STRATIGRAPHY AND RESERVOIR ASSESSMENT OF PRE-GIVETIAN STRATA IN NORTHEASTERN BRITISH COLUMBIA

Ayse Ibrahimbas[1] and Warren Walsh[2]

ABSTRACT

Northeastern British Columbia's conventional undiscovered resource is estimated at 30 Tcf, the majority of which is expected to be present in high risk deep stratigraphic and foothills plays. In northeastern British Columbia lower Paleozoic strata records the platform to basinal transition of a passive margin miogeocline. However, only limited data is available in the subsurface; the purpose of this study is to examine and correlate the subsurface data with existing surface studies, and assess the reservoir potential of these strata.

Exposure of basinal shales of the Road River Group to platform and shelf carbonates of the Kechika, Skoki, Nonda, Muncho-McConnell, Stone and Dunedin formations are present in the Cordillera. In the subsurface, platform carbonates present in the westernmost part of the basin are correlative with a much thinner and discontinuous succession of carbonates and evaporates. Periodic influx of clastics into the basin, mostly sourced from Peace River Arch (PRA), are observed as mature quartzose sediments either mixed in carbonates or deposited as sandstone sheets, as in Cambrian sandstones and Wokkpash Formation.

Potential reservoir zones exist in dolomite units of Middle-Lower Devonian Lower Keg River-Chinchaga, Dunedin and Stone formations, and in quartz arenites of the Wokkpash Formation. Textures observed in dolomites of the Chinchaga, Stone and Dunedin formations are dominated by micro to cryptocrystalline, anhedral to euhedral crystals, with little if any intercrystalline porosity. However, large saddle dolomite crystals, possibly filling vuggy or fracture porosity, offer potential for reservoir development. Drill Stem Tests (DST's) show low to high permeabilities, with gas recoveries from these zones. Quartz arenites of Wokkpash Formation contain mature sandstones with carbonate cement. No visible intercrystalline porosity is observed in thin sections; however, microfractures may provide some porosity and permeability. Limited DST measurements from this unit show low-average permeability with some fluid recovery. This unit may have fractured reservoir potential, depending on the density of the open fractures and the fracture patterns in a suitable trap setting.

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INTRODUCTION

Increase in the demand for supplies and the declining production of the known hydrocarbon plays in Western Canada Sedimentary Basin (WCSB) has caused not only an increase in exploration studies but also a need in reassessment of the available wells and plays. Deep stratigraphic and foothills plays hold great potential for future gas supply, which presently have been explored very little in northeastern British Columbia. Previously subeconomic reservoirs, determined from DSTs and production tests, are now in need of reevaluation with the aid of improved seismic and drilling techniques, due to current and future expected increase in demand.

The main objective of this study is to correlate Pre-Keg River/Chinchaga strata in northeastern British Columbia. These subsurface correlations are based on 65 wells that penetrate the Lower Paleozoic strata and are tied to paleogeography and outcrop studies done previously by other authors (Taylor and Stott, 1999; Ferri *et al.*, 1999; Pyle and Barnes, 2000, Taylor and Stott, 1973; Fritz, 1980C; Gabrielse, 1981; Taylor *et al.*, 1979; Thomson, 1989) (Figure 1). A stratigraphic framework is constructed for the Lower Paleozoic using cross section correlations and literature data.

The second objective of this study is an assessment of hydrocarbon potential in Pre-Keg River/Chinchaga strata. A detailed study is done using drill cutting sample descriptions, thin section descriptions, DST results, and well site reports.

This study addresses the issues:

- Regional subsurface correlation of Pre-Keg River/Chinchaga strata,
- Correlation of this strata with the outcrop equivalents,

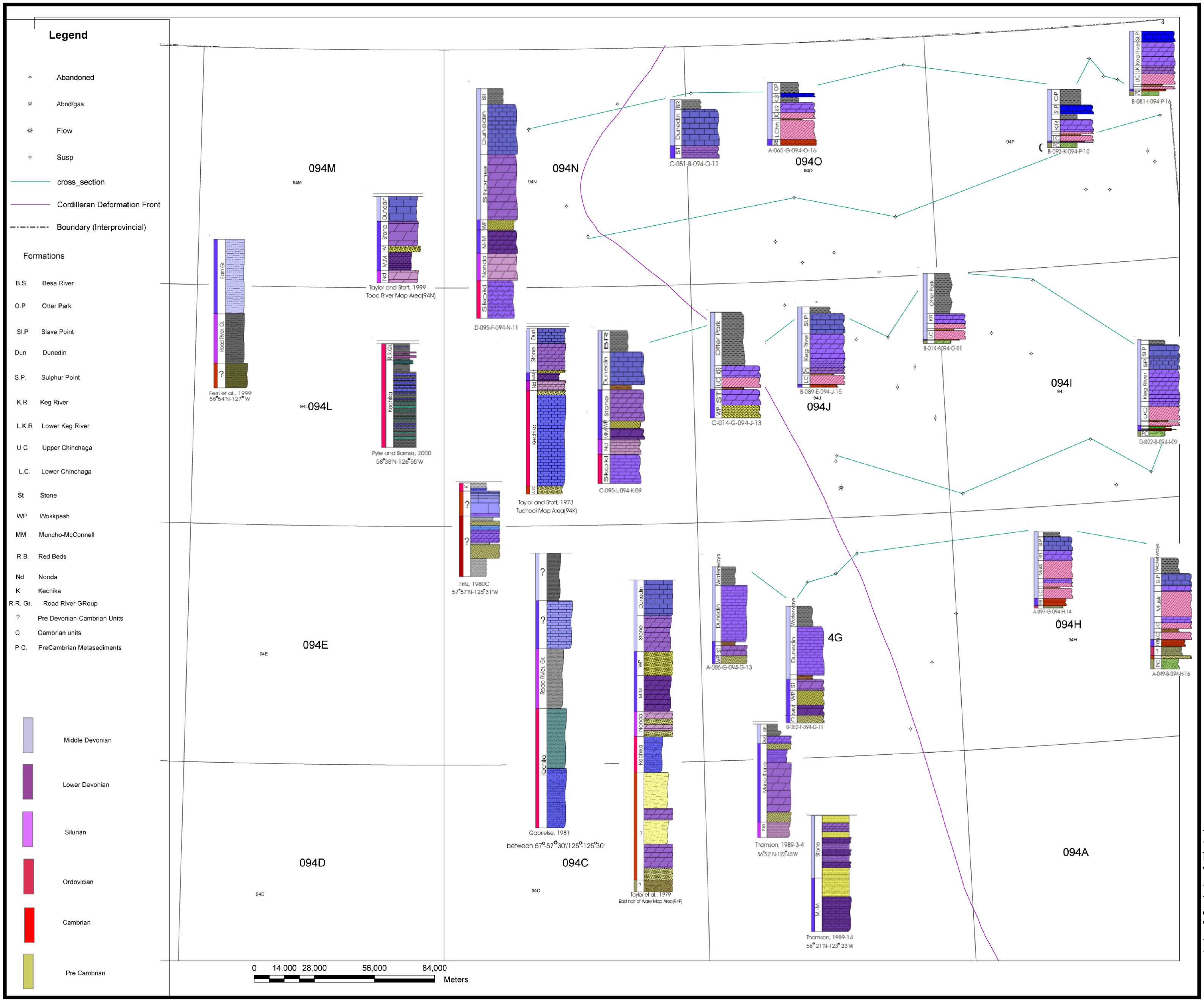

Figure 1. Map showing the previous studies by Taylor and Stott, 1999; Ferri *et al.*, 1999; Pyle and Barnes, 2000, Taylor and Stott, 1973; Fritz, 1980C; Gabrielse, 1981; Taylor *et al.*, 1979; Thomson, 1989

- Geologic setting and major paleogeographic elements,
- A top database of the 65 wells penetrating this interval,
- Thin section study for both correlation of the units and reservoir quality assessment,
- Assessment of potential reservoir units.

