Horizontal Drilling for Geothermal Power Generation in the Williston Basin (Canada)

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Keywords

Sedimentary basin, Williston Basin, horizontal drilling, geothermal, energy, Saskatchewan

ABSTRACT

Successful geothermal resource exploration in a hot sedimentary aquifer (HSA) requires two main contributing factors: hot fluid in permeable rocks and high well productivity. Modern well design has made sweeping the heat from the reservoir possible. DEEP developed a unique geothermal field design to maximize flow rates and optimize an important regional geothermal resource.

DEEP's "ribcage" geothermal well field design is globally unique and may be a transformative application of modern oil and gas drilling, completions and stimulation design applied for the first time on a renewable energy project. The project is advancing with local world class oilfield expertise and redeploying that uniquely skilled workforce into a new clean energy industry for Canada.

DEEP is positioned to be the first commercial geothermal power producer in Canada with operations in the Province of Saskatchewan near the United States border. Since 2018, DEEP has drilled the six deepest wells into the Canadian side of the Williston Sedimentary Basin, all more than 3,450 m deep.

To maximize well productivity, DEEP drilled its first horizontal well in October 2020. This was the first 90° horizontal fluid production well in the world to be drilled and hydraulically stimulated for the purposes of geothermal power generation and the first step in constructing an initial 20-Megawatt (MW) geothermal power plant.

The horizontal well was drilled to a total measured depth of 5,672 m (3,450 m vertical depth) which includes a 2,000 m horizontal section. It was completed with a cemented liner and a 20-stage multicycle stimulation sleeve system, and hydraulically stimulated using the latest horizontal well techniques. The highest temperature measured during open hole logging was 127°C.

Extended testing of the geothermal system was completed in March 2021, producing from the horizontal well and injecting into previously drilled vertical wells. This large volume production

and injection loop test was required to refine the reservoir model, lateral well lengths and well spacing for the array design. Drilling and testing results indicate that temperature and potential flow rates from the geothermal reservoir in the Deadwood Formation are sufficient to support multiple geothermal power facilities. Feasibility engineering was completed in June 2021.

1. Introduction

DEEP Earth Energy Production Corp. ("DEEP") is planning a geothermal power generating project in southeast Saskatchewan with an initial phase output averaging 26 MW of power to the grid. Future phases may increase the project output up to a minimum of 100 MW (summer) to 160 MW (winter) to the grid.

DEEP's power generation project will be the first of its kind 'green energy' producer of baseload electricity in Canada. For every 1 MW of clean energy produced by the Southeast Saskatchewan Geothermal Project, approximately 1,200 homes can be removed from non-renewable power generation sources.

Currently, 74% of Saskatchewan's power comes from traditional carbon-based generation methods (coal and gas fired power plants). By supporting Canada's commitment to powering our future with clean electricity, the project will eliminate approximately 155 kilotonnes of CO2 from the atmosphere each year.

The DEEP Project is located over two geologic formations with high temperature brine in the southeast region of Saskatchewan, near Estevan; the Deadwood and Winnipeg. This naturally occurring subsurface heat source initiated the interest in harnessing the geothermal resource to help meet the region's green energy power demand. The development plan has focused in on a higher porosity interval within the lower Deadwood Formation to access the hot subsurface brine from the reservoir.

Stratigraphic correlation and mapping of the basal Deadwood clastics showed a continuous sandstone depositional and temperature fairway capable of supporting numerous 20 MW Binary power projects by the utilization of multiple arrays of horizontal wells.

Positioned in an east-west well orientation the first development array will consist of 10 production wells and 8 injection wells. The wells will be drilled from 3 surface pads, each pad located approximately 2.25 kms apart, as shown in figure 7 below. All pads will be connected by a production and injection pipeline system.

Brine will be pumped from producer wells to the surface at approximately 120° Celsius. The produced brine commingles in a 24-inch header before being delivered to an Organic Rankine Cycle Plant (ORC) where the heat is converted to electrical power.

2. Geology

The DEEP project area is located within the intracratonic Williston Basin. The Williston Basin is centrally located on the North American continent straddling the Canada/United States border. The basin is an ellipsoidal, bowl-shaped depression that forms the southeast extremity of the Western Canadian Sedimentary Basin (WCSB) and is separated from the Alberta Basin by the Sweetgrass Arch (Gerhard 1982; Kent and Christopher 1994). The sedimentary section of the

Williston Basin reaches a thickness of over 4,800 m in northern North Dakota, and the stratigraphic section demonstrates that the predominant depositional environment was a shallow sea from the Cambrian to the late Cretaceous (Gerhard et al. 1990). DEEP defined a target area that mapped as the highest temperature area of the Willison Basin in Canada based on a review of the publicly available subsurface database and academic studies. Subsequent drilling by Deep has confirmed the high temperatures.

