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# Use of Silicate Mud to Control Borehole Stability and Overpressured Gas Formations in Northeastern British Columbia

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## Abstract

A freshwater silicate based drilling fluid, containing 20-30% sodium silicate by volume, was successfully used to drill a gas well in northeastern British Columbia. Major drilling issues in the area include borehole instability in 500 plus meters of highly dispersible Ft. Simpson shale, high pressure gas zones and potential moderate-severe lost circulation.

Despite problems of severe lost circulation and high mud weights, the caliper log on the silicate well showed <1% hole enlargement over the Ft. Simpson shale and 12% enlargement over the entire intermediate section. Typical offset calipers with other water-based muds average 48% and 31% enlargement over the Ft. Simpson and entire well section, respectively.

Rates of penetration with silicate mud were generally better than offset wells. Uphole formations drilled to 1060 meters with a low solids, lower density silicate fluid (1195 $kg/m^3$ mud density) drilled at an average of 19.2 m/hr. Offsets drilled with gel-chemical or gel-PHPA systems over the same interval normally averaged 12.6 m/hr.

This paper describes the planning and drilling of the first well with a drilling fluid containing silicates up to 30% concentration. Topics discussed include borehole stability, rates-of-penetration, motor performance, drilling fluid stability and properties, and environmental aspects of silicate disposal.

## Introduction

Drilling for Sulfur Point and Slave Point gas bearing formations in Northeastern British Columbia (Figure 1) presents difficult challenges. The ~ 2200-2500 meter wells have problems with deviation, pressures, lost circulation, borehole instability or any combination of these issues. In general, the overriding drilling challenge in this area is a time dependent borehole instability problem associated with the use of conventional water-based drilling fluids.

When drilling with gel-chemical or gel-PHPA fluids, as commonly practised in the area, an intermediate casing string is run and cemented in order to minimize the instability. Without the intermediate casing string, major amounts of ream/clean and difficulty in evaluating and casing/cementing the well are common.

## Standard Well Profile and Design

The Fort Simpson shale is a late Devonian weak, brittle, shale of high quartzitic content. The smecitic content of the shale is normally less than 1-2%. Wells in Northeastern British Columbia usually encounter 500+ meters of the Fort Simpson shale package. Historically, an intermediate casing string is set soon after drilling the Fort Simpson shale in order to avoid instability related wellbore problems (Figure 2). After setting of the intermediate casing string, a further 250-300 meters of hole is drilled to evaluate potential hydrocarbon pay in the Slave Point and Sulfur Point are drilled to total depth (TD).

Attempts to drill to TD without running intermediate casing has traditionally been met with reaming and cleaning and/or logs bridging in the Fort Simpson section. Caliper logs have often been overgauge through the Fort Simpson by a minimum of 40-50% hole volume.

Normal drilling fluid practice in Northeastern British Columbia is to use of a fresh water based simple gel-chemical or gel-PHPA system. While these fluids have normally been successful when an intermediate casing string is used, attempts to drill with these mud systems without the intermediate casing string has often resulted in the instability problems. The instability is manifested within 3-5 days after drilling the Fort Simpson shale and prior to reaching total well depth. Use of more inhibitive fluids such as oil-based muds have worked, however, the environmental clean-up costs associated with the more inhibitive fluids in Northeastern British Columbia have been limiting.

## Drilling Fluid Selection

Drilling the Slave Point and Sulfur Point wells to total depth without the need for an intermediate casing string is potentially cost saving. Realizable savings include the cost of the casing string, time saved for running casing, cementing and associated rig modifications to drill the main hole section as well as the ability to drill smaller hole size. Estimated cost savings to drill to TD as compared to setting an intermediate string are in the range of $180 K cased to $350 K abandoned.

In order to accomplish the goal of drilling without an intermediate string, borehole instability needed to be addressed. A silicate drilling fluid was selected in this application based upon its ability to provide an excellent sealing mechanism on the borehole wall, especially across the Fort Simpson shale. For the well described in further detail below, Adsett c-2-B, the concentration of silicate used in the drilling fluid was 25-30% by volume. This high concentration was chosen to provide maximum stability across the shale sections of the well and insure good hole conditions while evaluating the well.

Additional benefits expected from the silicate included pressure control uphole from potentially overpressured Debolt and Banff formations as well as "sealing" of the downhole gas pay zones to prevent influx of drilling fluid solids and filtrates.

## Sodium Silicate Chemistry

**Silicate Development:** Sodium Silicate is not new to the drilling industry. Its first recorded use dates to the 1930's when it was incorporated into a drilling fluid to control heaving shale.(1) Silicate went on to be used successfully on over 100 wells in the Texas and Louisiana Gulf Coast. Silicate based formulations of this era tended to use 30-50% v/v silicate and a silicate ratio of 3.2. (sodium silicate ratio refers to the ratio of $SiO_2$ to $Na_2O$. For example a "2.0" ratio silicate is describe as 2 parts $SiO_2$ to 1 part $Na_2O$). Despite excellent shale inhibition properties, silicate based drilling fluids were deemed to be lacking in other fluid properties such as rheology control. Without the environmental pressures that exist today there was little incentive to overcome these deficiencies and by the mid 1940's the use of silicate in drilling fluids had stopped.