GEOLOGIC SETTING AND PALEOGEOGRAPHY

During the Lower Paleozoic, deposition within the WCSB occurred in a miogeocline on the passive margin of the western North America. This miogeocline formed as a result of Late Proterozoic rifting, hosting Uppermost Proterozoic to Lower Devonian rocks with distinct periods of rifting and extension. This resulted in complex paleogeography and the depositional fabric variation observed in Lower Paleozoic rocks. The southern Canadian Cordillera, including the study area, is named the Southern Cordilleran Upper Plate Zone by Cecile *et al.* (1997) and has characteristics of an upper plate margin in an asymmetric rift setting, as described by Lister *et al.* (1991). The upper plate margin is defined by a narrow continental shelf with continent ward crustal highs produced by steeply dipping extensional faults. These abrupt variations in the basement structure affect the depositional setting.

The major paleogeographic elements in northeastern British Columbia during the Lower Paleozoic were the Kechika Trough and adjacent MacDonald Platform, representing deep marine deposition and carbonates defined as a Continental Shelf province respectfully (Figure 2). The Cratonic Platform to the east has thin, shallow to restricted marine sediments (Cecile *et al.*, 1997; Morrow and Geldsetzer, 1988). Lower Paleozoic sedimentation was also affected by paleotopographic highs such as the Peace River Arch, the MacDonald High and the Tathlina High. The Liard Line and Great Slave Lake Shear Zone are northeast trending basement lineaments, which also affected the Lower Paleozoic paleogeography (Cecile *et al.*, 1997).

STRATIGRAPHY

Stratigraphic studies on Lower Paleozoic strata of northeastern British Columbia have been done since the late 60's, mostly as surface studies for individual map areas (Ferri *et al.*, 1999; Fritz, 1980; Gabrielse, 1981; Pyle and Barnes, 2000; Taylor *et al.*, 1979; Taylor and Stott, 1973, 1999; Thomson, 1989; Cecile and Norford, 1979). Pugh (1973) completed a detailed study of the subsurface of Lower Paleozoic stratigraphy in northern and central Alberta, in which he defined the nomenclature used in more recent studies. Hein and McMechan (1994), Meijer Drees (1994), and Slind *et al.* (1994) have compiled available subsurface studies and demonstrated the stratigraphic relationships of the Lower Paleozoic units in a regional sense within the WCSB. The nomenclature used for this study is based on their work (Figure 3).

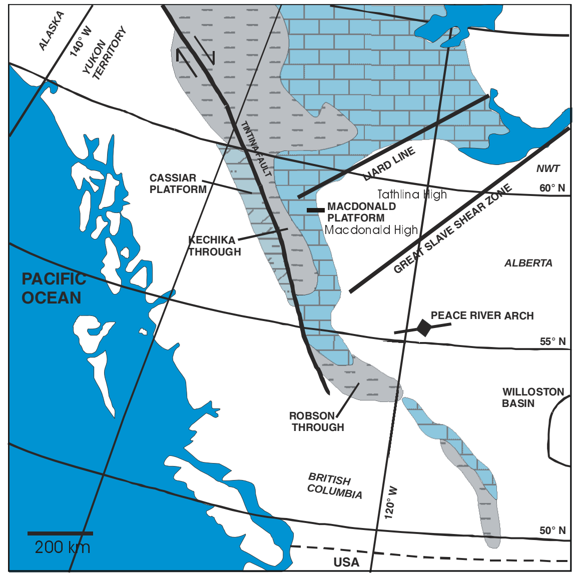

Figure 2. Map of the lower Paleozoic palegeography with the major depositional and the structural elements (Modified from Cecile et al., 1997)

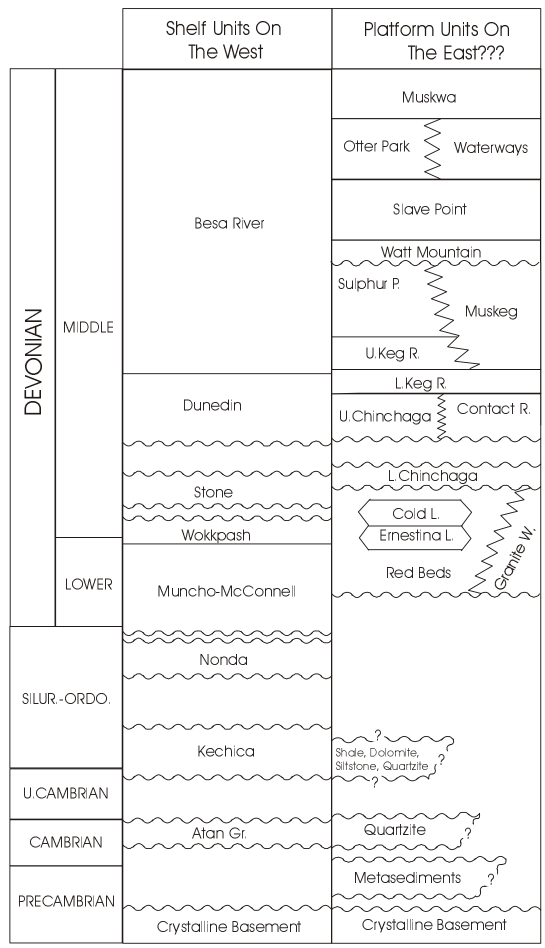

Figure 3. Generalized stratigraphic chart for this study for Precambrian and Lower Paleozoic in northeastern British Columbia. (Also compiled from Slind et al., 1994; Hein and McMechan, 1994; Meijer Drees, 1994). Time intervals, unit thicknesses and erosional or depositional effects are not shown to scale

Pre-Cambrian Metasediments: The oldest strata penetrated by the wells in the study area are the fine clastics of Pre-Cambrian age. The drill cutting samples of green to olive grey coloured mudstone and siltstone with chlorite are similar to those of the Middle Proterozoic Muskwa Assemblage, as described by Taylor and Stott (1973). The wells penetrating this succession are mostly in the northeastern part of the study area, where the strata unconformably underlies Mid-Devonian evaporates (Figures 4, 5 and 6). The Muskwa assemblage is interpreted as a possible re-entrant into the ancestral North-American plate that affected much of the northeastern British Columbia. Thomson (1981) suggests from the seismic reflection data that more than 2000 m of pre-Middle Devonian strata is present, most of it as the Muskwa assemblage in the western margin of the plains in southeastern Fort Nelson Map area (94J).

Cambrian: The Cambrian strata consists of quartz arenite, which unconformably overlies Pre-Cambrian rocks. This unit is composed of mature quartzarenites, siltstones and orthoquartzites that are correlated to the Middle Cambrian Atan Group in the northern Rocky Mountains and the quartzites of the Gog group in the south (Taylor and Stott, 1973; Hein and McMechan, 1994).

The sandstones are fine to medium grained and fairly well sorted. The diagenetic minerals include syntaxial quartz overgrowths, pore filling carbonate cement, and pyrite cement, especially in the siltstones (Figure 7).

In well BRC HTR ET AL RING a-49-B/94-H-16 (Figure 8), a 12m zone of red beds composed of poorly sorted floating quartz grains in a hematite bearing matrix underlies the sandstones and unconformably overlies the pre-Cambrian strata. A few highly corroded feldspar grains are also visible, however there are no other lithic fragments present. These sediments are probably more distal equivalents of the red fanglomerate deposits of the Atan Group described by Taylor and Stott (1973). Gehrels and Ross (1998) suggest a large region of the northwestern Canadian Shield for provenance of these sandstones because of the broad range in age of the detrital zircons sampled. The high maturity of these sandstones may also be due to recycling of detritus from older units.

