The Main Controlling Factors of Glutenite Development and Their Impacts on Oil Energy Extraction

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Abstract: The glutenite reservoirs discovered in the Jiyang depression in Bohai Bay contribute greatly to proven oil and gas resources, which have reached 1.27 billion cubic meters. Both insufficient studies on the glutenite distribution and incomplete understanding of the corresponding geology restrict further oil energy extraction. Hence, it is necessary to study the controlling factors of glutenite development. Sedimentation, tectonic faults, geophysical data, etc., was used in this paper to study these factors. Four main controlling factors involved in the development of glutenite fan bodies have been studied and summarized: the fault ramp controls the glutenite fan, the fault characteristics control the glutenite acreage, the fault throw controls the thickness of the glutenite, and the dimensions of the incised valleys control the glutenite transport capacity. Based on this geological understanding, this paper analyzes the relationship between oil productivity data and the factors controlling conglomerate development. With this, the reservoir in the study area is divided into a high production area, medium production area, and low production area. The C913 well was deployed in the predicted high production area. The daily oil production reached 88 t/d, and the energy exploitation effect was good. Therefore, this study provides important guidance for the further extraction of oil energy.

Keywords: main controlling factors; incised valley; fault throw; glutenite; oil production

1. Introduction

The glutenite body is a kind of block-like geological rock body, which is composed of sandstone or conglomerate [1,2]. The glutenite reservoirs have a variety of rock types, such as sandstone, conglomerate, muddy conglomerate, sandy mudstone, etc. It can be developed as a single fan body or a group of fans superimposed together, and is usually developed in the steep slope zone of a continental faulted. The genetic types of glutenite include nearshore subaqueous fan, alluvial fan, turbidite fan, fan delta, etc. The seismic reflection of glutenite is strong amplitude in the top surface boundary, low frequency inside, and no obvious stratification. Glutenite oil and gas reservoirs are generally close to their provenance and have many development stages [3]. The reservoirs usually have large thicknesses, high productivity per unit area, and great exploration potential [4]. The lithology of glutenite reservoirs changes rapidly, the reservoir connectivity is difficult to describe, and exploration and development are difficult [5–8]. Therefore, to predict the distribution of glutenite bodies, it is first necessary to systematically study the characteristics and control factors of glutenite development.

The Chezhen Sag has the characteristics of a typical continental faulted lake basin in China. Its steep slope zone glutenite is extremely well developed. The oil and gas resources are approximately 150 million tons and form the main target for the next exploration [9]; however, since exploration began in 1996, only a few exploratory wells have obtained
economical oil production, which forms a large contrast with the excellent accumulation background. For example, the actual average daily oil production of the failed wells CD3 and GX13 is only 0.1 t/d. This may be due to the unclear distribution of glutenite bodies and unclear factors controlling development. Many scholars have analyzed the controlling factors for the development of glutenite fans and determined that the distribution of glutenite fans is mainly influenced by factors such as paleostructure, paleoclimatic fluctuations in lake level, and hydrodynamic forces [10,11]. At present, the control mechanism of these conventional factors on the development of glutenite bodies is relatively clear, but research work has found that the Chezhen Sag is rich in fault assemblages and fan types, and their controlling factors have not been systematically studied by scholars. This paper takes the glutenite body in the Guojuzi area of the Chezhen Sag as an example, studies the correlations of various characteristic parameters of the glutenite body distribution with the fault fan combination type, incised valley thickness and depth, and systematically explains the development of the glutenite. On the basis of the geological study, this paper links the main control factors of glutenite with the actual production of petroleum energy, and also provides a guidance to promote the oil production.

2. Geological Background

2.1. Location and Strata

The Chezhen Sag is a secondary depression in the northern part of the Jiyang Depression in the Bohai Bay Basin; to the east is the Zhanhua Depression, to the west is the Qingyun Uplift, to the south are the Wudi Uplift and Yihezhuang Uplift, and to the north is the Chengzikou Uplift (Figure 1). The Chezhen Sag is a rift-like continental basin with a narrow distribution from north to south and extends from east to west. The Guojuzi Sag is located in the Northeastern Chezhen Sag. The main faults include the Da 34 fault, Dawang Beida 35 nose structure, Guo 6 East fault, Chengdong Uplift, and secondary depressions divided by the Guo 4 and Guo 2 faults; Guojuzi is one of the three sub-sags in the Chezhen Sag.

