Overview of the age, evolution, and petroleum potential of the Eagle Plain Basin, Yukon

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Abstract: New mapping, biostratigraphy, geochemistry, and organic petrology results have led to new insights into the structural evolution, depositional history, and resource potential of the Eagle Plain Basin. Apatite fission-track modelling resolves at least two distinct heating–cooling cycles and suggests that sediment was sourced from the east, as well as from the south. A recently identified marine-slope setting in the west of the basin represents a new petroleum play. Advances in understanding the age and depositional history of the Eagle Plain Group derive from new fossil localities, a new bentonite age, and detrital zircon data. Initiated in the Cenomanian, or possibly latest Albian, deposition continued until the late Maastrichtian, although post-Coniacian deposits may have been subsequently eroded, or bypassed across southern parts of the basin. New petroleum resource appraisals include new petroleum exploration-play concepts, as well as qualitative assessments of unconventional oil and gas potential.

Résumé : De nouveaux résultats tirés de travaux de cartographie, de biostratigraphie, de géochimie et de pétrologie organique ont accru notre compréhension de l’évolution structurale, de l’histoire sédimentaire et du potentiel en ressources du bassin d’Eagle Plain. La modélisation des traces de fission dans l’apatite a permis de déterminer l’existence d’au moins deux cycles distincts de réchauffement-refroidissement et laisse à penser que la source des sédiments se situait à l’est, de même qu’au sud. La reconnaissance récente d’un contexte de talus marin dans l’ouest du bassin définit une nouvelle zone pétrolière. De nouvelles localités fossilifères, un nouvel âge sur bentonite et des données sur les zircons détritiques ont fait progresser notre compréhension de l’âge et de l’histoire sédimentaire du Groupe d’Eagle Plain. Amorcé au Cénomanien, ou peut-être à l’Albien terminal, le dépôt de sédiments s’est poursuivi jusqu’au Maastrichtien tardif. Toutefois, des dépôts postérieurs au Coniacien ont peut-être été subséquemment érodés ou ne se sont pas accumulés dans les parties méridionales du bassin. L’estimation des nouvelles ressources en hydrocarbures tient compte de nouveaux concepts de zones d’exploration pétrolière ainsi que d’évaluations qualitatives du potentiel en pétrole et gaz non conventionnels.

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INTRODUCTION

Preparation for activities carried out under the Geomapping for Energy and Minerals (GEM) program in Yukon sedimentary basins began in late 2008 with a workshop attended by researchers and stakeholders from the Federal and Yukon governments, academia, and the energy industry. Objectives included producing new framework geoscience maps, syntheses, and energy resource assessments of sedimentary basins within and bordering Yukon, thus providing community planners with the geoscience information they need to make informed land use decisions; and providing the private sector with new energy plays that will focus future exploration programs, which will lead to greater exploration effectiveness and less cumulative impact on fragile northern ecosystems.

New developments in understanding the age, stratigraphic history, and thermotectonic evolution of the study area stemming from work carried out within northern Yukon and adjacent areas under the GEM Yukon Basins project, as well as follow-up work under successor GEM projects, are briefly summarized in this report. Reliable biostratigraphy underpins most other aspects of sedimentary-basin study, such as the depositional history, seismic stratigraphy, structural evolution, and ultimately the resource potential. Accordingly, a major focus of the project centred on the ongoing problem of determining the age of the Eagle Plain Group, which is considered here in some detail.

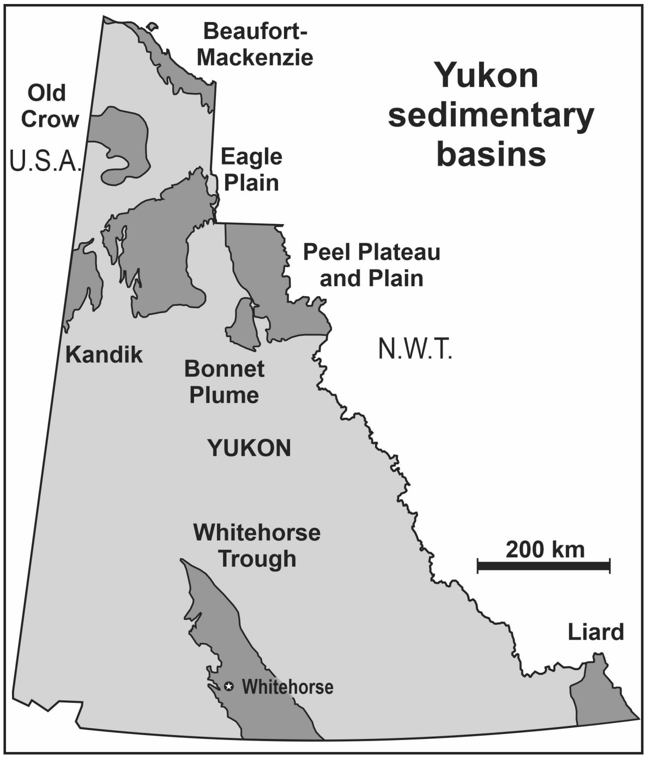

Figure 1. Yukon sedimentary basins (*modified from* Yukon Energy, Mines and Resources, 2020).

Of the eight sedimentary basins across Yukon, activities focused on the Eagle Plain Basin and adjacent northern basins: Kandik and Bonnet Plume basins, Peel Plateau, and North Slope–Beaufort Basin (Fig. 1). Additional relevant activities were carried out in the Whitehorse Trough and Liard Basin, but are not highlighted in this summary. In addition to field-based bedrock mapping, stratigraphic and biostratigraphic studies, new laboratory studies on thermal history, geochemistry, and biostratigraphy for existing wells in the project area were undertaken (Appendix A), as well as digitizing and releasing previously unpublished archival data sets.