Sodium silicate did not see major drilling fluid interest until 1994 when a cooperative effort between BW Mud, Mobil NSL, BP Exploration and Shell Research led to sodium silicate being commercially used in the North Sea.(2) Silicate based muds used in the North Sea typically had 5-10% v/v silicate concentration in combination with an inhibiting salt such as potassium chloride.

Further laboratory testing with low ratio silicates at higher concentrations of total silicate in the drilling fluid showed excellent shale inhibition coupled with ease of use and better drilling fluid stability.(3) The use of 25-30% v/v sodium silicate as described in this paper was the first field application of this principle used in an oil or gas well.

**Silicate Structure:** Silicate molecules exist in alkaline solution as a mixture of monomers, dimers, trimers, cyclic forms as well as three dimensional and complex structures. The molecular weight distribution is dependent on a number of factors such as silicate ratio and concentration.(4) These soluble silicates are known to participate in four different types of reactions: gelation (polymerization), precipitation, surface charge modification (e.g., clay dispersion), and hydration/dehydration. Gelation refers to the self-polymerization or condensation of soluble silicate structures to form a hydrous, amorphous gel structure of silicate. Gelation is brought on by a drop in pH with polymerizaton beginning to rapidly occur at pH <10.5. Precipitation of silicate refers to the cross-linking of silicate molecules by multivalent cations (i.e., $Ca^{+2}$ , $Mg^{+2}$, $Al^{+3}$, $Fe^{+3}$, etc). It is generally believed that as the silicate in the mud comes into contact with the slightly acidic (pH 6-8) and multivalent-rich pore water, a localized gelation reaction, coupled with a minor amount of precipitation, takes place to block both the influx of mud and pressure into the formation. A number of excellent papers have been written further detailing possible mechanisms for shale inhibition.(2,5)

Although the gelation and precipitation of silicate is a desirable process on the shale surface, if the entire mud begins to experience gelation or precipitation then mud problems will result. Potential mud problems include excessive rheology and a decrease in the silicates ability to inhibit shale. By running a 2.0 ratio silicate and a high concentration of silicate in mud, the mud has much greater tolerance towards $CO_2$ and multivalent metal contaminants. The higher degree of mud stability corresponds to a drilling fluid which is simpler to maintain at correct parameters.

## Modified Well Profile and Design

The better borehole stability anticipated from the silicate drilling fluid allows a greater flexibility in well design for wells such as Adsett c-2-B. Figure 3 shows the new casing design planned at c-2-B. The intermediate casing string normally used in these wells was removed, with drilling from surface shoe to total depth in one operation. Ideally, this new design will lend itself to using smaller hole size than required for wells with an intermediate string. However, for the c-2-B well using silicates the same hole size of 222 mm was maintained (as used for intermediate string wells) as this was the initial field trial with silicate drilling fluids in the Adsett area. In addition, the significant potential for uphole pressures and lost circulation warranted using the larger hole size as a contingency for running an intermediate casing string.

Sodium silicates at 25-30% v/v concentrations have a natural density of 1130 $kg/m^3$. This density provided an advantage in the planning of the c-2-B well since the Debolt formation potentially contains higher than normal pressures. The silicate in this instance would provide initial density without having to use weighting agents. It was anticipated that the higher density silicate drilling fluid, containing less solids, would have potentially higher rates of penetration than the barite containing gel-chemical or gel-PHPA drilling fluids.

## Drilling Results

**General Recap:** The silicate drilling fluid was very successful in preventing borehole instability. Problems due to reaming and cleaning, logs bridging and other common instability results were not observed.

Despite the success of the silicate fluid, the proposed casing design (Figure 3) was not followed. Concurent difficulties of both massive lost circulation and high pressure gas influxes while drilling from 750 meters to 2200 meters led to the running of intermediate casing at 2292 meters in the Muskwa formation. The intermediate casing string was set below the Fort Simpson shale, thereby isolating the unstable shale sections. The remainder of the well below intermediate casing point to total depth was drilled without difficulty.

A total of 46.75 hours was lost to problems of lost circulation and high pressures. In spite of these problems, the c-2-B well was the fastest well drilled in the area. Figure 4 shows the day/depth curve of the c-2-B well as compared to recent offsets also drilled with an intermediate casing string.

Further details on borehole stability, rates-of-penetrations, drilling problems and silicate mud chemistry are described in the following sections.

**Borehole stability:** The silicate drilling fluid was primarily chosen to provide borehole stability in the difficult uphole and Ft. Simpson shale sections. In this aspect, the performance of the silicate drilling fluid was exceptional. In spite of the lost circulation and pressures experienced while drilling the well, no instability related hole problems were observed. The total amount of reaming and cleaning was 5.5 hrs. No difficulty was experienced obtaining logs, running casing or cementing.

The caliper log/cement volume log from Adsett c-2-B shown in Figure 5 depicts the success of the silicate drilling fluids as a borehole stabilizer across the Ft. Simpson shale. A caliper log from a nearby offset well is shown for comparison. The average volume enlargement across the Fort Simpson shale was less than 1% and was a total of 11.7% throughout the intermediate section (Table 1). Most of the hole enlargement occurred under the casing shoe to a depth of 575 meters. In addition, the caliper log at the most troublesome points in the well from 750 to 1300 meters shows only slight wellbore enlargement (less than 15% by volume) over the zones from 700-750 meters and 850-900 meters.