The Paleogene strata in this area are divided into the Kongdian Formation, Shahejie Formation, and Dongying Formation from bottom to top (Figure 2). The glutenite mainly developed in the Shahejie Formation. The Shahejie Formation is divided into members 1, 2, 3, and 4 vertically. The fourth member is dominated by beach bar sand deposits in shallow lakes, the third member is dominated by nearshore underwater fans in deep lake and semideep lake environments, the second member is dominated by shallow beach bar...
deposits, and the first member is mainly developed in semideep lakes. Most submarine fans are deposited near the shore. The 2nd and 3rd members of the Shahejie Formation are the main layers where nearshore subaqueous fans of glutenite have developed.

Figure 2. Stratigraphic development characteristics (Es1, Es2, Es3, and Es4 are short for members 1, 2, 3, and 4 in Shahejie Formation Eocene).

2.2. Types of Glutenite Fans

In the northern steep slope zone of the Guojuzi area, various types of glutenite fans, such as alluvial fans, fan deltas, nearshore underwater fans, and turbidite fans, are widely developed (Figure 3). The remaining resources were approximately 220 million cubic meters, which were suitable for exploration. Important targets are alluvial fans, which are the products of weathering and denudation of parent rock carried by seasonal currents. They are fan-shaped deposits formed in locations where the slope of the terrain becomes gentler [12,13]. The alluvial fan is divided into fan root, fan middle, and outer fan. The braided rivers are present in the middle fan, where the reservoir with high porosity and permeability [14–16]. Fan deltas are fan-shaped deposits formed from high sediment inputs into stable water bodies. They are mainly composed of fan delta plains, fronts, and front fan deltas. Fan delta plains and fronts develop branch channels with high porosity and permeability; front fan deltas are mainly composed of silty clay, which consists of sandy clay and has poor physical properties [17–19]. Nearshore underwater fans are gravity flow fans in which sediments directly enter the deeper waters of lakes, and most of their deposits are close to steep banks [20,21]. According to the differences in the provenance supply capacity, these fans can be divided into thick layers and thin layers. The thick layers have well-developed fan roots but poorly developed fan middle sections and fan margins; thin-layered fan bodies have well-developed interlayers, while glutenite has...
small vertical thickness and poor fan roots. The margins of a neutralization fan are well
developed [22,23], the reservoir performance of the nearshore underwater fan margins
is better than that of the fan root. A turbidite fan is produced by retransport and sliding
of a nearshore underwater fan glutenite body [24–26]. Its main trigger mechanisms are
earthquakes, gravity, waves, and other external forces. Due to secondary transport or
long-distance transport, its maturity, roundness, sorting degree, and reservoir porosity and
permeability are higher than those of nearshore underwater fans.

Various types of glutenite fans, such as alluvial fans, fan deltas, nearshore underwater
fans, and turbidite fans, have different sedimentation slopes, water depths, and deposition
times. The sedimentation depths of nearshore underwater fans and turbidite fans are deep
and are mainly developed in the third member of the Shahejie Formation; alluvial fans
and fan deltas have relatively gentle sedimentary slopes and shallow water bodies and are
mainly developed in the second and fourth members of the Shahejie Formation.

3. Methods

The study area is an old oil production area with complete geological data. We col-
lected all 72 wells’ geological data, including structural information, seismic data, well strat-
ification data, rock section, oil production data, etc. The data are used for geological
restudies to predict high-oil production areas. The development of glutenite fans in the
study area may be affected by the characteristics of faults, fault throws, incised valleys,
and provenance supply. In this study, the single factor analysis method was used to analyze
the relationship between the four factors and the development of glutenite to determine
the controlling factors affecting the development of glutenite.