During a total of 7 weeks of fieldwork carried out in the Eagle Plain Basin between 2009 and 2012, stratigraphic sections were measured, predominantly in Cretaceous strata, and targeted mapping was carried out, largely focused on the deformed margins of the basin. Field personnel consisted of Geological Survey of Canada (GSC) and Yukon Geological Survey employees, collaborating university researchers, and their students. Field assistants from the Vuntut Gwitchin First Nation in Old Crow, Carleton University, and the University of Calgary provided energetic and effective support.

Processing, compilation, and analysis of field data and samples continue to provide insights into the region's geological evolution, reflected in numerous publications, presentations, and theses. Appendix A tabulates the project's publication record and academic legacy; and Appendix B summarizes some economic impacts of the project.

REGIONAL SETTING

The Eagle Plain sedimentary basin (Fig. 1) is a Cretaceous intermontane basin in northern Yukon, lying within the Foreland Belt of the northern Canadian Cordillera. Located close to the Laurentian cratonic margin (Fig. 2), it is largely separated from the intact craton by the Richardson Trough (Fig. 3), which was active in early and middle Cambrian time, concurrent with block faulting and basaltic magmatism in areas to the south and west (e.g. Fritz, 1997). The Paleozoic successions underlying the Eagle Plain area formed a promontory of shallow-water deposits on Laurentian continental crust lying between two Paleozoic oceans (Lane, 2007). This region of platformal deposits has been referred to as the Porcupine Platform, Yukon stable block (or simply Yukon Block) by numerous authors (e.g. Cecile and Norford, 1993; Norford, 1997; Morrow, 1999). The presence of an extensive area of high-velocity (7.1–7.2 km/s) crust beneath much of the Richardson Trough and adjacent areas to the north (O'Leary et al., 1995) is inferred here to reflect mafic underplating due to lithospheric extension leading to the formation of the Neoproterozoic Franklinian continental margin and the subsequent Cambrian development of the Richardson Trough (Fig. 3).

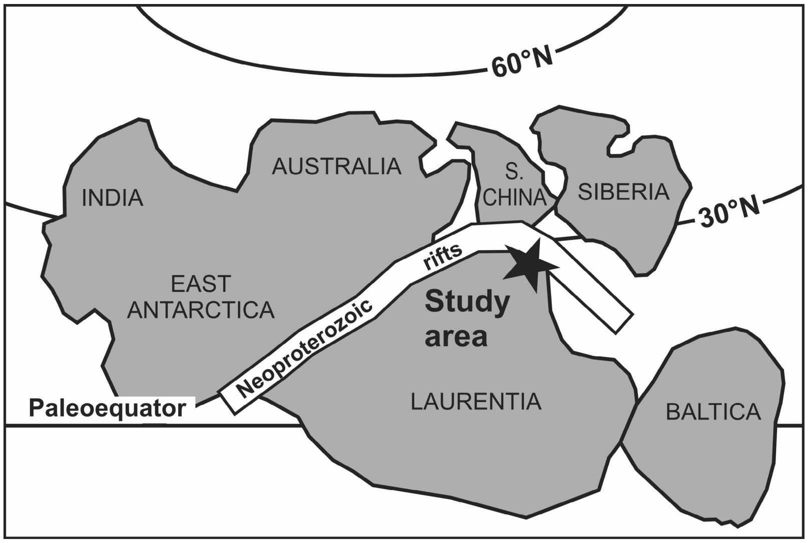

Figure 2. 'Traditional' overview map of northern part of Rodinia, showing general location of the Eagle Plain region (star) adjacent to the continental margin of Laurentia, after the Cryogenian initiation of the Franklinian continental margin. The precise positions of the rifted continents relative to Laurentia remain uncertain. Paleolatitudes are shown. *Adapted from* Meert and Torsvik (2003).

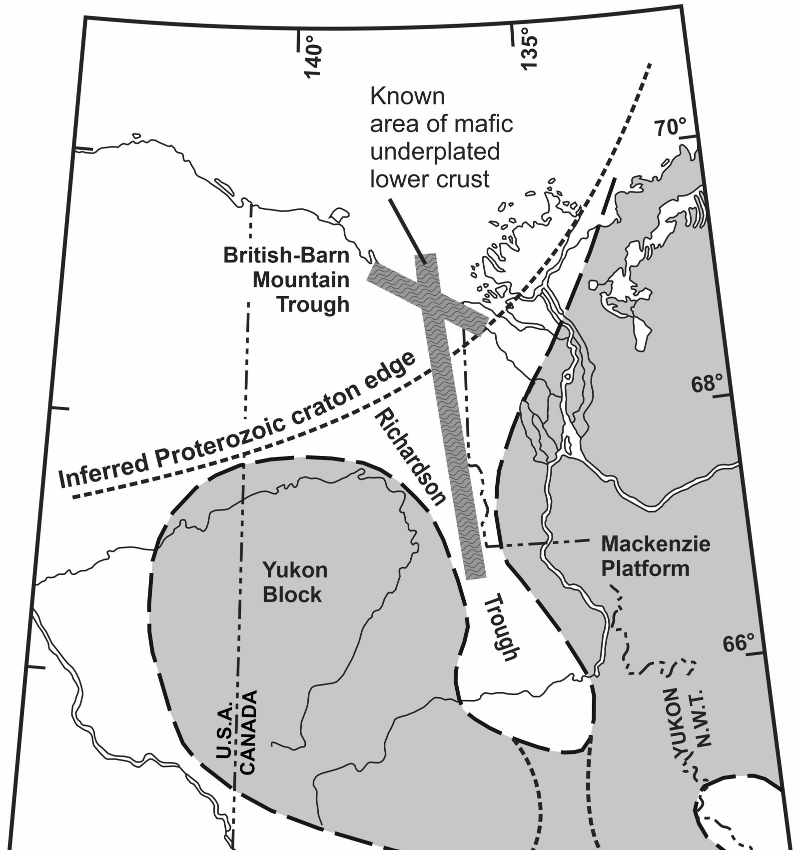

Figure 3. Generalized Ordovician paleogeography, showing regional distribution of the high-standing Mackenzie Platform and Yukon Block versus the basinal Richardson Trough and Selwyn Basin (*adapted from* Lane, 2007). Continuity between the Richardson Trough and Selwyn Basin is conjectural (*see* Morrow, 1999). The inferred Proterozoic craton edge influenced the location and orientation of structures throughout Phanerozic time, including the Devonian Ellesmerian deformation front (Lane, 2007), the ancestral Aklavik Arch (Norris, 1997a), and Late Cretaceous–Paleogene deformation trends and strain intensity (Lane, 1998). Area of documented high-velocity basement (Vp = 7.1–7.2 km/s) *compiled from* O'Leary et al. (1995).

