Case study: Analysis of the correlation between casing deformation and fracture zone in Changning Block, Sichuan

Chen Zhaowei\textsuperscript{1,4}, Cao Hu\textsuperscript{1,2}, Zhou Xiaojin\textsuperscript{3}, Gou Qiyong\textsuperscript{3}, Zhang Haozhe\textsuperscript{1,2}

\textsuperscript{1} CNPC Engineering Technology R&D Company Limited, Beijing, China
\textsuperscript{2} China University of Petroleum (Beijing), Beijing, China
\textsuperscript{3} PetroChina Southwest Oil & Gas Field Shale Gas Research Institute, Chengdu, China
*Corresponding author: chenzwdri@cnpc.com.cn

Abstract: Casing deformation is an engineering problem that restricts the efficient development of shale gas in the Sichuan Basin. This paper analyzed the correlation between 67 casing deformation points and 256 fracture zones in the N201 wellfield, and conducted a statistical analysis of the distribution of the orientation of fracture zones, which may have/have not caused casing deformation. The Mohr–Coulomb criterion was used to analyze the stress state and the slip risk of these fracture zones. The results show indicate the following. (1) Fracture zone is the main factor leading to casing deformation. (2) Fracture zones with 60º–90º and 110º–120º orientations are likely to cause casing deformation, whereas fracture zones with 50º–70º orientation are relatively less likely to cause casing deformation. (3) The analysis of stress state shows that the orientations of high-risk fractures range from 74º–100º and 130º–160º, the orientations of medium-risk fractures range from 64º–74º, 100º–130º, and 160º–170 º, and the orientations of low-risk fractures are in the range of 0º–64º and 170º–180º. The theoretical results are basically consistent with the field statistical results. These results provide an explanation for the field statistical results in theory. This work not only demonstrates that a fracture zone is the major geological factor that causes casing deformation, but also provides a feasible method for us to predict the casing deformation in the future.

1. Introduction
Since 2009, China has begun to develop shale gas in the Changning and Weiyuan Clocks of Sichuan Province mainly using horizontal well and hydraulic fracturing technologies. Notably, casing deformation occurred in more than 30% of the horizontal wells during hydraulic fracturing. This not only led to a decreases in the number of viable fracturing stages, but also reduced the overall life cycle of the well. These phenomena can seriously restrict the efficient development of shale gas.

Many scholars have conducted studies on the problem of casing deformation in different aspects. For example, Hu et al. established a finite element model for two cases of cementing and non-cementing. Their results showed that under the condition of cementing, the deformation of the casing was greater, and the deformation was more concentrated near the fault. When the cementing was not strengthened, the deformation of the casing was smaller, and the deformation degree became more moderate \cite{1}. In two separate works, Chen et al. analyzed the regularity of field data and proposed that fault slip and hydraulic fracturing are the main geological (internal cause) and engineering (external cause) factors that lead to casing deformation, respectively \cite{2,3}. According to Li et al., the slippage of natural fracture surface is the ultimate cause of extremely serious casing deformation, whereas a cement sheath plays an auxiliary role in casing deformation \cite{4}. Wang et al. simulated the process of casing shear damage using finite element method and reported that the mechanism of
casing damage can be attributed to the slippage of shale reservoirs \[5\]. In separate studies, Guo et al. reported that fault slip can lead to casing deformation at the heel; moreover, there is a higher risk of casing deformation under the conditions of high external stress and internal pressure \[6-7\]. Meanwhile, Yin et al. established a three-dimensional (3D) finite element model with different casing wall thicknesses and angles between the casing and the fault. They described casing deformation with curvature and concluded that the maximum curvature of the casing decreased by only 8% when the casing wall thickness doubled; moreover, the maximum curvature of the casing decreased significantly with the decrease of the angle \[8\]. Xi et al. analyzed the multi-arm caliper data of shale gas wells in Western Canada and found that the proportion of shear deformation in this area is 52.2% \[9\]. In summary, most experts believe that casing deformation is caused by fault (fracture zone) slip induced by hydraulic fracturing. Furthermore, field engineers have also realized that fracture zones may be the major geological factor causing the occurrence of casing deformation. However, which fracture zones are more likely to cause casing deformation among so many fractured zones have yet to be investigated. Although finding a solution to this problem is important in solving the casing problem, only a few studies are available at present.

