# THE EARLY DETECTION OF SEMI-PERMEABLE FILTRATION BARRIERS BY USING SAR INTERFEROMETRY

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## ABSTRACT

The faults are universal in the petroleum reservoirs. Some of them are Semi-Permeable Filtration Barriers (SPFBs) such that a SPFB becomes fluid/gas permeable if a pressure threshold is exceeded. This may cause sudden changes in reservoir structures and, eventually result in negative impacts on production. This paper deals with early SPFB detection and characterization. We consider some case studies of reservoirs with SPFBs, and present a new methodology for SPFB detection. This includes the following groups of methods: mapping of surface responses to deep geodynamic and fluid-dynamic events (incl. SAR interferometry), 3D-mapping of faults in the reservoir and adjacent formations, separation of SPFBs from other dislocations. The methodology implementation is demonstrated with the case study of underground gas storage.

***Index Terms—*** gas reservoir, barrier, permeability, geodynamic, SAR interferometry

## 1. INTRODUCTION

Almost all natural hydrocarbon reservoirs are tectonized by tectonic dislocations (faults). In almost every reservoir, there is a multitude of faults over the wide range of continuity, fault and fault zone thickness, fault throw. These faults can dramatically effect on the reservoir development and hydrocarbon recovery. They are liable to seal the fluid flows and as the result cause reservoir compartmentalization into autonomous blocks.

The literature on the subject of faulted reservoirs is quite voluminous. Many geologists and geophysicists search for the methods to reveal *subseismic* faults, which are below the seismic-survey resolutions (e.g. [6]). The reservoir engineers have been involved in prediction of fault sealing capacity [9], and the challenge there is in how to estimate oil/gas relative permeability across fault barriers, and, in particular, to answer the question whether these barriers can act as absolute ones.

This article concentrates on the faults which happen to change their permeability performance during production from 'permeable' to 'sealing' barrier, and *vice-versa*. During exploration and pre-production, a sealing barrier can be indicated by the significant pressure difference across the specific fault. During production, it certainly can be revealed by fluid flow streamlines which are not passing through the fault.

For briefly, we refer such kind of faults to as *semi-permeable filtration barriers* (SPFBs) and recognize two types of SPFBs which are distinguished by the reverse direction: 'permeable → sealing' barrier (SPFB 1) and 'sealing → permeable' barrier (SPFB 2).

The factors affecting the fault sealing properties are deduced from its geological history and nature. Fault is a fracture, discontinuity, fissure or joint, resulted from paleostress strain relief. Faults stay in a stress-strain state in almost all hydrocarbon reservoirs where there are two rock blocks displaced relative to each other along the fault that could course juxtaposition of differently permeable lithologies.

Faults are filled up with fault rocks which are clastic and abraded wall rocks such as fault gouge, clay smear, breccia, deformation bands etc. There are lithologies among the fault rocks (e.g. hydrophilic clayey or sandy aleurolites) which become fluid/gas permeable if a threshold capillary pressure is exceeded. They play a part of sealant in the SPFB development.

A consequence of the above is the following list of factors affecting fault zone sealing properties:

- fault zone architecture,
- fault rocks lithology,
- the reservoir fluid type and saturation, and
- stress conditions.

The first three are appraisable on the basis of well logging, field research, and seismic data [5, 8]. The fourth listed factor is mostly interesting in the context of this article. If all other factors are the same, the stress conditions of the fault determine openness of the fault zone, fault rocks compaction, and thus the fault transmissibility and permeability. Numerous geodynamic observations strongly suggest that this factor is time-variant. It is this phenomenon of time-varying stress-strain conditions that produces SPFBs. We suggest the permeability performance reversals of both SPFB 1 and 2 are the result of stress and strain changes which occur during reservoir production.

## 2. SPFB-BEARING RESERVOIRS: CASE STUDIES

Consider some examples of how the SPFBs make themselves evident during production of gas reservoirs (see details in Table 1).

