Subsurface Aquifer Study to Support Unconventional Oil and Gas Development, Liard Basin, Northeastern British Columbia (NTS 094J, K, N, O)

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Introduction

The Liard Basin in northeastern British Columbia is highly prospective for unconventional gas and oil development (Figure 1). Stacked, regionally extensive, unconventional reservoirs have great potential for long-term development, which will eventually encompass large continuous areas. Validation of this potential in northeastern BC occurred in 2012, when both Apache Corporation (Apache) and Paramount Resources Ltd. announced major shale gas discoveries in the Liard Basin (Macedo, 2012; Adams, 2013).

Industry has had great success in developing unconventional reservoirs elsewhere in northeastern BC using horizontal wells stimulated by multiple hydraulic fractures, or frac jobs. Each frac requires large amounts of water, depending upon the particular frac design. Stimulated reservoirs eventually flow back much of the frac fluid, contaminated by various chemicals used in the frac process and by naturally occurring materials from the reservoir. Companies developing unconventional hydrocarbon resources thus require water sources capable of delivering large water volumes at high rates, and water disposal zones capable of accepting comparable volumes and rates.

Although surface water or shallow aquifers may be suitable locally for source water, deeper aquifers with brackish or saline waters offer options to avoid conflicts with other water consumers and possible negative environmental impacts. In addition, only deep subsurface aquifers are suitable for water disposal, to avoid contamination of potable water supplies at surface or in shallow aquifers.

Petrel Robertson Consulting Ltd. (PRCL) has recently completed a comprehensive six-month study of deep subsurface aquifers in the Liard Basin for Geoscience BC, in support of systematic sourcing and disposal of frac waters for unconventional hydrocarbon development.

Keywords: *Liard Basin, shale gas, aquifer, Bovie fault zone, Mattson Formation, Fantasque Formation, Rundle Group, Dunvegan Formation, Chinkeh Formation*

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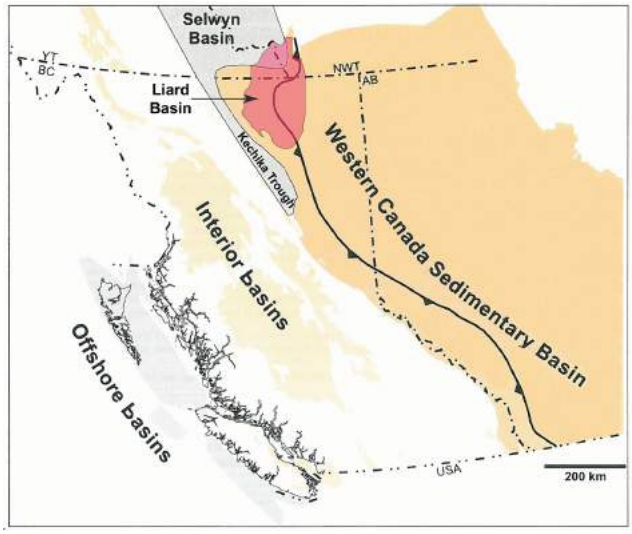

Figure 1. Liard Basin, northeastern British Columbia (from Ferri et al., 2011).

Regional Setting

The Liard Basin is a structurally bounded segment of the Western Canada Sedimentary Basin in northeastern BC, and extends into the Northwest Territories and Yukon (Figure 1). It hosts a relatively undeformed sedimentary section measuring several thousand metres thick (Figure 2). Morrow and Shinduke (2003) described the Liard Basin as a late Paleozoic and Cretaceous depocentre bounded on the east by the Bovie fault zone, along which several stages of movement have occurred. Extensional faulting during the Carboniferous and Early Cretaceous provided accommodation space for abrupt westward thickening of the Upper Carboniferous (Mattson Formation) and Cretaceous sections (Figure 2). Morrow and Shinduke (2003) also noted at least two episodes of contraction during the late Paleozoic and the latest Cretaceous Laramide orogeny, both of which contributed to structural complexity and conventional hydrocarbon trapping opportunities in the Bovie fault zone. Structural elevations drop 1000 m or more from east to west across the highly complex Bovie fault zone, which cannot be adequately characterized without detailed seismic control (McLean and Morrow, 2004).

