Material constituents and mechanical properties and macro-micro-failure modes of tight gas reservoirs

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Abstract
In this work, a series of intensive laboratory tests are conducted to measure the material constituents, mechanical properties, and to examine macro-micro-failure modes of various types of rocks from tight gas reservoirs in the Da Qing oilfield in China. A set of key parameters are experimentally determined, including porosity, mineralogical compositions, microstructure, Young’s modulus, Poisson’s ratio, triaxial compressive strength, as well as macro- and micro-morphology failure modes. The relationships of these parameters are systematically analyzed, and the effects of the material constituents and microstructure characteristics such as cementation type, porosity, and mineral composition on rock mechanical properties are revealed as well as the patterns of micro- and macro-failures in types of rocks are investigated. The result shows that the micro-failure mainly exhibits features of transgranular and intergranular porous polymer fracture, and the macro-failure modes are mainly three types: shear-dominated, mixed shear–tensile and mixed tensile–shear. The mixed tensile–shear failure has mainly tensile fractures with branch fractures crossing each other, which forms a complex system fracture network. These findings are of importance for “sweet pot” evaluations, wellbore stability analysis, and hydraulic fracturing design for oil and gas production in tight gas reservoirs.

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Keywords
Tight gas reservoir, mechanical properties, failure modes, mineral composition, porosity, micro-
structure, grain size

Introduction

Tight gas reservoirs are generally defined as matrix permeability of less than 0.1 mD, matrix
porosity of less than 10%, gas saturation of less than 60%, and water saturation of greater
than 40% (Clarkson et al., 2012; Holditch, 2006; Walls, 1982). Due to the rapid decline of
the conventional reserves, tight gas reservoir with the characteristics of huge quantity of
reserves and extensive distribution has become an increasingly important strategic supple-
mentary resource in the energy industry (Aguilera, 2014; Dai et al., 2012). Because of the
poor fluid flow characteristics, it is important to expose as much rocks as possible to open
up more opportunities for the natural gas to enter the wellbore. Currently, horizontal well
drilling and multistage hydraulic fracturing are commonly used to improve well productivity
by creating efficient complex fracture networks (Panaghi et al., 2015; Spencer et al., 1991;
Xu et al., 2017). For economic and safe developments of tight gas reservoirs, the mechanical
characteristics of rocks in tight gas reservoirs is important for solving the mechanics insta-
bility of borehole and carrying out reservoir fracturing (Hart et al., 2012; Li et al., 2019; Zhu
et al., 2014, 2015). The mechanical characteristics are largely determined by material con-
stituents and environmental factors (Baud et al., 2014; Li et al., 2012). The material con-
stituents include mineral composition, microstructure, texture, and mechanical properties
(Engelder and Plumb, 1984; Jeng et al., 2004; Prikryl, 2001; Zhao et al., 2016). The envi-
ronmental factors include water content, confining pressure, stress path, loading rate, tem-
perature, etc. (Chen et al., 2017; Haimson, 2006). Material constituents such as porosity,
mineral composition, grain size, and microstructure are the most important factors that
influence the rock strength and deformability. Usually, lower porosity (Cantisani et al.,
2013; Jeng et al., 2004; Ulusay et al., 1994), higher quartz content (Bell, 1978; Bell and
Lindsay, 1999), larger grain size (Fredrich et al., 1990; Hatzor and Palchik, 1997; Meng and
Pan, 2007; Olsson, 1974; Robertson, 1955; Wong et al., 1996), greater grain contact
(Dobereiner and DeFreitas, 1986), and greater packing density (Bell and Lindsay, 1999)
result in a higher strength for rocks, such as granites, marbles, and sandstones. Also, a
denser (less porosity) or a finer (smaller grain size) texture generally resulted in higher
strength (Hatzor and Palchik, 1997, 1998). While such relations vary significantly as a
result of the natural diverse irregularity, and complex microstructure of rocks, there are
no universal relations which can be used for even a same type of rocks. Motivated by these,
the main objective of this research is to investigate mechanical characteristics of rocks in
tight gas reservoirs. A large number of laboratory tests have been performed to measure the
mechanical characteristics for granites, marbles, and sandstones at room temperature, of
which triaxial compress experiments, X-ray diffraction (XRD), scanning electron micro-
scope (SEM), and thin section observations were carried out for rocks of the tight gas
reservoir in Da Qing oilfield, and then stress–strain curves, strength and deformation char-
acteristics, fracture modes, mineral composition, and porosity were obtained in a given
pressure and temperature environment. It is revealed that the material constituents and
regularities affect the mechanical properties of rocks in tight gas reservoirs significantly.
Sample materials