The Neoproterozoic continental margins and the Richardson Trough are major crustal discontinuities that largely controlled the orientation and intensity of deformation throughout Phanerozoic time. Examples of specific regional-scale reactivation features include the Dave Lord–Keele Range fold-and-thrust belt, and the Husky Lakes fault system, which reactivated the northern (Franklinian) continental margin; and numerous structures defining the Richardson Mountains including the Richardson fault array (e.g. Norris, 1985, 1997a). The Paleozoic structural evolution of the region is summarized in Lane (2007; *see also* Lane and Gehrels, 2014; Lane et al., 2015, 2016).

The early Mesozoic tectonic history of the northern Yukon region is poorly understood because strata of Triassic age are only locally preserved in thin remnants (Dixon, 1998). Jurassic and Early Cretaceous strata are more widely preserved across the northern parts of the region and are locally imaged in the subsurface of the northern part of the Eagle Plain Basin. They record marine strata deposited throughout Jurassic and Early Cretaceous time as a subsiding epicratonic marine depocentre evolved through progressive rift stages into the Arctic Ocean basin to the north of the study area (e.g. Dixon, 1991, 1997; Poulton, 1997). Successive rifting phases appear to have ended during Albian time, temporally overlapping with the first indications of orogenic foredeep deposition in the region (Dixon, 1993). Late Cretaceous to Cenozoic deformation in the Eagle Plain region produced northerly trending structures, related to the eastward convergence of Arctic Alaska, coincident with easterly trending structures, related to the northward progression of Cordilleran deformation. Their trends preserve indicators of mutual interference, demonstrating coincident structural evolution in the southwestern part of the Eagle Plain Basin (Lane, 1998). This deformation culminated in Paleogene time with intense deformation prograding northward onto the Beaufort Sea shelf (Lane and Dietrich, 1995; Lane, 2004, 2014).

STRATIGRAPHY AND DEPOSITIONAL SETTING

Overviews of the regional stratigraphy of northern Yukon, and the Eagle Plain–Peel Plateau area in particular, include multiple contributions for Proterozoic and younger successions in Norris (1997b), as well as by Morrow (1999) for lower Paleozoic successions, Dixon (1998) for Permian and Triassic successions, and Dixon (1992) for Cretaceous successions of the Eagle Plain Basin; additional earlier publications are cited in these works.

Cretaceous stratigraphy in the Eagle Plain Basin was described by Mountjoy (1967), who defined the Eagle Plain Formation and measured its type section on Fishing Branch River (section 116J-2, Norris, 1981a). The measured section comprises a total of 1067 m, including 389 m of shale, siltstone, and sandstone, overlain by 678 m of well-exposed sandstone units interbedded with (largely covered) shale and siltstone. Only this upper unit was defined as the Eagle Plain Formation, with the formation's base located within the uppermost 40 m of the high river bluff at the base of the section. Subsequently, Dixon (1992) reviewed the expansion of its usage through time and redefined the unit as a group comprising four mappable units previously utilized in the regional mapping (e.g. Norris, 1981a). The upper three formations (Fishing Branch, Burnthill Creek, and Cody Creek) correspond to the map units used by Norris; however, Dixon divided Norris' Kwr unit into the Parkin and Whitestone River formations, with only the former being included as the basal formation of the Eagle Plain Group (Fig. 4).

The following formation definitions are summarized from Dixon (1992):

- Parkin Formation: A shale-dominant section, of Cenomanian age and marine-shelf setting, lies with abrupt unconformity on the Whitestone River Formation and grades upward into the Fishing Branch Formation. A basal transgressive sandstone member is prominent (type section: log depths 548.6–697.4 m in exploration well West Parkin YT C-33).
- Fishing Branch Formation: This interbedded sandstone, siltstone, and shale unit deposited in a westerly deepening, storm-dominated shelf setting has a gradational basal contact and an abrupt upper contact. A Cenomanian age was suggested, but the unit was not definitively dated (type section: log depths 484.6–548.6 m in exploration well West Parkin YT C-33).
- Burnthill Creek Formation: This poorly exposed shale-dominant succession contains thin sandstone beds. It has an abrupt lower contact and an upper contact that is defined as the base of the first prominent sandstone and may be abrupt locally. The latter is considered a facies boundary because it may occur at different stratigraphic levels across the basin. The depositional setting is marine, though uppermost beds may be nonmarine in the south (type section: log depths 485.5–676 m in exploration well West Parkin YT D-51).
- Cody Creek Formation: This succession of thick, well-exposed sandstone units, commonly pebbly or conglomeratic in the south and interbedded with recessive shales, is the uppermost unit in the Eagle Plain Group; thus, an upper contact is not defined. Although largely removed by erosion, its thickest remnants are in the southern part of the basin. The depositional setting is interpreted to be predominantly nonmarine in the south, but marine in the northwest (type section: from surface to log depth 485.5 m in exploration well West Parkin YT D-51).