The Deadwood Formation represents the first transgressive event as Cambrian seas transgressed the low-relief and irregular Precambrian surface. The Deadwood geothermal-reservoir sand (DEEP sand) was deposited on a shallow platform/epeiric sea on the north side of the Transcontinental Arch near the equator (Lake at al. 2021).

Depositional environments were interpreted using the DEEP Border-1 drill core. The Precambrian shows evidence of deep tropical weathering and alteration consistent with an equatorial-latitude regolith. Deadwood Formation sedimentation initially started in an aeolian and dune environment directly on the Precambrian basement. This sediment is overlain by a thick package of mature, porous deltaic and fluvial sediments that grade upward to offshore sands (informally referred to as the DEEP sands). After the deposition of the DEEP sands, the deltaic focus shifted due to a drop in sea level. The DEEP sands are overlain by brackish lagoons, fluvial channels and capped by aeolian sands and subaerial exposure surfaces. The final Deadwood Formation sedimentation by a marine transgression resulted in deposition of a tight, tidal-flat carbonate package adjacent to aeolian dunes (Lake et al. 2021). In the DEEP project area, the Deadwood Formation is unconformably overlain by the Winnipeg Formation (Anderson 1988).

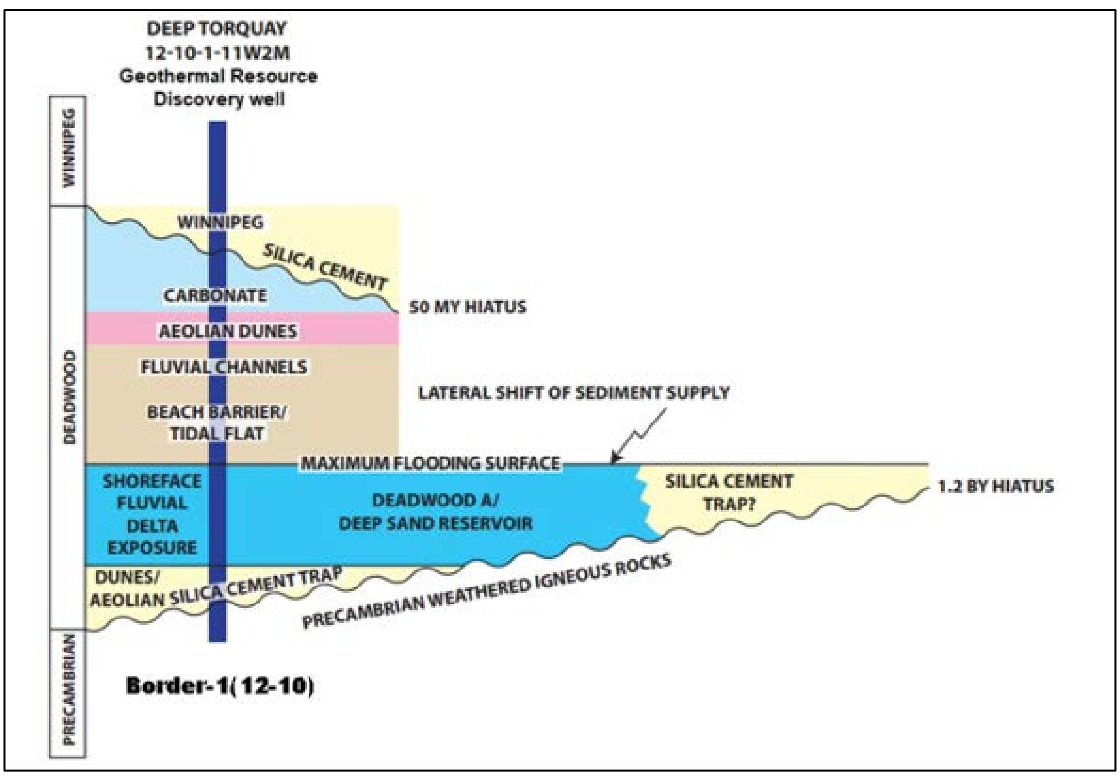

Figure 1: Depositional Environment

Schematic detail of Deadwood Formation depositional environments interpreted from the Border-1 (12-10) well [Lake et al, 2021].

DEEP has regionally mapped the basal Deadwood Formation in southeast Saskatchewan. In DEEP's conceptual depositional model, a world-class delta existed in southeastern Saskatchewan during the Cambrian period. The sediment was carried by a major continent-draining river. The river ran through a valley system between Precambrian highlands, and the deltaic sediments were deflected southwards by the prevailing wind direction at the time. Additionally, an interpreted fluvial-to-estuarine system south of the Precambrian high, along the Canada/United States border may also have been the source of sand in the DEEP and Aquistore project areas. The DEEP wells corelate to those seen at the Aquistore (Boundary Dam) carbon sequestration project 25 km to the northeast near the town of Estevan, demonstrating the potential for a large fairway of consistent stratigraphy.