Microscopic images of rock samples

First, a total of 18 rock samples of sandstone, sandy mudstone, sandy limestone, and sandy argillaceous limestone were cored from the Fu Yang and Gao Tai Zi tight gas reservoirs in Da Qing oilfield in China. In order to obtain the general relationship between the mechanical properties and material composition and porosity of tight sandstone reservoir rock samples, the core samples need to be macroscopic homogeneous without mechanical weak plane or joint plane. The cored samples are sliced into thin pieces. The cross sections of these slices are then examined using Quanta 450 multipurpose SEM (Figure 1). A set of microscopic images is obtained and shown in Figure 2. Cementation type, contact relation, interstitial material, particle size of the debris, and sorting features are observed and quantified from these images. The source of core rock samples and lithology evaluation results are summarized in Table 1.

According to cementation types, the rock core samples are divided into five groups from A to E, and the following characters are found from these microscopic images:

- For specimens A1 to A4, the cementation type is pore contact, the main contact type is line spot, the main interstitial filling is clay, and the grain size is from 0.03 mm to 0.25 mm.
- For specimens B1 to B5, the cementation type is membrane pore, the main contact types are spot and spot line, the main interstitial fillings are clay and little calcite, and the grain size is from 0.03 mm to 0.24 mm.
- For specimens C1 to C5, the cementation type is pore basement, the contact type is spot, the main interstitial filling is calcite, and the grain size is from 0.12 mm to 0.32 mm.

Figure 1. Quanta 450 multipurpose scanning electron microscope.
Figure 2. Images of microstructures of rocks viewed on a microscope.
For specimens D1 and D2, the cementation type is membrane, the contact type is spot line, the interstitial filling is calcite, and the grain size is from 0.03 mm to 0.20 mm. For specimens E1 and E2, the cementation type is pore, the contact types are line and spot line, the interstitial fillings are clay, calcite and other minerals, and the grain size is from 0.16 mm to 0.36 mm.

Porosity and mineral composition of sample materials

The porosity, mineralogical composition, and content are acquired by porosity and XRD experiments (Li et al., 2019). The instrument used in the experiment is TD-3500 X-ray diffractometer in Figure 3 produced by Dandong Tongda Technology Co., Ltd. The results are summarized in Figure 4.

The porosities of specimens are in a wide range of 1.68%–27.09%. The mineralogical composition, content of quartz, anorthose, calcite, clay, orthoclase, and ankerite have wide ranges of 13.8%–49.3%, 9.41%–62.7%, 0.86%–20.8%, 0%–32.54%, and 0%–2.56%, respectively. As is known, tight sandstone reservoir usually refers to the sandstone reservoir with porosity distribution less than 10%. However, many samples in the study have larger porosity, more than 10%, even up to 20%, such as samples of A1–A4, B5, C5, E1, and E2. The cementation types of these rock samples are mainly pore type or pore contact type, and the particle contact is mainly point and point line contact. The clay content is low and the degree of cementation is not high, which can be clearly seen in the microscopic images results in Figure 1. As a result, the pore channel between particles forms a favorable space or channel for oil and gas seepage and accumulation, which is a high-quality reservoir for oil and gas reservoir research.

Table 1. Core samples and lithology evaluation results.