3.1. Fault Characteristics

To clarify the control of fault characteristics on the development of glutenite, the fault
characteristics are described in terms of three parameters: fault type, footwall block occurrence,
and hanging wall block lithology. Glutenite is described according to two parameters:
fan type and scale (Table 1). Their combinations are listed in order, and the geological data of the study area, such as geophysical data, logging data, and sedimentary facies distribution maps, are then obtained. The characteristics of glutenite development corresponding to the characteristics of faults in the study area are identified. Finally, the development characteristics of the fault-glutenite combination are determined, and the control relationship between the fault and the development of the glutenite fan is clarified.

### Table 1. Fault and glutenite characteristics.

| Fault Type          | Foot Wall Block Occurrence | Hanging Wall Block Lithology | Glutenite Fan Type                          | Glutenite Scale |
|---------------------|---------------------------|------------------------------|---------------------------------------------|-----------------|
| Planar fault        | Convex                    | Clastic rock                 | Alluvial fan, Fan delta                    | Large           |
| Listric fault       | Convex                    | Granite                      | Nearshore, underwater fan, Turbidite fan   | Small           |
| Step fault          | Concave                   |                              |                                             |                 |
| Ramp-flat fault     |                           |                              |                                             |                 |

3.2. Fault Throw

The formula for calculating the fault throw is: [27]

\[ D_i = H_i - h_i \]

Here, \( i \) represents a certain geological historical period, \( D \) represents the fault throw, \( H \) is the thickness of the footwall block, and \( h \) is the thickness of the hanging wall block. Assuming the basin subsidence amplitude is equal to the thickness of the sediment, the difference between the thicknesses on the two sides of the fault equals the difference between the subsidence amplitudes (Figure 4). According to the results of sequence stratigraphy in the study area, reliable stratigraphic units are determined and combined with drilling and regional structure data to calculate the fault throw.

![Figure 4. The calculation principle of fault throw in the study area.](image)

3.3. Incised Valley Development

First, the type of incised valley was determined by using the seismic profile observation method. The depth of the valley and thickness, width, and length of glutenite were measured, and the relationship between them was analyzed. Incised valleys are channels for the migration of glutenite, and their shape and size exert certain controls on the scale of glutenite. Different incised valley types correspond to different scales of glutenite. There are two causes of incised valleys: the first cause is paleomorphological lowlands and valleys formed by uneven denudation or secondary faults; the second cause is a valley controlled by a fault transition zone, which appears as the intersection of two or more faults, is often a place where multiple rivers converge, and is a channel for coarse clastic sediments to enter a lake basin.

Second, based on the seismic reflection characteristics of the corresponding Guojuzi area, the shape of the glutenite trench, the horizontal distribution range, and the vertical...
depositional thickness were determined. The relationship between the glutenite valley shape and its thickness and width was established (Table 2).

**Table 2.** Standards for classification of incised valley types.

| Glutenite Type    | Incised Valley Thickness/m | Incised Valley Width/m |
|-------------------|---------------------------|------------------------|
| Wide-deep         | 70–120                    | >2000                  |
| Narrow-deep       | 50–100                    | 1000–1500              |
| Wide-shallow      | 30–50                     | 1500–2000              |
| Narrow-shallow    | 30–50                     | <1000                  |

4. Results

4.1. Fault-Glutenite Types and Characteristics

Based on the geophysical data, combined with the different lithological characteristics of the hanging wall in the study area, a detailed study of the characteristics of fault type, source supply capacity, seismic reflection characteristics, development location, and scale of gravel fan rock was performed. The gravel fan bodies could be divided into eight categories (Table 3, Figure 5).