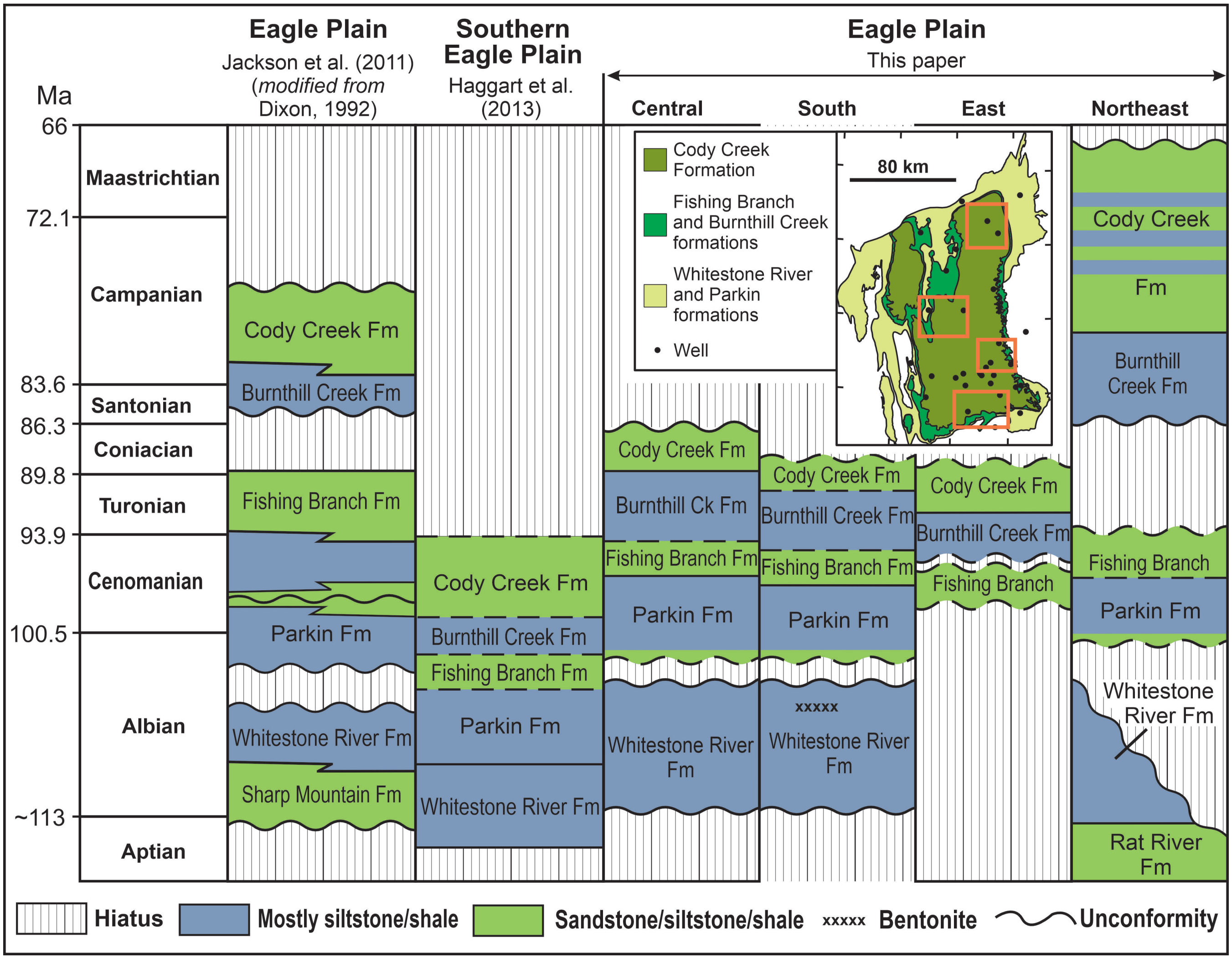

Figure 4. Recent interpretations of the lithostratigraphy of the Eagle Plain Basin. Variations in thickness and age distribution occur across the basin. The four columns under the 'This paper' heading refer to parts of the basin where data exist to suggest meaningful constraints on the unit ages. The four areas outlined in red on the inset map (*compiled from* Norris, 1985; Lane, 2013c; L.S. Lane, unpub. data) correspond to the columns. Whitestone River Formation strata are preserved in the south and northeastern parts of the basin but are absent along much of its eastern margin. Unit boundaries are solid where some data, typically biostratigraphy, constrain its approximate position, and dashed where speculative. The unconformity at the top of each column refers to the present-day erosion surface and not original extents. Thermal maturation data (e.g. Link and Bustin, 1989; Reyes et al., 2013; L.S. Lane, unpub. data) indicate that 3–4 km of strata have been removed since Cretaceous time in most areas. In the northeast, the unconformity at the base of the Parkin Formation has removed much of the Whitestone River Formation so that it locally lies directly on Rat River strata.

Recent results support and expand on previous interpretations of the Eagle Plain Group as being deposited principally in a marine-shelf setting. Evidence of a marine-slope setting for the Parkin formation has been documented in the western part of the basin (Jackson et al., 2011; Jackson, 2012). Well and surface sections tend to support a generally northwesterly thickening trend for the Eagle Plain Group as a whole (Dixon, 1992; Jackson, 2012). The Fishing Branch Formation preserves evidence of a nonmarine setting in the southeast (Jackson, 2012), whereas the Cody Creek is largely nonmarine except toward the northern part of the basin (Dixon, 1992; Bell, 2018).

AGE AND EVOLUTION OF THE EAGLE PLAIN BASIN

In his bulletin defining the Eagle Plain Group, Dixon (1992) noted the scarcity of age-diagnostic taxa, the prevalence of reworking, and the poor preservation of recovered fossils, in contrast to the underlying Whitestone River Formation. There, an Albian age was reliably established, based on abundant foraminifera and locally on macrofossils. On the basis of the available data, he inferred a Cenomanian age for the Parkin and Fishing Branch formations, the former being the only reliably dated unit in the group. A possibly

Turonian to Santonian age was inferred for the Burnthill Creek Formation, and a Turonian to Santonian age was assumed for the Cody Creek Formation, although the presence of certain fossils suggested that a Cenomanian age was also possible (Fig. 4). Dixon further proposed their correlation with the Cenomanian–Turonian Boundary Creek and Santonian–Campanian Smoking Hills sequences in the Mackenzie Delta region. However, such a correlation requires assumptions about regional stratigraphic sequences, the continuity of which has not been documented.

