visible on reflection seismic images (Fig. 6) the formation's thickness is considerable and possibly thicker in KTZ (Fig. 33, Transects 3, 4, and 5). Estimates of its original thickness beyond those limits are, by necessity, interpretive.

In summary, Keele Arch region may have been expressed by enhanced subsidence of south KTZ.

Maastrichtian to Eocene

An orogeny to the west imposed horizontal stresses that produced northeast-verging thrust faults detached on Saline River Formation salt, and a deep foreland basin under Mackenzie Valley (Fig. 7, Transect 1). Norman and Mackay ranges fall along the western boundary of KTZ (Fig. 6), suggesting that the zone had an influence on their development. 'St. Charles' and McConnell ranges developed by structural inversion of the Cambrian normal faults that defined the eastern limits of KTZ and McConnell graben.

The upper boundary of the East Fork Formation is an unconformity (Yorath and Cook, 1981 and Dixon, 1999) upon which non-marine siliciclastics of the Summit Creek Formation were deposited into that portion of the foreland basin extending from south of Keele River into Brackett Basin.

In summary, the last phase of Keele Arch region development consisted of foreland subsidence and deposition in Brackett Basin (Fig. 6, Arch Segment 3). North of Brackett Basin, the northern Franklin Mountains rose with the result that no record of Mesozoic deposition has been preserved in the vicinity of Arch Segments 1a and 2. Consequently, those segments are relics of earlier arches.

AXIS TRENDS

By plotting together the paleo-arch and sag axes related to Keele Arch region (Fig. 34a) it is possible to break the arch into its component parts. Within Keele Tectonic Zone all axes combine to form arch Segments 2 and 3 (Fig. 34b and c). Segment 1, northeast of KTZ, consists of the Cambrian subsidence and pre-Devonian, pre-Cretaceous, and mid-Cretaceous uplift (arch) phases. South of KTZ, the sag axes range in age from Early Cambrian to mid-Ordovician and are well constrained to the east side of the present-day Mackenzie River (Segment 4E). The uplift axes fall into two groups. The eastern set coincides with the sag axes and ranges in age from the latest Silurian to the uplift of McConnell Range during the Eocene. The second group, located about 50 km to the west (Segment 4W), ranges in age from the Cambrian to the mid-Cretaceous. While the mid-Cretaceous arch axis can be confidently placed in the western set (Fig. 27, Transect 6), it is important to note that this lateral separation of earlier axes may, in part, be a function of a lack of data. There is a 25 km seismic data gap across Mackenzie River and a large area within which the Proterozoic to Early Devonian stratigraphic record is missing.

Keele Tectonic Zone, within which are found Segments 2 and 3, corresponds to a gravity low, bounded to the north and south by steep gradients (Fig. 34b). In the south, for much of its length Segment 4E corresponds to a narrow low-gravity trend that may be due to the presence of relatively less dense Cambrian strata in McConnell graben. The southern uplifts (4W) follow a low gravity arch that progressively weakens southward into an area of high gravity values south of Johnson River.

When overlain on today's topography (Fig. 34c) Keele Tectonic Zone is seen to be bounded by topographic features whose development it likely influenced. The zone's western boundary coincides with southern Jacques Range, Discovery Ridge, and Mackay Range, and its eastern boundary with