Thus, the current paper took the fracture zones of the N201 well field in Changning Block as the research object and studied the correlation between casing deformation and fracture zone. First, we investigated the correlation between the fracture zones by ant-tracking and microseismic signals, after which the location of casing deformation was statistically analyzed. Preliminary results indicated that the fracture zone is the main controlling factor of casing deformation. Second, 256 fracture zones were divided into two types according to whether or not they were correlated with casing deformation. Statistical data of the strikes of the two types of fracture zones were generated, and their distribution patterns were observed using rose charts. Finally, based on the Mohr–Coulomb criterion, the mechanical activities of the fracture zones were analyzed along with the slipping risks of the fracture zones in different directions. Comparing the field statistical results, we found that the strikes of fracture zones can easily slide in this block, thus providing a basis for predicting casing deformations in the future.

2. Statistics of correlation between fracture zone and casing deformation

The Changning shale gas area is located in Southwest part of Sichuan Basin, across Changning County, Gongxian County, Xingwen County, and Junlian County in Yibin, Sichuan Province. In the regional structure, this part belongs to the South Sichuan low steep bend belt and the Lou mountain fold belt. The Changning anticline structure is mainly developed in the area, the structure is relatively simple, and the overall direction is NWW-SEE. The N201 well field is located in the Southwest wing of the Changning anticline structure.

By September 6, 2019, 161 wells have been fractured in Changning Block, Sichuan Province. As there are 55 wells with casing deformation, the casing deformation ratio is 34.2%. The total effective abandoned length is 6737.5 m. The casing deformation statistics in Changning over the past years can be seen in Table 1. The table shows that the casing deformations before 2014 and in 2018 are the most serious, with deformation rates of as high as 60.0% and 53.3%, respectively.

| Time (year) | Number of fractured wells (number) | Casing change well number (number) | Casing deformation rate | Well Length abandoned (m) |
|-------------|-----------------------------------|-----------------------------------|------------------------|--------------------------|
| 2014 before | 10 | 6 | 60.0% | 1400.5 |
| 2015        | 21 | 4 | 19.1% | 1024.0 |
| 2016        | 21 | 3 | 14.3% | 0.0 |
| 2017        | 16 | 2 | 12.5% | 334.0 |
| 2018        | 45 | 24 | 53.3% | 2160.4 |
In view of the problem of casing deformation in shale gas fracturing, some papers [1-9] reported that faults can be considered as the major geological factor leading to casing deformation. In recent years, some techniques have been developed for small-scale fault recognition [10], including edge detection [11], intrinsic coherence [12], curvature body [13-14], ant-tracking faults [15-16], likelihood body [17-18], and azimuthal anisotropy inversion [19-20]. Ant-tracking faults technology has been applied to identify small faults scattered throughout the N201 well field and to compare the location correlation between small faults and casing deformation points. Taking platform M as an example, casing deformation occurred in 4 wells of platform M, comprising a total of 9 casing deformation points. Figure 1 presents the distribution of fracture zones identified by ant-tracking faults tracking technology on platform M. As can be seen, the red lines represent fracture zones associated with the casing deformation point. The blue lines indicate fracture zones that cross or pass the wellbore but do not cause casing deformation. The pink dots indicate casing deformation points. Out of 9 casing deformation points of platform M, 6 appeared around the fracture zone, accounting for 66.7% of the total. According to the statistics of the whole N201 well field, which we obtained using the same method (Table 2), there are 16 platforms and 67 casing deformation points in total. Among these, 57 are directly through or close to the fracture zone, accounting for 85.1% of the total.