**Lost Circulation and Pressures:** The major problems encountered in the drilling of the c-2-B well, and the determining factor in setting an intermediate string of casing, were lost circulation and high gas pressures. Large losses of silicate drilling fluid (over 20 $m^3$) started at 750 meters while drilling the Ft. St. John group. Simultaneous with losses in the Ft. St. John, the well would pressure up on connections with a resulting flow of fluid back into the wellbore. Increasing mud weight to 1190 $kg/m^3$ controlled the fluid influx, however losses continued at an average rate of 1-2 $m^3/hr$ while drilling.

Additional gas kicks at a depth of 1052 m were encountered upon entering the Debolt while drilling at a density of 1240 $kg/m^3$. Further gas kicks, typically high pressure but of rather low volume, occurred at 1077 meters, 1098 meters and 1126 meters. Attempts to control the gas kicks with increases in density invariably lead to further episodes of major lost circulation. At 1203 meters, mud density was decreased to 1210 $kgm/m^3$ to stem losses while still maintaining some control of pressure kicks. At this point, losses averaged 1 $m^3/hr$ while drilling with tank gains of 1-3 $m^3$ while tripping.

Further sharp gas kicks were taken at 1261 meters and 1296 meters while drilling the Shunda and Pekisko formations. Mud weight was raised to 1350 $kg/m^3$. The recurrent theme of losses while drilling and gaining fluid while tripping continued for a further 750 meters, well into the Ft. Simpson shale at 2064 meters. Gas influx was finally controlled by increasing mud density to 1465 $kg/m^3$. No further significant losses occurred to casing point at 2292 meters.

Losses of drilling fluid to the formation while drilling the entire intermediate section totalled 325 $m^3$. The large volume of losses, coupled with the high mud weight needed to control the gas influxes, lead to the decision to run intermediate casing prior to drilling the Sulfur Point and Slave Point potential sour gas bearing zones. Throughout all of the difficulties experienced with lost circulation and gas influxes, the wellbore stability conditions were excellent. Trips into and out of the well were excellent and the total amount of reaming was 5.5 hours.

While running intermediate casing, a further 40 $m^3$ of silicate mud was lost. The total amount of drilling fluid lost to the wellbore in the intermediate section was 365 $m^3$.

**Drilling Time/Rate of Penetration:** Silicate drilling fluids are commonly formulated using polymers for viscosity and filtration control. Bentonite is not a normal additive in silicate muds. As a result, an unweighted silicate fluid contains few solids but will be weighted, similar to a brine system. A 30% v/v silicate clear brine carries a base density of 1130 $kg/m^3$. It was expected that the heavier silicate fluid would drill at a similar rate to gel-chemical fluids since the amount of solids in the silicate fluid would be minimial, if unweighted.

The rate-of-penetration (ROP) of the silicate fluid was as fast or faster than the ROP on three close and recent offset wells (Table 2). Prior to 1050m on c-2-B, where lost circulation occurred, the ROP was 1.5 times faster than the average unweighted offset gel-chemical or gel-PHPA drilled wells. A portion of the increased ROP was likely due to a downhole motor used while drilling at c-2-B. However, the higher density silicate fluid did not adversely impact on the rate of penetration.

As the drilling fluid density was increased at c-2-B to handle gas influxes at depths over 1050 meters, the ROP decreased. Compared to the offset wells, where much higher densities were not required, the ROP at c-2-B was less than most of the offset wells. The use of a PDC bit from 1500 – 2064 meters was effective at providing a higher rate of penetation at c-2-B.

The c-2-B well was the pacesetter well in the Adsett area (Figure 4). Despite the 52 hours of lost time due to gas kicks and lost circulation, the benefits seen with the higher rates of penetration and good borehole stability led to the fast drilling time.

**Silicate Performance:** Prior to undertaking the c-2-B well, one of the unknowns of drilling the first well with 30% v/v silicate was the stability of the drilling fluid system in terms of rheology, filtration control, silicate ratio stability, silicate depletion, etc.. Ideally, the mud system should be easy to use with a minimum of fine tuning required to maintain good drilling fluid properties.

***Mud weight:*** The 30% v/v silicate mud had an initial mud weight in the range of 1150-1180 kg/m$^3$. Although the mud weight was initially high, the majority of the density was from the weight of the soluble silicate material. The total amount of solids in the unweighted mud system averaged 2-3 % with the concentration of bentonitic solids ranging from 12-20 kg/m$^3$. The silicate prevents the dispersion of clays into the mud which aids in keeping the solids concentration of the mud system relatively low. Figure 6 displays the changes in mud density with depth in the intermediate section. The mud weight of silicate was deliberately increased after a gas kicks in the Debolt section.

The drilling fluid was initially weighted with calcium carbonate, and then with barite as higher densities were required for the gas influxes. Neither the calcium carbonate or barite appeared to effect the silicate ratio, silicate concentration or drilling fluid rheology. It was speculated that because of the high pH of the drilling fluid (12.0 to 12.5), a high grade calcium carbonate source would be insoluble and have very little free calcium would be available for reaction with the soluble silicate. [(6)]

***Silicate ratio:*** The silicate ratio was measured a minimum or four times daily using a titration method to determine $Na_2O$ and $SiO_2$ content.[(7)] The daily average silicate ratio ($SiO_2$:$Na_2O$) is shown in Figure 7 and indicates that the silicate ratio was steady at ~2.0. The only significant decrease in silicate ratio occurred from 1350 – 1650 meters where sump water was used as the make-up water. A change back to fresh water saw the gradual rise of the ratio to near the 2.0 value. The silicate ratio stability at c-2-B suggests that $SiO_2$ and $Na_2O$ were being consumed at approximatly the same rate. This indicates that the silicate ratio did not need adjustment with either pure alkali (i.e. caustic) or a $SiO_2$ source (i.e. a high ratio silicate). In practise, daily additions of a base silicate material with a ratio of 2.0, should be able to provide the correct concentations of silicate and alkali.