Further stratigraphic and regional seismic studies and drilling are required to define the regional depositional framework in more detail as well as the relationship between the reservoir at the DEEP project area and the sands to the north. DEEP's interpretation was built from sparse well control. The distances between control points are large (i.e., greater than 10 km).

3. Drilling History

During 2018-2020, DEEP drilled five vertical and deviated wells and one horizontal well. The Wildcat Border-1 well was drilled a few kilometres north of the United States border through the deepest rocks of the basal clastic sedimentary section and terminated in Precambrian basement. Border-1 was the deepest well drilled in Saskatchewan at the time. 198 m of core was cut in the Winnipeg, Deadwood and Precambrian Formations, with a 98.4 percent recovery rate.

The Border-1 well was drill-stem tested and subsequently production tested. Initial test results were positive, however a slotted liner was run across the entire Winnipeg, Deadwood, Precambrian intervals and further tests were required to determine exactly where the fluids were coming from. Subsequent Nitrogen-lift testing conclusively demonstrated that only the Deadwood Formation had potential as an exploitable zone.

The Border-1 results were sufficient to sanction additional wells and prior to the Nitrogen-lift test on Border-1, fractures observed on image logs suggested that the Precambrian could possibly source and circulate hot brine. The Precambrian along with the Deadwood Formation continued to be investigated in the exploration wells that followed, Border 2A, 2B, 3 and 4. The Precambrian proved disappointing with few fractures on the image logs, however petrophysical logs and formation testing continued to indicate the Deadwood Formation was perspective and would be the focus for further development.

The production data from the vertical and deviated wells show the DEEP target sand to be productive, but the sand lacked the thickness to produce hot brine using vertical wellbores at the rates necessary for the project design. Continued evaluation of all well data led to the proposal of the Border-5Hz horizontal well. The horizontal well was a proof-of-concept test to demonstrate that horizontal wells would be capable of the flow rates necessary for a viable commercial geothermal power project. The DEEP Border-5Hz well targeted the main porosity unit of the Cambrian basal clastic Deadwood Formation. The horizontal well was drilled to a total measured depth of 5,672 m (3,450 m total vertical depth) with a 2,000 m horizontal section. No significant issues were encountered during drilling and the geological and operations staff were able to maintain the well trajectory in the reservoir target zone for a significant portion of the lateral length. This well demonstrated the viability of horizontal drilling, supports the geophysical analysis, and further demonstrates reservoir continuity. Additionally, a hydraulic well stimulation was completed to test the efficacy for dealing with the reservoir laminations and compartmentalization interpreted from core and increased the overall well deliverability.