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| Year | Count | Percentage | Total |
|------|-------|------------|-------|
| 2019 | 48    | 33.3%      | 1818.6|
| Total| 161   | 34.2%      | 6737.5|
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Figure 1. Distribution of fracture zones and casing deformation points on platform M
Table 2. Casing deformation points in the N201 well field

| Number | Well number | Casing deformation depth (m) | Is there any crack zone? | Number | Well number | Casing deformation depth (m) | Is there any crack zone? | Number | Well number | Casing deformation depth (m) | Is there any crack zone? |
|--------|-------------|-----------------------------|--------------------------|--------|-------------|-----------------------------|--------------------------|--------|-------------|-----------------------------|--------------------------|
| 1      | A-1         | 3274.6                      | yes                      | 24     | G-1         | 2795.0                      | yes                      | 47     | J-6         | 3094.0                      | yes                      |
| 2      | A-1         | 2789.5                      | yes                      | 25     | G-3         | 2973.0                      | yes                      | 48     | J-6         | 2615.0                      | no                       |
| 3      | A-3         | 2974.0                      | yes                      | 26     | H-3         | 3246.0                      | no                       | 49     | K-4         | 3100.0                      | yes                      |
| 4      | A-3         | 2587.7                      | yes                      | 27     | H-4         | 4026.0                      | yes                      | 50     | K-6         | 3816.1                      | yes                      |
| 5      | A-6         | 3488.7                      | yes                      | 28     | H-4         | 3815.0                      | yes                      | 51     | K-6         | 3638.0                      | yes                      |
| 6      | A-6         | 3412.9                      | yes                      | 29     | H-4         | 3761.0                      | yes                      | 52     | K-7         | 3394.5                      | yes                      |
| 7      | A-6         | 3277.7                      | yes                      | 30     | I-1         | 2829.0                      | yes                      | 53     | L-8         | 4158.4                      | yes                      |
| 8      | A-7         | 3623.0                      | yes                      | 31     | I-2         | 4208.0                      | yes                      | 54     | L-9         | 3722.8                      | yes                      |
| 9      | B-5         | 3930.0                      | yes                      | 32     | I-4         | 3910.0                      | yes                      | 55     | M-3         | 4222.0                      | yes                      |
| 10     | B-6         | 3509.8                      | yes                      | 33     | I-5         | 3399.0                      | yes                      | 56     | M-5         | 4885.8                      | no                       |
| 11     | B-6         | 2937.1                      | yes                      | 34     | I-5         | 3029.4                      | yes                      | 57     | M-5         | 4702.0                      | no                       |
| 12     | C-2         | 2560.0                      | yes                      | 35     | I-6         | 2000.0                      | yes                      | 58     | M-6         | 3818.0                      | no                       |
| 13     | C-6         | 3180.0                      | yes                      | 36     | I-6         | 3570.0                      | yes                      | 59     | M-7         | 4198.2                      | yes                      |
| 14     | D-1         | 3255.0                      | yes                      | 37     | J-4         | 3303.0                      | no                       | 60     | M-7         | 3931.0                      | yes                      |
| 15     | D-5         | 3004.0                      | yes                      | 38     | J-4         | 4331.0                      | yes                      | 61     | M-7         | 3734.6                      | yes                      |
| 16     | D-6         | 2860.0                      | yes                      | 39     | J-4         | 3839.7                      | yes                      | 62     | M-7         | 3694.0                      | yes                      |
| 17     | E-6         | 4121.8                      | yes                      | 40     | J-4         | 3772.0                      | no                       | 63     | M-7         | 3484.0                      | yes                      |
| 18     | F-1         | 3892.0                      | no                       | 41     | J-4         | 3610.2                      | yes                      | 64     | N-5         | 2320.0                      | yes                      |
| 19     | F-1         | 3853.0                      | no                       | 42     | J-5         | 3810.0                      | yes                      | 65     | N-7         | 2824.6                      | yes                      |
| 20     | F-1         | 3820.0                      | yes                      | 43     | J-5         | 3471.7                      | yes                      | 66     | O-4         | 4266.2                      | yes                      |
| 21     | F-2         | 3887.0                      | yes                      | 44     | J-5         | 2925.0                      | no                       | 67     | P-4         | 4355.0                      | yes                      |
| 22     | F-2         | 3741.7                      | yes                      | 45     | J-6         | 3352.0                      | yes                      |        |             |                             |                          |
| 23     | F-2         | 3613.0                      | yes                      | 46     | J-6         | 3195.1                      | yes                      |        |             |                             |                          |
Microseismic data can also be used to describe the fracture zones. We have established the following criteria for identifying fractures with microseismic signals: (1) most of the microseismic signals overlap, (2) the microseismic signals are linear, (3) microseismic signals with larger magnitudes appear, and (4) the microseismic signals are asymmetrical and far apart from the hydraulic fracturing sections. Due to the cost problem, not all wells have undergone microseismic monitoring. The collected microseismic data of 9 wells in 3 platforms (platforms I, J, and K) in the N201 well field are shown in Figure 2. As can be seen, the blue points represent the microseismic events (the size represents the magnitude), the gray line represents the well trajectory, the ellipses represent the fracture zones identified with microseismic data, the red dots represent the casing deformation points associated with the fracture zones, and the green dots represent the casing deformation points that are independent of the fracture zones. A total of 20 casing deformation points can be found in platforms I, J, and K. Of these, 15 deformation points associated with the fracture zone, accounting for 75.0%. Meanwhile, there are 5 deformation points that are independent of the fracture zone, accounting for 25.0% of the total.