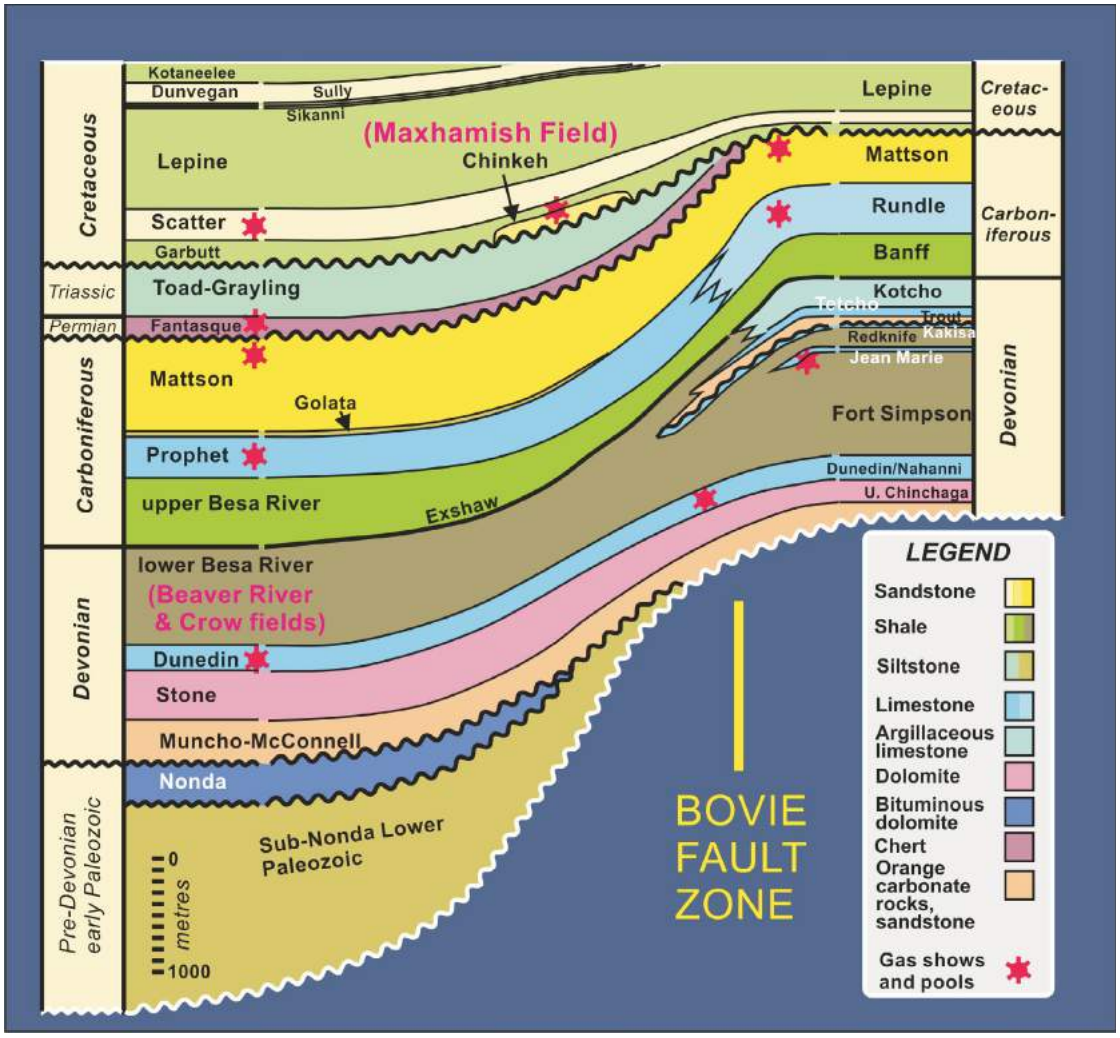

Figure 2. Schematic west-east cross-section, Liard Basin, northeastern British Columbia (from Morrow and Shinduke, 2003; published with permission of the Canadian Society of Petroleum Geologists).

