Evaluation of the Rock Properties in Structurally Deformed Areas Based on Outcrop Analogues for Offshore Fields in Azerbaijan*

Shahriyar Alkhasli[1], Gasham Zeynalov[1], and Aydin Shahtakhtinskiy[1]

Search and Discovery Article #51461 (2018)**
Posted February 5, 2018

*Adapted from extended abstract based on oral presentation given at AAPG International Conference and Exhibition, London, England, October 15-18, 2017

[1]eiLink R&D, Khazar University, Baku, Azerbaijan (shahriyar.alkhasli@khazar.org)

Abstract

Deformation bands have been evidenced from both outcrop observations and subsurface data worldwide. These features form in variety of tectonic settings and are known to influence the rock properties in various ways. The aim of this study is to quantify the impact of deformation bands and their kinematics on reservoir properties for a wide range of rock types based on the field measurements in the outcrops of Yasamal Valley located in the western part of the South Caspian Basin. The study reveals deterioration of rock properties through deformation bands depending on several structural, lithological and petrophysical factors. An integrated approach was put together to understand the impact of these factors including the measurements of natural gamma radioactivity, permeability, dip and strike across the range of facies and distribution of deformation bands using portable tools. Additionally, Routine and Special Core Analyses were performed on the outcrop plugs with and without bands to estimate the alteration of the rock properties at the micro-level supported by petrographical description, SEM, XRD and CT scan tests. Interpretation of data shows that no bands occur in the rocks with shale volume greater than 32% as determined from the field gamma ray measurements. Moreover, the probability function of the band occurrence for a range of clay content was determined. High amount of calcite cement observed in the field appears to increase the number of deformation bands and significantly reduce porosity and permeability of the host rock. A petrographic analysis of the collected samples allowed to determine the impact of the mineralogical composition on degradation of rock properties. Laboratory results from the collected outcrop samples containing single deformation band show 33% and 3% decrease in permeability and porosity, respectively, in comparison with the adjacent host rock plug without a deformation band. No obvious correlation between bed dip and strike with concentration of deformation bands could be identified. The occurrence of bands and their subsequent influence on rock properties is a complex function of several factors that either counteract or enhance each other. Nevertheless, clay content is amongst the dominating parameters affecting the occurrence, concentration and the type of deformation bands.

Introduction

The current study is concerned with deformation bands (DB), which have been evidenced from both outcrop observations and subsurface data worldwide and extensively investigated by several authors. These features form in variety of tectonic settings and are known to influence the rock properties in various ways. One of the pioneering studies was done by Aydin (1978) in Entrada and Navajo sandstones who described DB as small faults with displacement of a few millimeters to a few centimeters, which is below seismic resolution and cannot be readily detected by conventional well logs. Therefore, more efforts were put to characterize them from core data and outcrop analogues. Since DB are known to influence the fluid flow in porous media, attempts were made to quantify their impact at pore and reservoir scales. This requires understanding of the genesis and characteristics of DB and their relationship with rock properties.

The aim of this study is to create a predictive model for formation of DB and to evaluate the rock properties in structurally deformed areas of the hydrocarbon fields in Azerbaijan based on outcrop measurements and laboratory experiments. The scope of the research includes examination of correlation between bed dip and number of DB observed along and across steeply dipping and overturned parts of the plunging anticline. Similarly, the effect of mineralogical composition (clay content), which is believed to control elastic properties of rocks, was also investigated through estimation of shale volume of sandstones derived from field measurements of natural gamma radioactivity. Additionally, mudstones, which sandwich a sandstone layer, may potentially act as stress absorbers and influence the concentration of DB in the area, which is also introduced in this article.

Finally, the influence of DB on rock filtration properties is quantified through abundant measurements of permeability on the outcrop samples in the laboratory and on the surface of the rocks using a portable permeameter. A descending trend is observed between permeability of sandstones and number of DB across the studied anticline. Furthermore, reduction of initial rock porosity and permeability caused by a single DB is determined on the micro-scale. The magnitude of reduction of the reservoir properties was then compared with available mineralogical composition, grain size, facies type, etc., to identify the key controlling factors.

Geological Setting

Azerbaijan is located in the Caucasus region of the Alpine-Himalayan fold belt and its main geo-structural elements are the South Caspian Basin in the eastern and the Kura Basin in the western parts (Figure 1). The eastern part of the Kura Basin, named Lower Kura sub-basin, and the South Caspian Basin (SCB) are similar in terms of their geologic structure and development history, both being characterized by high sedimentation rates in the relatively recent Pliocene-Quaternary time.

The Productive series (Lower Pliocene), considered to be the main reservoir rock in the South Caspian and nearby Kura basins, was accumulated by the Paleo-Volga, Paleo-Amu Darya, and Paleo-Kura rivers (Aliyeva, 2005; Green et al., 2009; Jones and Simmons, 1996; Reynolds et al., 1998) after the isolation of the Caspian Lake from the global ocean in the early Pliocene. In the Kura basin, the thickness of mud-rich argillaceous sediments of the Productive Series, brought by the Paleo-Kura river, reaches more than 2 km; however, sand-rich sediments brought by the giant Paleo-Volga river increase in thickness and reservoir quality towards the Absheron Peninsula of the SCB.