U. Cambrian(?)-Silurian-Ordovician: The strata overlying the Cambrian quartzites in the east are grey-green waxy shales interbedded with siltstones and dolomites, as described from drill cutting samples. The strata lies between the Lower-Lower Middle Devonian Red Beds and the Cambrian quartzites. When using the cross-sections and the petrophysical logs they may be correlated with either the fine-grained clastics of the Mount White and the Earlie formations overlying the Gog Group (Slind *et al.*, 1994) or remnants of the Silurian-Ordovician strata (Figures 8 and 9). These strata are penetrated by only two wells in the southeast of the study area, and are absent in the west, suggesting that they are not continuous but rather locally deposited or preserved.

In the west, limestones of the Kechika Formation, dolomites of the Nonda Formation, and the base of the Muncho-McConnell Formations are all correlated to Ordovician-Silurian strata deposited in the platform setting (Figure 3). There are only a few wells further northwest that penetrate the Nonda and Skoki Formations, indicating the eastern subsurface edge of the platform (Figures 4 and 5).

Lower and Lower-Middle Devonian: Lower Middle Devonian strata on the platform is represented by red beds of interbedded shale, siltstone and dolostone, along with dolomites and anhydrites of the Ernestina Lake Formation and finally locally thin salt beds of the Cold Lake Formation. At the northern margin of their area of preservation, the lower Paleozoic rocks form the erosional escarpment of Meadow Lake. It was the limit of a Middle Devonian sea within which the lower Elk Point evaporites were deposited along the margins of the basin (Meijer Drees, 1986). The base of these units coincides with the pre-Devonian erosional unconformity.

In the west, the Wokkpash Formation, quartzites of the regressive phase of the Muncho-McConnell Formation and the unconformably overlying sandy and silty dolomites of the Stone Formation represent the Lower and Lower-Middle Devonian. The Wokkpash Formation, which conformably overlies the Muncho-McConnell, is a succession of nearshore dolomitic quartz arenite (Figures 8 and 9). The unit is extensively correlated in the subsurface of the study area, with thicknesses up to 100 m in the well logs. It is also extensive in the mountains and mapped further south in the Halfway Map Area by Thomson (1989), to the north in Tuchodi Lakes Map Area by Taylor and Stott (1973) and in the Toad River Map Area by Taylor and Stott (1999). The unit is composed of fine to large grained moderately sorted quartz arenites with a number of diagenetic sequences. The earliest diagenetic feature is the growth of syntaxial quartz overgrowth; the original grain fabric is not visible. Rare, mostly dolomitized carbonate cement has infilled the crystalline pore space. Some zones were subjected to extensive pyrite participation and in one slide, poikilotopic anhydrite cement is also seen, all indicating a complex diagenetic history. The quartz arenites are extensively strained having a dense fabric of microfractures (Figure 10). Nadjivon and Morrow (in press) described the unit as indicative of shallow marine foreshore to nearshore environment, with moderate to high energy levels such as a barrier bar complex (Figure 11).

The Lower Elk Point evaporates are unconformably overlain by anhydrites and dolomites of the Chinchaga Formation on the east, and the sandy dolomites of the Stone Formation on the west by transgression (Figure 12). The Chinchaga Formation is composed of interbedded anhydrites and dolomites with dolomite thicknesses increasing towards the west. The unit is divided into two zones of Upper and Lower Chinchaga by a regional unconformity, which can also be traced between the Stone and overlying Dunedin formations. This unconformity can be traced extensively as a widespread detrital unit (Ebbutt Member), which can be seen in all of the cross sections. The abrupt influx of clastic material, especially quartzose sandstones may be indicative of a sudden emergence of a source area containing clean quartzitic sediments. The transgression period after this clastic influx resulted in deposition of lagoonal to open marine carbonates of the Dunedin Formation in the west and

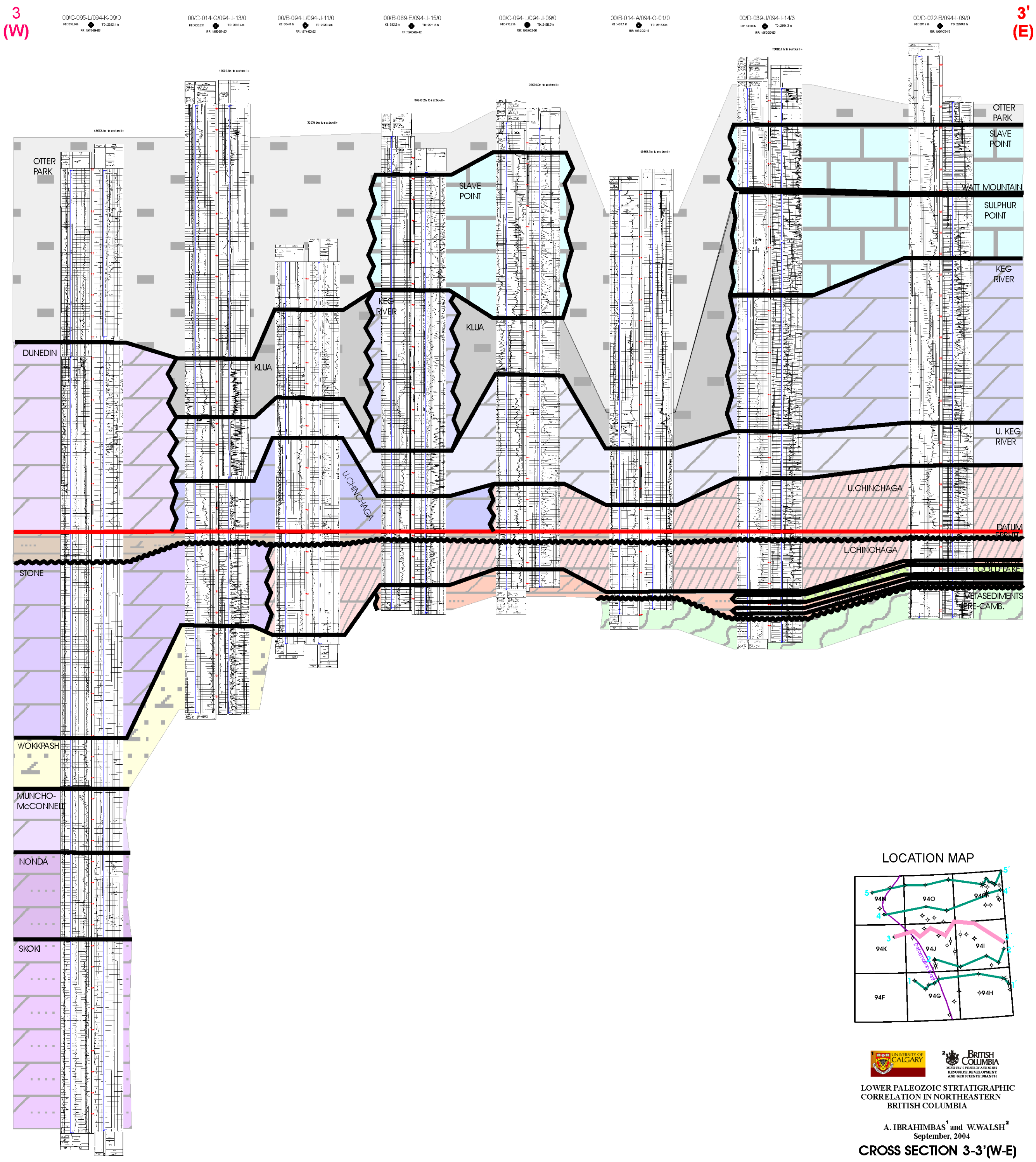

Figure 4. Stratigraphic subsurface correlation of the Lower Paleozoic strata. Cross Section 3-3'.