Study Methodology

Relevant well data were collected across aquifer intervals from public and proprietary sources and supplemented with regional geological mapping and information from outcrop. Consistent regional correlations were created by constructing a grid of regional stratigraphic cross-sections tied to core and sample cuttings data; these formed the foundation for picking a stratigraphic database focused on potential aquifer intervals.

Regional gross isopach maps of each potential major aquifer unit were produced, and net porous reservoir isopach maps were prepared where sufficient supporting data could be assembled. Hydrogeological characterization was undertaken, drawing on a well test database comprising 256 tests from 157 well entities. Formation permeabilities and reservoir pressures were interpreted from drillstem tests screened for adequate data quality. Pressure-elevation graphs were used to characterize regional aquifer systems. Formation water samples from drillstem test recoveries were geochemically analyzed and the data summarized for each regional aquifer unit.

Mattson Formation

Four aquifer intervals were investigated in detail: Mississippian platform carbonate rocks (comprising the Rundle Group, including the Debolt Formation; the younger Fantasque Formation is included in this aquifer interval as well), Mattson Formation sandstone, Lower Cretaceous sandstone (Chinkeh and Scatter formations) and Upper Cretaceous Dunvegan Formation sandstone and conglomerate (Figure 2).

Geological mapping in the Liard Basin is constrained by scarce and irregularly distributed well control (see Figure 3). Regional stratigraphic cross-sections demonstrate that major stratigraphic units can be carried across the basin, but that finer scale subdivisions are difficult to correlate between widely spaced wells. Abrupt thinning of the entire section at the eastern margin of the basin near the Bovie