**Table 1. Outline of Gazli, Yamburg and Qaradag reservoirs**

| Field<br>Parameter | Gazli | Yamburg | Qaradag |
|---|---|---|---|
| Structure type. | Anticline. | Anticline. | Homocline. |
| Trap type | Layer-arch | Massive | Litho. sealed |
| Length x Width | 38 x12 km | 160 x 45 km | 6 x 3 km |
| Reservoir | Hor. IX | Cenomanian | Hor. VII+VIIa |
| Reservoir age | $K_2$cm | $K_2$cm | $N_2$ |
| Depth | 680-880 m | 1080-1210 | 2600-4000 |
| Thickness | 100 m | 60-110 m | 100 m |
| Initial pressure | 7.2 MPa | 11.5 MPa | 30-40.5 MPa |
| Avg porosity | 19.6 % | 27 % | 14 % |
| Avg permeabily | 1170 mD | 470 mD | 85 mD |

### 2.1. The Gazli gas field

The Gazli gas field is located nearly 100 km northwest of Bukhara city, Uzbekistan. The basic parameters of the reservoir considered, Horizon IX are given in Table 1.

The event that led to SPFBs manifestations was emergency flowing of Well 108 located at the crestal position of Horizon IX. The emergency flowing had happened before the production started, and it lasted for about 21 months. In this period, the loss of gas approached to 2% of initial reserves. The production started one year after the accident had been eliminated.

The reservoir pressure field was smooth before the accident, in average 7.2 MPa. Reservoir pressure monitorring revealed that a lateral cross-flow took place throughout the flowing period, plus about 6 months after it. The reservoir pressure field ended up as the three shelves radiated outward from Well 108 (pressure 7.04, 7.09, 7.13 MPa), thus revealing the two impermeable barriers, which divided the reservoir into three autonomous blocks [2]. See [3] for the block structure of the area on regional scales.

To summarize briefly, the above barriers had been gas permeable before, during and sometime after the emergency flowing period, as evidenced by the far lateral gas cross-flow and the pressure-drop throughout the reservoir. This in turn changed the stress conditions of the reservoir in such a way that the barriers became gas impermeable SPFBs 1.

### 2.2. The Yamburg gas field

The Yamburg gas field is located at the Lower Ob region, West Siberia. The basic parameters of the considered reservoir are given in the Table 1. The initial reservoir pressure was consistent with the hydrostatic one, with no sign of tectonic heterogeneity of the reservoir. Therefore, based on hydrodynamic homogeneity concept, the reservoir has been produced over the years with the wells operating at the pool roof, in the maximum net gas pay zone.

The production drawdown period began when the *ultimate gas recovery factor* (UGR) was just 0.3, i.e. very early. By the moment of UGR$\approx$0.6, about one third of the reserves was contained in the dead zones screened by the SPFBs. At the time, there was a pressure sink in the recovery zone where the reservoir pressure dropped down to one third of the initial one. In the dead zones, the reservoir pressure remained nearly at the initial level.

Evidently the mechanism of SPFBs formation was the same as in 2.1: some barriers turned into impermeable SPFBs 1 due to compaction resulted from the pressure drop. But in this case SPFBs area is a part of some concentric zonal structure of consediment genesis. The SPFBs area is a *transition zone* between the near-crest zone of highly productive reservoir and the near-bottom zone of low productive reservoirs [2].

Similar things happened in Urengoi, Medvezhye and many other West-Siberian gas giants [1]. In all of them, the production drawdown period began at very low UGR values. Significant volume of reserves remained in the dead zones behind the barriers of SPFB 1 type, located in transition zones. Note that we have observed similar transition zones in many oil and gas fields in Timan-Pechora, Volga-Ural and other provinces [2]. They appear to be highly-fractured and directly related to known surface circular atmogeochemical and geophysical anomalies.

### 2.3. The Qaradag underground gas storage

The Qaradag multi-horizon field [4] is located 30 km southwest of Baku city, Azerbaijan. It is confined to the southeast branch of a compound fold, with a mud volcano at its crest.

The gas-condensate reservoir of Horizon VII+VIIa (see Table 1) is the homocline dipping east at 50º, with the gas column of about 1 km. There is a remarkable fault at the northeast of the horizon. During production period, the pressure difference of the order 4-5 MPa has persisted across this fault.

The reservoir was operated since early 1950s in depletion mode up to the 1980s. At the time the apical reservoir pressure was about 0.4 MPa, i.e. 10 times less than the initial one. Soon after, an underground gas storage (UGS) was established at this reservoir. Thereafter, the reservoir pressure underwent regular rises and falls, with pressure difference about 0.6 MPa during UGS fledging years and 1.2 MPa at present.

