Fracture-cave carbonate reservoir permeability modelling based on conventional log and well deliverability prediction: A case study of the Amu Darya Gas field in Turkmenistan

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Abstract. The carbonate fracture-cave reservoir is developing in carbonate gentle slope reef flat in east Amu Darya Gas field. Due to the serious heterogeneity of fracture-cave reservoirs, it is difficult to evaluate the productivity of different wells and different reservoir sections. Based on conventional log, core, image log and magnetic resonance log. The sensitive parameters contributed to reservoir permeability are studied, and the conventional log, magnetic log and image log of key well are set up to match core permeability and propagate other fracture-cave carbonate wells. Finally based on log porosity and permeability model result, the well deliverability is evaluated and the well deliverability evaluation results are match with the DST results. The Amu Darya Gas field carbonate fracture-cave permeability model and deliverability evaluation flowcharts and methods were build up and can give instructions for other fracture-cave carbonate reservoir.

1. Introduction
The reservoir properties of carbonate are highly heterogeneous due to the multiple control of structure, diagenesis and sedimentation. In particular, fractures have a great effect on the physical properties of carbonate reservoirs. It is also because of the influence of fractures that the reservoir seepage space is communicated, and the permeability of the reservoir is greatly improved. The fracture and cave can communicate the flow matrix in carbonate and greatly improve the permeability and play important role for commercial deliverability in carbonate. But the petrophysical evaluation, especially permeability evaluation and deliverability evaluation are big challenges in fractured and caved carbonate reservoir. This paper takes the wells in the central part of the Turkmenistan Amuhe gas field on the reef beach in the body zone as an example. Combined with conventional analysis, core analysis and DST and NMR logging etc., the key parameters affect the permeability are studied and the permeability modeling and deliverability evaluation based on key well and key parameters are propagated to other wells with same fractured-cave reservoir. The actual production test results are also matched with the modeling results, which should have a great promotion and application value for the fracture-cave reservoir permeability and productivity evaluation.
2. Geology brief introduction
Amu Darya Right Bank block project is the biggest onshore conventional gas project in oversea. The block is located in the northeast part of Amu Darya basin. The Amu Darya right bank block is composed of the Zarchu Fault terrace, the Beshkent depression and southeast Gissar abdution zone. The platform, the platform edge reef flat and slope reservoirs were developed in the target Callovian-Oxfordian carbonate formations. The Sandykly uplift [1-3] is the subset structure unit of the Zarchu Fault terrace. The platform edge up slope and down slope reef flat composite bodies were developed in the Sandykly uplift (Figure 1). The reservoir property is considered poor and no exploration operations in this area. But the basement fault is growing in Sand slope, and there are landform twists in the upward side of fault. The Zarchu fault was strike slip because of Himalayan stage compressing stress. The slope reef flat was cracked because of strong structural action and organic acid or hydrothermal fluid were corroded through fracture and formed the fracture-cave reservoir body [4-5].

3. Carbonate reservoir property characters
The permeability and porosity relationship in Sandi slope shows in the Figure 2. The porosity is between 1%-16%. The average porosity is 5.15%. The permeability is between 0.001md-1000md, the average permeability is about 84.78md. The reservoir is low porosity and middle permeability reservoir. The relationship between the permeability and porosity shows complex nonlinear relationship, the fracture also put on strong impacts to permeability.

![Figure 1. Sandykly and neighbor sedimentary and structure schematic diagrams.](image)

4. Fracture-cave carbonate petrophysical evaluation and permeability model
M-1 well is one key exploration well in Sandykly slope. The good fracture-cave reservoir body in the target Callovian-Oxfordian carbonate formations. There are complete log suites in this well, which include conventional log, FMI log, DSI (Dipole Shear Image) log and NMR (Nuclear Magnetic Resonance) log etc.