According to the statistics above, the correlation between small faults and casing deformation is relatively strong. From the field statistical data, we can verify that the small faults and hydraulic fracturing are the main geological and engineering factors that lead to casing deformation, respectively [1-6].

3. Relationship between the strikes of fracture zones and casing deformation

The geological factor causing casing deformation is the fracture zone. Therefore, in order to prevent casing deformation, it is necessary to further explore the relationship between fracture zones and casing deformation. The main properties of fracture zones include the strike, dip, length, and density. This paper focuses on the statistical relationship between the strikes of fracture zones and casing deformation.

The tangent line of the fracture zone close to the wellbore is taken as the direction line of the fracture zone, as shown by the green line in Figure 1. The strikes of fracture zones related to the casing deformation data in the N201 well field are statistically analyzed. We identified a total of 16 platforms and 58 fractured zones, as shown in Table 3.

![Figure 2. Microseismic events and casing deformation points of platforms I, J, and K in the N201 well field](image)

Table 3. The strikes of fractures zones related to the casing deformation in the N201 well field

| Fracture zone number | Strike | Fracture zone number | Strike | Fracture zone number | Strike | Fracture zone number | Strike |
|----------------------|--------|----------------------|--------|----------------------|--------|----------------------|--------|
| 1                    | 0°     | 16                   | 86°    | 31                   | 68°    | 46                   | 75°    |
| 2                    | 72°    | 17                   | 33°    | 32                   | 60°    | 47                   | 114°   |
| 3                    | 72°    | 18                   | 45°    | 33                   | 44°    | 48                   | 27°    |
| 4                    | 123°   | 19                   | 26°    | 34                   | 70°    | 49                   | 26°    |
| 5                    | 67°    | 20                   | 87°    | 35                   | 107°   | 50                   | 33°    |
| 6                    | 70°    | 21                   | 116°   | 36                   | 107°   | 51                   | 36°    |
| 7                    | 82°    | 22                   | 68°    | 37                   | 34°    | 52                   | 111°   |
The distribution of fracture zones in the strike range is shown in a rose diagram. As indicated in Figure 3, the strikes of fracture zones associated with casing deformation in the N201 well field are mainly concentrated within the ranges of 60°–90° and 110°–120°.

The strikes of fracture zones crossing or passing the wellbore but not causing casing deformation in the N201 well field were also analyzed statistically. We counted a total of 198 fracture zones. Table 4 presents the statistical data.

| Strike Range | Number |
|--------------|--------|
| 48°–53°      | 8      |
| 0°–10°       | 9      |
| 67°–120°     | 10     |
| 120°–180°    | 11     |
| 72°–124°     | 12     |
| 77°–119°     | 13     |
| 113°–124°    | 14     |
| 82°–125°     | 15     |

Figure 3. The strikes of fracture zones related to the casing deformation in the N201 well field.