In the initial phase of the UGS, it was discovered that the aforementioned fault became gas permeable, i.e. evolved to SPFB 2. As with 2.1 and 2.2 cases, there is a good reason to believe that the SPFB 2 occurred as a result of the changes in the fault stress conditions caused by the reservoir pressure variations.

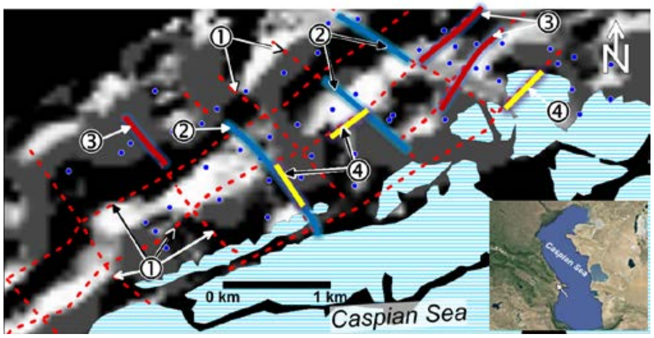

Fig. 1. Interferogram produced using ALOS PALSAR data from 2009-11-3 and 2010-3-21 and SPFBs at UGS Qaradag. Dots, the UGS wells. Caspian region in the insert. See text for explanations

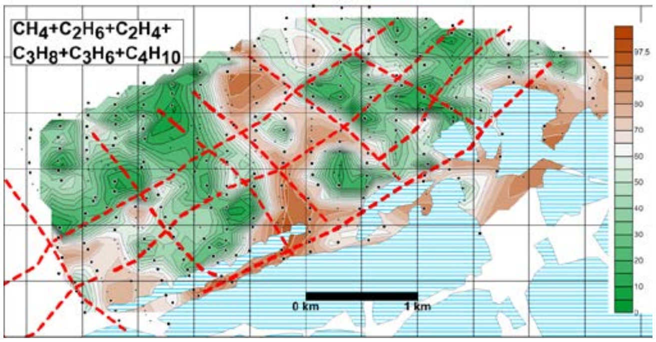

Fig. 2. The light alkanes and alkenes sum content in subsoil air, UGS Qaradag. Contours in percentiles of frequency distribution. Dots, sampling points. Red lines, the SPFBs (see Fig. 1).

## 3. THE SPFB DETECTION METHODOLOGY

In the past few decades, extensive body of knowledge was accumulated on geodynamic activity of the Earth's upper crust and related phenomena. The following areas are directly related to this work:

- Monitoring of the Earth surface by various methods (surface or space geodetic leveling, geotechnical monitoring of deformations of underground constructions, etc.) have provided an idea of the oscillabile movement of the Earth's upper crust and related stress and strain.
- Modern "theory of geogas", which embraces abundant atmogeochemical evidence, considers the geogas micro-bubbles as the main carrier of both gas phase and solid nano-particles from the interior to the earth's surface.
- Geochemical monitoring of tectonic dislocations of different scales leads to viewing the tectonic dislocations as basic geogas-transfer channels.
- Combined geochemical and geotechnical monitoring gives a strong ground to believe that the fault opening oscillations form the basic mechanism of pumping the fracture water up in the dislocation.
- The outcomes of numerous surface gas surveys demonstrate that every petroleum field is accompanied by the surface anomalies of gaseous and volatile hydrocarbons.

It follows from above that in all the geological settings, the Earth's upper crust is a subject to vertical oscillations by the action of the tidal and tectonic forces. The tidal forces give rise to the relative high-frequency component of these oscillations (hours, days), neotectonic ones are the driving force for long-period oscillations.

These oscillations activate the perturbation of the stress condition of geologic media. The stress energy dissipates through the faults by its transformation to frictional energy and fracture propagation. In other words, these perturbations result in reciprocal displacements of the adjacent blocks of rocks along the faults. Under stress release, the faults open out.

Using this line of reasoning, we are led to the following pre-requisites to the presented methodology:

(i) The adjacent blocks of rocks are always differentially mobile; (ii) The borderlines between the adjacent blocks of rocks are periodically well transmissive for formation fluids; (iii) The fluid-transmitted geochemical signal is detectable at the surface; (iv) The points (i), (ii), (iii) are well presented in the petroleum fields, at that in the near real time scale.

The methodology is based on the concept of consediment phenomena and permanent neotectonical activity of petroleum-bearing structures. It uses various methods grouped as follows.

