Wellbore Stability Mechanism and Countermeasures of Igneous Formations in Shunbei Oilfield

Wenjian Zhong*, Yang Yu, Jingtao Liu and Shaoan Li
Petroleum Engineering Technology Research Institute of Sinopec Northwest Oil Field Company, Urumqi, Xinjiang, P.R.C

*Corresponding author email: Zhongwenj-xbj@sinopec.com

Abstract. Shunbei oilfield is located in the Midwest of Tarim Basin. Since 2018 many wells in the block have encountered broken formation, directional wells wellbore collapsed seriously, resulting drilling sidewells, with a huge loss of drilling costs. The influencing factors of igneous formation stability include internal and external factors. The internal cause refers to the formation instability caused by the strength anisotropy and strong in-situ stress nonuniformity of igneous formation. The external cause refers to various factors that cause the change of the external environment of the formation caused by drilling engineering, including the physical and chemical interaction between the drilling fluid and the formation, well trajectory and mechanical disturbance of the drilling string, etc. Based on the analysis of the influencing factors of wellbore stability in igneous rock, the technical countermeasures of wellbore stability in igneous rock formation are put forward and field tests are carried out. In the Permian fractured formation of Shunbei oil field, the idea of "prevention first, combination of prevention and blocking" is adhered to the first principles. Low density and low viscosity drilling fluid with low displacement is adopted to prevent the occurrence of lost circulation. The wellbore of the igneous rock intrusion in santamu formation of Ordovician is easy to collapse. By adopting special sealing structure and strengthening plugging and anti-collapse, combined with slurry plugging and well washing and refining engineering measures, the safe drilling of the igneous rock can be ensured.

1. Introduction
Shunbei oilfield is located in the Midwest of Tarim Basin, with an area of 19979km² and a resource of $1.7 \times 10^9 t$, including $12 \times 10^8 t$ oil and $5 \times 10^{11} m^3$ natural gas. Since the major exploration breakthrough in August 2016, the development speed of the block has been accelerating. However, since 2018, many wells in the block have encountered broken formation, directional wells have collapsed seriously and block has been blocked frequently, resulting in several times of back filling and sidetracking, resulting in huge loss of drilling cycle and economic benefits.

Shunbei oilfield is composed of a series of carbonate fault solution marine oil and gas reservoirs distributed along the fault zone with a buried depth of more than 7000m. It has the characteristics of oil-bearing and uneven enrichment along the fault zone as a whole. The geological prediction of Shunbeiy well deployed in this block is that in 7830-7920 m drilling, the fracture surface is encountered, the formation is broken and the stress is concentrated, and there is a huge risk of collapse and block falling in the process of directional drilling. The reservoir buried depth of Shunbei oil and gas field is 7600-8800m. There are igneous intrusions (covering an area of 117km²) in santamu formation of the oil and gas field. The borehole collapse pressure is very high.
2. Drilling Difficulties

Igneous rock refers to the rock formed by the condensation and crystallization of magma or lava flow under high temperature conditions. The igneous rock, which accounts for 95% of the total volume of the earth's crust, is widely distributed in different geological times around the world. The common igneous rocks are intrusive rocks (gabbro, diorite, granite), extrusive rocks (basalt, andesite, rhyolite), pyroclastic rocks (tuff, volcanic breccia, agglomerate, etc.), while the most common igneous rocks with wellbore instability are altered, weathered basalt, tuff and diabase, which often cause downhole complexity Accident, prolonging drilling cycle, increasing drilling cost, thus increasing exploration risk.

1) The thickness of Permian in Shunbei oil and gas field is 410-480m, and the microfractures between dacite (about 200m thick) and tuff are developed, which is easy to cause lost circulation. For example, well xb1-1h lost 25 times, 245.4m³ of drilling fluid and 260.8m³ of cement slurry when drilling in the Permian formation. It took a long time to deal with the downhole complex situation, resulting in an extended drilling period of 45.96d.