***Silicate Depletion:*** Due to the lost circulation experienced at c-2-B, it was difficult to monitor the exact depletion rates of silicate. When lost circulation events did not occur or were less than 2 m$^3$/day, it appeared that over a 24 hour period approximately 1.5 m$^3$ of silicate needed to be added to maintain silicate and alkali concentrations. With an average circulating volume increase of 1.7 m$^3$/day, 0.5 m$^3$ of silicate was needed for volume and 1.0 m$^3$ was either lost on cuttings or through downhole losses.

***Mud Rheology:*** The mud demonstrated to have a relatively constant rheology. Figure 8 shows the rheological parameters stability in the intermediate hole section as a function of the varying density. The rheological stability with the silicate - polymer system was evident when the mud was weighted with $CaCO_3$ and $BaSO_4$.

In addition, the $CO_2$ contamination from the Debolt gas kicks did not affect either drilling fluid rheology or silicate concentration. The combination of a low 2.0 ratio silicate, the tolerance of polymers to $CO_2$ and a high concentration of silicate buffered the mud from any problems arising from $CO_2$ contamination.

## Conclusions

Drilling with a 30% v/v silicate drilling fluid represented the initial field trial of such a high concentration of silicate. While drilling of the Adsett c-2-B well did not meet all of the anticipated goals, a number of key conclusions on the use of silicates can be identified.

- A freshwater 30% v/v silicate drilling fluid provided excellent borehole stabilization properties across a variety of shale and sand sequences. The hole enlargement with the silicate fluid was less than 12% across the entire intermediate hole section and less than 1% over the Ft. Simpson shale.
- The rheological and other drilling flud properties of the silicate drilling fluid were easily obtained and maintained.
- The rate of penetration of the silicate drilling fluid was at least as fast, and up to 1.5 times faster than offset wells drilled with bentonite based systems.
- The silicate ratio of 2.0 was very easy to maintain in the mud system without having to use extra amounts of caustic or highly concentrated silicate fluid.

## Acknowledgements

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**TABLE 1 – COMPARISON OF VOLUME ENLARGEMENT IN INTERMEDIATE HOLE SECTION**

| Well Locatio | Mud System | % Volume Enlargement in Ft. Simpson only | % Volume Enlargement over Intermediate hole | Total meters drilled | Meters of Ft. Simpson |
|---|---|---|---|---|---|
| | | | | | |
| a-100-G/94-J-2 | gel PHPA | 34.7 | 26.3 | 1857 | 435 |
| c-12-A/94-J-7 | gel PHPA | 49.8 | 25.6 | 2030 | 550 |
| d-35-I/94-J-2 | gel PHPA | 58.8 | 44.0 | 2191 | 545 |
| **Average** | | **47.8** | **31.9** | **2026** | **510** |
| | | | | | |
| **c-2-B/94-J-7** | **30% v/v silicate** | **< 1** | **11.7** | **1903** | **519** |

**TABLE 2 – COMPARISON OF PENETRATION RATES IN INTERMEDIATE HOLE SECTION**

| Parameter | Well Locations * & Mud System | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | c-2-B silicate | d-35-I gel PHPA | d-81-I gel chem | c-12-A gel PHPA | a-100-G gel PHPA | b-81-G gel PHPA | b-64-G gel PHPA | c-57-G gel chem |
| Surf csg-1060 m | | | | | | | | |
| ROP (m/hr) | 19.2 | 18.9 | 17.4 | 17.8 | 8.5 | 8.7 | 9.9 | 10.6 |
| Mud weight (kg/m3) | 1195 | 1155 | 1145 | 1150 | 1120 | 1110 | 1085 | 1075 |
| WOB (daN * 1000) | 9 | 16-18 | 18 | 8-10 | 10-15 | 14-18 | 6-12 | 9-14 |
| | | | | | | | | |
| 1060-1500m | | | | | | | | |
| ROP (m/hr) | 3.0 | 5.0 | 5.9 | 3.2 | 2.7 | 4.1 | 3.2 | 3.4 |
| Mud weight (kg/m3) | 1350 | 1130 | 1100 | 1110 | 1120 | 1130 | 1085 | 1150 |
| WOB (daN * 1000) | 12-14 | 17-18 | 18 | 14-18 | 12-15 | 12-16 | 10-15 | 9-17 |
| | | | | | | | | |
| 1500-2000m | | | | | | | | |
| ROP (m/hr) | 4.8 | 4.2 | 6.2 | 3.8 | 8.7 | 4.8 | 4.6 | 3.3 |
| Mud weight (kg/m3) | 1430 | 1230 | 1145 | 1180 | 1110 | 1140 | 1100 | 1285 |
| WOB (daN * 1000 ) | 6-8 | 10-18 | 18 | 14-16 | 6-10 | 2-9 | 2-10 | 16-19 |
| | | | | | | | | |
| 2000-csg pt | | | | | | | | |
| ROP (m/hr) | 2.2 | 3.6 | 3.2 | 3.4 | 7.2 | 5.2 | 4.3 | 3.1 |
| Mud weight (kg/m3) | 1450 | 1225 | 1180 | 1180 | 1140 | 1160 | 1150 | 1295 |
| WOB (daN * 1000) | 16-19 | 6-13 | 18-19 | 15-16 | 8-16 | 12-18 | 10-16 | 15-19 |
| | | | | | | | | |