| Sample number | Well number | Layer     | Depth (m) | Lithology                          |
|---------------|-------------|-----------|-----------|------------------------------------|
| A1            | Gao22       | Gao Tai zi| 1850      | Silty fine-grained lithic arkose    |
| A2            | Gao7        | Gao Tai zi| 2000      | Siltstone                          |
| A3            | Gao28       | Gao Tai zi| 2000      | Siltstone                          |
| A4            | Gao19       | Gao Tai zi| 2000      | Siltstone                          |
| B1            | Fu28        | Fu yu     | 1950      | Argillaceous siltstone             |
| B2            | Fu22        | Fu yu     | 1950      | Argillaceous siltstone             |
| B3            | Fu14        | Fu yu     | 1950      | Fine sandy siltstone               |
| B4            | Fu30        | Fu yu     | 1950      | Argillaceous siltstone             |
| B5            | Fu8         | Fu yu     | 2100      | Fine-grained lithic arkose          |
| C1            | Gao27       | Gao Tai zi| 1900      | Calcareous fine sandstone           |
| C2            | Gao21       | Gao Tai zi| 1900      | Calcareous medium sandy fine sandstone|
| C3            | Gao25       | Gao Tai zi| 1900      | Calcareous fine sandstone           |
| C4            | Gao29       | Gao Tai zi| 1900      | Calcareous fine sandstone           |
| C5            | Gao11       | Gao Tai zi| 1800      | Ostracoda layer                     |
| D1            | Fu11        | Fu yu     | 1970      | Silty fine-grained lithic arkose    |
| D2            | Fu15        | Fu yu     | 1970      | Fine sandy siltstone               |
| E1            | Fu10        | Fu yu     | 2100      | Medium sandy fine-grained lithic arkose|
| E2            | Fu31        | Fu yu     | 2100      | Fine sandy medium-grained feldspathic sandstone |
Triaxial experiments

Testing equipment and procedure
Second, the mechanical properties of these rocks from the tight gas reservoir were measured using a TAW-2000 triaxial rock mechanics experiment system (Figure 5). The maximum...
loading capacity of the servo-controlled system is 2000 KN, and the maximum confining pressure is 120 MPa. During the experiments, the axial force, axial deformation, and circumferential deformation are measured by load sensors, axial linear variable differential transformer (LVDT), and circumferential LVDT, respectively.

Cylindrical specimens are prepared with 25 mm in diameter and 50 mm in length (Du et al., 2016). The average depth of coring is 1100 m. Triaxial measurements are then carried out for each of the samples under the same condition after the axial and radial LVDT’s being installed. The minor in situ stress is about 13.25 MPa, which is set up as a uniform confining pressure. The load control pattern is used, and the rate of loading is set as a constant of 300 N/s until failure.

Stress–strain curve and failure modes

The triaxial stress–strain curves of the cored specimens under the same confining pressure are presented in Figure 5.

The findings from triaxial tests are summarized as follows:

- The stress–strain curves are all almost linear at low-stress levels, and these curves are quite close as shown in Figure 6.
- These curves rise up nonlinearly to their peaks, while deviating from each other. After reaching a peak, the stress dropped with increasing strain at different rates.
- The specimens go through three stages: elastic, yield, and destruction or plastic flow (A2) after the peak stress.
- The peak stress is the lowest for specimens A1 to A4, and highest for D1 and D2.
- The axis strains are all less than 3% except A2, and a large plastic deformation are observed in A2.
Rock mechanics

The mechanical parameters were calculated according to standard methods (Fairhurst and Hudson, 1999; ISRM, 1983), including Young’s modulus (E), Poisson’s ratio (μ), triaxial compress strength (TCS), triaxial residual stress, strain at peak point (εₚ), and elasticity strain (εₑ) for representing strength, deformation, and brittleness. The results are summarized in Table 2.

Figure 6. Stress–strain curve from triaxial experiments.
Discussions

The rock mechanical properties and failure modes are determined by material constituents (composition, texture, and structure) and experiment environmental factors (water content, confining pressure, stress path, loading rate, temperature, etc.). In this study, how these material constituents influence the mechanical behavior is analyzed.

For brittle rocks such as tight sandstone, marble, limestone, etc., when considering the relationship between porosity, grain size, material composition, and rock strength, the previous studies (Hall–Petch theory) mainly focused on the linear relationship between the porosity, the particle size, and uniaxial compression. In addition, some scholars considered the strength anisotropy of rock from the microscopic point of view and analyzed the influence of the shape optimization direction of mineral belt and crystal mosaic texture on the uniaxial compressive strength of rock. Because the analysis of the relationship between petrography, microstructure, and rock strength were based on the uniaxial strength without considering the effect of confining pressure, thus, the results lost universality and rationality. In consideration of this problem, Li et al. (2019) considered the influence of confining pressure and pore pressure on the compressive strength and elastic modulus of rock, and the influence of anisotropy changes in X, Y, and Z directions when they worked together with Daqing Oilfield. However, the core samples are mainly composed of siltstone and argillaceous siltstone. The premise of the research is that the samples have been idealized, and the samples with regular anomalies have been removed. In addition, due to the single sample of rock mineral composition, the research on the reaction of minerals and microstructure to macro- and micro-fractures has not been comprehensively considered. Based on the previous research results and deficiencies, the comprehensive research on the rock