**Table 3.** Types and characteristics of glutenite bodies in the Guojuzi area.

| Fault Types     | Glutendiene Scale | Strata Occurrence | Seismic Emission Characteristics | Hanging Wall Lithology | Glutendiene Developmental Position |
|-----------------|-------------------|-------------------|---------------------------------|------------------------|-----------------------------------|
| Listric fault   | Small             | Convex            | High-angle oblique              | Granite                | At the slope                       |
| Planar fault    | Small             | Concave           | Low-angle oblique               | Granite                | At the slope                       |
| Step fault      | Small             | Concave           | High-angle oblique              | Granite                | In the fault corner                |
| Step fault      | Small             | Convex            | Low-angle oblique               | Granite                | Near the fault side of the step    |
| Ramp-flat fault | Mid-small-        | Convex            | Low-angle oblique               | Granite                | Near the fault side of the slope   |
| Ramp-flat fault | Large             | Convex            | Mound-shaped                    | Clastic rock           | Near the fault side of the step    |
| Step fault      | Large             | Convex            | Lamellar-shaped                 | Clastic rock           | At the foot of the slope           |
|                 |                   | Concave           | Lenticular-shaped               | Clastic rock           | In the groove                      |

4.2. Fault Throw

The fault throws of the layers in the Guojuzi area range from 310.5 to 1342.8 m (Table 4). The maximum value was located in the S4 layer fault in the G2 well area, and the minimum value was located in the S2 period fault in the Guo6 well area. In general, the faults around Well G2 and Well C913 were larger than those around Well G6.

**Table 4.** Fault throw in the steep slope zone of the Guojuzi area.

| Well | Layer | Fault Throw/m |
|------|-------|---------------|
| G2   | S2    | 855.1         |
| G2   | S3    | 916.9         |
| G2   | S4    | 1342.8        |
| G6   | S2    | 310.5         |
| G6   | S3    | 436.6         |
| G4   | S2    | 1047.3        |
| G4   | S3    | 1278          |
| C913 | S3    | 1311.2        |
|      | S3    | 1192          |

4.3. Incised Valley

4.3.1. Incised Valley Types

Six incised valleys mainly developed in Northern Guojuzi (Figure 3); among them, the source supply capacities of four incised valleys in the west were relatively small, and the scales of incised valleys 5 and 6 in the east were relatively large. According to their shapes, the incised valleys mainly include wide-deep, wide-shallow, narrow-deep, and narrow-shallow types (Figure 6), and their conveying capacities as migration channels differ. The wide and deep type had the strongest transport capacity and could form large-scale glutenite bodies; the wide-shallow type had strong transport capacity and could form medium-scale glutenite bodies; and the narrow and deep type had strong transport capacity and could form medium-scale glutenite bodies. The narrow and shallow type had the poorest transport capacity and could form small-scale glutenite bodies.

**Figure 5.** Types of glutenite bodies and seismic reflection characteristics in the Guojuzi area. (a). Listric-convex type-granite-small glutenite body; (b). Planar-concave type-granite-small glutenite body; (c). Step-concave type-granite-small glutenite body; (d). Step-convex type-granite-small glutenite body; (e). Ramp-flat-convex type-granite-small glutenite body; (f). Step type-convex type-clastic rock-large glutenite body; (g). Gentle slope type-convex type-clastic rock-large glutenite body; (h). Step-concave-clastic rock-large glutenite body.
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Figure 6. Types of incised valleys in the steep slope zone of the Guojuzi area.
4.3.2. Incised Valley Features

According to the incised valley characteristics statistical table for the Guojuzi area (Table 5), the study area contained all four incised valley types. Given the statistical results, the incised valley scale in the G2 well area was the largest, with the incised valley thickness as great as 116 m and the incised valley width as much as 3750 m. It is a wide and deep valley; the scale of the valleys in the G6 and G4 well areas was second only to that in the G2 well area; their thicknesses were greater than 70 m, and the incised valley widths were more than 2000 m. They were wide and deep incised valleys and narrow and deep incised valleys, respectively. In the D354 well area, there was a narrow and shallow incised valley with an incised valley thickness of only 39 m and an incised valley width of 482 m, making it the smallest incised valley in the region.