Haggart et al. (2013) reviewed archival and new macrofossil, foraminifera, and palynomorph age determinations from predominantly southern exposures to infer that all of the Eagle Plain Group is Albian to Cenomanian in age (Fig. 4). They also reviewed the evolution of nomenclature, as well as the progression of understanding of the age ranges of the units. However, several outcrops in their study are in poorly exposed areas, where unit contacts can only be approximated, and thus some units may be misidentified. Such issues further complicate any assessment of the age extent of the basin.

Quesnel et al. (2017) examined foraminifera from two wells, one in the northern part of the Eagle Plain Basin and the other toward the basin centre. Consistent with earlier interpretations, they concluded that the top of the Whitestone River Formation lies within the early late Albian; furthermore, they showed an abrupt disappearance of numerous foraminiferal taxa coincident with the upper contact of the unit, which is consistent with the interpretation of an unconformity. They also reported on a bentonite from within an outcrop of the Whitestone River Formation that yielded a thermal ionization mass spectrometry zircon age of 105.56 ± 0.25 Ma, thus placing a maximum limit on the age of the Eagle Plain Group in the southern part of the Eagle Plain Basin.

Bell (2018) examined the palynology of the Cody Creek Formation of the Eagle Plain Basin as part of a broader regional study extending to the adjacent Late Cretaceous–Paleogene Bonnet Plume Basin and the Brackett Basin of the southern Mackenzie Plain. She reiterated that the impoverished nature of the fossil assemblages and significant reworking of fossil material make age determinations and biostratigraphic correlations difficult. Strata from the Cody Creek Formation, the youngest unit in the Eagle Plain Group (Fig. 4), yields assemblages of six different ages: late Albian to Cenomanian (or younger), Turonian (or younger), mid-Coniacian (or younger), Santonian to (?)early Campanian, mid- to late Campanian, and late Maastrichtian. However, the assemblages proved difficult to correlate with previously established biozones due to limited diversity. They potentially correspond to zones 4, 5, 6, 7, and 10 of Nichols and Sweet (1993). Zones 4 to 7 span the Coniacian to earliest Maastrichtian (Bell, 2018, Fig. 6-3), and zone 10 is latest Maastrichtian in age (Nichols and Sweet, 1993).

The presence of Carboniferous spores and dinoflagellate cysts of Jurassic and mid-Cretaceous age in Cody Creek Formation strata indicates that Upper Cretaceous sediments in the Eagle Plain Basin are sourced, at least in part, from Carboniferous, Jurassic, and mid-Cretaceous sedimentary rocks (Bell, 2018). This is consistent with earlier findings from the underlying units (Dixon, 1992).

Strata from the northern part of the Eagle Plain Basin (Bell Basin) produced younger biostratigraphic ages than the southern part of the basin, with intermediate ages characterizing the central part of the Eagle Plain Basin. This trend suggests that either deposition of Upper Cretaceous strata was time transgressive from south to north, supporting the interpretation of a prograding foredeep deposit adjacent to the rising Cordillera (Dixon, 1992; Bell, 2018) and/or that older, recycled palynomorph populations completely dominate the assemblages in southern parts of the basin and that in situ taxa are extremely scarce or absent (J. Dixon, pers. comm., 2019).

In their overview of the Eagle Plain Basin, Lane et al. (2021) illustrated key aspects of the spatial and temporal ranges of the Eagle Plain Group. Current understanding of the regional variations is represented in Figure 4, in which specific areas with some local age control are highlighted. Two ongoing issues complicate the assignment of ages to the Eagle Plain Group. First, generally poor exposure and shallow bedding dips contribute to the difficulty in assigning isolated outcrops to specific units. Second is the challenging process of finding, identifying, and dating various flora and fauna in rocks where recovery, preservation, and taxonomic diversity are poor, and where the recovered fossils are commonly dominated by recycled older taxa. Also, wells typically provide useful sources of biostratigraphic information; however, the prevalence of recycling is further complicated by the potential occurrence of cavings from higher units in the well.

More recently, detrital zircon (DZ) analyses, together with petrographic descriptions of various sandstone outcrops from the Eagle Plain Group, have shown some promise in determining maximum depositional ages and in distinguishing units, providing useful information where biostratigraphy is unavailable or uncertain. In one example, a Cody Creek sandstone was found to contain a late Albian zircon population, inferred to be derived from Cordilleran magmatism farther south (e.g. Haggart et al., 2013; L.S. Lane, unpub. data). In additional DZ samples processed to date, those with Cretaceous populations appear to cluster around a few specific ages, which suggests that the young age clusters reflect resedimented ash-derived grains originating from one or more distinct Cordilleran arc-related magmatic events in the 110 to 90 Ma range (Mortensen et al., 2000) but are not necessarily similar to the depositional ages of the sandstone units. The stratigraphic chart in Figure 4 incorporates both biostratigraphic and zircon evidence to estimate the age and spatial distribution of the Cretaceous succession across the Eagle Plain Basin. Detailed results will be presented in future publications. However, available DZ data (L.S. Lane, unpub. data) demonstrate that significant thicknesses of Eagle Plain Group strata are younger than Cenomanian (Fig. 4), refuting the hypothesis of Haggart et al. (2013) that the entire succession in the southern part of the Eagle Plain Basin is restricted to the Albian and Cenomanian.