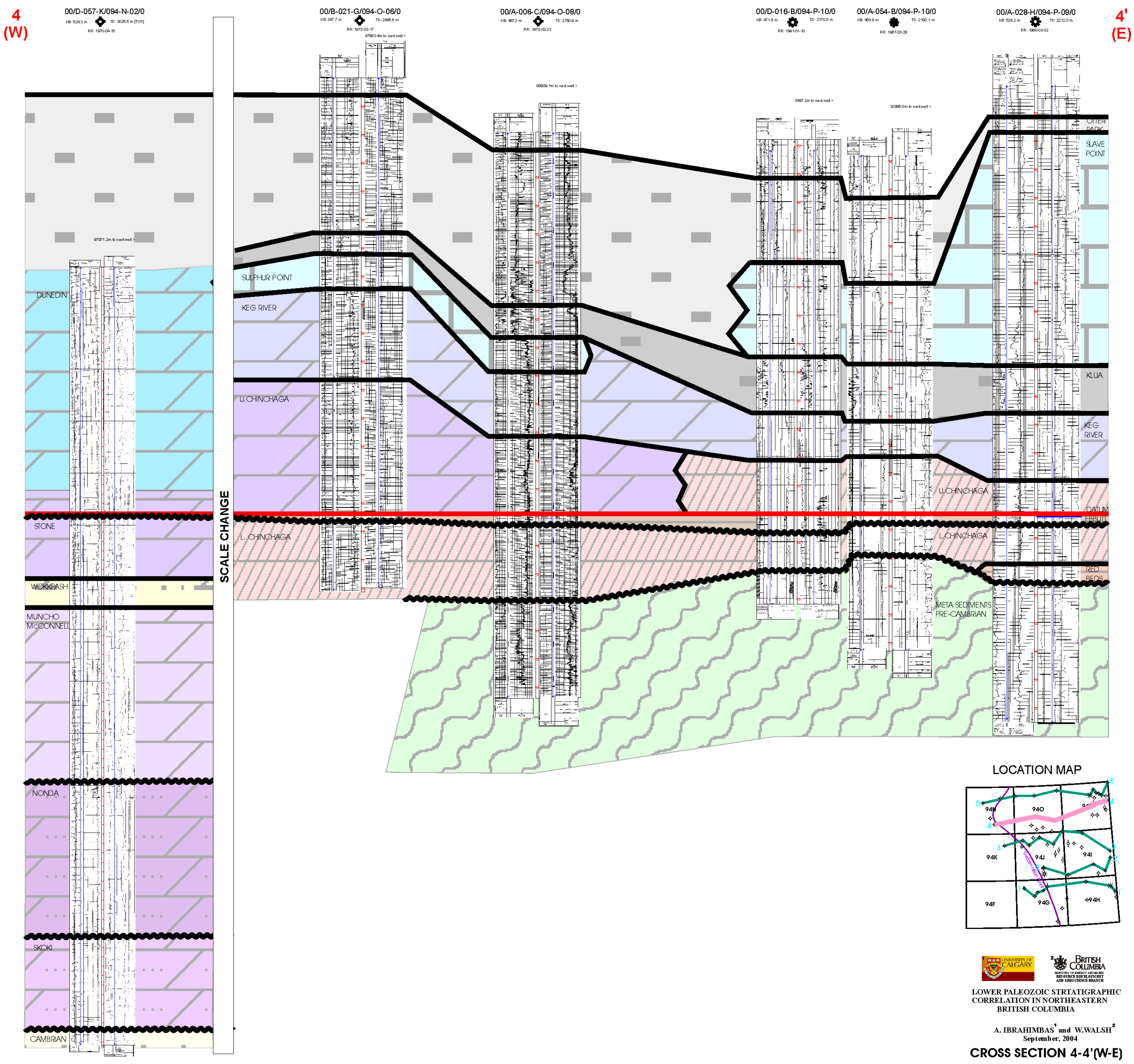

Figure 5. Stratigraphic subsurface correlation of the Lower Paleozoic strata. Cross Section 4-4'.

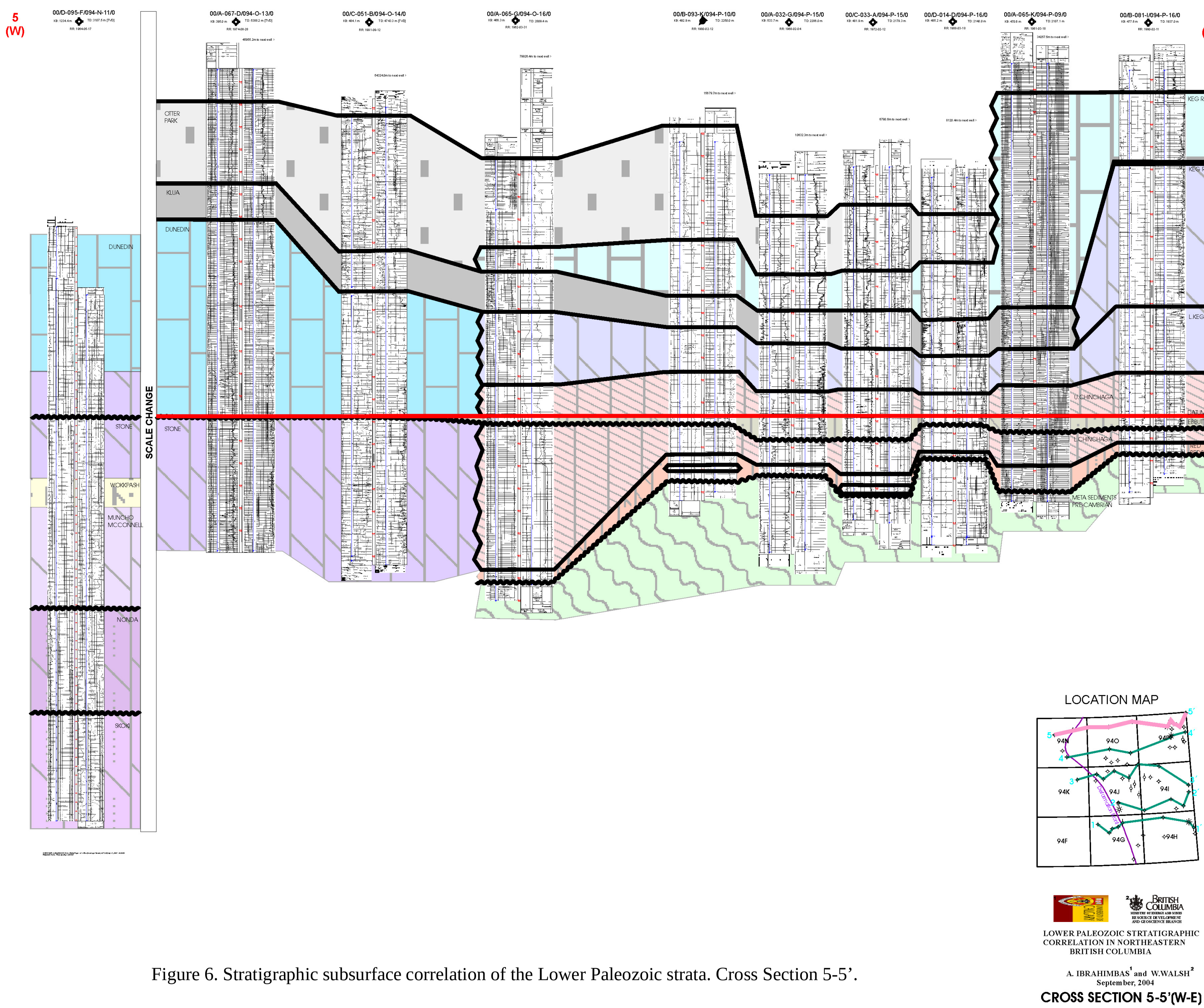

Figure 6. Stratigraphic subsurface correlation of the Lower Paleozoic strata. Cross Section 5-5'.

