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Research paper

Upper Paleozoic hydrocarbon systems in the Sverdrup Basin, Canadian Arctic Islands

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ABSTRACT

The upper Paleozoic (Carboniferous to Permian) succession of the Sverdrup Basin in the Canadian Arctic Islands has the potential to contain significant hydrocarbon reserves, though it has never been a primary exploration target. To better constrain previous estimates and hydrocarbon play possibilities, this study completed evaluations of source rock quality and extent and thermal maturity. This study also incorporated new understandings of reservoir units and their stratigraphic relation to source rocks, trapping configurations and timing of hydrocarbon migration. Several hydrocarbon source units were identified within the upper Paleozoic formations of the Sverdrup Basin including the Emma Fiord, Trappers Cove, Antoinette, Assistance, Sabine Bay, van Hauen and Trold Fiord formations. The Emma Fiord and Trold Fiord formations are both found to be oil prone, with the remainder of the sources being gas prone. The upper Paleozoic succession is interpreted to be gas prone due to dominant kerogen types and high average thermal maturity. Many of the older concept plays put forth for the upper Paleozoic succession have been determined to be unviable. However, modern plays that implement new understandings of the basin have the potential to be viable. This study has found that the upper Paleozoic succession of the Sverdrup Basin is promising for gas discoveries with new plays such as salt diapirism plays, or plays similar to the Barents Sea Gohta play. New hydrocarbon rock source data also suggests the potential for a new oil and gas play on northern Prince Patrick Island. This new research could lead to significant resource discoveries that have been previously overlooked.

1. Introduction

Exploration for hydrocarbons in the Canadian Arctic Islands began during the 1960s and continued until 1986 with over 120 wells drilled (Rayer, 1981; Embry and Beauchamp, 2008) and acquisition of over 90,000 line km of seismic (Harrison, 1995). Several noteworthy discoveries were made during this period, the majority of which are natural gas hosted in structural traps within Mesozoic strata (Chen et al., 2000). The upper Paleozoic (Carboniferous and Permian) succession was not the primary exploration target, and only 42 of the wells drilled in the Sverdrup Basin penetrate upper Paleozoic strata, and most of these are along the basin edge. No significant hydrocarbon discoveries have been made within the upper Paleozoic section, though the presence of hydrocarbons was noted in many localities.

In their assessment of hydrocarbon resources of the Sverdrup Bain, Embry et al. (1983) stated that the upper Paleozoic section contains an average expectation of 39.9 TCF of gas and 844 MBbls of oil. These values were determined from the expected reservoir characteristics of 11 conceptual hydrocarbon plays within the upper Paleozoic section. Rock units with observed porosity, or which could potentially have porosity, such as sandstones, debris flows, shelf margin and reefal carbonates, were assessed as conceptual plays. However, the authors had very limited data on hydrocarbon source rocks or thermal maturity, and stratigraphic relationships were incompletely understood at that time.

This study uses a petroleum systems approach which considers source rock; thermal maturity, reservoir units and their stratigraphic relation to source rocks, trapping configuration, and their relation to timing of hydrocarbon migration, and preservation (e.g., Magoon and Dow, 1994). Recently acquired geochemical and geological data create an opportunity to assess the viability of previously proposed plays, especially on the basis of source rocks and hydrocarbon charge and to propose new conceptual plays.

2. Geological setting

The Sverdrup Basin is a major depocentre located in the Canadian Arctic Islands (Fig. 1). It covers over 300,000 km^2 of the northern

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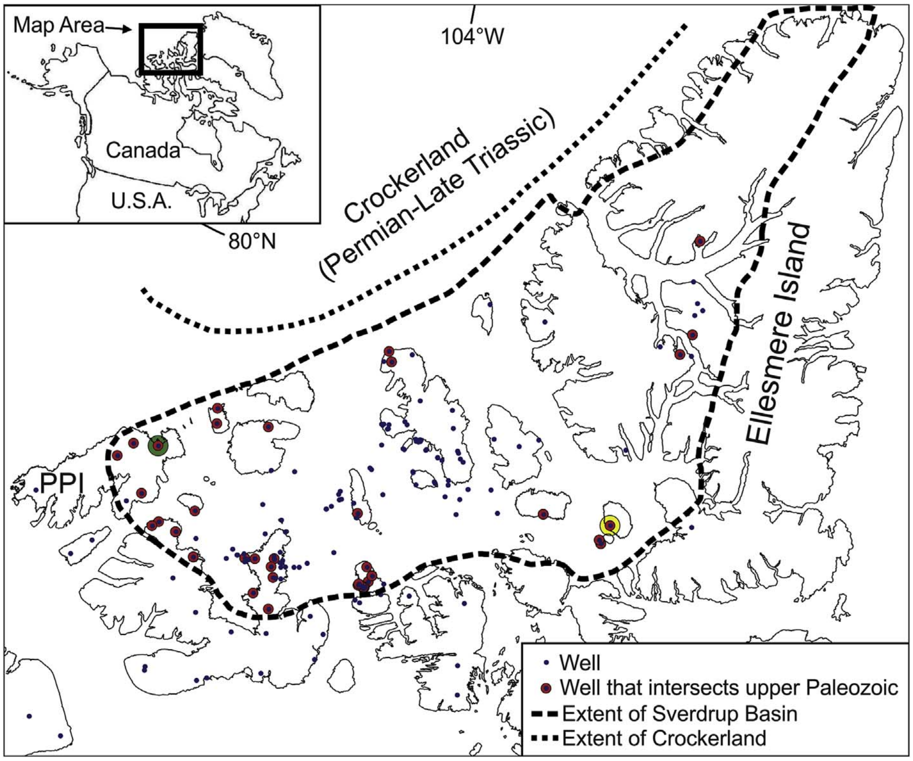