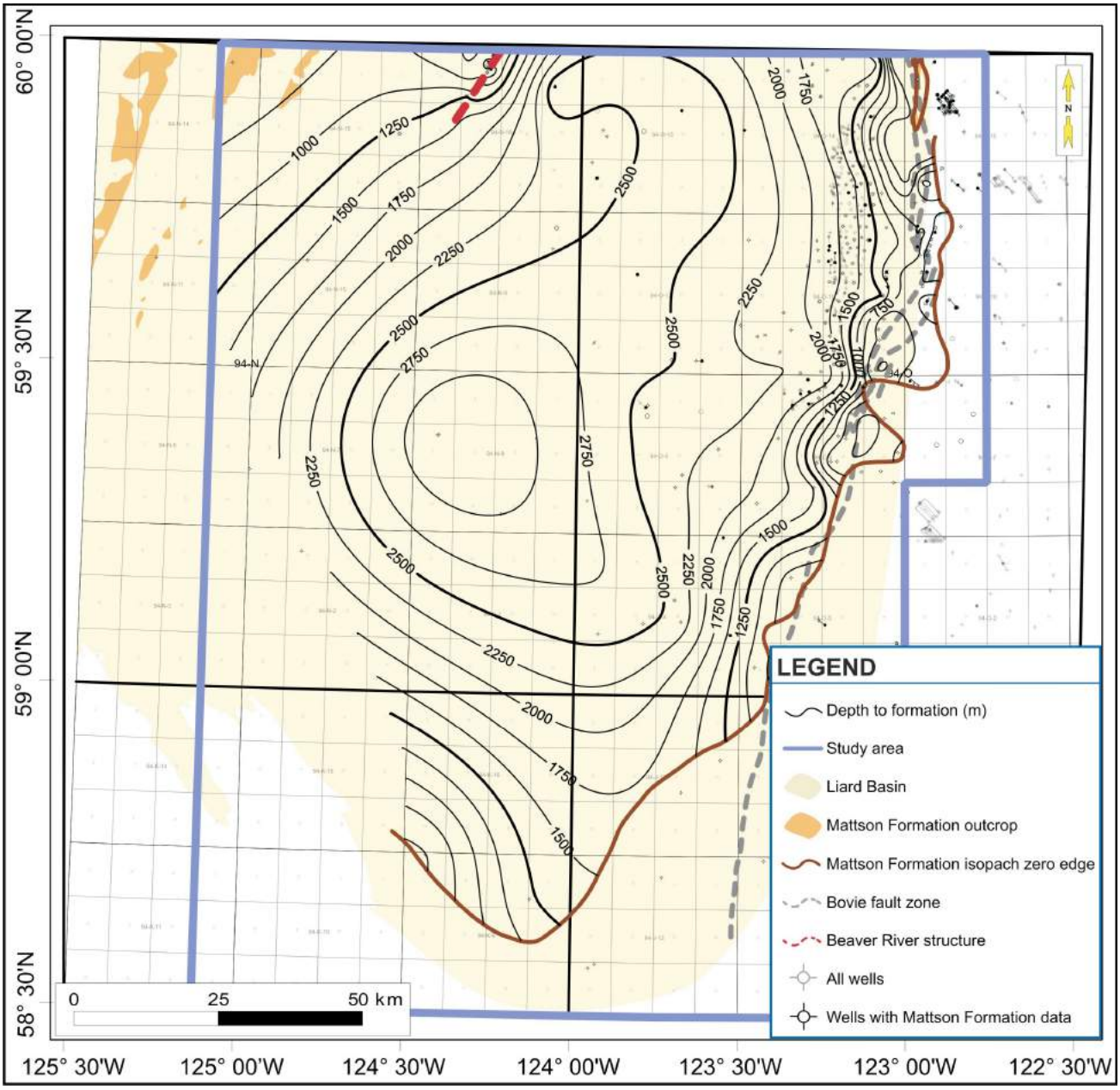

Figure 3. Depth to formation map, Mattson Formation, northeastern British Columbia.

fault zone makes correlations challenging in that area, even though well control is generally denser here.

Analysis of the Mattson Formation, the most prospective aquifer interval, is summarized in this paper as a representative example of the work completed. Conclusions for all four investigated intervals are presented at the end of this paper.

Regional Geology

In the Liard Basin, the top of the Mattson Formation lies at depths varying from <500 m along the Bovie fault zone to >3000 m near the basin centre (Figure 3). Subsurface distribution in the west is complicated by structural elements, and very scant well control in central and western areas makes burial depth uncertain over most of the basin.

The Mattson Formation grades upward from marine shale of the Golata Formation below, and is overlain unconformably by the Fantasque Formation or Kindle Formation succession of younger rocks.

At its type section in Yukon, the Mattson Formation consists of coarsening- and sandier-upward prodeltaic fine clastic rocks, overlain by deltaic to fluvial and floodplain strata. Richards et al. (1993) interpreted the Mattson Formation to have been deposited as fluvially dominated,

wave- and tide-influenced deltas of lobate form. In the east and north, thick braided-stream sandstone occurs interbedded with finer grained and coaly delta plain deposits. Southward, the Mattson Formation grades to a fully deltaic section and in northeastern BC, passes into prodelta clastic rocks and equivalent basinal shale.

Figure 4, a gross isopach map of the Mattson Formation, shows it to thicken abruptly westward from the eastern isopach zero edge and into the Bovie fault zone. Northwestward, toward the deltaic depocentre in Yukon and NWT, it thickens to >800 m. Southward and away from the source area, it thins to an apparent isopach zero edge in the southern Liard Basin. Presence of the Mattson Formation in two wells in NTS 094K/09 is rather problematic; these sections are difficult to correlate, and may relate more to time-equivalent Stoddart Group deposition to the south. If this is the case, there may be little Mattson Formation rock south of NTS 094O/04 and N/01.

Well control is not sufficient to break out clear subunits or depositional trends within the Mattson Formation, but clean, thick, reservoir-quality sandstone is common in many wells. Mattson Formation sandstone is typically a quartzarenite; minor framework components include chert, phosphate and detrital carbonate grains. Silica is the primary cement, mostly in the form of quartz overgrowths.