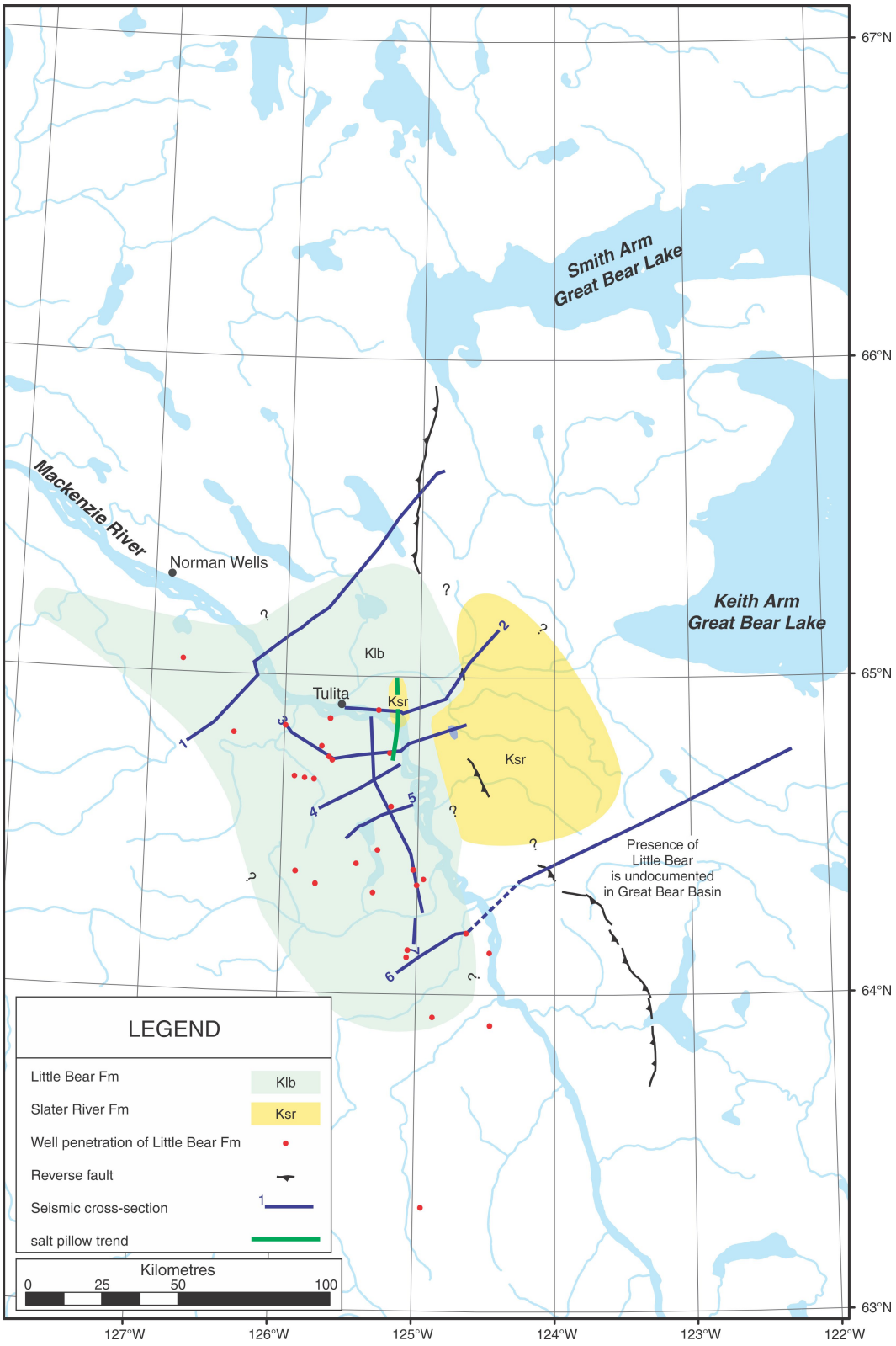

Figure 30. Late Campanian paleogeology map after close of Little Bear Formation deposition.