Studies by Jackson (2012) and Bell (2018) have led to a better understanding of the basin's evolution, and further publications based on these results are in preparation. In particular, these new results lend support to the concept of a westward thickening of the units, combined with new evidence for slope-facies depositional environments in the same direction for the Parkin Formation (Jackson, 2012). Also, in paleontological studies, the common occurrence of recycled taxa provides potentially valuable clues to the provenance of the sediment. For example, Bell (2018) speculated that the Ogilvie Mountains could be the source of reworked Carboniferous spores. Reworked mid-Cretaceous dinoflagellates have ages and paleogeographic positions consistent with derivation from sources in the Whitestone River or Parkin formations. Other reports cite common Permian, Triassic, and Jurassic taxa as well as Carboniferous taxa in the Parkin Formation.

THERMOTECTONIC EVOLUTION

Understanding the history of sedimentation/burial and tectonism/uplift in a sedimentary basin requires a multidisciplinary approach that incorporates regional mapping and structural analysis, biostratigraphy, organic petrology, and thermal history to quantify the time-temperature path of any stratigraphic interval. This information is critical for syntheses of regional tectonic models, and it is also relevant information for the assessment of a basin's petroleum potential.

An important parameter in understanding tectonic history, as well as the hydrocarbon resource potential in any region, is the peak temperature encountered, using organic petrology. Hundreds of outcrop localities with new vitrinite-reflectance data, as well as new data from existing petroleum exploration wells, have created a more comprehensive regional overview of thermal-maturation patterns across the northern Yukon region (Allen et al., 2011, 2015; Fraser et al., 2012; Reyes et al., 2013). A new database of these findings has been compiled and will form the basis of future publications. Some key findings pertain to the wide extent of the regional burial/heating history prior to Paleogene exhumation. These data also provide a vital geological constraint for apatite fission-track modelling.

Multikinetic apatite fission-track (MK-AFT) thermochronology is a powerful technique for reconstructing the low-temperature (<200°C) thermal history of sedimentary basins within the upper 2 to 6 km of the Earth's crust. It exploits the composition-dependent temperature sensitivity of AFT parameters to resolve more details of the thermal history than conventional methods. New methods of data interpretation and modelling previously developed at GSC Calgary, and further refined and tested during the GEM program, are currently being applied to samples from the project area, where multicompositional detrital apatite grains are common in many of the sandstone units. The MK-AFT method can resolve multiple thermal events because it treats different apatite compositional groups as separate thermochronometers that are sensitive to different parts of the thermal history. The goal of this activity is to acquire regional high-resolution thermochronology data to constrain the burial/exhumation and thermal history of the basin. The MK-AFT samples from this region resolve multiple thermal events that occur between 50°C and 200°C, a temperature range that encompasses petroleum-generation reactions and certain mineralization processes (Issler and Lane, 2016; Issler et al., 2021, 2022).

Publications describing the thermotectonic evolution of several transects through the project area are in preparation. Results thus far show that at least two distinct heating/cooling cycles can be distinguished by the AFT data. The first is related to latest Devonian and early Carboniferous burial of a continental margin by the northerly derived Ellesmerian Orogen clastic wedge (e.g. Lane, 2007), followed by exhumation. Subsequent mid- to Late Cretaceous reburial by Cordilleran clastic detritus (i.e. Eagle Plain Group) was followed by Paleogene to recent exhumation (Issler and Lane, 2016; Issler et al., 2018, 2022).

Published interpretations of the paleogeography of the Cretaceous Eagle Plain Group infer a dominant northward sediment transport into the basin, derived from the rising Cordillera in the south; however, thicknesses of the Parkin through Burnthill Creek strata tend to increase toward the west (e.g. Dixon, 1992; Jackson, 2012). The thermochronology results suggest that some sediment also was sourced from the rising Richardson Mountains in the east and that the basin hingeline probably lay approximately along the eastern limit of preserved Cretaceous strata.

PETROLEUM POTENTIAL

Hannigan (2014), in a new petroleum resource appraisal utilizing GEM data and publications, noted that new petroleum exploration-play concepts not previously defined required a reassessment of the basin's conventional hydrocarbon potential. In this new report, he also considered a qualitative assessment of the unconventional oil and gas potential, which had not previously been considered. He concluded that the basin's total oil and gas potential is 52.2×10^6 m^3 (329 MMB) of oil and 96.7×10^9 m^3 (3.4 TCF) of gas (in-place mean volumes), including discovered reserves of 3.2×10^6 m^3 (20 MMB) of oil and 4.6×10^9 m^3 (165 TCF) of gas; furthermore, he also concluded that 94% of the oil and 95% of the gas resource remain to be discovered.

In a separate scoping-study report on unconventional oil and gas potential in Yukon, Hayes and Archibald (2012) investigated eight prospective basins, including the Eagle Plain Basin. There, the prospects for tight reservoirs and shale reservoirs were considered. They concluded that tight-reservoir petroleum systems, primarily for gas, exist in Paleozoic carbonate rocks and in the Late Devonian Imperial Formation underlying the basin. Also, based on Jackson et al. (2011), they interpreted potential tight-gas targets in isolated sandy mass-transport deposits in the Cretaceous section in the northwestern part of the basin. Hayes and Archibald (2012) also concluded, based on Fraser et al. (2012), that early Paleozoic, Devonian, Carboniferous, and Cretaceous shale units all presented tight-reservoir potential under appropriate maturation conditions. As part of their analysis, Hayes and Archibald also considered new Rock-Eval geochemistry from existing wells (Lane et al., 2010), and high-resolution aeromagnetic data from a survey flown over the basin in 2009, the results of which were released as a suite of 14 GSC Open File maps in 2010 (e.g. Kiss, 2010).