Table 2. Measured or observed results for mechanical parameters.

| Code | E (MPa) | \(\mu\) | TCS (MPa) | TRS (MPa) | Failure mode |
|------|---------|--------|-----------|-----------|-------------|
| A1   | 3667.5  | 0.103  | 63.41     | 37.14     | Shear       |
| A2   | 4608.6  | 0.117  | 74.40     | 65.37     | Shear       |
| A3   | 4780.1  | 0.116  | 69.34     | 68.87     | Shear       |
| A4   | 5513.7  | 0.149  | 78.88     | 50.57     | Shear       |
| B1   | 8657.1  | 0.126  | 108.72    | 32.12     | Shear       |
| B2   | 11,811.8| 0.133  | 144.91    | 11.17     | Shear       |
| B3   | 11,880.0| 0.146  | 165.08    | 121.34    | Shear       |
| B4   | 13,008.6| 0.107  | 120.98    | 79.91     | Shear–tensile|
| B5   | 13,157.0| 0.124  | 208.14    | 111.46    | Shear       |
| C1   | 15,492.8| 0.138  | 180.78    | 112.57    | Tensile–shear|
| C2   | 16,046.2| 0.113  | 190.47    | 94.34     | Tensile–shear|
| C3   | 16,691.5| 0.133  | 164.64    | 78.04     | Shear–tensile|
| C4   | 17,820.9| 0.143  | 181.86    | 81.41     | Shear–tensile|
| C5   | 20,046.6| 0.118  | 205.60    | 84.62     | Shear–tensile|
| D1   | 18,638.8| 0.135  | 194.11    | 111.2     | Shear       |
| D2   | 19,681.1| 0.126  | 219.00    | 142.59    | Shear       |
| E1   | 15,775.3| 0.127  | 171.30    | 89.05     | Shear       |
| E2   | 19,847.7| 0.11   | 185.34    | 113.06    | Shear       |

TCS: triaxial compress strength; TRS: triaxial residual stress.
material, mechanical characteristics, and macro- micro-fracture model of the tight sandstone reservoir in Daqing Oilfield was carried out, which had far-reaching significance for the development of the tight sandstone reservoir in the later stage.

1. Through the systematic analysis of rock macro-strength analysis, it is concluded that the TCS strength of E2 is higher than that of E1, which may be due to the small crystal size of E1 rock sample, that is, the relatively low-energy consumption of crystal crack initiation and intergranular growth. The TCS of D2 is higher than that of D1, which is caused by the degree of cementation, which can be verified by clay content and thin section results in Figure 1. The TCS value of C1–C4 is relatively close due to their similar porosity, particle size, and mineral composition; C5 is damaged in the test and no comparison was made. The TCS value of B1–B5 is B5 > B3 > B4 > B1 > B2 from high to low. The higher the content of quartz and clay, the higher the cementation degree, the denser the rock, and the higher the rock strength. Similar results can be verified in B4 and B1 rock samples. The TCS of B3 is higher than that of B4, which may be caused by the smaller porosity of B3. The TCS of B5 is higher than that of B3, which may be caused by the grain size. There is little difference in the macroscopic strength of TCS of A1–A4 rocks. Compared with the maximum A4 and minimum A1, the TCS of A4 is higher than that of A1 may be caused by the smaller porosity and slightly higher clay content in A4. Generally speaking, the porosity of a rock sample is the largest, so its strength is the lowest. B sample has high clay content and the small porosity, leading to a high TCS. C sample has small porosity, large crystal size, high quartz, and calcium content, and its overall strength is high. D sample has low porosity and medium clay content, which makes its strength high; E sample has medium porosity, medium crystal size, and thus a medium TCS.