The strikes of fracture zones crossing or passing the wellbore but not causing casing deformation in the N201 well field were also analyzed statistically. We counted a total of 198 fracture zones. Table 4 presents the statistical data.
Table 4. Strikes of fracture zones crossing or passing the wellbore without causing casing deformation in the N201 well field

| Fracture zone number | Strike | Fracture zone number | Strike | Fracture zone number | Strike | Fracture zone number | Strike | Fracture zone number | Strike | Fracture zone number | Strike | Fracture zone number | Strike | Fracture zone number | Strike | Fracture zone number | Strike | Fracture zone number | Strike | Fracture zone number | Strike |
|----------------------|-------|----------------------|-------|----------------------|-------|----------------------|-------|----------------------|-------|----------------------|-------|----------------------|-------|----------------------|-------|----------------------|-------|----------------------|-------|----------------------|-------|
| 1                    | 100°  | 26                   | 70°   | 51                   | 57°   | 76                   | 118°  | 101                  | 68°   | 126                  | 117°  | 151                  | 86°   | 176                  | 71°   |
| 2                    | 75°   | 27                   | 43°   | 52                   | 85°   | 77                   | 148°  | 102                  | 52°   | 127                  | 53°   | 152                  | 97°   | 177                  | 154°  |
| 3                    | 56°   | 28                   | 121°  | 53                   | 72°   | 78                   | 105°  | 103                  | 52°   | 128                  | 61°   | 153                  | 97°   | 178                  | 110°  |
| 4                    | 31°   | 29                   | 64°   | 54                   | 83°   | 79                   | 51°   | 104                  | 34°   | 129                  | 114°  | 154                  | 71°   | 179                  | 112°  |
| 5                    | 64°   | 30                   | 49°   | 55                   | 95°   | 80                   | 39°   | 105                  | 67°   | 130                  | 59°   | 155                  | 68°   | 180                  | 98°   |
| 6                    | 30°   | 31                   | 30°   | 56                   | 114°  | 81                   | 36°   | 106                  | 70°   | 131                  | 30°   | 156                  | 31°   | 181                  | 116°  |
| 7                    | 146°  | 32                   | 84°   | 57                   | 108°  | 82                   | 56°   | 107                  | 87°   | 132                  | 69°   | 157                  | 105°  | 182                  | 102°  |
| 8                    | 69°   | 33                   | 51°   | 58                   | 62°   | 83                   | 61°   | 108                  | 87°   | 133                  | 68°   | 158                  | 97°   | 183                  | 81°   |
| 9                    | 162°  | 34                   | 90°   | 59                   | 65°   | 84                   | 67°   | 109                  | 87°   | 134                  | 35°   | 159                  | 127°  | 184                  | 119°  |
| 10                   | 89°   | 35                   | 90°   | 60                   | 27°   | 85                   | 51°   | 110                  | 79°   | 135                  | 80°   | 160                  | 107°  | 185                  | 102°  |
| 11                   | 82°   | 36                   | 0°    | 61                   | 63°   | 86                   | 57°   | 111                  | 66°   | 136                  | 10°   | 161                  | 90°   | 186                  | 116°  |
| 12                   | 70°   | 37                   | 118°  | 62                   | 90°   | 87                   | 94°   | 112                  | 70°   | 137                  | 38°   | 162                  | 75°   | 187                  | 125°  |
| 13                   | 128°  | 38                   | 34°   | 63                   | 58°   | 88                   | 114°  | 113                  | 66°   | 138                  | 45°   | 163                  | 60°   | 188                  | 127°  |
| 14                   | 119°  | 39                   | 68°   | 64                   | 109°  | 89                   | 88°   | 114                  | 79°   | 139                  | 56°   | 164                  | 78°   | 189                  | 108°  |
| 15                   | 127°  | 40                   | 28°   | 65                   | 80°   | 90                   | 109°  | 115                  | 54°   | 140                  | 100°  | 165                  | 96°   | 190                  | 153°  |
| 16                   | 99°   | 41                   | 164°  | 66                   | 52°   | 91                   | 77°   | 116                  | 59°   | 141                  | 114°  | 166                  | 89°   | 191                  | 52°   |
| 17                   | 135°  | 42                   | 67°   | 67                   | 49°   | 92                   | 63°   | 117                  | 64°   | 142                  | 93°   | 167                  | 111°  | 192                  | 88°   |
| 18                   | 147°  | 43                   | 78°   | 68                   | 177°  | 93                   | 162°  | 118                  | 156°  | 143                  | 90°   | 168                  | 96°   | 193                  | 59°   |
| 19                   | 45°   | 44                   | 76°   | 69                   | 93°   | 94                   | 69°   | 119                  | 57°   | 144                  | 100°  | 169                  | 156°  | 194                  | 46°   |
| 20                   | 143°  | 45                   | 49°   | 70                   | 81°   | 95                   | 72°   | 120                  | 89°   | 145                  | 19°   | 170                  | 132°  | 195                  | 54°   |
| 21                   | 169°  | 46                   | 76°   | 71                   | 80°   | 96                   | 66°   | 121                  | 142°  | 146                  | 63°   | 171                  | 108°  | 196                  | 69°   |
| 22                   | 109°  | 47                   | 73°   | 72                   | 62°   | 97                   | 37°   | 122                  | 101°  | 147                  | 111°  | 172                  | 104°  | 197                  | 72°   |
| 23                   | 116°  | 48                   | 60°   | 73                   | 50°   | 98                   | 112°  | 123                  | 124°  | 148                  | 20°   | 173                  | 55°   | 198                  | 108°  |
| 24                   | 117°  | 49                   | 38°   | 74                   | 56°   | 99                   | 96°   | 124                  | 52°   | 149                  | 66°   | 174                  | 37°   |
| 25                   | 108°  | 50                   | 51°   | 75                   | 47°   | 100                  | 62°   | 125                  | 89°   | 150                  | 75°   | 175                  | 94°   |
Similarly, a rose diagram is presented in Figure 4, which indicates that the strikes of fracture zones crossing or passing the wellbore without casing deformation in the N201 well field are distributed in the range of $0^\circ$–$180^\circ$ and are mainly concentrated within the range of $50^\circ$–$70^\circ$.