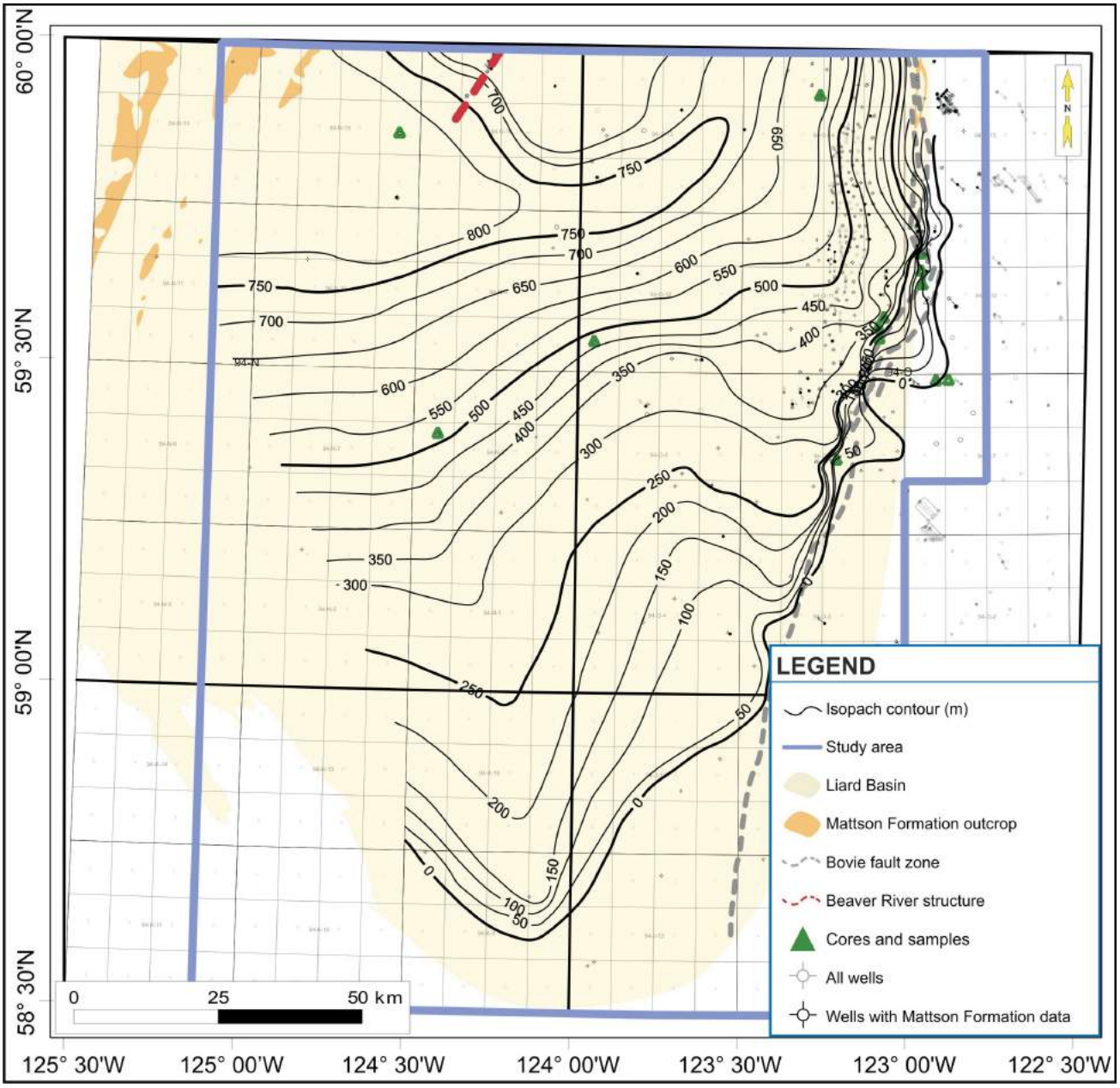

Figure 4. Gross isopach map, Mattson Formation, northeastern British Columbia.