The petrophysical evaluation is based on conventional log first. The GR was used to calculate shale volume. The sonic slowness was used to calculate porosity. The Archie equation was used to calculated water saturation [6]. The reservoir porosity cutoff is about 4%. The petrophysical results are
shows in the Figure 3: The No.1-No.5 is gas zone, The No.6 and No.7 is gas water zone, The No.8 is gas bearing water zone, and the No.9-No.12 is water zone. The porosity calculated by sonic is matched well with core analysis result in Track 7. But there are big errors between the permeability calculated by CMR with core analysis permeability result. The porosity calculated by sonic is match with the core analysis porosity result in Figure 4-a, the correlation coefficient is about 0.82. If the core overburden pressure were corrected, the correlation ship between the core analysis porosity and sonic porosity would be better. But relationship between the permeability by core analysis and CMR permeability is much worse in Figure 4-b, the correlation coefficient is only 0.18. The worse relationship between core permeability and CMR permeability is because of fractures. The accurate fracture identification and fracture-cave reservoir permeability evaluation is import for fracture-cave carbonate reservoir. The following shows the fracture-cave reservoir permeability model procedures by conventional log, Image log and CMR log respectively incorporated with core analysis result.

**Figure 2.** Porosity and permeability relationship in Sandykly Slope.

**Figure 3.** M-1 well petrophysical result plot.
4.1. The permeability model evaluation by conventional log

If there is no radial resistivity variation and no fracture, the deep resistivity and shallow resistivity should be in superposition. The horizontal fracture can strengthen the lateral resistivity focus effect and reduce measured resistivity, and horizontal fracture can strengthen the deep resistivity more focus effect than shallow lateral resistivity and LLD<LLS, the resistivity shows the negative difference. In fact, the high angle fractures supply the low resistance channel and decrease the lateral resistivity and LLD>LLS, the resistivity shows the positive difference. The deep and shallow lateral resistivity difference is up to fracture angle [7-8]. The deep resistivity is higher than shallow resistivity in M-1(Figure 3), which indicates the high angle fractures developed in M-1 well. Based on above analysis, the FI=LLD/LLS is used to reflect the fracture responses. GR, sonic DT, density RHOZ and FI are used together and the core analysis results are used as the associated conditions to model permeability through Multi-Resolution Graph-Based Clustering methods. The Figure 5 shows the permeability result base on above methods, the correlation coefficient is about 0.65.

4.2. Dipole shear image permeability model

The fracture infiltration performance can reflect the fracture openness, radial extension level and connect conditions, the stoneley wave as a tube wave, can used to evaluate the formation permeability. The stoneley wave can radial expand and shrink through borehole wall in borehole. The drilling mud (or mud filtrate) will flow in and out along fractures, which cause the decrease of stoneley wave amplitude. The stoneley wave energy will not attenuate in the invalid fractures. The dipole shear image log can supply the stoneley wave, compressional wave and shear wave etc. The stoneley wave has the high radial detection depth, the reflection and attenuation of stoneley wave mainly happens in the good permeability interval. The QFM calculated by dipole shear image log can used to reflect the fracture. Based on Multi-Resolution Graph-Based Clustering methods [9-11], The GR, DT, density RHOZ, neutron porosity TNPH and fluid flow index QFM and core permeability as associated conditions are used to model permeability. The figure 5b shows the relationship between the model permeability and core permeability, the correlation coefficient is 0.64.

4.3. Resistivity FMI log permeability model

The Resistivity image log can reflect the borehole rock resistivity, and can directly pick different strike fracture, and quantitatively evaluate the fracture density VDC, the fracture hydrodynamic width VTL and fracture apparent porosity VPA. The VPA, DT, density RHOZ are used and core permeability is used as associated conditions to model permeability based on Multi-Resolution Graph-Based
Clustering methods. The Figure 5c shows the relationship between model permeability and core permeability, the correlation coefficient is 0.65.