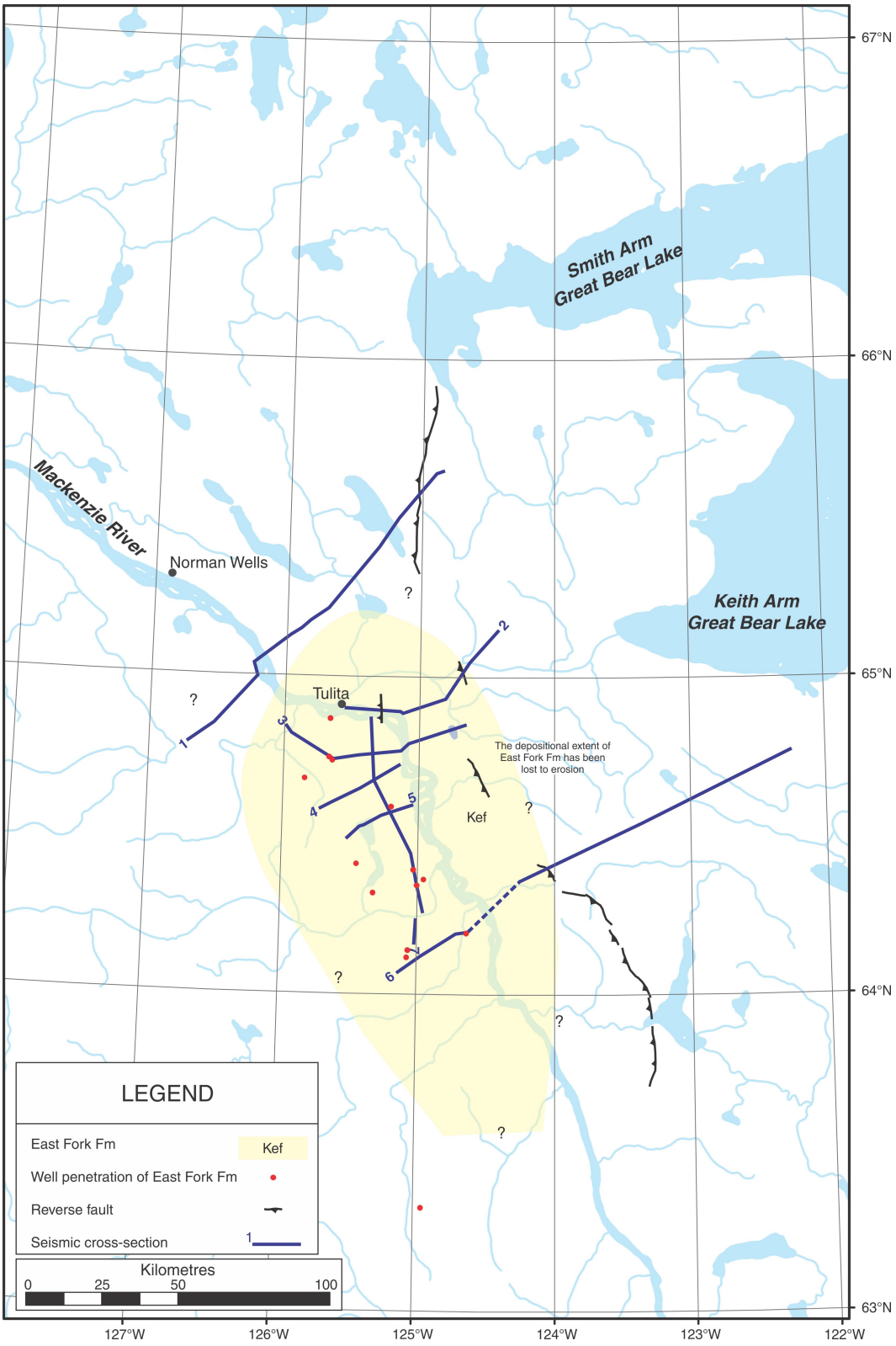

Figure 32. Maastrichtian paleogeology map after close of East Fork Formation deposition.

'St. Charles' Range. Its northern limit marks a change in the character of the northern Franklin Mountains. The south boundary of the zone corresponds geographically to the northern terminus of McConnell Range. The previously discussed interrelationship between the southern Cambrian sags (components of Trend 4E) and McConnell Range is readily apparent but the southern uplift trend (Trend 4W) does not appear to have noticeably influenced today's topography.

A number of structural features are unique to the Keele Arch. In particular, the inverted normal faults along the east side of the arch are directly related to the initial formation of the Mackenzie Trough. Salt pillows in the middle of the arch are concentrated in thicker evaporite deposits within Mackenzie Trough. The northern Franklin Mountains form a set of significant topographic features because resistant lower Paleozoic carbonates along the Keele Arch were minimally covered by subsequent deposition and so required little erosion of the Cordilleran structures to expose the lower Paleozoic strata within their cores.

ECONOMIC IMPLICATIONS

A full investigation into the economic implications of Keele Arch region is beyond the scope of this study. However, a feature as large and tectonically active it must have played a role in the development and distribution of a potential hydrocarbon reservoir, seal, and source rocks, the development of structural traps, and possibly to have influenced maturation.

The Cambrian clastics play has been of considerable economic interest since 1974 when gas was discovered in Mount Clark Formation sandstones at the Tedji Lake K-24 borehole and has been successfully explored since then, yielding one oil and four additional gas discoveries (Hannigan et al., 2011). Cambrian clastics play reservoirs are provided by porous basal sandstones in the Mount Clark Formation and to a lesser extent by sandstone horizons within the Mount Cap Formation. Primary source material is the organic algal-rich shale beds in the Mount Cap Formation. Shales within the Mount Cap Formation and Saline River Formation evaporites provide the necessary seals (MacLean, 2011).