Complete Well Locations: c-2-B/94-J-7; d-35-I/94-J-2; d-81-I/94-J-2; c-12-A/94-J-7; a-100-G/94-J-2; b-81-G/94-J-2; b-64-G/94-J-2; c-57-G/94-J-2

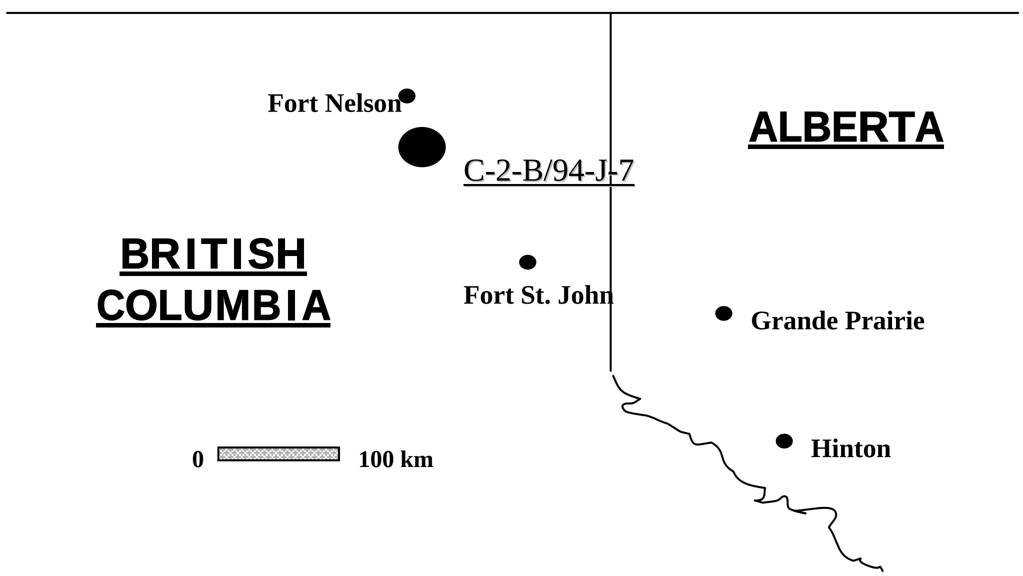


**Fig 1: Location of Canadian Hunter Adsett c-2-B/94-J-7 well in Northeastern British Columbia**

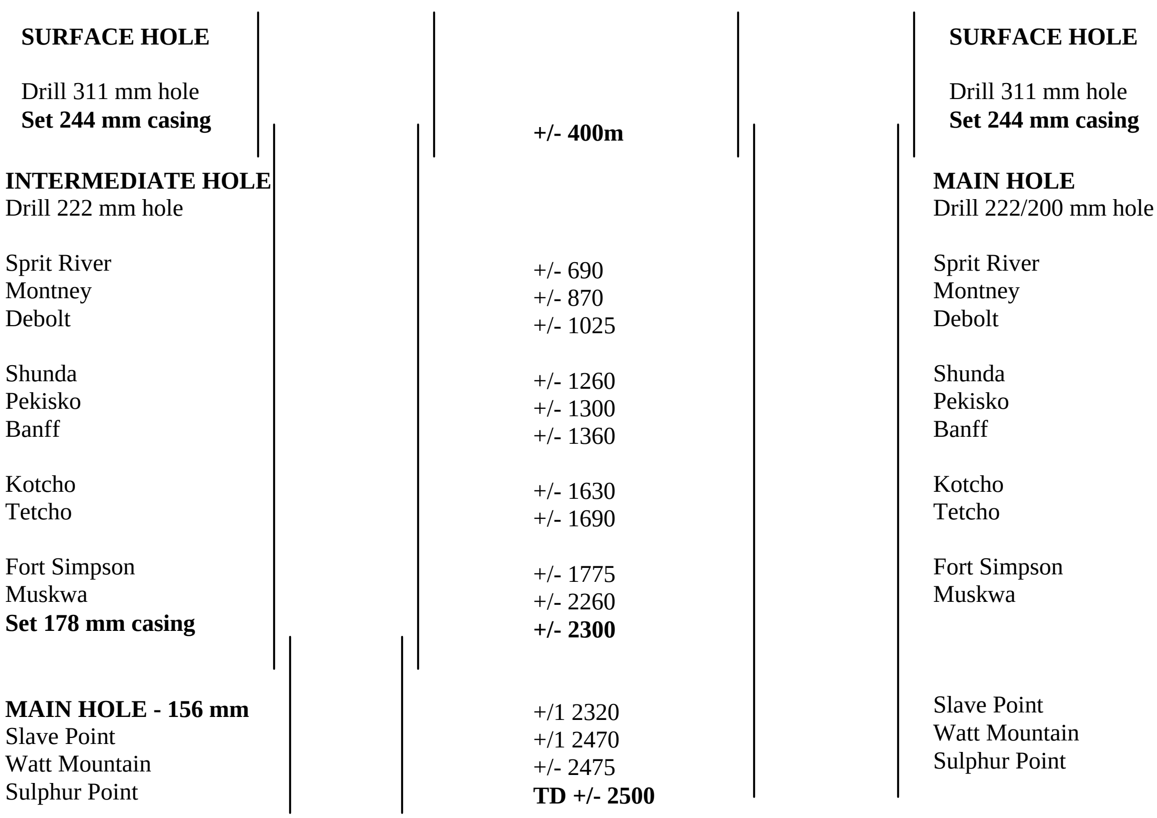


**Fig. 2 – Standard Casing Design with Intermediate String**

**Fig. 3 – Modified Casing Design without Intermediate Casing String. Fort Simpson Shale is not Cases Until Total Depth is Reached.**

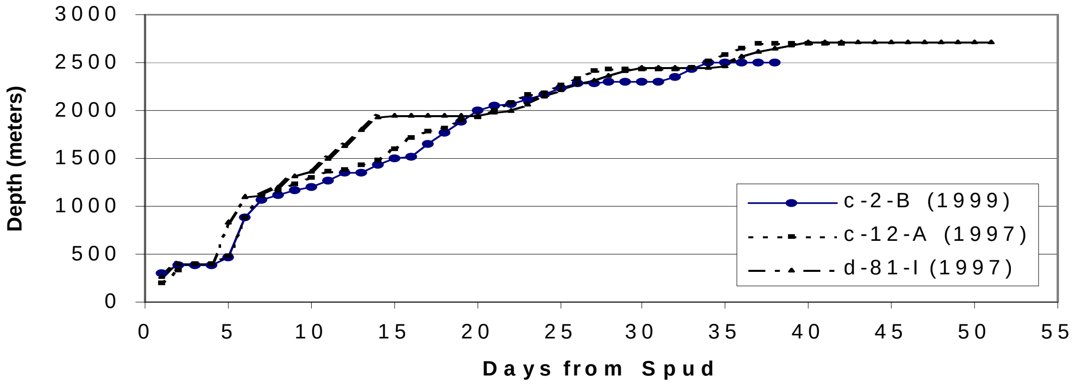


**Fig 4. – Depth/Days Progress Curves for c-2-B, Silicate Well, and most Recent Offset Wells. The Offset Wells were Drilled with Gel-PHPA Drilling Fluids and had Intermediate Casings Strings set at 2436 m (c-12-A) and 2444 m (d-81-I).**