4.4. NMR log permeability model
The nuclear magnetic resonance is considered as the most effective methods to evaluate the reservoir architecture. The T2 distribution measured by NMR has good consistency with reservoir pore architecture. The conventional NMR permeability is used T2 cutoff to differentiate the free fluid and immovable capillary bound water and clay bound water. The conventional NMR permeability has good match result with core permeability in pore-cave carbonate, in fracture-cave carbonate the conventional NMR permeability has poor relationship with core permeability because of fracture, such as the relationship shows in Figure 4-b. The fracture can connect small pore and big pore, connect capillary bound water pore and free fluid big pore, even can connect pore occupied by clay bound water. Tiny pore occupied by clay bound water, small pore occupied by the capillary bound water and big pore occupied by free fluid should be considered together to model permeability. The tiny pore, the small pore and big pore parts should altogether to model permeability. Based on above consideration, the NMR T2 distribution are divided into three parts: the clay bound pore (0-3ms), the capillary bound pore and free fluid pore. The permeability model result there are very good correlation coefficient, the correlation coefficient is 0.94 (Figure 5d).

![Figure 5](image.png)

**Figure 5.** ModeL PERM&CORE PErm.(X:Model Perm(md),Y:Core Perm(md)).

5. Fracture-cave carbonate deliverability predication and application
The composite property index P was built up by integrated the porosity and permeability effect in fracture cave carbonate reservoir [12]. The equation shows in the following:

\[ P = \sqrt{K\phi} \]

The composite property index P of M-1 Well (Track 14 in Figure 6) is computed by NMR model permeability and porosity. P can used to represent the fracture-cave carbonate reservoir property parameter and can used to reflect and predicate the well deliverability. The DST1 3860-3870m shows no gas before acidization and daily gas production is 662m³. The sonic porosity is about 5% and NMR
model permeability is 0.03md, and there is almost no fracture in this interval. There is almost free fluid big pore in this DST1 interval and composite property index P is less than 0.2, so there is almost no commercial production in DST1 interval. The fractures and caves are developed in DST2 interval 3778-3826m, the sonic porosity is about 4.7% but NMR model permeability is about 5.95md, the composite property index P is about 2, which indicate good deliverability. The DST daily gas is about $81.77 \times 10^4 m^3$ in 14.3mm choke size. The permeability analysed by DST build-up is about 5.3md, which is close to NMR Model permeability. The NMR T2 distribution model permeability has good match relationship with actual DST test result.

![Figure 6. M-1 well composite result plot.](image)

The M-1 NMR Model Result was propagated to the other well E-1(Figure 7). The detail production information shows in the following table 1. The Daily production and Thickness*P relationship shows in the Figure 8, which shows good linear relationship.

| Well | DST Interval | Thickness*P | Choke size (mm) | Daily Production ($10^4 m^3$) | NMR Model Perm.(md) | DST Buildup Perm (md) |
|------|--------------|-------------|-----------------|-------------------------------|---------------------|----------------------|
| M-1  | 3778-3826m   | 15.42       | 12.7            | 73.24                         | 5.9                 | 5.2                  |
|      | 2128-2132m, 2139-2153m | 8.287       | 12.7            | 33.5                          | 4.2                 | 2.7                  |
| E-1  | 2167-2172m   | 3.712       | 12.7            | 35.18                         | 4.1                 | 17.2                 |
|      | 2184-2170m   | 3.574       | 12.7            | 14.6                          | 2.8                 | 1.7                  |
Figure 7. E-1 well composite result plot.

Figure 8. The Correleationship between the Daily Production & Thickness x P.
6. Conclusion

(1) The Fractured and Caved reservoir was formed in the following situations: Fault strike slip motion, the disruption between slope reef flat with strong structural motions and organic acid and thermal fluid dissolution with the fractures. Wireline log analysis result proves it again!

(2) The Fracture cave permeability model was carried out by conventional log, Dipole shear Image log, FMI and NMR etc. There are similar permeability relationships in conventional log, FMI, DSI; The NMR T2 model permeability has the best relationship with the core analyzed permeability.

(3) The composite property P was buildup by integrated with the porosity and NMR permeability model, the actual well DST result shows P has good linear relationship with the well deliverability.

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