Figure 4. The strikes of fracture zones crossing or passing the wellbore without causing casing deformation in the N201 well field

According to the statistical results, the fracture zones related to the casing deformation in the N201 well field are mostly concentrated in the range of $60^\circ$–$90^\circ$ and $110^\circ$–$120^\circ$. The fracture zones crossing or passing the wellbore without causing casing deformation are mostly concentrated within $50^\circ$–$70^\circ$. However, we have yet to determine why some fracture zones cause casing deformation while others do not.

4 Mechanical activity analysis of fracture zones

In this section, we use the fault slip hypothesis \cite{21} to analyze the mechanical activity of fracture zones in different strikes and to explain the statistics presented above.

The sliding phenomenon of the fault surface is essentially a friction effect. The classical friction law was originally called the Amontons theorem. However, because of the thorough study of friction conducted by Coulomb, the friction law later became known as the Coulomb criterion. This is expressed as

$$\tau = S_n + \mu \sigma_n,$$

where $\tau$ is the shear stress on the fault surface, $\sigma_n$ is an effective normal stress on the fault surface, and $S_n$ is the internal cohesion of the fault surface. Given that the cohesion of natural fracture is very small compared with the shear stress and normal stress acting on the fault surface, it can be neglected. In addition, $\mu$ represents the friction coefficient. For different types of rocks, under high effective normal stress (greater than 10 MPa), the friction coefficient of the fracture surface is independent of sliding speed, surface roughness, and normal stress. The friction coefficient varies in a smaller range of $0.6$–$1.0$ \cite{22}. According to the Coulomb criterion, when the shear stress of fault surface is smaller than the sliding resistance ($\mu \sigma_n$), the fault remains stable, and when the shear stress approaches or exceeds the sliding resistance, the fault slips. The effective normal stress is defined as $\sigma_n = S_n - p_p$. If pore pressure (e.g., hydraulic fracturing) is increased, the effective normal stress is reduced, which may lead to the sliding of natural fractures.