2. Under in situ stress, there is a high correlation between TSC strength and porosity of tight sandstone cored specimens, followed by the grain size of cored rocks; the correlation between elastic modulus, porosity, and permeability under in situ stress field of cored samples is consistent with the law of TCS, that is, they will increase with the increase of the mean grain size of rock particles but decrease with the increase of porosity, which can be verified by the porous fracture and sliding wing model in pore-emanated crack model (Baud et al., 2014) and empirical Hall–Petch relations (Fredrich et al., 1990). However, the overall correlation coefficient is relatively low under uniaxial strength, which may be caused by the enhancement of confining pressure of in situ stress field. What is more, under in situ stress, it can be concluded from the statistical analysis of mineral components and microstructure that TCS strength decreases with the increase of porosity. Besides, with the increase of crystal size, the TCS of rock is on the rise. With the increase of quartz and calcium content, TCS increases. With the increase of the percentage of feldspar, the TCS of rock shows a downward trend, which is due to the development of micro joints in feldspar minerals, and the energy consumption for the generation and expansion of micro cracks is much smaller than that of other minerals.

3. According to the fracture model under confining pressure, the fracture can be divided into shear failure, shear–tensile failure, tensile–shear failure, and tensile failure. Among them, the shear fracture is the most brittle, and it is easy to form brittle fracture network and shear self-supporting fracture after hydraulic fracturing, which is the favorable lithology for hydraulic fracturing. On the contrary, the main contribution of tensile fracture is Poisson’s ratio, which reflects the plasticity of rock. As a result, it is not easy to form complex fracture network after hydraulic fracturing, and its permeability and
conductivity are very low when proppant is insufficient. From the perspective of macro-fracture mode, with the increase of quartz content in reservoir rocks, its macro-fracture model appears mainly with shear failure. With the increase of calcium content in rock samples, the fracture model tends to be shear–tensile model, and the lithology tends to be brittle (Bell, 1978; Clarkson et al., 2012). In addition, compared with the micro image and the triaxial strength, it can be seen that the content of cement in porous rock is lower, the macro-triaxial compressive strength is low, as a result, the corresponding collapse pressure and the borehole stability is low, which may be a result caused by suffering a minor sedimentation or diagenesis (Hatzor and Patrick, 1998). As for the rock samples with high content of cement, of which the triaxial compressive strength is high as well as the collapse stress seems. The larger the content of cement, the higher the corresponding wellbore stability is. For reservoirs with high-calcium content, the fracture model displays mainly with shear–tension, which is easy to form complex fracture network after hydraulic fracturing. However, in terms of pure siltstone with high content of the quartz, which tends to form shear fracture after fracturing.

Mechanical parameters and material constituents

To investigate the relationship between the mechanical parameters and material constituents as well as porosity, the measured mechanical property results of Young’s modulus, Poisson’s ratio, triaxial compressive strength were plotted in Figure 5, together with porosity and material constituents of grain size, contents of in purities (quartz, calcite, orthose and anorthose, and clay), for all these 18 specimens. The specimen codes are shown in the horizontal axis. The measured Young’s modulus, Poisson’s ratio, and triaxial compressive strength are represented by histogram, and the value is displayed on the primary vertical axis. The porosity, grain size, and the contents of quartz, calcite, orthose, anorthose and clay are represented by various symbols connected by types of lines with values displayed on the secondary vertical axis.

From Figure 7(a), one can observe the overall quantitative relations between Young’s modulus and various material constituents. The contents of cementation type, porosity, grain size, quartz, calcite, and clay all have influence on Young’s modulus, but in different levels. The Young’s modulus is from low to high in pore contact, membrane pore, pore basement, and membrane and pore cementation. Young’s modulus has in general a negative correlation with porosity, and a positive correlation with grain size. For rocks with similar porosity and grain size, Young’s modulus decreases with the increase of the clay content, while increasing with the increase of quartz and calcite content.

Figure 7(b) reflects Figure 6 the overall quantitative relations between triaxial compressive strength (TCS) and the material constituents collectively. Also, the effect of cementation is similar with that to Young’s modulus. With the increase of porosity, TCS value decreases, while TCS will be enhanced with the increase of grain size. Figure 7(c) reflects the overall quantitative relations between Poisson’s ratio and the material constituents. Poisson’s ratio has no obviously relation with other parameters but the contents of orthose and anorthose, of which the Poisson’s ratio just increases a little. The effects of material constituents on the rock mechanical parameters are further analyzed quantitatively using curve fitting via the least-squares method and various basis functions. The quality of the curve fitting is represented by the correlation coefficient $R^2$: the higher the $R^2$ value, the stronger correlation
between the fitted curve and the data. Although the data are quite scattered ($R^2$ values are quite low) for these natural materials, some fitted curves are found and shown in Figure 8.