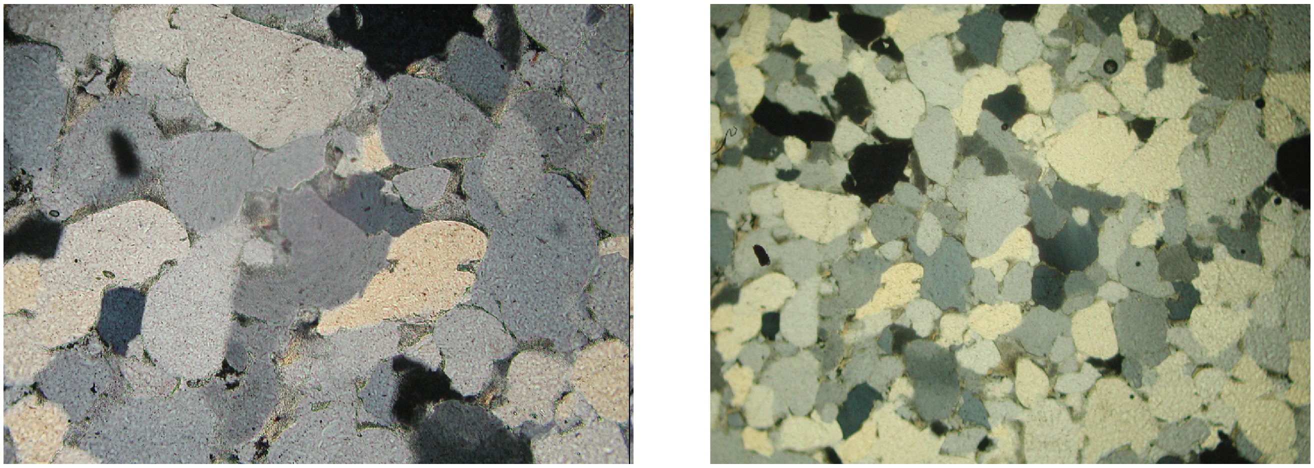

Figure 7. Photomicrographs of the Cambrian quartzarenite units from well A-49-B/94-H-16, 9760 m. (A) CPL, scale bar 0.25 mm (B) CPL, scale bar 0.5 mm .

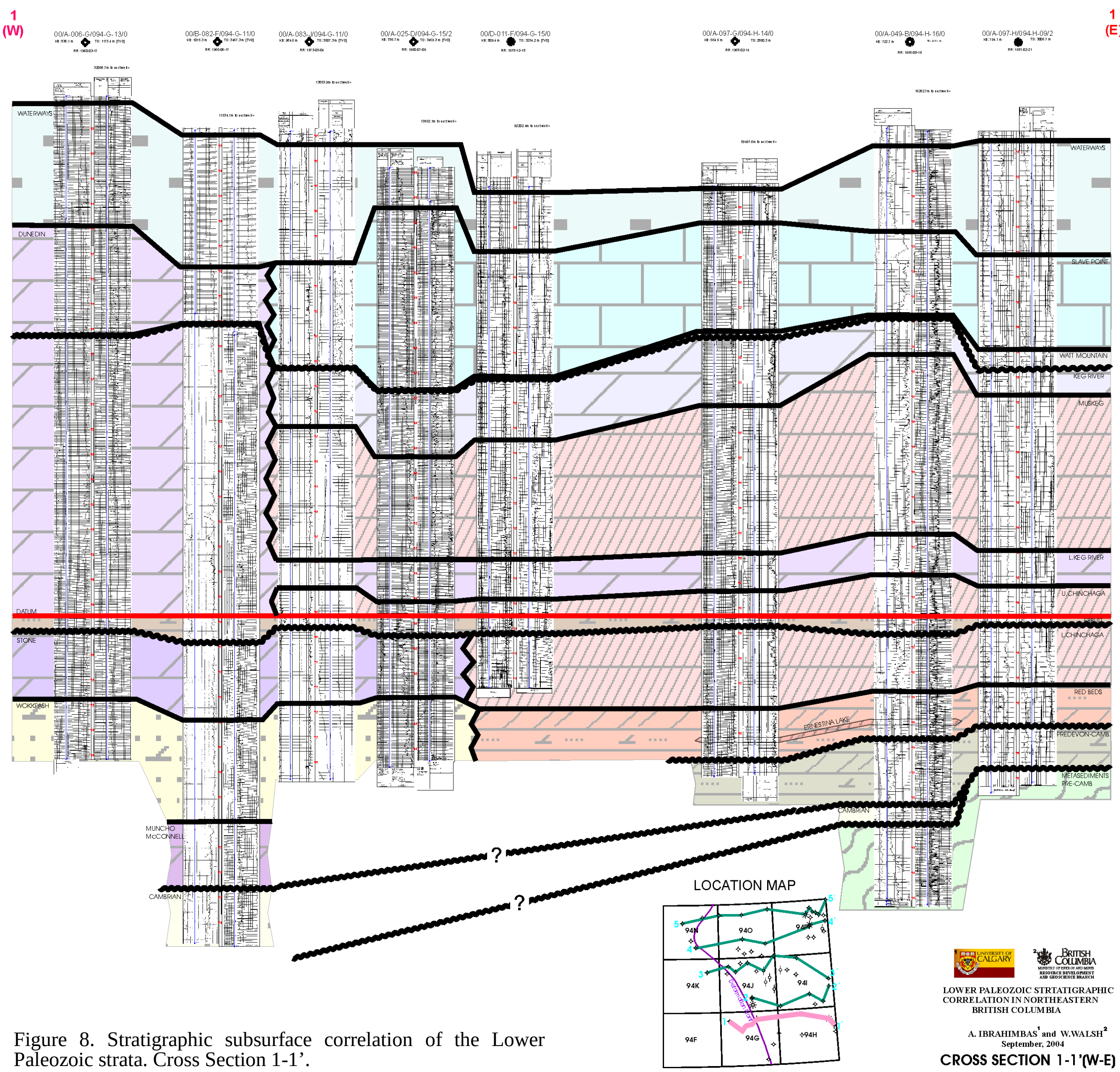

Figure 8. Stratigraphic subsurface correlation of the Lower Paleozoic strata. Cross Section 1-1'.