Reservoir Quality

Reservoir quality ranges from very poor in very fine grained rocks and tightly cemented sandstone to excellent in well-sorted quartz sandstone. Porosities locally exceed 20%, and permeabilities range into the hundreds of millidarcies (mD). Porosity is primarily intergranular, augmented by secondary solution of chert and carbonate grains.

Sample cuttings from the eastern Liard Basin wells document thicker, sand-dominated, variably cemented Mattson Formation sections. To the west, samples indicate a much poorer quality Mattson Formation reservoir. Natural fracturing was observed, particularly in more tightly cemented intervals, and is likely related to tectonic activity along the Bovie fault zone.

Reviewing drillstem test data and the porosity-permeability crossplot from available core analysis data (Figure 5), a porosity of 10% (equivalent to about 3 mD permeability) was selected as the net porous sandstone cutoff value. Net porous sandstone values were calculated from all wells with adequate logs, using a clean gamma-ray cutoff of 60 API units and the 10% porosity value on sandstone density logs. A net porous sandstone isopach map (Figure 6) shows total thicknesses ranging up to 18 m. The most consistent porosity development is in the relatively shallow sections along the Bovie fault zone, although several wells on the Beaver River structure and southward exhibit substantial porous sections as well. Wells in the central and southern parts of the basin exhibit limited or no net porous sandstone.

Hydrogeology

Seventy-nine drillstem tests have been conducted in the Mattson Formation in 41 wells, four of these straddling other formations. Tests are focused along the Bovie fault zone, where many Mattson Formation tests have been drilled pursuing structural trap objectives. Twenty-one valid water tests in 16 wells were identified, and relatively high permeabilities are common.

The Mattson Formation produces gas from a number of areally small, conventionally trapped, structural closures associated with the Bovie fault zone. It is in hydraulic communication with the Fantasque Formation and Rundle Group. True formation water is found within a relatively consistent range, from 12 497 to 34 095 mg/L.

Water Wells in the Liard Basin

Examination of existing water source and disposal/injection wells can assist in assessing the characteristics of deep saline aquifers. No water source wells in deep saline aquifers were identified in the Liard Basin.