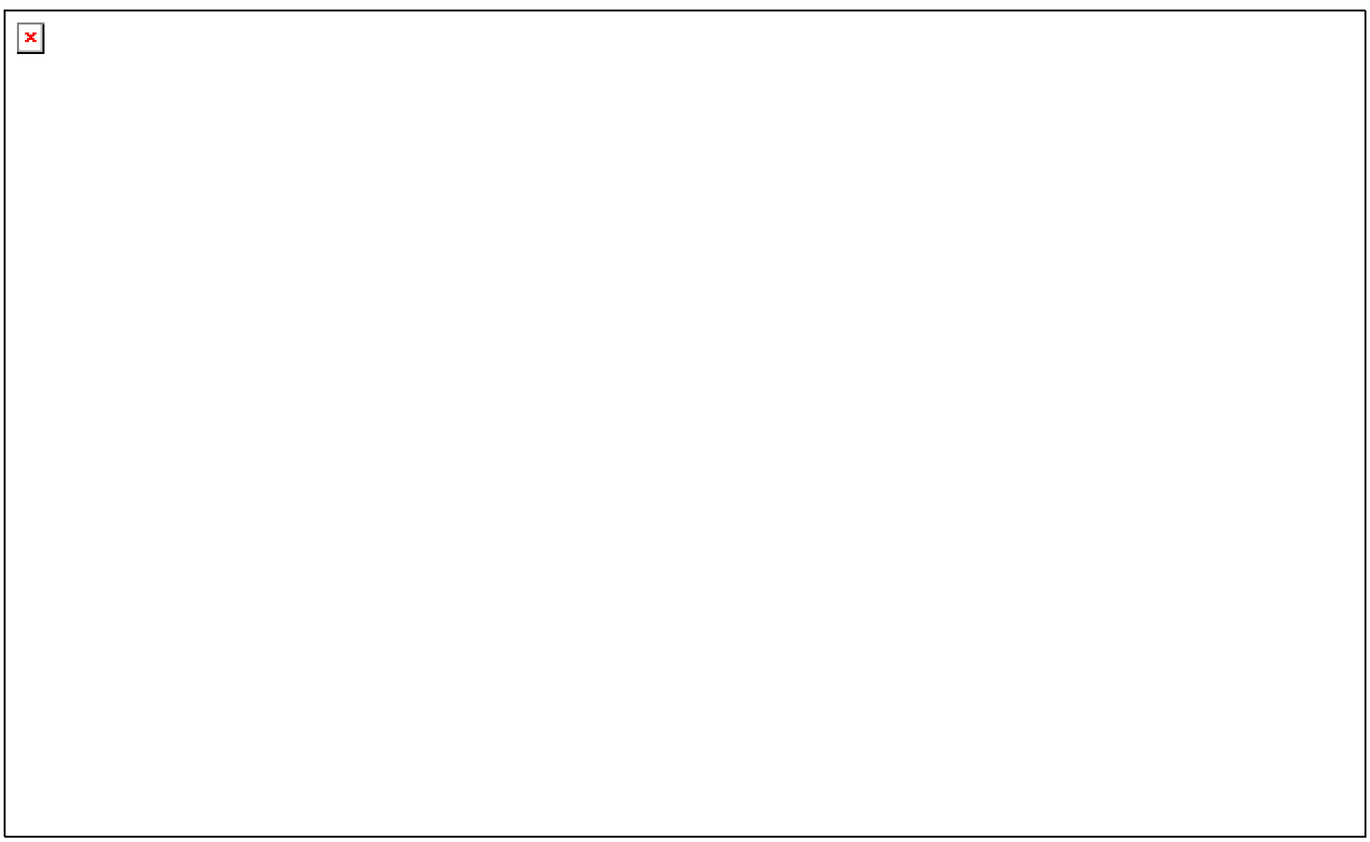

**Fig 5 – Caliper Log Comparison in Ft. Simpson Shale for c-12-A gel-PHPA (left) and c-2-B silicate (right) wells.**

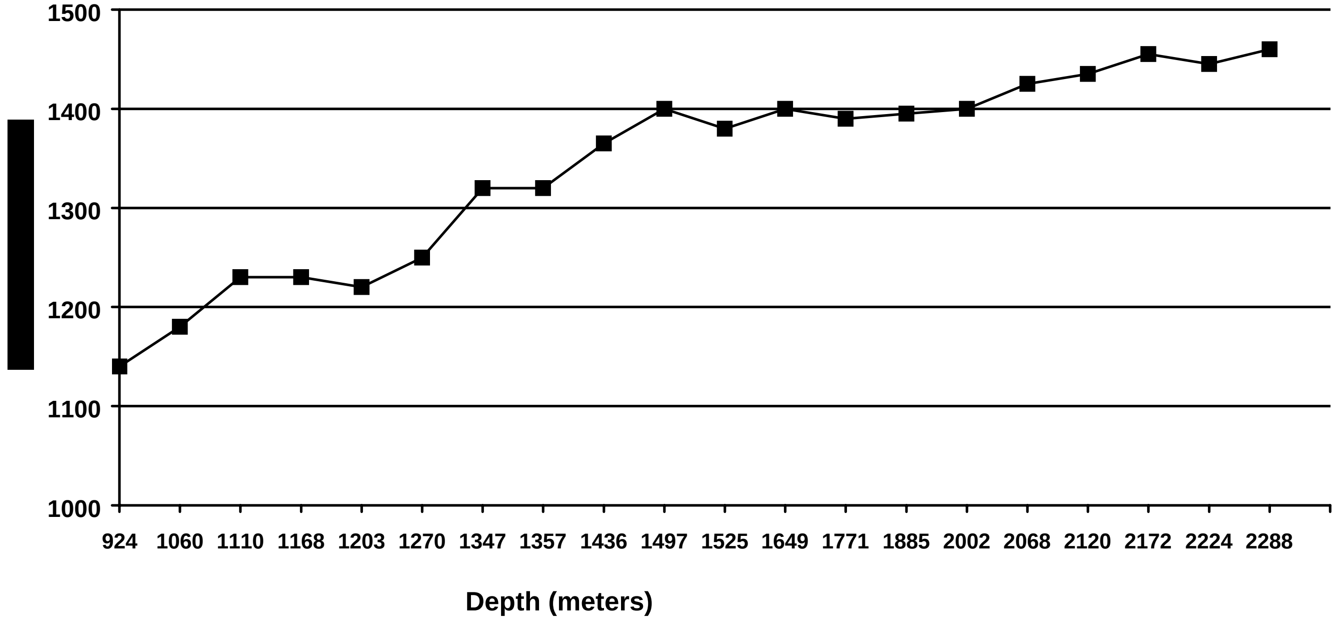


**Fig 6. – Plot of Drilling Fluid Density with Depth in the Intermediate Hole Section of c-2-B. Very Sharp Gas Kicks were Noted at 1051 meters, 1261 meters and 1296 meters. High Connection Gas and Background Gas was Observed from 1296 meters to Casing Point.**