2) The Ordovician santamu formation of Shunbei oil and gas field contains igneous rock intrusion with high formation collapse pressure, which is easy to occur in drilling. For example, the top drive of xb1 well was frequently stopped after five spudding in, in order to prevent the block falling of the intrusive section, the density of drilling fluid was increased from 1.38kg/l to 1.86kg/l, but the lost circulation occurred immediately.

3) The rocks in the deep Paleozoic strata of Shunbei oil and gas field are soft and hard interlaced, the rock strength is greater than 100 MPa, and the drillability is poor, which seriously affects the ROP.

3. Factors Affecting the Stability of Igneous Rock

The influencing factors of formation instability include internal and external factors. The internal cause refers to the geological characteristics (sensitive shale instability, weak cemented sand conglomerate instability, weathered shell or broken body instability, rheological salt gypsum formation instability and strength anisotropic formation instability) [1-5]and the geomechanical characteristics (low strength formation instability, strong ground stress non-uniform formation instability, etc.); the external cause refers to the external environment of the formation caused by human activities such as drilling engineering Various factors changed, including physical and chemical interaction between drilling fluid and formation, well trajectory, mechanical disturbance of drill string and other engineering factors.

Similar to the conventional formation, the influencing factors of wellbore instability in igneous formation mainly include geological factors, mechanical factors, physical and chemical factors of drilling fluid, engineering factors, etc.

3.1. Geological and Mechanical Factors

The main diagenetic minerals of basalt and diabase are relatively stable pyroxene and unstable basic plagioclase. The source of rock debris, crystal debris and glass debris is extensive, and the mineral composition is complex. From the view of metasomatic alteration petrology, it is believed that the intermediate and basic igneous rocks, especially the pyroclastic rocks, are susceptible to argillization (argillization) under the action of hydrothermal solution (contact with the formation fluid under high temperature or higher temperature), and plagioclase is often altered into kaolinite and montmorillonite minerals. However, it is difficult to distinguish clay minerals one by one under the microscope, so there is little research on the specific argillization process of igneous rock at present[6-8].

The special structure of igneous strata is also a potential factor of wellbore instability. The existence of mechanical weak plane and strength inhomogeneous structure weakens the strength of rock mass greatly. The hardness of apricot body and basalt matrix in amygdalobasalt (the amygdaloid body is mainly composed of calcite, opal and chlorite) is quite different. During the drilling process, it is affected by the released in-situ stress, exciting pressure, mechanical collision and other mechanical factors, and it is easy to produce stress concentration at the amygdaloid body, which leads to the collapse of basalt stratum. However, the basalt with developed pores often shows different degrees of lost circulation in engineering. The strong heterogeneity of basalt makes it have different engineering properties: when drilling into cryptocrystalline basalt, it will not leak or collapse; when drilling into basalt with developed
pores, it will show different degrees of well leakage; when drilling into amygdaloid basalt, it will collapse seriously; when drilling into "composite" basalt, it will leak or collapse. Using the simplified schematic diagram of diabase with a single fracture, we can study the influence of any position point and any angle micro fracture on the collapse pressure of diabase formation on the surface of diabase well wall. The classical weak plane theory criterion can be used to evaluate the theoretical model.

\[ \sigma_\theta - \sigma_r = \frac{2(C_w + \tan \phi_w (\sigma_r - \alpha p_p))}{(1 - \tan \phi_w \cot \beta) \sin 2\beta} \]  

(1)

\( \sigma_\theta, \sigma_r \) - circumferential stress and radial stress on the wall surface, MPa; 
\( C_w, C \) - cohesion between fractures and bedrock of rock sample, MPa; 
\( \alpha \) - effective stress coefficient, dimensionless; 
\( p_p \) - formation pore pressure, MPa; 
\( \beta \) - angle between the normal direction of the fracture surface and the maximum principal stress, ° 
\( \phi_{w, r} \), \( \phi \) - refers to the internal friction angle between cracks, and the internal friction angle of rock sample matrix,

For vertical wells, the three principal stresses on the wall surface are \( \sigma_r, \sigma_\theta, \sigma_z \). The maximum principal stress and the minimum principal stress are \( \sigma_r, \sigma_\theta \) can be expressed as:

\[ \sigma_r = p_w \]  