From Figure 8(a), we find that with increasing porosity, TCS value decreases as an exponential function with a reasonably high $R^2$ value of 0.633. Therefore, it can be confirmed that the porosity has a clear negative influence on the TCS of rocks, which is an understandable finding. Figure 8(b) shows that with increasing grain size, TCS value

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**Figure 7.** Mechanical parameters and material constituents as well as porosity measured for all core specimens. TCS: triaxial compress strength.
Figure 8. Relations of mechanic parameters and material constituents and fitted curves. TCS: triaxial compress strength.
increases logarithmically, with an $R^2$ value of 0.427. This shows that grain size in rocks has a positive influence on the TCS of a rock.

From Figure 8(c), it can be found that the porosity of a rock has a negative influence also on Young’s modulus. With the porosity increased, Young’s modulus decreases as an exponential function with an $R^2$ value of 0.668. On the other hand, with the increase of grain size, Young’s modulus $E$ increases as a logarithmic function with an $R^2$ of 0.423, seen in Figure 8(d).

From Figure 8(e), it can be found that the content of quartz and calcite has positive influence on TCS, but the confidence level is very low with an $R^2$ value of only 0.1012. On the other hand, with the increase of the contents of orthose and anorthoclase, TCS of rocks decreases as an exponential function with an $R^2$ of 0.162, seen in Figure 8(f).

From Figure 8(g), it can be found that the content of quartz and calcite has positive influence on Young’s modulus, but the confidence level is low with an $R^2$ value of 0.315. Figure 8(h) shows the influence of the contents of orthose and anorthoclase on Young’s modulus of rocks. It is obvious that the Young’s modulus $E$ decreases as an exponential function with an $R^2$ of 0.1185, seen in Figure 8(h).

Generally speaking, porosity and grain size of rock contribute the most to strength, followed by quartz, clay, and calcium content. Feldspar content also has some influence, but it is relatively weak.

**Macro- and micro-fracture morphology**

The macro-morphology fractures in all these 18 rock samples are shown in Figure 9. The cylindrical sample is 50 mm in length and 25 mm in diameter. Most of specimens exhibit rupture, frictional contacts between two fracture surfaces, and fragmentation flow (relative movement between particles or blocks and mutual crushing) (Figure 9), which indicates more brittle behavior at the macro-scale.

The failure patterns of rocks at macroscale can mainly classified in largely three groups. (1) shear-dominated failure modes, which are observed in specimens A1, A2, A3, A4, B2, B3, D2, E1, and E2; (2) Mixed shear–tensile failure modes, which are observed in specimens

![Figure 9](https://example.com/f9.png)

*Figure 9. Macro-morphology fractures characteristics of fractures in all these 18 rock samples.*
B1, B4, C3, C4, and D1; and (3) Mixed tensile–shear failure mode, which are observed in specimens C1 and C2.

The shear-dominated failure mode has a large plastic deformation with a crushed zone (A2 in Figure 9, for example). The major failure line is a shear band, which propagates through the entire specimens. The mixed shear–tensile failure mode has one main fracture with some branch fractures. The branch fractures mainly appear in the end of the specimen. The mixed tensile–shear failure mode has several main tensile fractures with a lot of branch fractures. The main tensile fractures are basically parallel to the axial loading direction, and the branch fractures have a small angle with respect to the axial stress direction that appear around the main tensile fractures. The main tensile fractures and branch fractures intersected with each other and formed a complex system of network of fractures.

The microscopic morphologies (Zhang et al., 2019) of fracture surface are shown in Figure 10.

Finally, Quanta 450 multipurpose SEM (Figure 1) is used to obtain the microscale images of the failure surfaces. At microscopic level, only local features can be viewed, and the failure surface images are significantly different from one type of rock to another, showing extremely complex nature of natural materials. Figure 10(a) shows the image of a local failure surface of A1. It shows a transgranular fracture, an intergranular fracture and a micro porous polymer fracture due to its high porosity, high content of quartz, and low content of clay and thus the highest brittleness, which can be proved by the low strain failure in the stress–strain curve. The shallow step pattern is the main form of transgranular fracture with the step direction indicated by the red arrows, which is caused by cleavage fracture.