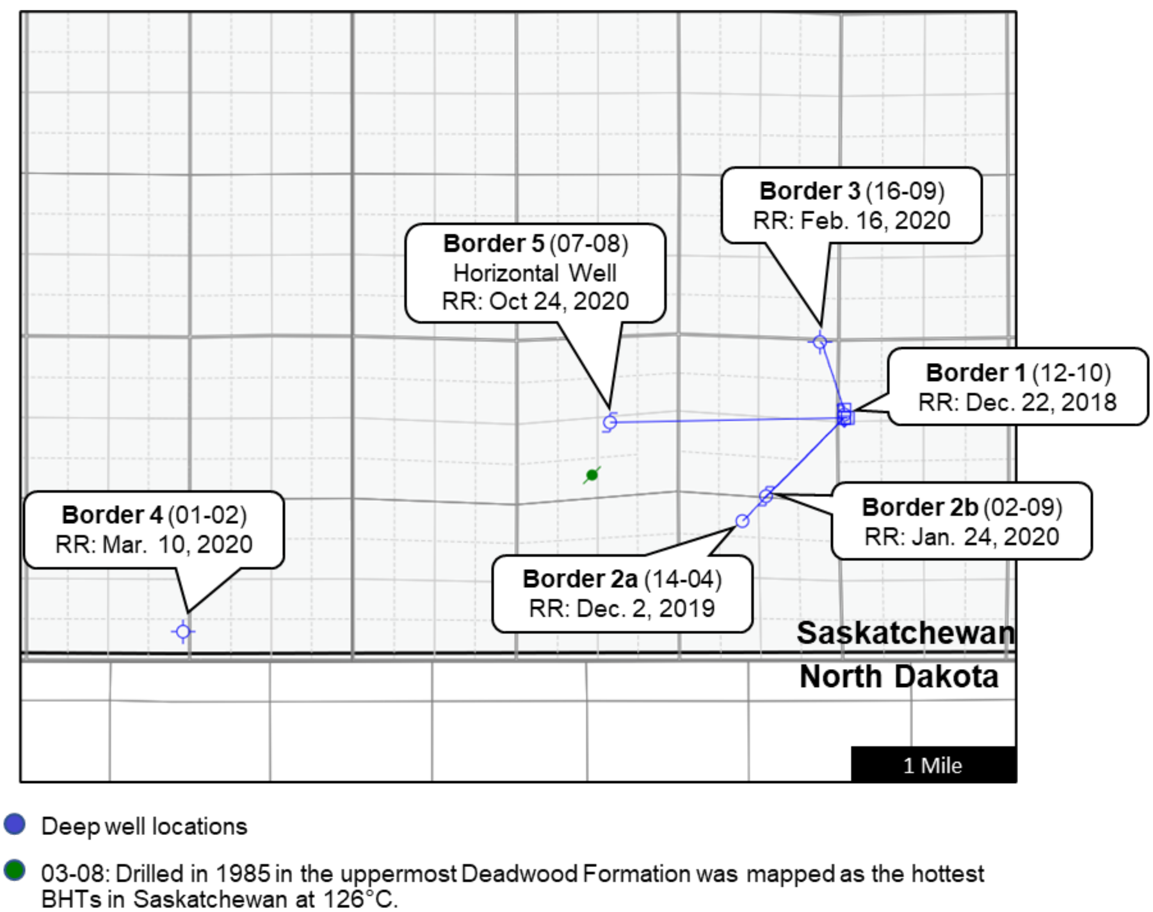

Figure 2: Well Locations

Table 1: Well Details

Summary of wells:

Well Surface Hole	**12-10-1-11W2**		**12-10-1-11W2**	**12-10-1-11W2**	**1-2-1-12W2**	**12-10-1-11W2**
Well Bottom Hole	**12-10-1-11W2**	**14-4-1-11W2**	**2-9-1-11W2**	**16-9-1-11W2**	**1-2-1-12W2**	**7-8-1-11W2**
Well Name	**Border 1**	**Border 2A**	**Border 2B**	**Border 3**	**Border 4**	**Border 5Hz**
Type	Vertical	Directional	Whipstock Directional	Directional	Vertical	Horizontal
Spud Date	14-Nov-18	26-Oct-19	29-Dec-19	25-Jan-20	09-Feb-20	11-Sep-20
Rig Release	22-Dec-18	02-Dec-19	24-Jan-20	16-Feb-20	10-Mar-20	24-Oct-20
Drilling Days	38	37	26	22	30	43
244.5mm Surface Casing (m)	405	503	n/a	402	406	354
177.8mm Int. Casing/Liner (mMD/mTVD)	3290	3825/3482	W.S. @ 2863mMD	2990/2870	2922	3681/3446
114.3 mm Liner Hanger (mMD/mTVD)	3212	n/a	2069/1913	2942/2823	2881	3547/3424
114.3mm Liner Depth (mMD/mTVD)	3530	n/a	3885/3619	3610/3489	3485	5672/3459
Liner Type	Slotted/ Solid	n/a	Slotted/Solid	Solid	Solid	Solid w/ Frac Sleeves
Winnipeg (mMD/mTVD)	3275	3606/3272	3544/3277	3385/3265	3320	3288/3277
Deadwood (mMD/mTVD)	3342	3677/3339	3613/3347	3455/3334	3385	3376/3344
Precambrian (mMD/mTVD)	3502	3928/3473	3772/3505	3613/3492	3548	n/a
Bottom Hole Temp. (°C)	125	117	121	122	120	127
Well TD (mMD/mTVD)	3530	3840/3496	3890/3624	3681/3560	3731	5672/3731

4. Reservoir Testing

Horizontal well Border-5Hz was tested for a total duration of 53 days and produced 89,112 m3 of brine. During the loop test the brine was re-injected into the reservoir using Border-1 and Border-3 vertical wells. Well performance from the horizontal well and both injection wells were as anticipated and demonstrated reservoir continuity. Border-5Hz flowed at a minimum rate of 1728 m3/day with a long-term production rate of 2000 m3/day. DEEP rented an ESP with an operating range of 1500 m3/day – 3250 m3/day. The flow test started at 1500 m3/day and was later stepped up to higher rates.

This test provided the dataset required to finalize the design parameters of the development array including the lateral length, well spacing and completion design. The distance between producers and injectors was optimized to maintain reservoir pressure and minimize thermal breakthrough times.

Two chemical tracer programs were executed simultaneously during this flow test. A unique set of tracers were used to determine the detailed efficacy of the hydraulic stimulation along the length of the horizontal well.

A separate set of tracers and dedicated test protocol were designed to test for potential short-circuiting zones such as high permeability stratigraphic units or fractures that could lead to premature thermal break through. In this test, unique tracers were pumped into each of the injection wells and sampled daily in the production well. As anticipated, no reservoir tracers from injectors was detected in the production well during flow testing which greatly de-risks the probability of early thermal breakthrough during power generation.

5. Reservoir Engineering

Reservoir simulation was completed using TOUGH3 software developed and licensed by Lawrence Berkeley National Lab. The TOUGH family of codes has been a primary geothermal reservoir simulator used worldwide since the 1980’s. Reservoir model parameters were based on downhole geophysical logs, core analysis, and well test pressure transient analysis results.