(2)

\[ \sigma_\theta = \sigma_h (1 - 2 \cos 2\theta) + \sigma_h (1 + 2 \cos 2\theta) - p_w \]  

(3)

When the rock on the surface of the borehole wall does not slip along the micro fracture, the Coulomb Moore criterion can be used to calculate the formation collapse pressure, which is expressed as:

\[ \sigma_\theta - \alpha p_p = (\sigma_r - \alpha p_p) \cot \left( 45^\circ - \frac{\phi}{2} \right) + 2 C \cot \left( 45^\circ + \frac{\phi}{2} \right) \]  

(4)

The calculation formula of formation collapse pressure is as follows:

\[ p_w = \frac{\sigma_h + \sigma_h - 2(\sigma_h - \sigma_h) \cos 2\theta + \alpha p_p \left( \cot \left( 45^\circ - \frac{\phi}{2} \right) - 1 \right) - 2 C \cot \left( 45^\circ + \frac{\phi}{2} \right)}{2[\tan \phi_w + (1 - \tan \phi_w \cot \beta) \sin 2\beta]} \]  

(5)

If the rock on the surface of the shaft wall slips and loses stability along the micro fracture, the weak plane theory can be used, and the collapse pressure calculation formula can be expressed as:

\[ p_w = \frac{[\sigma_h + \sigma_h - 2(\sigma_h - \sigma_h) \cos 2\theta](1 - \tan \phi_w \cot \beta) \sin 2\beta - 2 C_w + 2 \tan \phi_w \alpha p_p}{2[\tan \phi_w + (1 - \tan \phi_w \cot \beta) \sin 2\beta]} \]  

(6)

Formulas 5 and 6 can be used to evaluate and analyze the borehole wall stability of diabase formation with microcracks, and calculate the equivalent density of collapse pressure used to stabilize the fractured diabase formation.

3.2. Physical and Chemical Factors of Drilling Fluid

The special petrologic characteristics of igneous strata determine the special physicochemical characteristics after the interaction with drilling fluid. If the drilling fluid can not effectively seal the formation fractures, the drilling fluid will enter the fracture surface along the fractures, which will reduce the sliding resistance of the rock along the fracture surface, reduce the rock strength, and increase the formation collapse pressure; on the other hand, the tuff and basalt mudstone in this type of formation are similar to the mudstone in nature, which is very easy to hydrate, expand and disperse, when the drilling fluid can not effectively inhibit the formation hydration, With the increase of soaking time, the wellbore will collapse. When part of the wellbore collapses, if the viscosity of the drilling fluid is low, it does not have good rock carrying capacity (the size of the falling block is often large), and it cannot clean the bottom of the well in time, it can also induce downhole complex situations such as sticking and reaming. In the process of drilling, if the annular velocity of drilling fluid exceeds the critical
velocity, the drilling fluid will form turbulence and erode the well wall, which will lead to well collapse; if the annular velocity is too low to effectively carry out the basalt falling block, it may cause downhole complex situations such as tripping, stuck, pump holding, lost circulation, etc. A large number of studies have proved that smectite is the main clay mineral in the igneous rock formation with wellbore instability, with high relative and absolute content. The physical and chemical properties of the formation are characterized by strong dispersion and / or expansibility. These clay minerals are often hydrated (in the form of expansion or dispersion) in contact with the drilling fluid filtrate that is not compatible, which leads to wellbore instability[9-12].

The composition and relative content of the igneous rock intrusions of santamu formation of Ordovician in Shunbei 1 well, the igneous rock bedrock and the fillings between the fractures of mudstone and queerqueke formation of Adong 1 well are measured and analyzed by using the indoor X-ray diffraction instrument. Table 1 and table 2 show the distribution of igneous rock and mudstone mineral components and content of Ordovician santamu formation in Shunbei 1 well. From table 1, it can be seen that the clay content of the igneous rock intrusive body of santamu formation is 33% - 38%, quartz content is 8%, 27%, calcite content is 30%, 15%, and quartz content is high. Generally, this kind of igneous rock has high rock strength, hard and brittle rock mass, and weak hydration effect. From table 2, it can be seen that the clay minerals of Ordovician santamu formation mudstone in Shunbei 1 well block are mainly Yimeng mixed layer, accounting for 91% and 88% respectively, but the mixed layer ratio is very low, indicating that the content of montmorillonite is very low, and contains a small amount of chlorite and kaolinite. It is judged that the mudstone of Ordovician santamu formation is mainly non expansive clay, with weak hydration and expansion capacity.