During the earliest Cambrian, Keele Arch region affected the distribution of Mount Clark Formation and its reservoir sands (Fig. 10a). The formation was absent from the pre-extension high as well as the Mahony and Bulmer arches but present under Mackenzie Plain and in McConnell graben.

Later, Keele Arch region would have influenced the distribution of source and seal facies. Mount Cap and Saline River formations are thickest within the Mackenzie graben of Keele Tectonic Zone. MacLean (2011) postulated that the finer grained fractions of the Cambrian sediment would have been winnowed from shallow areas and transported into the deep water grabens. By this rationale, Keele arch, which at this time consisted of the Mackenzie and McConnell grabens, would contain fewer reservoir facies but more potential source rocks and seals, including the well documented thick and mobile evaporites of the Saline River Formation. MacLean (2011) did acknowledge that wedges of coarser material can be found along steep escarpments so may exist along the graben boundaries.

By the mid-Ordovician (Fig. 17) potential source rocks within KTZ were buried to a greater depth than those in the surrounding areas and held there longer (i.e. until the Late Silurian) (Fig. 9). It is possible that Cambrian potential source rocks attained a higher level of thermal maturity within the KTZ compared to outside the zone.

The mid-Devonian Kee Scarp reef / Ramparts platform play was established very early in the exploration history of the Northwest Territories when the Norman Wells oil field was discovered in 1920. There, the highest quality reservoir occurs in reef margin, foreslope, and high-energy shoal facies of the Kee Scarp reefal Member of Ramparts Formation (Al-Aasm and Azmy, 1996; Yose et al., 2001 in Hannigan et al., 2011). Exploration efforts in pursuit of similar reef-related reservoir should perhaps be focused along the west flank of the Norman Wells high and the latest Silurian (sub-Devonian) Keele Arch where conditions may have favoured reef development.

The Canol Formation of the Horn River Group has recently become an exploration target for unconventional resources. Maturation would have been suppressed along the Keele Arch during the pre- and mid-Cretaceous uplift phases effectively pushing the zone of optimum maturity westward, away from the Keele Arch.

Lower Cretaceous siliciclastics of the Martin House and Mahony Lake formations are possible reservoirs and the source of one gas blowout and 3 gas flows (Hannigan et. al., 2011). It is possible that shoreline facies favourable for reservoir development were deposited on the flanks of a subsiding pre-Cretaceous Keele Arch. Sediments suitable for the development of source and seal rocks would have been less common. Significant thicknesses of these rocks were later removed by erosion during the mid-Cretaceous arch phase and the high-standing ridge would have inhibited maturation. Keele Arch region therefore poses a very high exploration risk for Early Cretaceous plays.

Upper Cretaceous and younger strata are not considered exploration targets (Hannigan et al., 2011).

CONCLUSIONS

The name Keele 'Arch' is not entirely appropriate, given that much of the feature began as a chain of grabens and largely remained as such until the Ordovician. Today it includes Brackett Basin. The name, however, has

gained wide acceptance, much as 'Peace River Arch' has been accepted for a feature with a similar history. It is not proposed, therefore, to rename the feature.

Keele Arch, south of the 66th parallel, began as a Cambrian graben and, through time, has presented itself in both arch and sag form. South of Smith Arm of Great Bear Lake, arches developed over pre-existing Cambrian grabens, the largest of which was Mackenzie Trough, an early manifestation of Keele Tectonic Zone. Arches there were generally higher and better developed than in the northeast where the axes diverged north of the grabens and beyond their zone of influence.

Solid evidence for a pre-Cretaceous arch, beyond the limits of south Keele Tectonic Zone, is difficult to find and the timing of its development is poorly constrained due to the long hiatus represented by the sub-Cretaceous Unconformity.

Keele Tectonic Zone experienced three phases of uplift: 1) Pre-Devonian (mid to late Silurian), 2) pre-Cretaceous, and 3) mid-Cretaceous (Cenomanian).