Table 5. Statistical table of incised valley characteristics in the Guojuzi area.

| Well | Incised Valley Thickness/m | Incised Valley Width/m | Type          |
|------|---------------------------|------------------------|---------------|
| D354 | 39                        | 482                    | Narrow-shallow|
| G4   | 73                        | 2170                   | Wide-deep     |
| G2   | 116                       | 3750                   | Wide-deep     |
| G6   | 45                        | 1565                   | Wide-shallow  |
| GX13  | 71                       | 1340                   | Narrow-deep   |
| G14  | 48                        | 1220                   | Narrow-shallow|
| CD3  | 59                        | 998                    | Narrow-deep   |
| C913  | 98                       | 2660                   | Wide-deep     |
| C918  | 42                       | 976                    | Narrow-shallow|

5. Discussion

5.1. Fault Characteristics Control Glutenite Development

5.1.1. Fault Characteristics

1) Types of boundary faults

The northern boundary of the Guojuzi area rifted along several main faults during its evolution, forming a “limited retreat type” boundary. The tectonic style and its activity patterns have caused obvious differences in the corresponding glutenite type [28–32], development scale, and reservoir performance. Specific faults and their combinations control the development of particular sand bodies and hydrocarbon reservoirs, and the types of boundary faults can be divided into planar fault, listric fault, step fault, and ramp-flat fault [33,34]. The area near a planar fault mainly develops thick layers of nearshore underwater fan deposits. The lithologies are coarse and mixed, and the stages are not obvious. Mudstone barriers are lacking, and the fan margin is poorly developed. The area near a listric fault mainly develops nearshore underwater fans, which are close to the fault. Compared with the fan body of a planar fault, front slump turbidite fans are relatively well developed, the glutenite is relatively thin, and certain mudstone interlayers are interlayered vertically. Step faults are a group of normal faults with approximately similar occurrence. The hanging wall of each fault declines in turn, and the profile presents a step shape. These areas are often composed of nearshore underwater fans and turbidite fans. Alluvial fans and fan deltas are also sometimes developed, nearshore underwater fans and fan deltas are often developed above two steps, and deep-water turbidite fans and slump turbidite fans form on lower steps. Ramp-flat fault is a fault that varies from steep to flat and back to steep again has a ramp-flat-ramp geometry at-ramp geometry. Alluvial fans and fan deltas are often present in the valleys between the main section and the buried hills, and the footwall of the faults close to the front are often encountered.

2) Stratigraphic occurrence of footwall block

The stratigraphic occurrences of footwall blocks in the Guojuzi area can be divided into convex and concave. The fault forms can be divided into planar fault, listric fault, step fault, and ramp-flat fault. According to their combinations, they can be divided into
eight types. The study area has mainly developed the following five forms: convex-listric combination, concave-listric combination, concave-planar combination, concave-step combination, and convex-ramp-flat combination.

Convex-listric combination (Figure 7a): The formation period of the convex strata in the study area basically coincided with the depositional period of glutenite, so the topography had a certain control on the deposition of glutenite. Glutenite was deposited in the low-lying places near the faults in convex strata; the shape was often lenticular, the scale was relatively small, and turbidites were mostly underdeveloped. Convex-ramp-flat (Figure 7b) combination: The deposition of glutenite was affected by residual mounds in the strata, most of which are deposited on the low-lying side of a convex mound near the fault. The scale of the glutenite that formed depends on the size of the space inside the residual mound. Alluvial fans and fan delta glutenite were mostly developed on the inner side of a remnant mound, and turbidite deposits were mostly developed on the outer side of a remnant mound.

![Figure 7](image-url)

**Figure 7.** The types of boundary faults and the distribution pattern of glutenite rock in the steep slope belt in Guojuzi area. (a). Convex-listric combination; (b). convex-ramp-flat combination; (c). concave-listric combination; (d). concave-step combination; (e). concave-planar combination).

Convex-listric combination, concave-planar combination (Figure 7c,e): Concave strata occurrences had large accommodation spaces; large glutenite deposits can be formed with sufficient provenance, and large glutenite bodies that easily slide can continue to form in front of a turbidite sand body. Concave-step combination (Figure 7d): Nearshore underwater fan deposits were mostly developed at one step of the ladder, and turbidite deposits were developed in concave strata. Due to the limited accommodation space at the second step, the scale of nearshore underwater fans was relatively small, and the scale of turbidite deposits was generally larger.