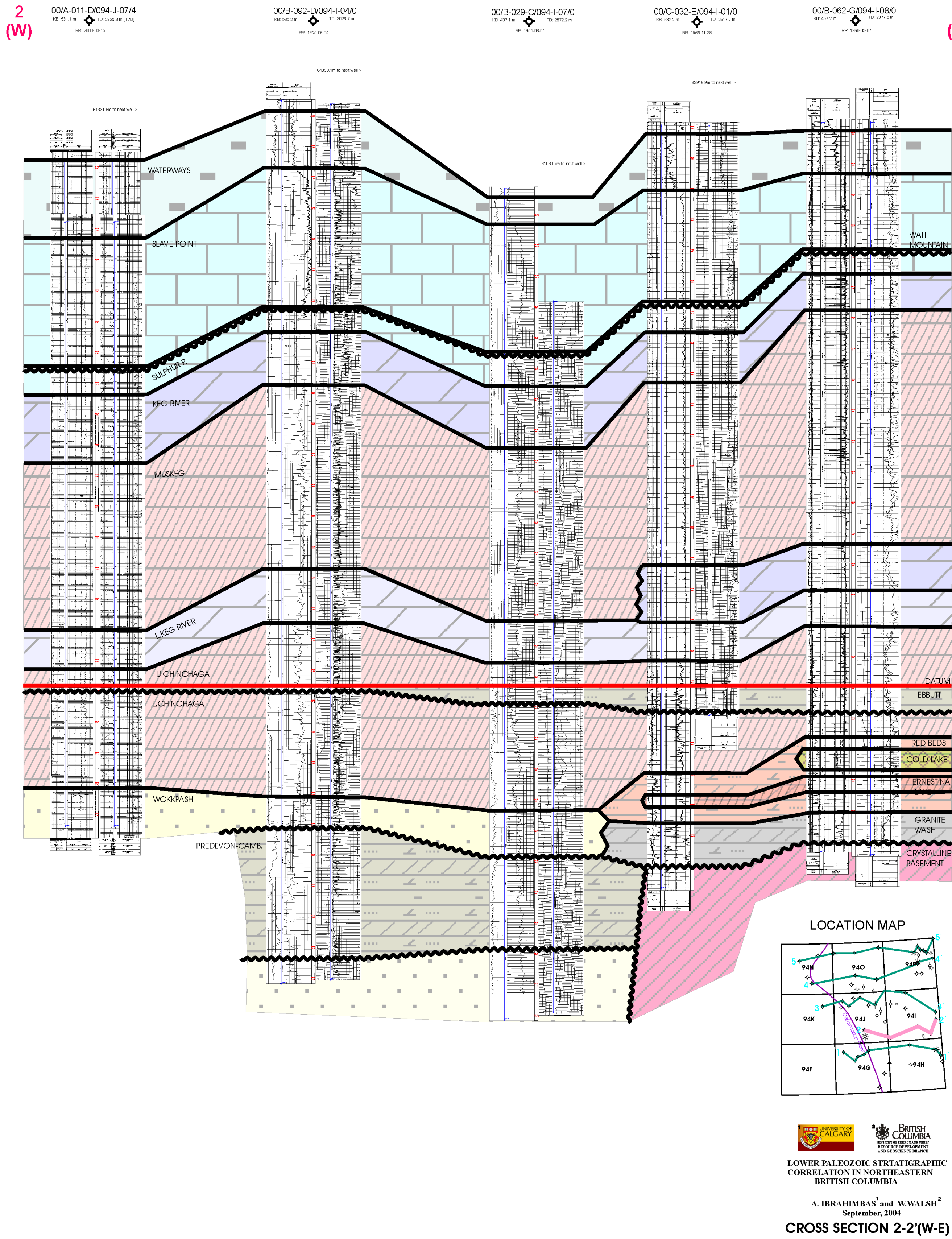

Figure 9. Stratigraphic subsurface correlation of the Lower Paleozoic strata. Cross Section 2-2'.

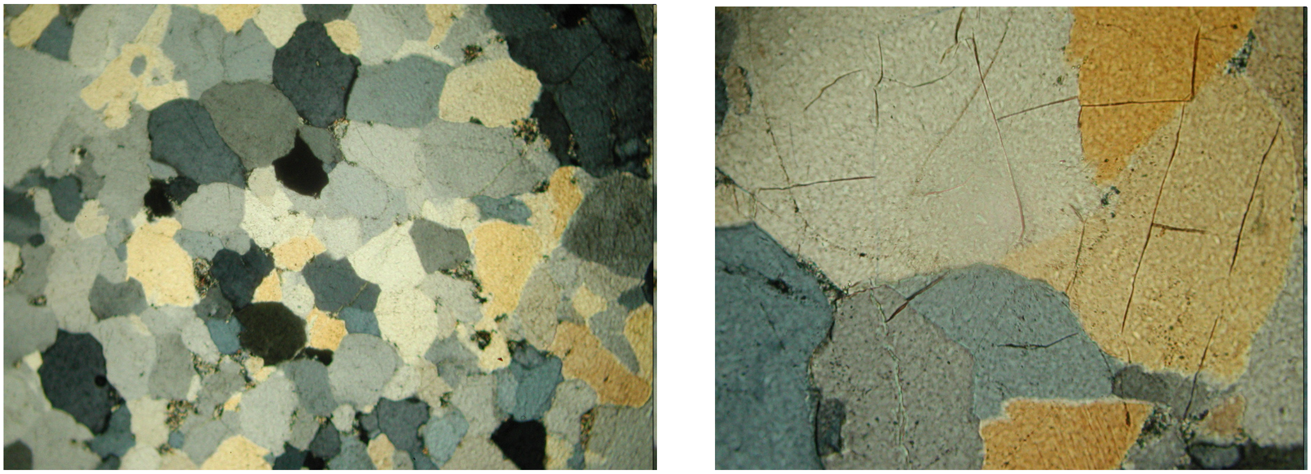

Figure 10. Photomicrographs of the Wokkpash sandstone units from well A-11-D/94-J-7, 2727.5 m. (A) CPL, scale bar 0.5 mm (B) CPL, scale bar 0.25 mm.

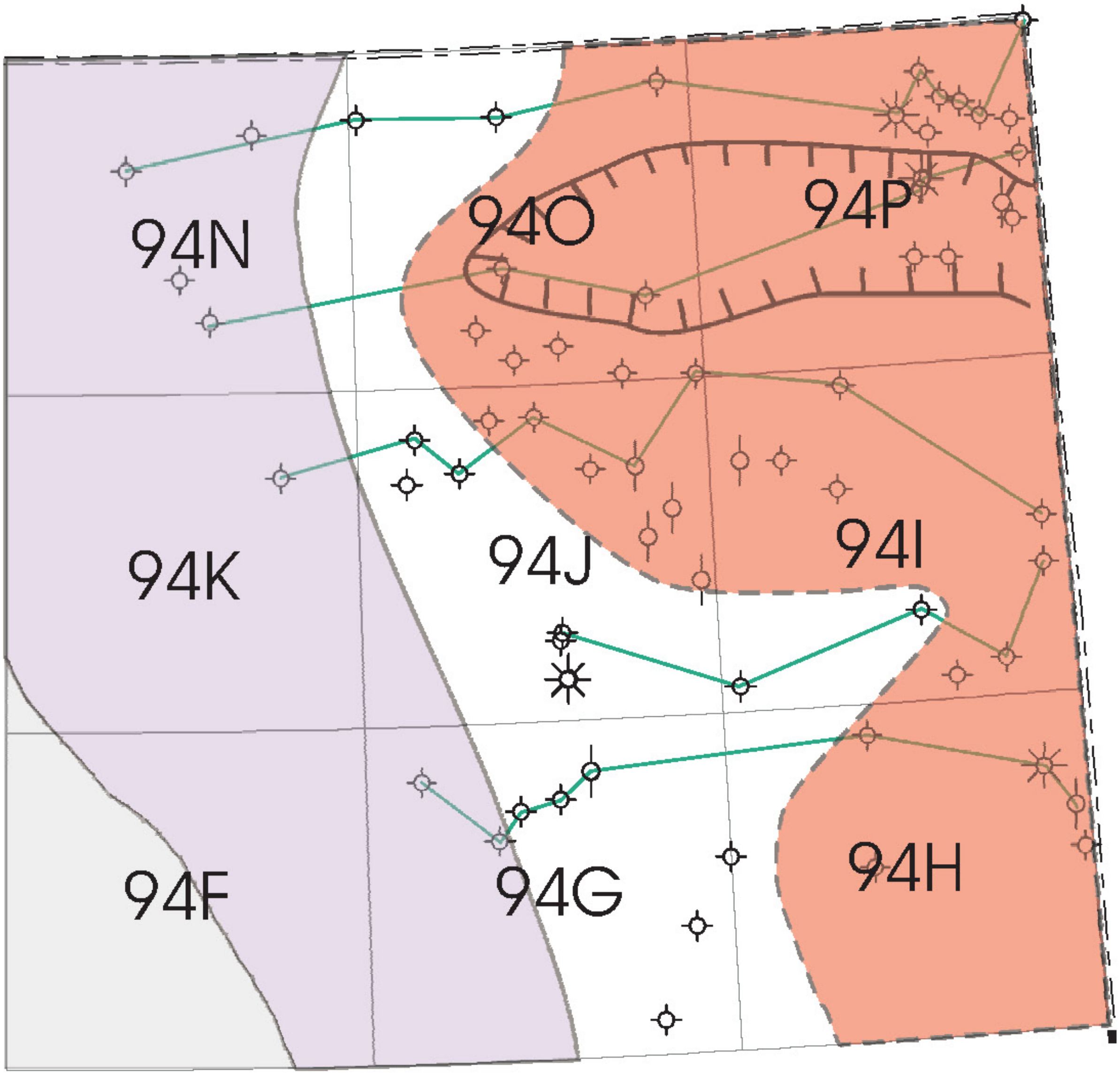

Figure 11. Paleogeography during the deposition of the Wokkpash Formation.