**Figure 10.** Electron microscope images of fractograph in six typical specimens.
The steps are parallel to the crack propagation direction and perpendicular to the crack surface. In this pattern, the additional free surface is minimal and thus the required energy to generate such surfaces is also minimal. It also can be seen that the steps direction is random and messy for A1, A2, C2, D1, and E1. This may be due to the local isotropic behavior of these rocks with regard to deformability and strength. The step direction for B2 has a clear and consistent direction, which may be caused due to the local anisotropy with respect to deformability and strength. The quantity of steps is more in A1, A2, and B2, showing a greater amount of cleavage minerals for those specimens. The intergranular fractures are shown in cream color circles. Such fractures are formed and extended along the grain boundary, which can be clearly observed in A2 and E1. As shown in Figure 9, micro pores and micro cracks are found in C2, whose tracks are marked by blue lines. These micro cracks extend and join together, forming a complex system of network of fractures. The failure surface is both rough and smooth (some mirror place shown in green circle), indicating both plastic and brittle deformation occurred simultaneously in the failure process.

Conclusions

The microstructure, porosity, mineral compositions, mechanical properties, and macro-micro-failure modes have been experimentally studied for various types of rock in tight gas reservoirs in the Da Qing oilfield in China. The effect of material constituents on mechanical properties of rocks is determined. The following conclusions can be derived from the study.

Both Young’s modulus and triaxial compressive strength decrease significantly with the porosity increasing with the grain size, and contents of quartz and calcite.

- Poisson’s ratio increases a little with the increasing content of orthose and anorthoclase.
- The failure patterns of rocks at macroscale can be categorized in largely three groups. (1) shear-dominated failure modes; (2) Mixed shear–tensile failure modes; and (3) Mixed tensile–shear failure mode. The shear-dominated failure mode has a large plastic deformation with a crushed zone. The mixed shear–tensile failure mode has one main fracture with some branch fractures, which forms a complex system of network of fractures.
- At microscopic level, it can be viewed that local features, and the failure surface images are significantly different from one type of rock to another, showing extremely complex nature of natural materials. These local microscope features observed provide some support for the macroscopic failure modes.

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References

Aguilera R (2014) Flow units: From conventional to tight-gas to shale-gas to tight-oil to shale-oil reservoirs. *SPE Reservoir Evaluation & Engineering* 17(2): 190–208.

Baud P, Wong TF and Zhu W (2014) Effects of porosity and crack density on the compressive strength of rocks. *International Journal of Rock Mechanics and Mining Sciences* 67(4): 202–211.

Bell FG (1978) Physical and mechanical properties of the Fell sandstones, Northumberland, England. *Engineering Geology* 12(1): 1–29.

Bell FG and Lindsay P (1999) The petrographic and geomechanical properties of sandstones from the Newspaper Member of the Natal Group near Durban, South Africa. *Engineering Geology* 53: 57–81.

Cantisani V, Rubini A and Miniagio G (2013) CEUS and strain elastography in gastric carcinoma. *Journal of Ultrasound* 16(3): 123.

Chen G, Li T, Wang W, et al. (2017) Characterization of the brittleness of hard rock at different temperatures using uniaxial compression tests. *Geomechanics & Engineering* 13(1): 63–77.

Clarkson CR, Freeman M, He L, et al. (2012) Characterization of tight gas reservoir pore structure using usans/sans and gas adsorption analysis. *Fuel* 95(1): 371–385.

Dai J, Ni Y and Wu X (2012) Tight gas in china and its significance in exploration and exploitation. *Petroleum Exploration and Development* 39(3): 277–284.

Dobereiner L and DeFreitas MH (1986) Geotechnical properties of weak sandstone. *Géotechnique* 36(1): 79–94.

Du S, Shi R, Guan P, et al. (2016) New inspiration on effective development of tight reservoir in secondary exploitation by using rock mechanics method. *Energy Exploration & Exploitation* 34(1): 3–18.

Engelder T and Plumb R (1984) Changes in in situ ultrasonic properties of rock on strain relaxation. *International Journal of Rock Mechanics and Mining Sciences & Geomechanics Abstracts* 21(2): 75–82.

Fairhurst CE and Hudson JA (1999) Draft ISRM suggested method for the complete stress-strain curve for intact rock in uniaxial compression. *International Journal of Rock Mechanics and Mining Science & Geomechanics Abstracts* 36(3): 281–289.

Fredrich JT, Evans B and Wong TF (1990) Effect of grain size on brittle and semibrittle strength: Implications for micromechanical modelling of failure in compression. *Journal of Geophysical Research Solid Research* 95(B7): 10901–10920.