From the perspective of the development volume of glutenite, a concave strata combination was better than a convex strata combination, and the listric and planar combinations were mostly better than the step and ramp-flat combinations, depending on the development of the first and second steps.

(3) Lithologies on the hanging wall of faults

When studying glutenite deposits affected by faults, attention must be paid to the rock types of the hanging wall of the fault. Provenance lithologies with strong weathering resistance provide less sediment, and the scale of the glutenite body corresponding to its footwall is smaller. The Guojuzi area can be divided into granite and clastic rock hanging wall blocks. The weathering resistance of granite was stronger than that of clastic rocks, and the corresponding glutenite body on the footwall was relatively small. In contrast,
the volume of glutenite corresponding to a hanging wall with clastic rock was larger (Figure 3).

5.1.2. Fault-Ramp Control Glutenite Fan Type

There was only one main fault developed for the planar and listric faults (Figure 7a,e). The footwall mainly developed nearshore underwater fans. The water body was usually deep and little affected by waves, the porosity and permeability were low. When the water body was shallow, the waves could pass over the sedimentary fan. The nearshore underwater fan body after wave transformation had higher porosity and permeability.

There were two steps in the step fault (Figure 7d). When the water body of the upper step was deep, the main nearshore underwater fans were developed, and fan deltas developed locally. When the water body was shallow, fan or fan delta deposits were dominant. When the lower step had a deep-water body, it mainly developed turbidite fans. Under the influence of various trigger mechanisms, the sediments on the upper step might slide down the lower step to form a turbidite sand body. Under the condition of sufficient provenance supply, the lower steps developed nearshore underwater fan deposits.

There are three steps on the ramp-flat fault (Figure 7b). The upper steps have shallow water bodies, with mainly fan deltas and local alluvial fans. The thickness of glutenite in the low-lying Guojuzi area between the uneven denudation zone and the boundary was large, and the two steps were well developed. Nearshore underwater fan deposits and turbidite fan sand bodies were developed in front of the nearshore underwater fan.

Planar type and listric faults corresponded to the development of nearshore underwater fans. The upper steps of step faults developed nearshore underwater fans or fan deltas, and the lower steps developed turbidite fans. The high steps of slope-flat faults mainly developed alluvial fans and fan delta plain deposits. The middle steps developed nearshore underwater fans and fan delta fronts, and the lower steps developed deep-water turbidite fans and slump turbidite fans. Among them, step and sloped faults were limited by the accommodation spaces of the two steps, and their corresponding gravels were few. Thus, a listric or planar fault that developed on a main fault and its corresponding fan composed the most favorable combination for oil and gas resources.

5.1.3. The Fault Characteristics Control the Glutenite Acreage

The fault characteristics not only control the type of glutenite fan but also have a strong influence on the development area of the glutenite. According to the statistical results for different types of faults and their corresponding glutenite developmental scale (Table 6), it was found that a fault with granite in the hanging wall block corresponded to an average area of 0.14 km$^2$ for glutenite development, and the area of glutenite developed by faults with clastic rock in the hanging wall was 1.94 km$^2$ on average. The average area of glutenite faults with convex occurrence in the footwall block was 0.59 km$^2$, and the average area of glutenite associated with concave faults was 1.26 km$^2$. In terms of the development area of glutenite, clastic rocks were obviously better than granite, and concave faults were better than convex faults.