The pre-Devonian Keele Arch was primarily a product of uplift of Keele Tectonic Zone but it extended southward to include a ridge of Proterozoic strata. Both the pre- and mid-Cretaceous arches involved renewed uplift of Keele Tectonic Zone and, for the first time, uplift along a northeasterly trend toward Lac des Bois and, to the south, inversion of the McConnell graben. The mid-Cretaceous arch was a reactivated pre-Cretaceous uplift with the addition of a western limb south of Keele Tectonic Zone.

Keele Tectonic Zone experienced two phases of enhanced subsidence: 1) Cambrian to Middle Ordovician graben development, and 2) late Campanian to Paleocene subsidence of Brackett Basin.

South of Keele Tectonic Zone the geological history is not well defined. The separation of sags and uplifts presented in this paper may be illusory and a function of a lack of information. The Proterozoic block in the southwest remains an enigma, but, in the opinion of these authors, it remained high, near or above wave base, until the Early Devonian when it subsided under Root Basin. An alternative interpretation, involving significant vertical movements, would entail the block subsiding as part of the Cambrian Mackenzie Trough, later rising sufficiently high as to enable the removal, by erosion, of all pre-Devonian strata before subsiding under Root Basin.

Keele Tectonic Zone had a large influence on the development of many of the Laramide structures that dominate today's landscape. The McConnell and 'St. Charles' ranges are products of the inversion of large scale Cambrian normal faults that define the east side of Mackenzie Trough. Inversion began prior to the mid-Aptian and continued through the Paleocene. The Norman, Discovery, and Mackay ranges track its western boundary and the southern segment of the Jacques Range follows the zone's northern edge. This close correspondence is strongly suggestive of a tectonic linkage but the mechanism is, as yet, unknown.

The economic significance of Keele Arch is not well understood.

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Appendix A: Cross-section and transect reflection seismic lines

Schematic Cross-sections:

A: No seismic lines were used.

B: Reflection seismic lines that contributed to the construction of schematic cross-section B were: 1982 ARCO / Petro-Canada Lines 78X and 94X.

C: Reflection seismic line that contributed to the construction of schematic cross-section C was: 1999 AEC Line 7.

D: Reflection seismic lines that contributed to the construction of schematic cross-section D were: 1963 Western Decalta Line CA-03, 1971 Sigma Explorations Line CD-17, and 1984 Petro-Canada Lines 58X and 58XA.

E: Reflection seismic line that contributed to the construction of schematic cross-section E was: 1971 Sigma Explorations Line W01.

Transects:

Transect 1 is based on reflection seismic lines: 1983 NSM Resources Line 110, 1996 Ranger Lines F02 and L02, 2002 Devon Line 72694, and 1974 Acquitaine Lines 2W and 2E.

Transect 2 is based on: 2002 Devon Line 72681, and 1971 Acquitaine Lines 7 and 14.

Transect 3 is based on: 2002 Devon Line 105 and 1991 Chevron Lines 36X and 46X.

Transect 4 is based on: 2000 Northrock Line 292 and 1991 Chevron Line 26X.

Transect 5 is based on: 1991 Chevron Line 6X and 1974 Amoco Line DQN-04.

Transect 6 is based on: 1963 Western Decalta Line CB-11, 1971 Sigma Explorations Lines CD-17, and 1984 Petro-Canada Lines 58X and 58XA.

Transect 7 is based on: 1971 Sigma Explorations Lines CD-8ext, 8 and G10, 1999 AEC Line 10, and 1971 Sigma Explorations Lines CD-24A and CD-24B.

Metadata:

YEAR	OPERATOR	LINE NO	STACKED/ MIGRATED	ORIGINAL PROJECT NO.	NEB FILE REFERENCE
1963	Western Decalta	CA-03	Stack	unknown	unknown
1963	Western Decalta	CB-11	Stack	unknown	unknown
1971	Sigma Explorations	CD-08	Migrated	815–06–05–01	5552218
19701	Sigma Explorations	CD-08ext	Migrated	815–06–05–01	5552218
1971	Sigma Explorations	CD-24A	Migrated	815–06–05–01	5552218
1971	Sigma Explorations	CD-24B	Migrated	815–06–05–01	5552218
1971	Sigma Explorations	CD-17	Migrated	815–06–05–01	5552218
1971	Sigma Explorations	G-10	Migrated	815–06–05–01	5552218
1971	Sigma Explorations	W-01	Migrated	815–06–05–01	5552218
1971	Acquitaine	07	Migrated	673–06–05–07	5551090
1971	Acquitaine	14	Migrated	673–06–05–14	5551090
1974	Acquitaine	2-E	Migrated	039–06–06–033	5550662
1974	Acquitaine	2-W	Migrated	039–06–06–033	5550662
1974	Amoco	DQN-04	Stack	060–06–06–143	5550972
1982	ARCO / Petro-Canada	78X	Migrated	246–06–06–113	5551143
1982	ARCO / Petro-Canada	94X	Migrated	246–06–06–113	5551143
1983	NSM Resources	110	Migrated	9229-N9–03E	5553716
1984	Petro-Canada	58X	Migrated	9229-P28–02E	5553735
1984	Petro-Canada	58XA	Migrated	9229-P28–02E	5553735
1991	Chevron	06X	Migrated	9229-C4–10E	5553634
1991	Chevron	26X	Migrated	9229-C4–10E	5553634
1991	Chevron	36X	Migrated	9229-C4–10E	5553634
1991	Chevron	46X	Migrated	9229-C4–10E	5553634
1996	Ranger	F02	Migrated	9229-R36–01E	5553837
1996	Ranger	L02	Migrated	9229-R36–01E	5553837
1999	AEC	7	Migrated	9229-A61–02E	5553599
1999	AEC	10	Migrated	9229-A61–02E	5553599
2000	Northrock	292	Migrated	9229-N46–01E	5553729
2002	Devon	105	Migrated	9227-D30–01E	5553578
2002	Devon	72694	Migrated	9227-D30–01E	5553578
2002	Devon	72681	Migrated	9227-D30–01E	5553578

Appendix B: a series of paleocross-sections illustrating the evolution of Keele Arch region from the latest Precambrian to present

Figure B1. Transect 1: A series of paleocross-sections illustrating the evolution of Keele Arch region from the latest Precambrian to present. Based on reflection seismic lines: 1983 NSM Resources Line 110, 1996 Ranger Lines F02 and L02, 2002 Devon Line 72694, and 1974 Acquitaine Lines 2W and 2E. *See* Figure 6 for location and to Appendix B for seismic line references.

Figure B2. Transect 2: A series of paleocross-sections illustrating the evolution of Keele Arch region from the latest Precambrian to present. Based on reflection seismic lines: 2002 Devon Line 72681, and 1971 Acquitaine Lines 7 and 14. *See* Figure 6 for location and to Appendix B for seismic line references.

Figure B3. Transect 3: A series of paleocross-sections illustrating the evolution of Keele Arch region from the latest Precambrian to present. Based on reflection seismic lines: 2002 Devon Line 105 and 1991 Chevron Lines 36X and 46X. *See* Figure 6 for location and to Appendix B for seismic line references.

Figure B4. Transect 4: A series of paleocross-sections illustrating the evolution of Keele Arch region from the latest Precambrian to present. Based on reflection seismic lines: 2000 Northrock Line 292 and 1991 Chevron Line 26X. *See* Figure 6 for location and to Appendix B for seismic line references.

Figure B5. Transect 5: A series of paleocross-sections illustrating the evolution of Keele Arch region from the latest Precambrian to present. Based on reflection seismic lines: 1991 Chevron Line 6X and 1974 Amoco Line DQN-04. *See* Figure 6 for location and to Appendix B for seismic line references.

Figure B6. Transect 6: A series of paleocross-section illustrating the evolution of Keele Arch region from the latest Precambrian to present. Based on reflection seismic lines: 1963 Western Decalta Line CB-11, 1971 Sigma Explorations Lines CD-17, and 1985 Petro-Canada Lines 58X and 58XA. Interpretation of the geology within the seismic data gap is based on surface exposures mapped by Cook et al. (2010). *See* Figure 6 for location and to Appendix B for seismic line references.

Figure B7. Transect 7: A series of paleocross-sections illustrating the evolution of Keele Arch region from the latest Precambrian to present. Based on reflection seismic lines: 1971 Sigma Explorations Lines CD-8ext, 8 and G10, 1999 AEC Line 10, and 1971 Sigma Explorations Lines CD-24A and CD-24B. *See* Figure 6 for location and to Appendix B for seismic line references.