Reservoir models were calibrated based on long term well tests conducted in 2020 and 2021. Multiple well field designs were investigated to determine the number of production and injection well pairs. Reservoir simulations were run to generate key performance metrics, reservoir pressure and temperature changes, at the wells with target output times of 25, 30, 40 and 50 years.

Simulations resulted in a final base case design of 10 production wells and 8 injection wells to meet the specified target flow rate, minimize capital costs, and maintain a reasonable pressure balance.
Preliminary subsurface design optimizes the well spacing (750 m) and configuration to produce 20-33 MW of power. Each well will be drilled to a depth of 3.5 km plus a horizontal length of 3-4 km.

This base case 10-8 production/injection well scenario includes alternating parallel production and injection wells at a maximum spacing of 750 m and a horizontal open hole completion length of 3,000-4,000 m. Results indicate the well field configuration is important and hydrodynamic control of the system can be maintained. By varying volumetric flow rates at the edge production wells internal well field pressures can be controlled over time to maximize system sustainability and reduce artificial lift.

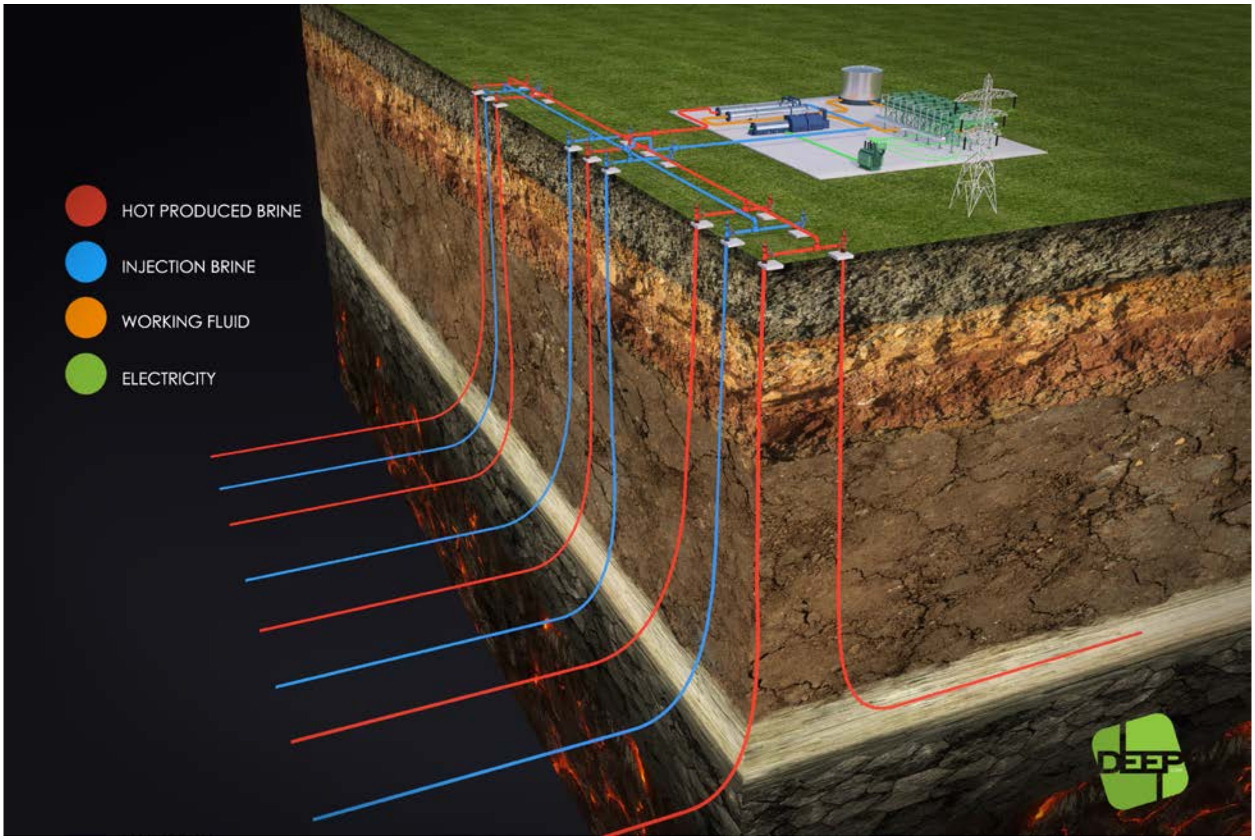

Figure 3: Field layout

A sensitivity study was done on reservoir parameter changes to understand the impacts of reservoir quality to the overall system performance. Results indicate changes in well spacing, lateral length, and outer production well flow rates can be used to mitigate reservoir risk and implement a successful development array.

6. Development Scenarios

The hot brine will be produced from 10 horizontal production wells and 8 injection wells drilled to a vertical depth of approximately 3,500 m plus a horizontal segment of 3,000-4,000 m resulting in a total well bore length of approximately 7,000 m. Based on reservoir testing and sampling performed during the feasibility stage, the brine has a relative density of 1.22 kg/L and a temperature of 120^{0}C at surface.