Table 6. Fault characteristics and development area of glutenite in the Guojuzi area.

| Fault Feature Type                          | Glutenite Development Area/km$^2$ |
|--------------------------------------------|----------------------------------|
| Listric-convex-granite type                | 0.08                             |
| Planar-concave-granite type                | 0.13                             |
| Step-concave-granite type                  | 0.17                             |
| Step-convex-granite type                   | 0.09                             |
| Ramp-flat-convex-granite type              | 0.26                             |
| Step-convex-clastic rock type              | 0.94                             |
| Gentle slope-convex-clastic rock type      | 1.42                             |
| Step-concave-clastic rock type             | 3.47                             |
5.2. Fault Throw Controls the Thickness of Glutenite

According to the relationship between the fault throw and the glutenite development index, there was a clear positive correlation between the fault throw and the thickness of the glutenite. The square value of the correlation coefficient was 0.7551, which shows that the thickness of the glutenite body increased with increasing fault throw (Figure 8). The fault throw can produce accommodation space for glutenite; in an active fault area, the accommodation space is generally large, so the thickness of glutenite also increases. This shows that the fault throw controls the thickness of the glutenite body.

![Graph showing the relationship between fault throw and glutenite thickness]  
**Figure 8.** The relationship between the fault throw and the thickness of a glutenite body.

5.3. Incised Valleys Control the Transport Capacity of Glutenite

The thickness, width, and length of glutenite indicate the ability of the incised valleys to transport sediments. The greater the thickness and width of glutenite are, the longer the extent, and the stronger the transmission capacity. Given the intersection of incised valley thickness and glutenite thickness, width, and length, the thickness of the incised valleys were considered positively correlated with the thickness, width, and length of the glutenite (Figure 9). Therefore, incised valleys controlled the transport capacity of glutenite.

![Graphs showing the relationships between incised valley depth and glutenite properties]  
**Figure 9.** The relationship between incised valley depth and glutenite thickness, width, and length.

5.4. Example of Energy Exploitation

The glutenite reservoir is a low-permeability tight one [8]. The traditional evaluation methods conventional parameters such as porosity and permeability cannot meet the requirements of fine exploration and productivity improvement [35,36]. Therefore, with the
help of relevant geological understanding, the identification of glutenite reservoir is more accurate and efficient by using the glutenite main control factors.

In well C916, which is located in the southeastern of the study area (Figure 3), the thickness of glutenite was 164 m with sufficient formation energy. The 8 mm nozzle was employed during the flow period. Additionally, the daily oil production was 79 t/d. The good exploration results from this well result in the other four development wells. However, the production of these new wells was very low and did not reach the expected productivity. The unclear understanding of the development law of glutenite fans leads to this failure. At present, there were 17 producing wells in the study area. The production data of these wells were compared with the main controlling factors studied in this paper, and the relationship between them was discussed.

A total of 11 development wells were located in the clastic rock hanging wall fault area. The other 6 wells were located in the granite hanging wall fault area. The average daily productions of these two well groups were 31.2 t/d and 5.4 t/d, respectively. It is not difficult to find that the oil productivity of the clastic hanging wall area was significantly better than that of the granite area (Figure 10). The data in Figure 11 could also reflect the relationships between oil well production and the fault throw, the incised valley depth, the incised valley width, respectively. All the factors were significantly positively correlated. The square values of the correlation coefficients were all about 0.8, which shows that the oil production increased with the enlargement of the fault throw, the incised valley depth and the incised valley width. We could conclude that more geological understanding of the glutenite directly accelerates the energy extraction.

| Hanging Lithology | Fault (m) | Incised Thickness (m) | Incised Valley Width (m) |
|-------------------|----------|-----------------------|--------------------------|
| Granite           | >780     | <55                   | >1200                    |
| Clastic Rock      | <780     | >55                   | <1200                    |

**Figure 10. The relationship between oil production and lithology of hanging wall.**

According to the actual situation of petroleum resource evaluation of glutenite in the study area, and referring to the study results of the same type reservoirs, we divide the glutenite reservoir into high producing areas, medium producing areas, and low producing areas (Table 7).
Table 7. Comprehensive evaluation standard of glutenite reservoir in the Guojuzi area.