IMPACTS

In the Yukon, active petroleum leases exist only in the Liard and Eagle Plain basins. There, new surface and subsurface data provide important additions to existing geochemistry, biostratigraphy, and thermal-maturation data (e.g. Lane et al., 2010; Obermajer et al., 2012; Reyes et al., 2013). These new data address a key outcome of the project: that greater accessibility of data will motivate the private sector to invest in exploration. In addition, new bedrock maps have begun to provide current, more-precise delineation of the distribution of map units as a basis to interpreting the analytical data (e.g. Lane, 2013a, b, c, 2017; Fallas et al., 2014). Also, a petroleum-exploration company recently invested $120 million to conduct a drilling program and a three-dimensional seismic survey in the Eagle Plain Basin (Appendix B). The GEM Yukon Basins project was acknowledged in the decision to invest there, based on various publications and presentations and GSC's participation in stakeholder workshops. Activities conducted in the Vuntut Gwitchin First Nation settlement region included extensive involvement of community members as integral members of the field team. Also, collaborations with the University of Calgary and Carleton University led to the completion of five undergraduate and five graduate thesis projects (Appendix A).

DISCUSSION

Reliable biostratigraphy underpins most other research activities in sedimentary basins. Accordingly, biostratigraphy continues to be a major focus of Yukon basins research. Some 50 internal paleontology reports, most of which focused on the Eagle Plain Basin, its margins, and adjacent basins, were produced during GEM (Appendix A). Historical and ongoing issues such as uncertain stratigraphic positions of some isolated outcrops, revisions to stratigraphic nomenclature over time (Dixon, 1992), and poorly resolved or conflicting age determinations from adjacent, or even individual, outcrops have resulted in conflicting age assessments for the Eagle Plain Group (e.g. Dixon 1992; Haggart et al.; 2013, McNeil et al., 2021). Also, progressive losses of paleontological capacity significantly impacted the analysis of processed samples and the assessment of stratigraphic ranges. Although numerous new fossil localities were established, from both outcrops and well samples, the units' age distributions continue to be debated.

A paucity of reliable biostratigraphy continues to hinder understanding of the Eagle Plain Basin's depositional history. Previous lack of areal coverage, together with issues of recycling, impoverished taxa, and poor stratigraphic definition, led to past interpretations of unit ages that relied on various assumptions and considerations: 1) conflicting age assignments derived from differing fossil types; 2) distinguishing between those taxa that may be recycled and those that are in situ; and 3) determining whether various unconformities correlate and, if so, how (e.g. Dixon, 1992; Jackson et al., 2011; Haggart et al., 2013; Quesnel et al., 2017; McNeil et al., 2021). These have led to conflicting interpretations of unit ages, with significant implications for regional paleogeographic reconstructions.

Despite these ongoing challenges, broader geographic coverage of sampling, and new paleontology data, together with advances in detailed mapping, more-precise positioning of outcrop locations, local availability of interpretable seismic-reflection data, and a much-improved understanding of the Cretaceous thermotectonic history have somewhat mitigated the biostratigraphic impediments to understanding the basin's history.

The best-understood part of the basin is in the northeast (Fig. 4), where intensive sampling of archival seismic-shot-hole cuttings for palynology and foraminifera (Bell, 2018), and reanalysis of well-cutting samples (D.H. McNeil, unpub. GSC Paleontological Report DHM-2018-7, 2018) provide sufficient data to constrain the Santonian to Maastrichtian ages of the Burnthill Creek and Cody Creek formations in that area. Although the ages of the Parkin and Fishing Branch formations remain poorly understood, nearby mapping (Lane, 2017) and seismic interpretations (L.S. Lane, unpub. data) indicate that the unconformity at the base of the Parkin Formation is characterized by progressive erosional downcutting through the Whitestone River Formation.

The thinnest section is preserved in the eastern margin of the basin, in the vicinity of the Dempster Highway (Fig. 4). There, a transgressive sandstone lies directly on Carboniferous Hart River Formation and is overlain by approximately 200 m of poorly exposed shale, within which is a roadside quarry exposing sandstone. A short distance above this isolated sandstone is the base of the Cody Creek

Formation. The shale-dominant unit below the Cody Creek is interpreted as an abbreviated thickness of Burnthill Creek Formation, and the basal transgressive sandstone is attributed to the Fishing Branch Formation, which is consistent with regional reconnaissance mapping (Norris, 1981b). In this location, the sandstone in the Burnthill Creek Formation can be no older than earliest Turonian, based on detrital zircon populations. Therefore, some of the Burnthill Creek and all the overlying Cody Creek Formation must be Turonian or younger; their actual age range is possibly much younger. The Cody Creek Formation in the Ellen YT C-24 well, 55 km to the northwest in the central part of the Eagle Plain Basin (Fig. 4), is Coniacian, and the upper 271 m is no older than mid- to late Coniacian (Bell, 2018), which plausibly places an approximate upper limit on the remnant section at the eastern margin of the basin. The age of the underlying Fishing Branch basal transgressive sandstone is unconstrained. The truncated section at this locality appears to be typical of much of the eastern margin of the basin, reflecting its position close to the basin hinge line, to the east of which relatively little Late Cretaceous subsidence occurred.

A Coniacian age for the Cody Creek Formation in the Ellen YT C-24 well also provides an apparent local upper bracket to the preserved Cody Creek Formation in the central part of the basin (Fig. 4). However, if the taxa are recycled, the actual age could be younger. Also, a section of Parkin Formation to the west of this area is dated by palynology as being constrained to the Cenomanian (D.J. McIntyre, unpub. rept.,1987); however, the base of the unit is not exposed there and so its lower age extent is not constrained. Accordingly, the Burnthill Creek Formation in this area is constrained between the late Cenomanian and earliest Coniacian. In addition to previously noted complications related to recycling and impoverished taxa, age assessments in this part of the basin are further complicated by poor exposure, variable character and thickness of units, and the presence of local faults. In addition, positioning accuracy for some archival fossil localities may be approximate. Accordingly, conflicting age assessments that apparently refer to individual outcrops are more common in this area. Analysis of the existing information requires careful attention to the full range of uncertainties inherent in the various floral and faunal assessments, as well as the stratigraphy, structure, and locational accuracy.