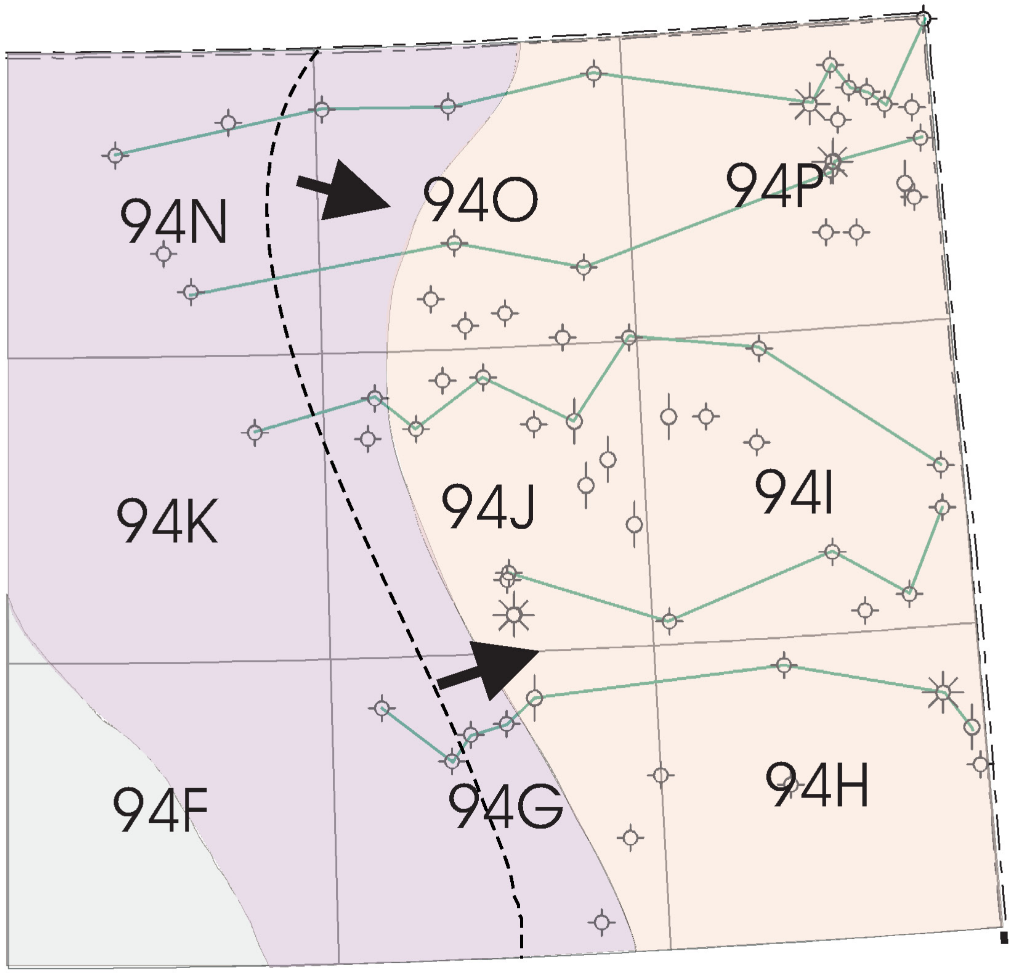

Figure 12. Paleogeography during the deposition of the Stone Formation.

dolomites and anhydrites of the Upper Chinchaga and dolomitized, bioclastic mudstones and wackestones of the Lower Keg River formations.

PETROLEUM SYSTEM POTENTIAL IN PRE-KEG RIVER/CHINCHAGA

Reservoir Potential

The only identified reservoir within the zone of interest is a high porosity zone lying in the boundary between the L. Keg River and Chinchaga Formations. The zone is generally within the L. Keg River pools, but may actually be a mappable unit in the northeastern part of the study area. The DST measurements from this zone show average-high permeability with recoveries as great as 4.18 MMCF/Day (Figure 13).

The Chinchaga Formation, comprising mainly of anhydrite and dolomite, displays occasional porosity development. The dolomites have a very compact grain arrangement with little if any intercyrstalline porosity. However, some wells display discrete zones with porosity. In well PCI EVIE LAKE B- 089-E/094-J- 15 DST#15 shows an average permeability, with gas recovery of 0.296 MMCF/Day. The gross pay of this zone is 20 m with a net pay thickness of 9 m. The thin sections from this interval comprise euhedral dolomite, with some rare intercrystalline porosity filled with pyrobitumen. There are also some large saddle dolomite crystals in these thin sections that might be filling either a vuggy porosity or fractured porosity (Figure 14). This unit may be of potential reservoir quality depending on diagenetic features and fracture density and aperture. In addition, a number of wells show modest gas recoveries of up to 0.37 MMCF/Day with low-average permeability within this unit, indicating hydrocarbon charge. Textures observed in dolomites of the Stone and Dunedin Formations are very similar to those in the Chinchaga Formation with DSTs showing low to high permeability and some gas recovery.

Quartz arenites of the Wokkpash Formation are regionally extensive in Lower Devonian strata. This unit was likely deposited in a nearshore environment as the regressive phase of the Muncho-McConnell Formation carbonates, which is then transgressed and overlain by carbonates of the Stone Formation. Wokkpash sandstones are mature with well-sorted and rounded quartz grains, which are overprinted with anhedral-euhedral syntaxial quartz overgrowths. The quartz overgrowth appeared to be an early phase of diagenesis that reduced porosity. The