Haimson B (2006) True triaxial stresses and the brittle fracture of rock. *Pure and Applied Geophysics* 163: 1101–1130.

Hart BS, Pearson R and Rawling GC (2012) 3-d seismic horizon-based approaches to fracture-swarm sweet spot definition in tight-gas reservoirs. *The Leading Edge* 21(1): 28–35. Interpreter’s corner.

Hatzor YH and Palchik V (1997) The influence of grain size and porosity on crack initiation stress and critical flaw length in dolomites. *International Journal of Rock Mechanics and Mining Sciences* 34(5): 805–816.

Hatzor YH and Plachik V (1998) A microstructure-based failure criterion for Aminadav dolomites. *International Journal of Rock Mechanics and Mining Sciences* 35(6): 797–805.

Holditch SA (2006) Tight gas sands. *Journal of Petroleum Technology* 58(6): 86–93.

ISRM (1983) Suggested methods for determining the strength of rock materials in triaxial compression: Revised version. *International Journal of Rock Mechanics and Mining Sciences & Geomechanics Abstracts* 20(6): 285–290.

Jeng F, Weng M, Lin M, et al. (2004) Influence of petrographic parameters on geotechnical properties of tertiary sandstones from Taiwan. *Engineering Geology* 73(1–2): 71–91.
Li DY, Wong LNY, Liu G, et al. (2012) Influence of water content and anisotropy on the strength and deformability of low porosity meta-sedimentary rocks under triaxial compression. *Engineering Geology* 126(7): 46–66.

Li Y, Chen SJ, Qiu W, et al. (2019) Controlling factors for the accumulation and enrichment of tight sand-stone gas in the Xujiahe Formation, Guang’an Area, Sichuan Basin. *Energy Exploration & Exploitation* 37(1): 26–43.

Meng J and Pan J (2007) Correlation between petrographic characteristics and failure duration in clastic rocks. *Engineering Geology* 89: 258–265.

Olsson WA (1974) Grain size dependence of yield stress in marble. *Journal of Geophysical Research* 79(32): 4859–4862.

Panaghi K, Golshani A and Takemura T (2015) Rock failure assessment based on crack density and anisotropy index variations during triaxial loading tests. *Geomechanics and Engineering* 9(6): 793–813.

Prikryl R (2001) Some microstructural aspects of strength variation in rocks. *International Journal of Rock Mechanics and Mining Sciences* 38(5): 671–682.

Robertson EC (1955) Experimental study of the strength of rocks. *Geological Society of America Bulletin* 66(10): 1275–1314.

Spencer CW, Lorenz JC and Brown CA (1991) Application of horizontal drilling to tight gas reservoirs. *American Association of Petroleum Geologists Bulletin* 75: 675.

Ulusay R, Tureli K and Ider MH (1994) Prediction of engineering properties of a selected litharenite sand-stone from its petrographic characteristics using correlation and multivariate statistical techniques. *Engineering Geology* 37: 135–157.

Walls JD (1982) Tight gas sands-permeability, pore structure, and clay. *Journal of Petroleum Technology* 34(11): 2708–2714.

Wong RHC, Chau KT and Wang P (1996) Microcracking and grain size effect in Yuen Long marbles. *International Journal of Rock Mechanics and Mining Sciences & Geomechanics Abstracts* 33(5): 479–485.

Xu C, Li P and Lu D (2017) Production performance of horizontal wells with dendritic-like hydraulic fractures in tight gas reservoirs. *Journal of Petroleum Science and Engineering* 148: 64–72.

Zhang J, Jin C, Xing L, et al. (2019) Mineralogy and geochemistry of the coal seam of Shanxi Formation in Guotun Mine, Juye Coalfield, North China. *Energy Exploration & Exploitation* 37(6): 1779–1803.

Zhao T, Guo W, Lu C, et al. (2016) Failure characteristics of combined coal-rock with different interfacial angles. *Geomechanics and Engineering* 11(3): 345–359.

Zhu H, Guo J, Zhao X, et al. (2014) Hydraulic fracture initiation pressure of anisotropic shale gas reservoirs. *Geomechanics and Engineering* 7(4): 403–430.

Zhu H, Guo J, Xu Y, et al. (2015) Stress field interference of hydraulic fractures in layered formation. *Geomechanics and Engineering* 9(5): 645–667.