(1) Mapping of land-deformational and geochemical anomalies as surface responses to deep geodynamic and fluid-dynamic events using synthetic aperture radar (SAR) interferometry, surface atmogeochemistry, some other morphotectonic methods.

(2) 3D-mapping of both seismically-mapped and sub-seismic faults in the reservoir and adjacent formations. It uses a wide range of geologic, geophysics and field-tests data, incl. seismics, well-logs, well tests (if available).

(3) The separation of SPFBs from other dislocations by using reservoir pressure distributions, fluids geochemistry, cross-hole exploration, etc.

The methods (1) run efficiently at zero exploration data. They can yield the first approximation of the SPFB framework of a prospect. Experience shows that the SAR interferometry and the surface gas survey that follows are the most informative.

## 4. THE METHODOLOGY EXAMINATION

The UGS Qaradag problem related to the operating experience problems of Horizon VII+VIIa. The operating experience indicated its strong heterogeneity (see Section 2.3). Clearly, there were filtration barriers in it, to be revealed.

All available data on the field and UGS Qaradag were invoked and re-interpreted; and they included seismic, field geophysical, production data, etc. In addition, SAR interferometry and the surface gas survey were carried out. So, they deserve a certain comment.

In the case of UGS Qaradag, we used a series of ALOS PALSAR data (23 cm wavelength) obtained in the repeated orbits interferometry geometry of observations. The classic DINSAR technique was used to generate the differential interferogram, with topographic phase to be subtracted from interferogram generated using SRTM DEM [7]. The PALSAR interferometric pairs were selected with regard to injection / withdrawal seasons, over which the dynamics manifestation might be most prominent with respect to the pairs with the shorter interferometric baselines. There were processed four interferometric pairs, two of them for injection season, and the other two for withdrawal season.

The gas survey was carried out during the gas injection period, i.e. against the reservoir pressure increase. The bedrock at depth 1 m was the media tested, with both sorbed phase and subsoil air to be sampled. The latter sampling was caused by the need of synchronization of the survey data with the injection schedule.

One of injection-related interferograms is exemplified in Fig. 1. For simplicity, it is drawn in the shaded relief mode, with the range -3 to +3 cm of the surface subsidence and bulging, correspondingly. The lines labeled 1 are the borderlines between the differentially mobile blocks of the day surface resulted from all the interferograms. It is significant that a keyboard-like picture was found due to SAR data: the mobile blocks reverse the direction in synchrony with UGS cycle mode.

The borderlines are the surface extensions of the SPFBs existing in the reservoir at the depths 3±0.5 km. These are the real filtration barriers. This fact is proved by the retro-data of water-encroachment dynamics (labeled 2 in Fig. 2), reservoir pressure dynamics (3), and contemporary gas-hydrodynamic testing (4). The barriers 4 can be considered as gas impermeable, whereas the bariers 2 and 3 are likely to be currently gas penetrable.

We can judge about the genesis of the aforementioned SPFBs by the results of the lithofacies analysis. The near-EW (on the strike) lines are the consediment small-displacement flexures; some of them are slightly seismically expressed. The near north-south (across the strike) lines are limited to transition zones at the edges of the delta-front facies. They are mostly the subseismic discontinuities.

The gas survey results (e.g. Fig. 2) show the following: The SPSBs are rooted beneath the reservoir and reach the day surface. The entire formation looks like it is constructed of vertical prisms faceted by the barriers. The prisms have their geochemical particularities. The barriers are channeling vertical gas emanations and, thereby, incasing the prism's geochemical particularity.

## 5. CONCLUSIVE REMARKS

In closing it may be said about the SPFBs that they are relatively small-scaled, geodynamically active faults in variably stress and deformation state. They are partitioning differentially mobile blocks of the upper crust. They act as conduits for upward fluid seepage from depth to the surface.

In the UGS Qaradag case study we deal with a 'mosaic-hinged' geologic system that contains hydrocarbon reservoirs and is penetrated by volatile hydrocarbons. The system has been in an artificially activated state for decades. Therefore, the movement amplitudes in the system are relatively large and, thus, measurable with comparatively rude techniques. In a juvenile situation, it is reasonable to expect much lesser amplitudes which could be measured with more sophisticated techniques including persistent scatterers techniques applied to shorter wavelength SAR data.

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