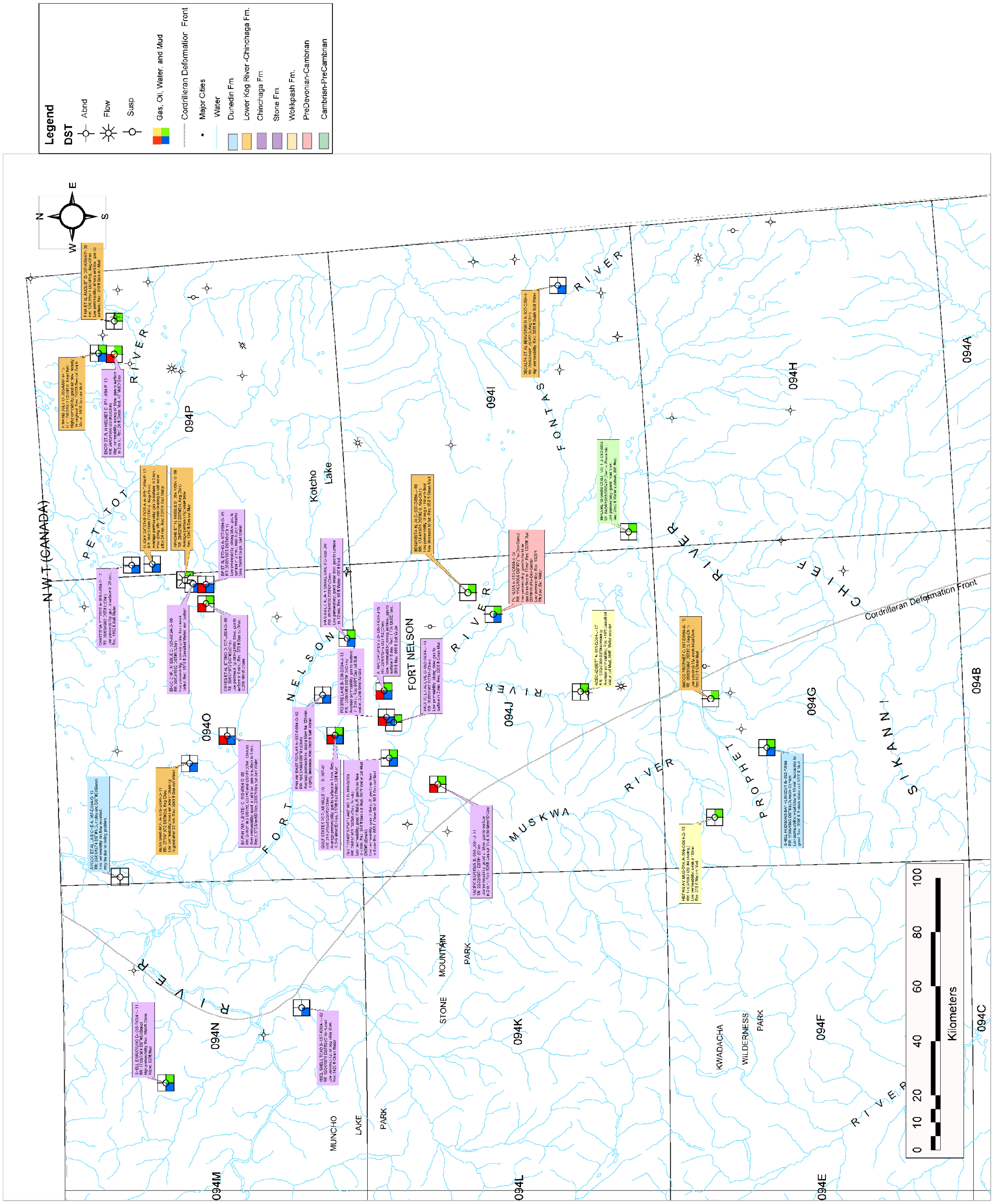

Figure 13. Hydrocarbon play map showing the DST results taken from the units of interest.

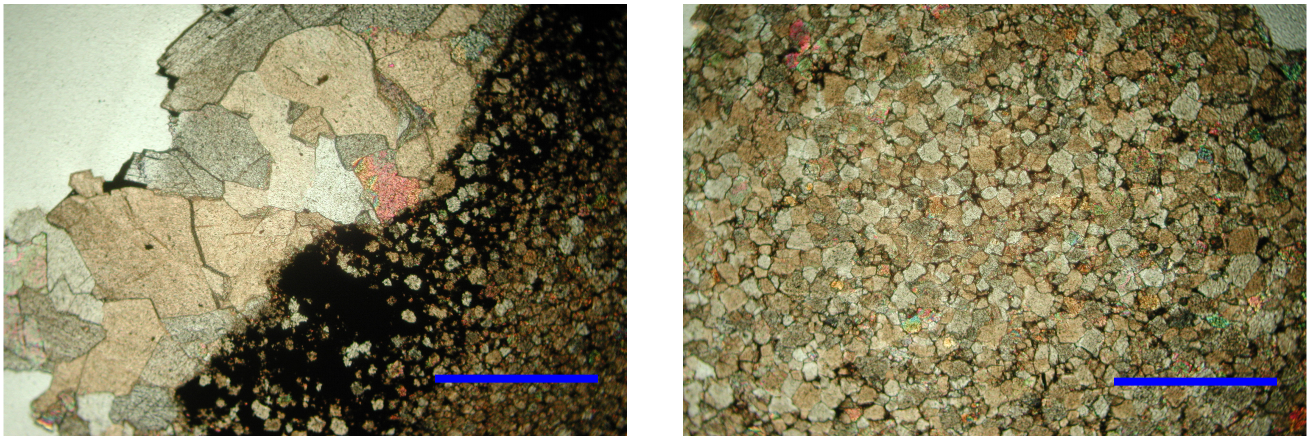

Figure 14. Photomicrographs of the Chinchaga Formation dolomites from well B-89-E/94-J-15, 8040 ft. CPL, scale bar 0.5 mm.

carbonate cementation pore fill also reduces porosity; therefore no visible porosity is evident in the thin sections. However, the unit has probably gone through an extensive stress regime, which is seen as high-density strain fabric. These intense microfractures crosscut the grains and the cement implying they had formed after the diagenesis (Figure 10). A few DST measurements taken from this unit show low-average permeability with some minor gas during tests. This unit may have reservoir potential depending on the density of the strain, open fractures, and the fracture patterns.

Source Rocks

Ordovician aged immature to mature, oil prone source rocks with TOC values up to 35% are reported from the Williston Basin of the WCSB by Osadetz and Haidl (1989) and Osadetz et al. (1989). However, no potential source rock has been reported for Pre-Devonian strata in the subsurface of WCSB. The Middle Devonian Elk Point Group contains several units with hydrocarbon potential including the Evie Member and Keg River Formation in British Columbia (Fowler et al., 2001). The Evie Member of the Klua Shale is mostly overmature in the study area. A few source facies had been recognized from the well logs within the Keg River Formation, which are source to some of the oils in Rainbow-Zama areas (Creaney et al., 1994).

There was no potential source rock observed in well logs or in the examination of drill cutting samples within the strata below Pre-Keg River-Chinchaga from wells studied. However, outcrop samples taken from the 94G map area analyzed from the Ordovician-Silurian aged Road River Group, which is the basinal off-shelf sediments equivalent of Kechika Formation, yield high TOC values of up to 10% where they are thermally overmature (Stasiuk, personal com.). This suggests that the unit might have generated significant amounts of hydrocarbons,. More detailed studies need to be done to understand the timing of hydrocarbon generation from these units and possible migration pathways in relation to the structural evolution of the area in order to understand if any of these hydrocarbons are trapped.

CONCLUSIONS

Geological history

The complex lower Paleozoic paleogeography and depositional setting are the result of variations in the basement structures such as the asymmetrical rift, and steeply dipping extensional faults that affected the deposition of the later formations. The main structural features that controlled deposition from west to east, basin to platform are the Kechika Trough, the MacDonald Platform, MacDonald and Tathlina highs, and the positive Peace River Arch. There are also the basement lineaments of the Liard Line and Great Slave Lake shear zone. The units were deposited on to the miogeocline of the Canadian Cordillera with basinal shales of the Road River Group, and offshore carbonates of the Kechika, Skoki, Nonda, Muncho-McConnell, Stone and Dunedin Formations. The equivalent strata is barely preserved in eastern Northeast British Columbia with a thin layer of U. Cambrian(?)-Silurian(?) strata overlain by the Lower-Middle Devonian evaporites. The mixed carbonates and sandstones units, and the sandstone sheets of the Cambrian sandstones and Wokkpash Formation are explained by periods of clastic influx during the carbonate sedimentation, sourced from the Peace River Arch.

Reservoir Potential

The dolomite units of L. Keg River-Chinchaga, Chinchaga and Stone formations and the quartz arenites of the Wokkpash Formation and Cambrian unit, likely have the best reservoir potential. In thin section, each of the carbonate units display similar characteristics such as micro to cryptocrystalline, anhedral-euhedral crystals with little if any intercrystalline porosity with large saddle dolomite crystals possibly filling vuggy or fracture porosity. DSTs show low to high permeabilities with recorded gas recoveries of up to 4.18 MMCF/Day from these zones. The Wokkpash Formation comprises mature quartzarenites with carbonate cement and there is no visible intercrystalline porosity in thin sections, though it may contain some porosity due to microfactures. The Cambrian quartz arenites also displays no visible porosity in thin section due to quartz overgrowths and pore filling carbonate cement. There is however, the possibility of some microporosity development and the potential for fracture enhancement. The DSTs from this unit displays low permeability with air blow and salt-water recovery.

Source Rock

No potential source rock has been identified from the subsurface of the study area. Rock Eval/TOC analysis from outcrop samples of the Ordo-Silur Road River Group taken from the 94G Map area show that the unit is over mature with TOCs as high as 10%. This unit was likely an excellent source for hydrocarbon generation. It may be a source for the reservoirs in the study area depending on the timing of thermal and structural evolution. A detailed thermal maturity modeling should be done for a better understanding of the thermal history of this unit.

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