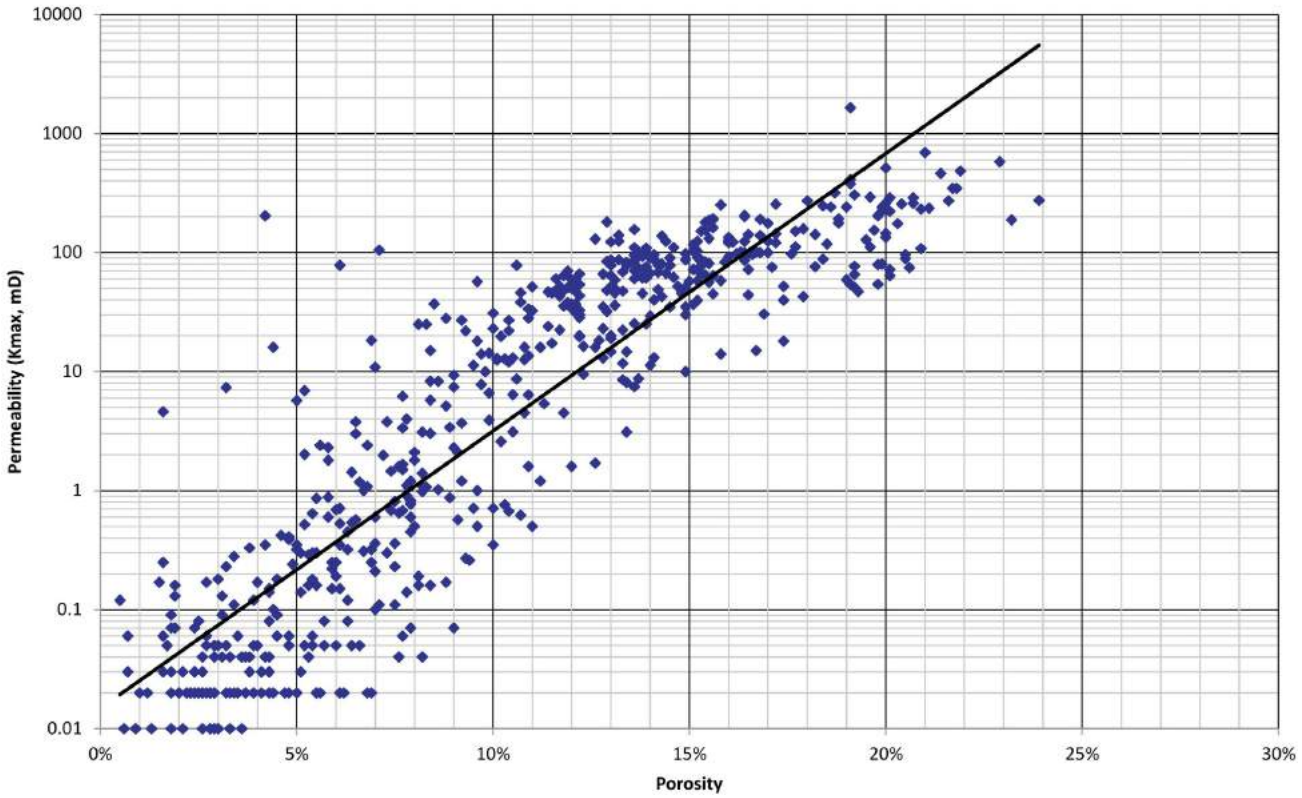

Figure 5. Porosity-permeability crossplot from core analysis data, Mattson Formation, northeastern British Columbia. Abbreviation: mD, millidarcies.