In the southern part of the Eagle Plain Basin, documentation of a 105.6 Ma bentonite within the Whitestone River Formation requires that this unit extend significantly into the late Albian in this area. This finding precludes a middle to early late Albian age for the unconformably overlying Parkin formation (Quesnel et al., 2017). Palynology results for the Parkin Formation include multiple localities where taxa constrain the age within the Cenomanian, along with dominant abundances of reworked older taxa in many of the localities studied (e.g. D.J. McIntyre, unpub. rept., 1987). Furthermore, in the Monster Formation exposed in an adjacent, more proximal Cordilleran foreland basin, to the southwest of the Eagle Plain Basin, a Cenomanian age is documented (Ricketts, 1988). There, the Monster Formation lies unconformably on Triassic and Paleozoic strata, and Albian-age rocks are absent. The taxa used to constrain a Cenomanian age for the Monster Formation are the same as those found in the Parkin Formation. Accordingly, a categorical rejection of a Cenomanian age for the unit (e.g. Haggart et al., 2013; Quesnel et al., 2017) is precluded.

CONCLUSIONS

In accordance with the initial objectives of the project, 32 new framework geological maps have been produced, with others in preparation. New energy resource assessments of the project area have defined new energy plays. Also, publication of new and archival analytical data has encouraged new economic activity and the employment of northerners.

Recognition of the complexity in the biostratigraphy of the Eagle Plain Basin can be considered as significant progress in its understanding, which will lead to more-refined models of the basin's depositional history and paleogeographic context. Important progress has also occurred during the GEM program in the areas of mapping, geochemistry, and thermotectonic evolution, which have had a demonstrable impact on the prospectivity and exploration activity in the basin.

Significant advances were made in understanding the age and depositional history of the Eagle Plain Group during GEM. However, the analysis and synthesis of the substantial body of new and archival biostratigraphic results are ongoing. Unlike the underlying Whitestone River Formation, which has been reliably dated by multiple criteria as being Albian in age where present beneath the Eagle Plain Basin, the age ranges of the overlying strata continue to be a topic of debate. Recycled taxa clearly dominate in situ taxa at most localities and must be considered when age ranges are assessed.

Although a Cenomanian age is generally valid for the Parkin Formation, the hypothesis that it may plausibly extend downward into the latest Albian has not been ruled out, particularly in the western (deeper) parts of the basin. Age interpretations older than latest Albian are effectively precluded in light of an early late Albian bentonite age within the underlying Whitestone River Formation. Few definitive age assignments exist for Fishing Branch Formation strata. Where such data do exist, in the southwestern part of the basin, a Cenomanian age is indicated. Locally, even its identification in the field is unreliable due to poor exposure and local faulting. Given its previous interpretation as a transgressive unit, its age range may prove to be time transgressive. The Burnthill Creek and Cody Creek formations must be time transgressive across the basin, based on the age assignments currently available from the Burnthill Creek Formation in the northeast and the Cody Creek Formation in the central part of the basin (Fig. 4).

The surface and subsurface mapping, together with the thermochronology and detrital zircon geochronology results, provides important constraints on the paleogeographic setting of the Eagle Plain Basin. Details of these results are in preparation for future publication. However, the lithostratigraphic columns (Fig. 4) reflect current understanding of the basin's evolution through the Late Cretaceous.

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Appendix A

Summary of GEM Yukon basins publications

The publications produced from 2009 to 2019 for the Yukon Basins project area are summarized in this appendix. Many of the products were initiated and/or produced through the GEM Yukon Basins project, but many were completed under successor GEM projects. These publications pertain directly to the geological evolution of Yukon's sedimentary basins and are relevant to their economic potential. Additional publications are in preparation. Most products reflect activities in the Eagle Plain, Bonnet Plume, and Peel basins, with additional contributions from the Liard Basin, Whitehorse Trough, and North Slope–Mackenzie Delta area.

Maps (46):

- Surficial geology, 16
- Bedrock geology, 16
- Potential field, 14

Books, chapters, and refereed journal papers (29):

- Paleontology, 11
- Geochronology and detrital zircon, 6
- Regional geology and tectonics, 4
- Petroleum geology and basin analysis, 3
- Stratigraphy and sedimentology, 3
- Seismic interpretation, 1
- Surficial geology, 1

Open File reports (22):

- Geochemistry, 6
- Thermochronology–geochronology, 5
- Petroleum geology, 4
- Surficial, 4
- Tectonics, 2
- Outreach, 1

Paleontology reports: 51

Theses: Ph.D., 2; M.Sc., 3; B.Sc., 5

Other publications: 16

Presentations: posters, 32; oral, 27

Appendix B

Major economic impacts of GEM activities in the Yukon

When the GEM program began, Northern Cross (Yukon) Limited was developing a new exploration program on approximately 1 300 000 acres under lease in the Eagle Plain. Publications produced under the GEM program in 2010 and 2011 (e.g. Lane et al., 2010; Allen et al., 2011), as well as presentations by T.L. Allen, T.A. Fraser, and L.S. Lane at conferences attended by Northern Cross (e.g. Lane, 2010), were relevant in this decision being taken. In late 2011, their exploration program was facilitated when the China National Offshore Oil Corporation (CNOOC) invested \$115 million in Northern Cross (Davidson, 2012). The funds were used to conduct a four-well drilling program in the 2012–2013 season and a 325 km^2 three-dimensional seismic survey in 2013–2014, at an estimated total cost of \$120 million (Tobin, 2014). Northern Cross acknowledged the role of the GEM Yukon Basins project in CNOOC's decision to invest in Northern Cross and their exploration program, citing in particular Open File 6652 (Lane et al., 2010), various presentations, and GSC's participation in stakeholder workshops.

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