| Reservoir Evaluation Parameters | Daily Average Oil Production (t/d) | Main Controlling Factors of Glutenite Reservoir | Conventional Reservoir Parameters |
|---------------------------------|-----------------------------------|-----------------------------------------------|----------------------------------|
|                                 |                                  | Hanging Wall Lithology | Fault Throw (m) | Incised Valley Thickness (m) | Incised Valley Width (m) | Porosity (%) | Permeability (×10^{-3} µm^2) |
| High oil production area        | >25                              | Clastic rock           | >1200           | >85                           | >2400                       | >12          | >3                           |
| Medium oil production area      | 10–25                            | Clastic rock           | 780–1200        | 55–85                         | 1200–2400                   | 10–2.7       | 0.2–3.2                      |
| Low oil production area         | <10                              | Granite                | <780            | <55                           | <1200                       | <5.1         | <0.4                         |
Under the guidance of this standard, it is predicted that the area around well C918 in the southeast is the high production area, the area around well G2, G4, and G6 in the middle of the study area is the medium production area, and the area near Well D354 in the northwest is the low production area. According to the prediction results of this paper, the C913 well was deployed in the high production area. The well was located in a fault area where the hanging wall lithology was clastic rock, and the fault throw was large. The corresponding incised valley was valley 6 (Figure 3), which was the largest valley in the study area. All the above factors were favorable for the development of glutenite fans, which were consistent with the controlling factors discussed in this paper. The daily oil production of the well reached 88 t/d, and the energy exploitation effect was good. The example of well C913 proved that the controlling factors of glutenite body discussed here had a positive effect on energy production and could be taken as the reference and guidance for the similar reservoir production.

6. Conclusions

1. Fault ramps control the glutenite fan type. Different faults have different water depths, which determine the type of glutenite. The footwalls of planar and listric faults mainly developed nearshore underwater fans. The upper steps of step faults mainly developed nearshore underwater fans; in the lower step, the was deeper, and mostly turbidite fans developed. The upper steps of ramp-flat faults mainly developed alluvial fans and fan delta plain deposits, the second steps (middle steps) developed nearshore underwater fans and fan delta fronts, and the third steps (lower steps) developed deep-water turbidite fans and slump turbidity.

2. The morphology of the footwall block of a fault in the study area could be divided into convex and concave, and glutenite developed on a large scale on concave strata. The lithology of the hanging wall of the fault could be divided into granite and clastic rock. A granite hanging wall corresponded to a small-scale glutenite body, and a hanging wall with clastic rock corresponded to a large-scale glutenite body.

3. Incised valleys control the transport and provide channels for the migration of glutenite. According to their shapes, there were wide-deep types, wide-shallow types, narrow-deep types, and narrow-shallow types. According to the relationship between the depth of the proximal valley near the glutenite in the mature exploration area and the thickness, width, and length of the glutenite, the transport index represents a method to predict the distribution range and thickness of glutenite by using the depth of nearby incised valleys. Six main incised valleys were developed in the northern part of Guojuzi, among which four incised valleys in the west had relatively small sediment supply capacities, while the eastern incised valleys 5 and 6 had relatively large sediment supply capacities.

4. Based on the analysis of the relationship between the main controlling factors of glutenite and oil productivity, this paper established an evaluation standard for glutenite reservoirs in the study area. The reservoir was divided into a high production area, medium production area and low production area. The high production area was located in the clastic rock hanging wall fault area, the daily average oil production was more than 25 t, the fault throw was more than 1200 m, and the thickness and width of the incised valley were more than 85 m and 2400 m, respectively. The middle production area was located in the clastic rock area, the daily average oil production was 10–25 t, the fault throw was 780–1200 m, and the thickness and width of the incised valley were 55–85 m and 1200–2400 m, respectively. The low production area was located in the granite hanging wall fault area, the daily average oil production was less than 10 t, the fault throw was less than 780 m, and the thickness and width of the incised valley were less than 55 m and 1200 m, respectively. Under the guidance of this standard, it is predicted that the area around well C918 in the southeast was the high production area. Newly developed oil wells in high-yield areas had a daily oil production rate of 88 t/d, and the oil energy production effect was very good.
Therefore, the main controlling factors of conglomerate development were of great significance to the oil production of similar reservoirs. Therefore, the main controlling factors of glutenite were of great significance to oil extraction.

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