Table 1. Mineral composition analysis of Ordovician igneous rock in Shunbei 1

| NO. | Clay  | Quartz | Plagioclase | Calcite | Gypsum | Pyrite | Anatase | Pyroxene |
|-----|-------|--------|-------------|---------|--------|--------|---------|----------|
| 1   | 38    | 8      | 30          | 4       | 3      | 18     |         |          |
| 2   | 33    | 27     | 3           | 15      | 13     | 4      | 5       |          |

Table 2. Clay mineral composition and relative content of Ordovician santamu formation

| NO. | Kaolinite | Chlorite | Illite Montmorillonite Mixed | Mixed layer ratio |
|-----|-----------|----------|-----------------------------|-------------------|
| 1   | 38        | 8        |                             | 30                |
| 2   | 33        | 27       | 3                           | 15                |

3.3. Drill String Vibration

According to heliosantos et al., the chemical action between the hard formation (such as basalt formation) and the drilling fluid is not obvious. The vibration of the drilling tool will cause serious damage to the borehole wall, resulting in the increase of the well diameter expansion rate, which may be the key factor affecting the borehole stability. The lateral acceleration of the drill string at the bottom of the well is obtained by the near bit sensor, which can reach 784m / S2 in serious cases. According to Newton's second law, the impact force of 8-inch-per-foot kick in 12.25-inch borehole on the borehole wall is more than 5T, and the huge impact force causes direct damage to the borehole wall. At the same time, according to the law of conservation of momentum, it can be estimated that in the 2-inch annulus, the kinetic energy transmitted by the drill string to the borehole wall is as high as 8.4kj, which makes the internal energy of the formation increase significantly, promotes the generation of fracture area, and induces complex underground accidents.
4. Measures for Keeping Wellbore Stability in Igneous Formation

4.1. Permian Leakage Prevention Technology

The Permian system of Shunbei oil and gas field is composed of dacite and tuff interbedding, with developed fractures, easy lost circulation and low loss pressure. Therefore, prevention should be taken as the main measure, from "plugging as the main measure" to "prevention as the main measure and combination of prevention and plugging". Before drilling, the microfractures should be sealed to enhance the stability of the wellbore. Through indoor plugging evaluation test, the formula of plugging agent is obtained: 2% ultrafine calcium carbonate +1% bamboo fiber +1% unidirectional pressure plugging agent +2% cationic asphalt +2% nano emulsion. The drilling fluid with low density (1.23-1.25 kg / L), low plastic viscosity (15-20 MPa · s), low shear force (4-6 PA) and low displacement (30-33 L / s) shall be used for drilling. Solid control equipment shall be used to control the solid content of the drilling fluid, control the tripping speed, avoid producing large exciting pressure and make the bottom hole pressure less than the leakage pressure. 10% ~ 15% sealing slurry is injected before drilling (the main formula is 1% polymer gel + 3% bamboo fiber + 2% asphalt + 2% one way pressure plugging agent +2%SQD-98 (thin) +1%CXD), so as to avoid leakage during drilling.

4.2. Safe Drilling Technology for Igneous Rock Intrusion

The igneous intrusive body of Ordovician santamu formation in Shunbei oil and gas field is formed by magma intrusion upward. Poisson's ratio is 0.206-0.268, elastic modulus is 29.1-37.9 MPa, compressive strength is generally higher than 150 MPa, collapse pressure coefficient is 1.55-1.65, which shows the mechanical characteristics of hard brittle rock. Igneous rock will cause serious damage to the bit, and the borehole wall is prone to collapse. Microfractures will be formed in the process of igneous rock cooling. The key point of collapse prevention is to block the microfractures, prevent and slow down the pore pressure transfer. Therefore, 2.0% - 3.0% asphalt material + 2.0% ultrafine calcium carbonate + 0.5% - 1.0% PB-1 + 5.0% strong plugging agent are added into the drilling fluid to enhance the plugging performance. Before drilling into igneous rock intrusion, the density of drilling fluid shall be adjusted to 1.65 kg / L to strengthen stress support; during the drilling process, the thick slurry plug with funnel viscosity greater than 120 s shall be used in time to carry the downhole falling block, and the drilling method of "advance one retreat two" shall be adopted in the project to avoid downhole failure.