Fig. 1. Outline of the Sverdrup Basin with wells (Wells outlined in red penetrate upper Paleozoic strata; green indicates the Satellite F-68 well and yellow indicates the Graham C-52 well; PPI = Prince Patrick Island).

portion of the Arctic Archipelago from Ellesmere Island in the northeast to Prince Patrick Island in the southwest (Embry and Beauchamp, 2008). The basin contains up to 13 km of upper Paleozoic to Paleogene strata. The Sverdrup Basin is a rift basin that formed on the northern side of the Laurussia paleocontinent. It was bounded to the north by a landmass (Crockerland; modern Arctic Alaska and Chuckhi) during the late Paleozoic and Triassic (Embry and Beauchamp, 2008) and intermittently connected at the northeastern end to Svalbard and the Barents Sea. Late Paleozoic palaeoceanographic conditions of the Sverdrup Basin were initially dominated by warm waters followed by a period of cooling starting around 295 Ma (Early Permian, Sakmarian), and increasingly acidic ocean conditions (Beauchamp and Grasby, 2012).

The Sverdrup Basin developed in 8 distinct phases starting in the Carboniferous and ending in the Paleocene (Stephenson et al., 1987; Beauchamp et al., 2000; Embry and Beauchamp, 2008; Hadlari et al., 2016; Midwinter et al., 2016) (Balkwill, 1978). Rifting occurred in three stages in Viséan to Bashkirian time, which was followed by (Beauchamp et al., 1989) passive subsidence in four stages with intermittent local uplift and fault-controlled subsidence in Early Permian time. Near the end of the Early Permian, a tectonic event known as the Melvillian Disturbance resulted in local volcanism, faulting, folding, and erosion with varying degrees of magnitude along the basin margin. Following this disturbance (Beauchamp et al., 1998), the basin underwent slow steady subsidence until the end of the Permian (Beauchamp et al., 2000). The Triassic brought in major changes in sedimentation rate and style with major clastic influx filling the central basin for the first time (Beauchamp et al., 2009). From Mid Triassic to Early Jurassic, high subsidence and low sedimentation resulted in accumulation of shale until the tectonic regime again shifted to (Beauchamp and Grasby, 2012) rifting in the Early Jurassic to Early Cretaceous. This return to extension and rifting significantly increased the subsidence rates in the Early Jurassic to Early Cretaceous culminating with a breakup unconformity in the Early Cretaceous as 'Crockerland' rifted away to form the Arctic Ocean (Beauchamp, 2016). The newly formed passive margin then shifted back to slow subsidence for the remainder of the Late Cretaceous. A substantial volcanic province was also active during the Cretaceous with periodic episodes of igneous intrusion and flows in the northeast section of the basin (related to the High Arctic Large Igneous Province; Buchan and Ernst, 2006) (Behar et al., 2001). Finally, regional rapid subsidence due to compressional loading in the NE part of the Sverdrup Basin, uplift and widespread deformation of the Eurekan Orogeny occurred throughout the Paleocene and Eocene (Embry, 1993). Since the Eocene, the basin has been under constant compression preventing further subsidence (Embry and Beauchamp, 2008). About 600 m of strata have been removed since the Eocene (Dewing et al., 2016).

Over 100 salt structures are present within the Sverdrup Basin cored by Upper Carboniferous evaporites (Thorsteinsson, 1974; Nassichuk, 1975). The timing for initiation of these structures is variable, commencing by at least the early Mesozoic in the western portion of the basin and the late Triassic in the east (Harrison, 1995; Harrison and Jackson, 2014).

Upper Paleozoic strata within the Sverdrup Basin are characterized by rift-related deposits followed by a shelf to deep basin succession that can reach thicknesses of up to 5 km in the centre of the basin (Embry and Beauchamp, 2008). The section contains 20 formations deposited from late Viséan to Lopingian; 347-252 Ma. The upper Paleozoic stratigraphy of the Sverdrup Basin can be broken into three first order tectonostratigraphic assemblages. For the purposes of this study, the third first order sequence has been split into two assemblages of second order sequences due to their hydrocarbon source potential (Fig. 2).

The first is the Viséan to Serpukhovian *early rifting assemblage* containing the Emma Fiord and Borup Fiord formations. The Emma Fiord Formation consists of a dark-coloured lacustrine shale, fluvial sandstone, and conglomerate which are locally found at the base of the succession. The Borup Fiord Formation comprises red-coloured conglomerates and sandstones of alluvial fan affinity. These formations are interpreted to record the onset of rifting (Emma Fiord) and early evolution (Borup Fiord) of the rift system (Embry and Beauchamp, 2008).

Next is the Bashkirian to Kungurian *late to post rift tectonics assemblage*. These include the Bashkirian basin-axial Otto Fiord Formation evaporites consisting of halite and anhydrite and coeval conglomerates of the Canyon Fiord Formation (Lower clastic member; Beauchamp et al., 1989), both of which recorded the last phase of rifting in the