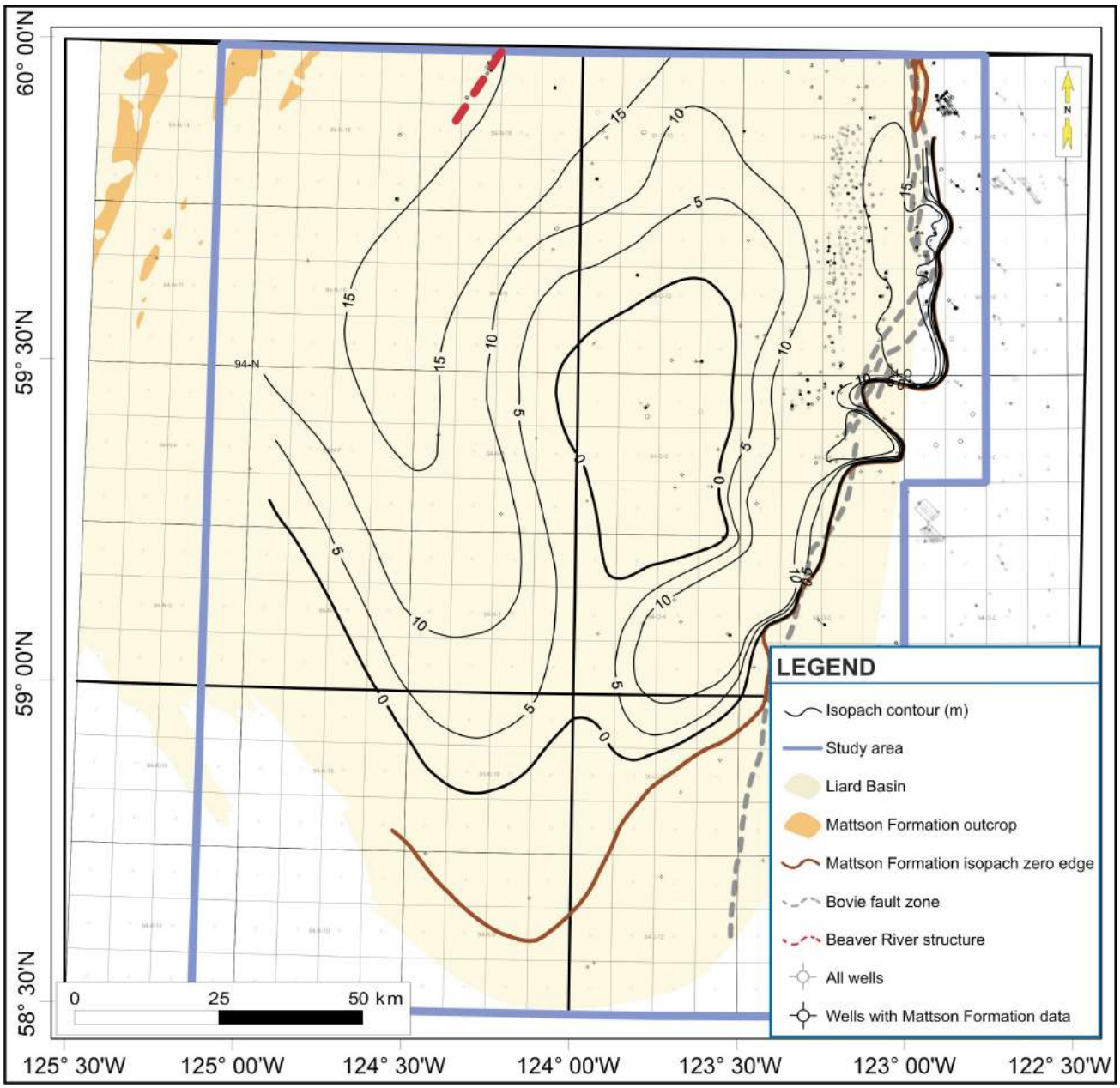

Figure 6. Net porous sandstone isopach map, Mattson Formation, northeastern British Columbia.

Eight water disposal zones in six wells were identified. Injection zones are Rundle Group (two zones), Mattson Formation (three zones), Fantasque and/or Mattson Formation (two zones) and Sikanni Formation (one zone).

Analyzing water well performance using only injection statistics entails some uncertainty, as injection rates and volumes are likely controlled by volumes available and not by the capacity of the zone being injected. However, the following observations can be made:

- Thick sand-rich Mattson Formation sections at Beaver River Field are capable of accepting high water volumes and rates; these waters were probably produced from gas wells with high water to gas ratios in the Beaver River Field.
- The Rundle Group can accept more modest water volumes in the Bovie fault zone area with appropriate stimulation. At least some of the water capacity appears related to matrix porosity development in dolomite.
- The Sikanni Formation, although not addressed in this study, has been used for water disposal by Apache in the east-central part of the basin. It is speculated that Apache needed this capacity to handle produced waters from its new shale play wells in the area.

Summary and Conclusions

Conclusions regarding subsurface aquifer potential in the Liard Basin are tempered by the limited distribution of wellbore data, particularly as many of the wells in more remote parts of the basin were drilled as exploratory tests several decades ago.

- Mattson Formation sandstone offers very good to excellent water source and disposal zone potential in the northern and northeastern portions of the Liard Basin. Depth of burial is quite shallow in the Bovie fault zone, but increases rapidly southward and westward. Waters are modestly saline. Crossformational connectivity of Mattson Formation tests with Rundle Group and Fantasque Formation tests indicates potential for very large aquifer volumes.
- Dunvegan Formation sandstone and conglomerate offer very good to excellent water source potential in the north-central part of the basin. Depth of burial is very shallow, making water sourcing attractive but likely precluding any water disposal potential.
- Rundle Group and Fantasque Formation rocks exhibit moderate reservoir potential in some wellbores, but reservoir quality appears to be substantially poorer than in the Mattson Formation. Tighter, more brittle rocks dominate both sections—carbonate rocks in the Rundle Group and siliceous sedimentary rocks in the Fantasque Formation, with relatively isolated better reservoir in dolomitized intervals, sandstone and fractured intervals.
- Chinkeh Formation sandstone exhibits moderate to poor aquifer potential. To the northeast, just east of the Bovie fault zone, a thick basal Cretaceous sandstone package on logs appears to have very good reservoir quality and water saturations. Combined with the substantial Mattson Formation potential, this area may have the best subsurface water source and disposal potential in the region.
- Scatter Formation sandstone exhibits poor aquifer potential in Liard Basin.

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