5. Conclusion

1) In the Permian fractured formation of Shunbei oil and gas field, it is easy to lost circulation. The idea of "prevention first, combination of prevention and blocking" is adhered to. Low density and low viscosity cutting drilling fluid with low displacement is adopted to prevent the occurrence of lost circulation.

2) According to the concept of "inhibition of hydration + film-forming isolation", the film-forming agent is optimized, and polyamine inhibitor and KCl are compounded to solve the problem of easy collapse when drilling Silurian water sensitive and hard brittle mudstone in Shunbei oil and gas field.

3) The borehole of Ordovician santamu formation igneous intrusions in Shunbei oil and gas field is prone to collapse. By adopting special sealing structure and strengthening plugging and anti collapse, combined with thick slurry plug well washing and refining engineering measures, the safe drilling of igneous intrusions is realized.

References

[1] Birchwood, R., Noeth, S., Hooyman, P., Winters, W., Jones, E., 2005. Wellbore stability model for marine sediments containing gas hydrates. In: The American Association of Drilling Engineers National Conference and Exhibition, pp. 5–7.

[2] Bobet, A., 2010. Characteristic curves for deep circular tunnels in poroplastic Rock. Rock Mech. Rock Eng. 43 (2), 185–200.

[3] Carranza-Torres, C., 2004. Elasto-plastic solution of tunnel problems using the generalized form
of the Hoek–Brown failure criterion. Int. J. Rock Mech. Min. Sci. 41(1), 629–639.

[4] Dickens, G.R., Quinby-Hunt, M.S., 1994. Methane hydrate stability in seawater. Geophys.Res. Lett. 21 (19), 2115–2118.

[5] Ding, Y., Luo, P.Y., Liu, X.J., Liang, L.X., 2018. Wellbore stability model for horizontal wells in shale formations with multiple planes of weakness. J. Nat. Gas Sci. Eng. 52,334–347.

[6] Fahimifar, A., Zareifard, M.R., 2009. A theoretical solution for analysis of tunnels below groundwater considering the hydraulic–mechanical coupling. Tunn. Undergr. Space Technol. 24 (6), 634–646.

[7] Fahimifar, A., Zareifard, M.R., 2014. A new elasto-plastic solution for analysis of underwater tunnels considering strain-dependent permeability. Structure and Infrastructure Engineering 10 (11), 1432–1450.

[8] Fuente, M.D.L., Vaunat, J., Marín-Moreno, H., 2019. Thermo-Hydro-mechanical coupled modeling of methane hydrate-bearing sediments, formulation and application. Energies 12, 2178.

[9] Gao, J.J., Deng, J.G., Lan, K., Song, Z.C., Feng, Y.T., Chang, L., 2017. A porothermoelastic solution for the inclined borehole in a transversely isotropic medium subjected to thermal osmosis and thermal filtration effects. Geothermics 67, 114–134.

[10] Zhao Zhiguo, Bai binzhen, he Shiming, Liu Biao. Ultra deep and fast drilling technology in Shunbei oilfield [J]. Petroleum drilling technology, 2017,45 (06): 8-13

[11] Liu Biao, pan Lijuan, Yi Hao, Li Shuanggui. Optimization design of wellbore structure of ultra deep wells containing diabase in Shunbei [J]. Petroleum drilling and production technology, 2016,38 (03): 296-301

[12] Zhao Hongshan, Feng Guangtong, Tang Bo, Zeng min. difficulties and technical countermeasures of speed-up of igneous drilling in Junggar Basin [J]. Petroleum machinery, 2013,41 (03): 21-26