Therefore, in order to determine whether or not the fault slips, we need to calculate the normal stress and shear stress on the fault plane. An intuitive calculation method is to use the three-dimensional (3D) Mohr circle, as shown in the figure below. Three main stresses, $\sigma_1$, $\sigma_2$, and $\sigma_3$, define the three Mohr circles, respectively. The point P between two small and large Mohr circles corresponds to the normal stress and shear stress in a plane in any direction. The specific method is to set the angle between the normal of fault plane and the $S_1$ and $S_3$ axes of the main stress as $\beta_1$ and $\beta_3$,:

$$\tau = S_n + \mu \sigma_n,$$
respectively. Then, we use $2\beta_1$ and $2\beta_3$ to first determine the points with two small circles, after which we draw the arc from the center of these two small Mohr circles. The intersection of these two arc lines is point P. When point P is on the Coulomb line, it is called the critical stress fracture \cite{23}, whereas when it is below the Coulomb line, the shear stress is smaller than the sliding resistance, and the fault is stable. When the point P is above the Coulomb line, the shear stress is larger than the sliding resistance, and the fault slips.

**Figure 5.** The shear stress and normal stress in any direction based on the 3D Mohr circle \cite{21}.

Next, logging and testing data are used to determine the magnitude and direction of in situ stress \cite{24}. In situ stress direction is mainly determined by electrical imaging logging data. Continuous borehole breakout can be observed from the imaging logging data of the N201 well field. According to the observed borehole breakout, we can infer the maximum in situ stress orientation, $S_{H\text{max}}$, which is 115°N. The direction of the in situ stress interpreted by several wells in the N201 well field is close to that of well N201 (the first well in N201 well field). The change of stress direction in this well field is small, as shown in Figure 6.

**Figure 6.** Distribution of geostress from the Wufeng Formation to the Longmaxi Formation in the horizontal well area of the Changning shale gas field

The vertical stress $S_{\text{vertical}}$ is determined based on density logging, and the equivalent density is about 2.6 SG. The original formation pressure $P_{\text{pore}}$ is 31.6 MPa, and the equivalent gradient is 1.4 SG. The minimum in situ stress $S_{\text{min}}$ is constrained by small-scale fracturing test data. The fracture closure pressure range is within 45.1–45.5 MPa, and the calculated equivalent density of $S_{\text{min}}$ is about 1.9 SG. Here, $S_{H\text{max}}$ is constrained by the observed borehole breakout. The uniaxial compressive strength of rock is between 65.0–75.0 MPa, and a caving width of about 60° is found at 2445.0 mTVD. The equivalent density of $S_{H\text{max}}$ is 3.5±0.15 SG.

The 3D Mohr circle and Coulomb failure line in the well area before fracturing can be established.
based on the fracture zone strike and in situ stress, as shown in Figure 7. According to the fault slip hypothesis \cite{21}, $\Delta P$ is the pressure difference required by the fracture to be activated. Under actual conditions, the pressure difference is equal to the difference between the actual fracturing pressure and the formation pore pressure. With a smaller $\Delta P$, the sliding risk is higher, and the pressure difference required for the slip of the fault is smaller. For the N201 well field, if the $\Delta P$ is about 0–800.0 psi (0–5.5 MPa), the fracture is of high risk, which is displayed in red; if the $\Delta P$ is about 800.0–1700.0 psi (5.5–11.7 MPa), the fracture is medium-risk, which is displayed in yellow; and if the $\Delta P$ is about 1700.0–2500.0 psi (11.7–17.2 MPa), the fracture is low risk, which is displayed in green.