Well bore profiles for the production wells have been developed using the information from the reservoir studies coupled with a hydrogeological flow model. The targeted field flow rate is expected to be approximately 960 L/s depending upon final reservoir and well performance.

Dynamic brine levels can be controlled by production rates on the outer producers and pressure buildup in the inner well array. Dynamic brine levels can vary ranging from 8 m above surface to 588 m below surface depending upon inner well field pressure control with a pressure delta of approximately 8 MPa between production/injection well pairs.

With a dense brine and relatively low dynamic water level, an electrical submersible pump (ESP) or top drive line shaft pump may be used to pump the hot brine up the well bores to surface. The pump's power requirements will be approximately 1 MW per well for a total pump load of 10 MW. The pumps will have to be placed well below the dynamic water level at an approximate depth of 800 m. The well bore casing profiles are shown in Figures 5 and 6 below.

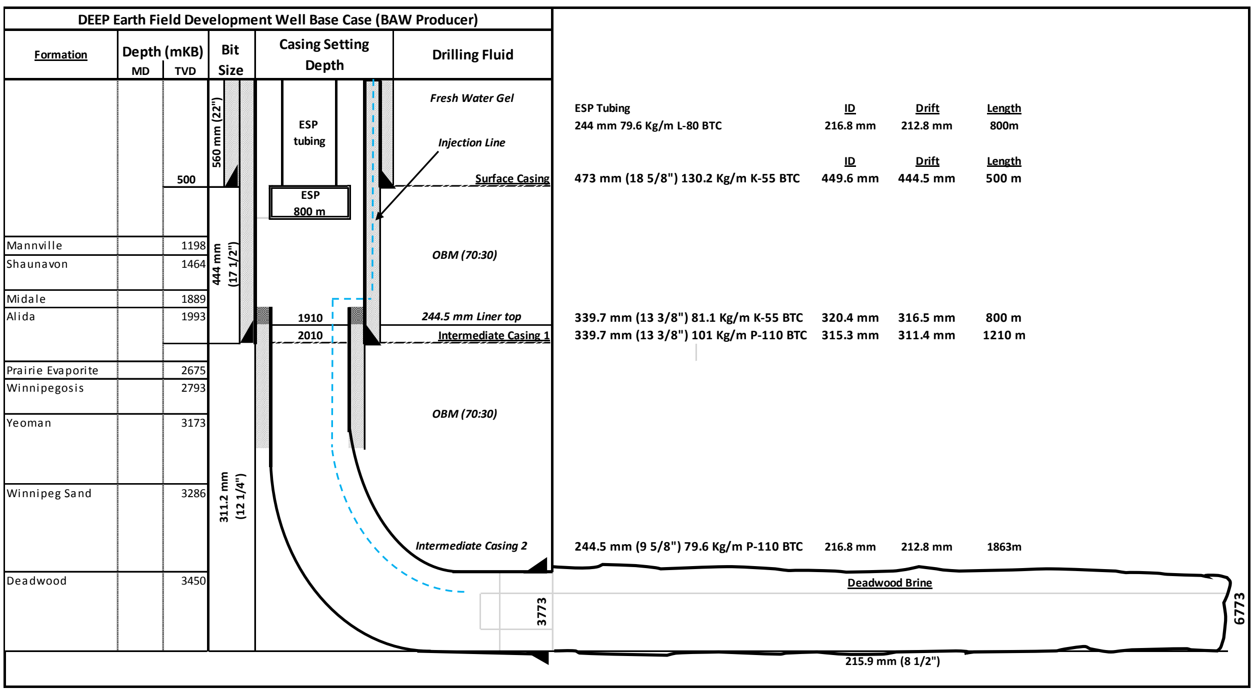

Figure 4: Production well profile

The injection well profiles are similar to that of the production wells with the addition of a tubing string and packer starting at a depth of 2,000 m extending to 3,800 m.