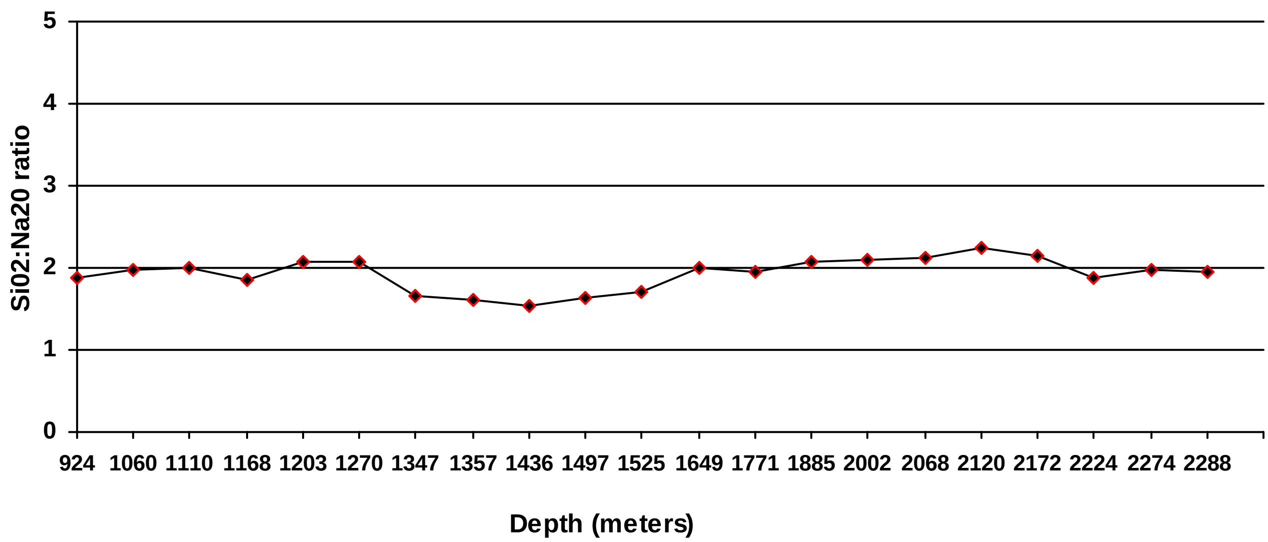


**Fig. 7 – $SiO_2$ and $Na_2O$ Ratio Maintained in Drilling Fluid at c-2-B while Drilling Intermediate Section. Ideal ratio of 2.0 was Consistent through the Section Except during the 1350-1649 meter Interval.**

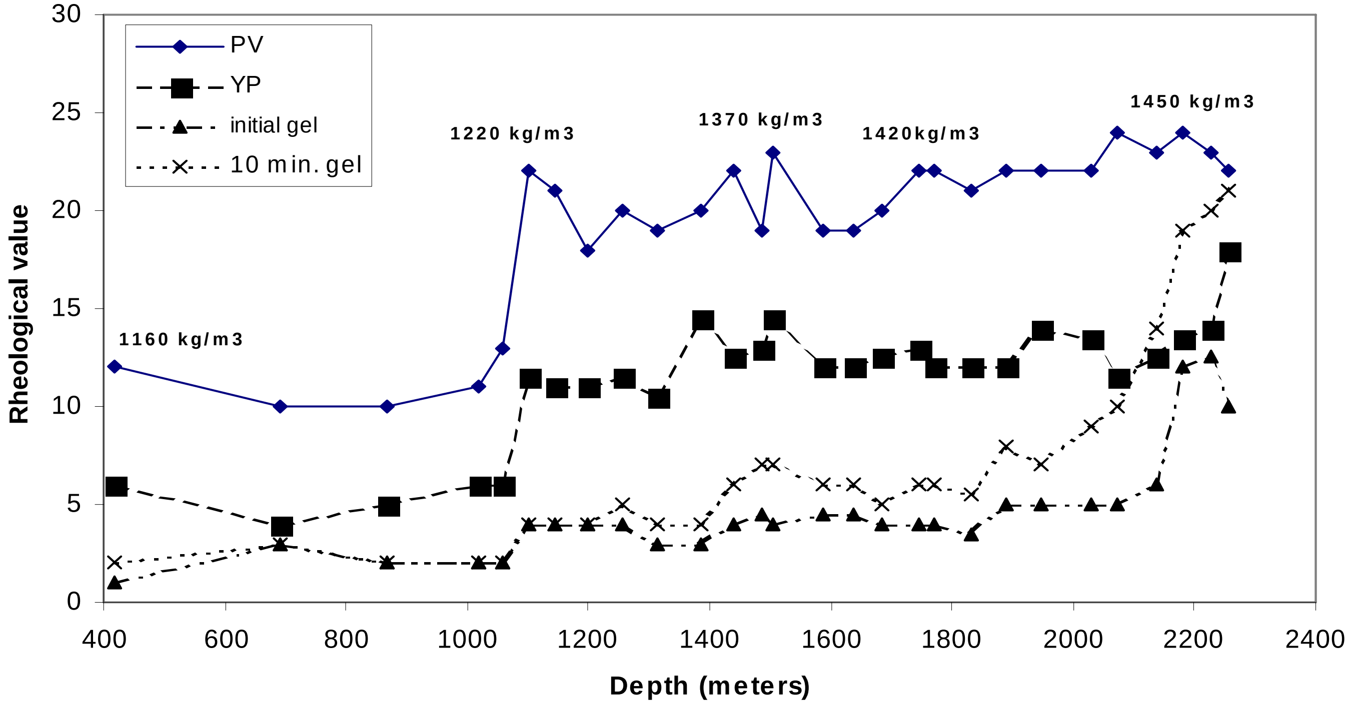


**Fig. 8 – Comparison of Rheological Parameters of Silicate Drilling Fluid in Intermediate Section of c-2-B Well. Increases in Density to Control Gas Influxes Increased Rheological Values. The Sharp Increase in YP and Gels near TD was Planned in Preparation for Running Logs. PV is Plastic Viscosity (mPa.s), YP is Yield Point (Pa), gel strengths are taken after 10 seconds and 10 minutes (Pa).**