**Figure 7.** Mohr circle diagram of the fracture zone in the N201 well field

In fact, the required $\Delta P$ is related to the angle between the fracture zone and $S_{H\text{max}}$. Therefore, this relationship should be described in the lower hemisphere stereonet. Figure 8 presents the strike diagram corresponding to the fracture zones in the mechanical analysis of the Mohr circle. As can be seen, the black solid line indicates the direction of $S_{H\text{max}}$. The point in the figure is the polar point of the fracture surface. The polar points are shown in three colors of green, yellow, and red according to intensity of the risks, namely, low, medium, and high sliding risks, respectively. The corresponding fracture zone strike lines are also presented using the green, yellow, and red colors. As shown in Figure 8(a), the strike of group I high-risk faults is about 87º±13º, with an angle of 28º±13º with the maximum in situ stress direction, whereas the strike of group II high-risk faults is about 145º±15º, with an angle of 30º ± 15º with the maximum in situ stress direction. As shown in Figure 8(b), the strike of group I medium-risk faults is about 69º±5º, with an angle of 46º ± 5º with the maximum in situ stress direction; the strike of group II medium-risk faults is about 115º±15º, with an angle of 0º–15º with the maximum in situ stress direction; and the strike of group III medium-risk faults is 165º±5º, with an angle of 50º±5º with the maximum in situ stress direction. As shown in Figure 8(c), among the low-risk faults, the strike of group I low-risk faults is about 32º±32º, with an angle of 83º±32º with the maximum in situ stress direction, whereas the strike of group II low-risk faults is about 175º±5º, with an angle of 60º±5º with the maximum in situ stress direction.
Comparing Figure 8 and Figure 3, we can see that the strikes of fracture zones associated with the casing deformation shown in Figure 4 are in the high-risk and medium-risk areas shown in Figure 8. Moreover, the strikes of fracture zones without casing deformation shown in Figure 4 are in the medium-risk and low-risk areas shown in Figure 8. The theoretical analysis results are consistent with the field statistical results, which we also explained. Notably, the in situ stress of the well area is relatively uniform, and the maximum horizontal stress direction slightly changes. This is the reason why all the well areas can be analyzed by using the Mohr–Coulomb criterion. In fact, there are some changes in the stress field in the well area, which can also explain why the local coincidence is not good. Alternatively, the fracture zones are more distributed within 60°–70°, which may be another reason for such a phenomenon.

This result not only proves that the casing deformation is caused by the sliding of fracture zones induced by hydraulic fracturing, but also provides a feasible method for predicting casing deformation. This method involves using the fault sliding hypothesis to analyze the pressure difference needed for the activation of fault, observing the fracture risks according to the lower hemisphere stereonet, and dividing the strikes into three risk levels: low, medium, and high. For the high-risk fracture zone, various measures can be taken, such as optimizing well trajectories, avoiding fracture zones, or optimizing perforations, using locations away from fracture zones, and so on.

5. Conclusion
(1) The correlation between the location of the fracture zones identified by ant-tracking faults and microseismic signals and the casing deformation points in the N201 well field is statistically analyzed. The results show that the fracture zone is the main controlling factor of casing deformation.
(2) The fracture zones identified by ant-tracking faults in the N201 well field can be divided into two groups based on the correlation between the fracture zones and the casing deformation points. The results show that the fracture zones within 60°–90° and 110°–120° are more likely to cause casing deformation, whereas the fracture zones within 50°–70° are less likely to cause casing deformation.
(3) The geomechanical model of the N201 well field is built to analyze the mechanical activity of fracture zones. The results indicate that the strikes of high-risk fracture zones are within 74°–100° and 130°–160°; the strikes of medium-risk fracture zones are within 64°–74°, 100°–130, and 160°–170°; and the strikes of low-risk fracture zones are within 0°–64° and 170°–180°. The theoretical analysis results are basically consistent with the field statistical results. Furthermore, the interpretation of the field statistical results is given in the corresponding theory.
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