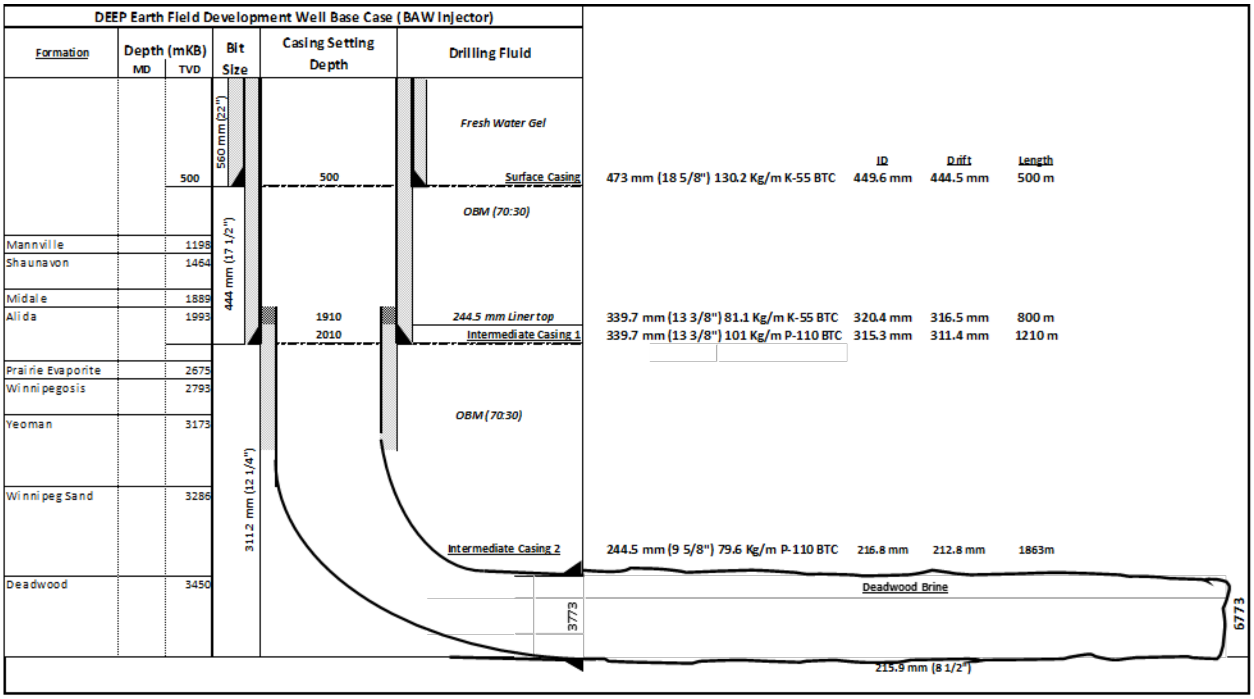

Figure 5: Injection well Profile

The production and injection wells will be spaced 750 m apart bottom hole and will be drilled from one of 3 multi well pads (Pads 1, 2 & 3). Surface locations have not been surveyed but are very close to the locations indicated on Figure 6.

Buried 16 inch brine injection pipelines will connect 4 injector wells from pad 1 (2 injectors), and pad 3 (2 injectors) to the ORC plant adjoining pad 2. Well pad 2 will have 2 producer wells and 4 injection wells with above ground piping connecting these wells to the ORC system.

10 horizontal production wells and 8 horizontal injection wells drilled in an east/west orientation and spaced at 750 m. The wells are located on three well pads positioned in a north/south orientation.

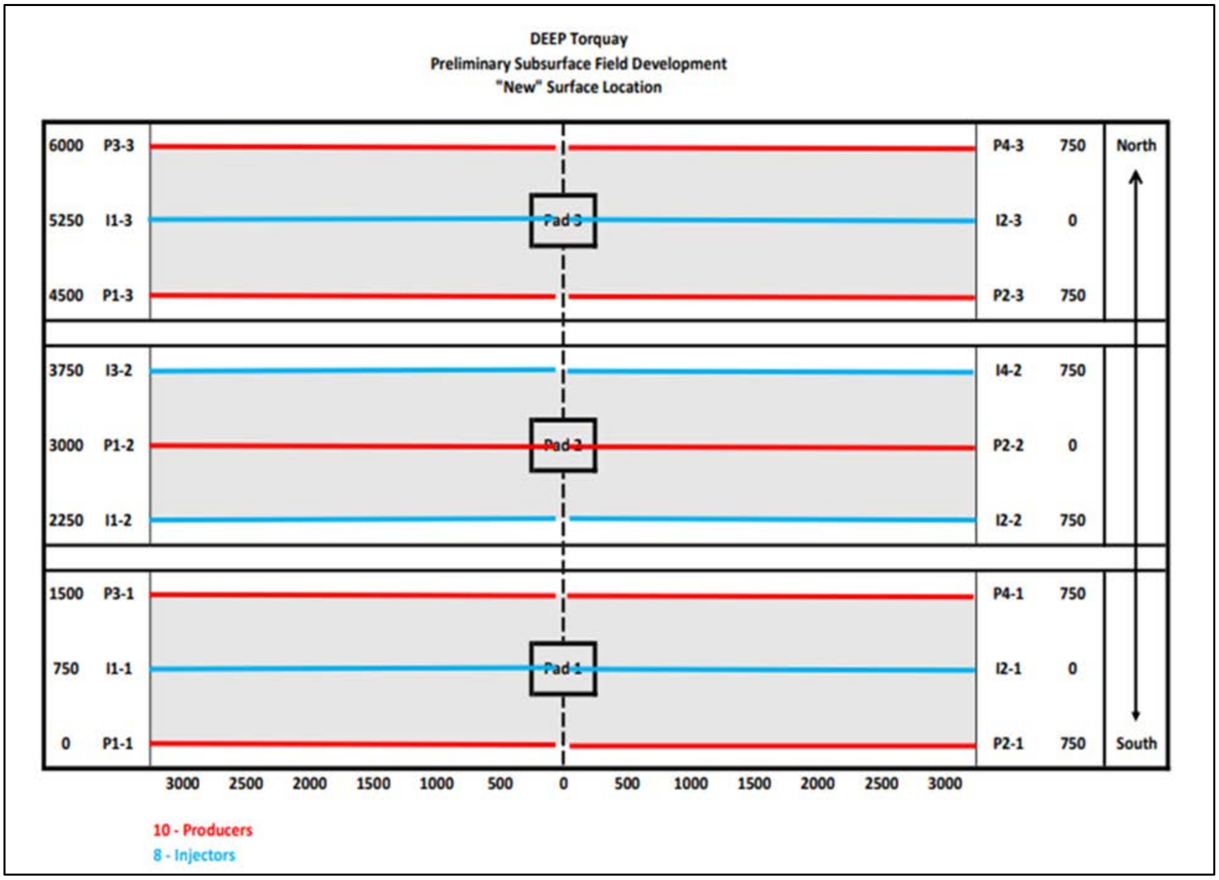

Figure 6:Well Layout

7. Conclusion

The DEEP Geothermal project concept evolved from a project that used vertical wells producing from the Deadwood and Winnipeg clastics with injection into the Cretaceous Mannville Groups, through to an investigation of the potential Precambrian fractures and regolith, to the current commercial design of Deadwood Formation exploitation by an array of horizontal producers and injectors. On a regional scale, DEEP mapped a possible large sand fairway with a reservoir and temperature suitable for geothermal exploitation. At the project level, DEEP defined the location and dimensions of the initial 20- MW array through drilling, seismic evaluation, well testing, and reservoir modeling. The successful results of DEEP's drilling program, five vertical/deviated wells and one horizontal well, have help inform the project planning and design during the feasibility stage of the project. The development will target the DEEP sand using long lateral (3,000-4,000 m) horizontal wells and the array will consist of 10 production wells and 8 injection wells spaced at 750 m. This "ribcage" geothermal well field design is globally unique and may be a transformative application of modern oil and gas drilling, completions and stimulation design applied for the first time on a renewable energy project. In conclusion, the parallel horizontal well field design will work to create a viable geothermal power system in the Deadwood Formation at DEEP Earth's Energy project site in southern Saskatchewan. This well design may prove to be transformative in lower temperature sedimentary geothermal fields around the world.

Acknowledgements

DEEP gratefully acknowledges the continued support from Natural Resources Canada for the funding announced in 2019 and for their ongoing support in the development of Canada's first geothermal power project. By re-deploying world class oilfield expertise on a renewable energy project for the first time in Canada, this Federal funding is providing employment opportunities in a sector hard hit by job losses. New opportunities created from this geothermal power project, such as heating for greenhouses and aquaculture (fish farming), will be a welcome economic boost for the province.

We are also grateful to the Government of Saskatchewan for their continued support for the energy industry in the province. With their support, DEEP's innovative clean energy project will demonstrate sustainable power for Saskatchewan, making progress on its emissions reduction goals. Like many other energy projects, progress on DEEP's geothermal power project would not have gone forward without the support and guidance from the Ministry of Energy and Resources, the Ministry of Environment and SaskPower. Working together, regulatory and permitting processes for geothermal energy were developed, facilitating progress on geothermal power production and innovative uses of geothermal heat for sustainable food growing opportunities.

REFERENCES

Anderson, Douglas B., "Stratigraphy and Depositional History of the Deadwood Formation (Upper Cambrian and Lower Ordovician), Williston Basin, North Dakota". Theses and Dissertations. (1988), 7-10.

Gerhard, Lee C. "Geological Evolution and Energy Resources of the Williston Basin,"UMR Journal -- V. H. McNutt Colloquium Series: Vol. 3, Article 8. (1982)

Gerhard, L.C., Anderson, S.B. and Fischer, D.W. Petroleum Geology of the Williston Basin. In: Interior Cratonic Basins. M.W. Leighton, D.R. Kolata, D.F. Oltz, and J.J. Eidel, (eds.). American Association of Petroleum Geologists, Memoir 51. (1990), p. 507-559.

Kent, D.M and Christopher, J.E.: Geological History of the Williston Basin and Sweetgrass Arch: in Geological Atlas of the Western Canada Sedimentary Basin, G.D. Mossop and I. Shetsen (comp.), Canadian Society of Petroleum Geologists and Alberta Research Council, (1994)

Lake, J,H., Marcia, K., Drobot, A., Groenewoud, L., and Marsh, A., 2021; Sedimentology of the Cambrian Deadwood Sands in Southeast Saskatchewan. CSPG Core Conference 2021