Many exposures exist in the Absheron Peninsula, which contain both structural and sedimentological elements described above. Yasamal Valley represented by the plunging anticline, has most favorable conditions for studying DB on the outcropping Productive Series and was chosen to be the main area of investigation for the study in question. The Yasamal anticline (also known as Shubany) is located in the Absheron Peninsula to the north-west of the SCB (Figure 2) and was formed because of folding during the late Pliocene (Gurevich and

Chilingar, 1995). It is a four-way dipping anticline with well-pronounced north/south pericline areas and flanks, dipping in the east and west directions. The structure is complicated by three longitudinal faults at the crest - one of which is a thrust fault (Alizadeh et al., 1966, Allen et al., 2003), possibly caused by overturning of the east limb of the anticline - and by series of latitudinal normal and reverse faults (Figure 3 a depicts some of these faults). The structure is asymmetric, with the west limb dipping at around 40 degrees, and the east limb dipping at near-vertical position. The overturned layers of the east limb can be observed along the entire flank. As it can be seen in Figure 4, the layers at the east limb are slightly declined from vertical position and are dipping towards the West. The field measurements were performed in three main locations: the south pericline (Log 1), and the southern (Log 2) and northern (Log 3) parts of the east limb (Figure 3a), where DB are widely distributed.

Outcrop observations reveal two well-exposed sandstone subunits: the thicker and coarser-grained sandstone outcrops of Balakhany VIII, and the thinner-bedded and finer-grained sandstone outcrops of Balakhany VI formations. These sandstone-prone units are deposited during periods of increased fluvial-deltaic discharge and sediment supply to the basin. Sand-prone settings mainly consist of amalgamated (massive) and braided fluvial sheet sandstones. Mudstone-rich settings comprising Balakhany V, VII, and IX intervals are dominated by alluvial plain and lacustrine facies.

The observed sandstones can be classified into two main types: 1) unconsolidated, relatively clean and 2) consolidated, calcite-rich. While the first type is observed across the entire structure, calcite-rich sandstones are locally distributed in the east limb, extending from its northern end about 2 km towards the south (refer to Figure 3a). The calcite-rich sandstones are abundant in DB, displaying complex distribution patterns (Figure 5). XRD data show that these facies have a sharp contrast in mineralogical composition (Figure 6). While the percentage of calcite in unconsolidated sandstones varies between 10% and 20%, in calcite-rich sandstones it reaches 40 to 50%.

Methodology

Distribution of DB across the plunging anticline in Yasamal Valley varies significantly, and as it will be demonstrated in this paper, depends on the structural complexity and lithology of the formations. The current day structure of Yasamal anticline suggests that the east limb is under relatively greater stress, as can be inferred from the steeply dipping and overturned layers (see Figure 4). Thus, it is fair to expect a decent number of DB on the outcrops of this flank.

One of the major reasons that DB form in highly porous clean sandstones is lack of ductility. The distribution pattern, type and quantity of DB alter with introduction of ductile minerals. This, in turn, affects the reservoir properties of the host rock. To characterize the reservoir properties and their relationship to DB and other influencing factors (bed geometry, mineralogy, net-to-gross, etc.) a set of tools such as portable Gamma Ray (GR) and Permeameter along with complex laboratory measurements were used. Portable GR tool (MGS-150) was used for stationary measurements of the natural radioactivity of the Balakhany Suite (Upper Productive Series) to construct a comprehensive GR log with 30 cm increments along the true stratigraphic thickness of the outcropping layers, as illustrated in Figure 4. To specifically relate ductility to DB, shale fraction (Vshale) was calculated from GR log using Steiber’s 1970 empirical equation (see Asquith et al., 2014). Tiny Perm II tool was used to measure rock’s air permeability at exact same locations as stationary GR measurement points to be able to relate and conduct an integrated analysis of the impact of DB on the reservoir properties together with laboratory experiments. Hence, the description of the facies and characteristics of DB were mostly counted along the path of the gamma ray log and permeameter measurements. The detailed facies description was made both across the stratigraphy and along a single stratigraphic unit within sandstone lithology to allow the analysis of the impact of DB on the whole sequence as well as along a single reservoir unit.

Successions of sandstone- and mudstone-dominated facies of the Balakhany Suite characterize repeated proximal and distal fluvial environments to high frequency base-level fluctuations, which resulted in channelized systems forming a layer-cake reservoir. Influence of such heterogeneous rock system on the conditions of deformation band formation is of particular interest. We believe that contrast in the elastic properties of successive beds may cause redistribution of stresses in individual sandstone units. Thickening of mudstone layers adjacent to the sandstone unit could shift its compressional load out of deformation band formation window. This phenomenon is assessed in terms of so-called "sandwich net-to-gross" (see Figure 7), defined as:

$$Sandwich\ NTG = \frac{Sandstone\ TST}{Sandstone\ TST + Mudstone\ TSTupper + Mudstone\ TSTlower} \qquad (1)$$

Factors controlling rock properties in structurally deformed areas cannot be fully evaluated and described by field measurements alone (GR and permeameter). Therefore, composite analysis of thin section petrography and laboratory tests as RCAL, SEM, XRD, and CT were carried out to proclaim the impact of those factors. All measurements were performed both sequential and parallel to the field measurements.

The sampling strategy of the representative rock units was paid a special attention as it later affects the analysis of all information in integration. For example, the sister-plugs with and without a DB, were sampled (Figure 8) within a short distance (1-2 cm) from each other to minimize any dissimilarity associated with different sedimentological structures or features.

Mineralogical identity of sister-plugs was validated with XRD and SEM measurements. The former provides fractional content of minerals (e.g. Figure 6), while the latter displays spatial distribution of oxides and their percentages in the sample. Porosity and permeability of the plugs were measured using helium porosimeter and air permeameter (at 400 psi confining pressure).

Characteristics of deformation bands are essential inputs for geological modeling and fluid flow simulation of reservoirs. While porosity estimation can be readily achieved through conversion of a thin section to a binary image and further processing, permeability modelling is by far more complex, and requires sophisticated numerical modelling techniques. Within the scope of the current study we used a simple harmonic averaging methodology of serial beds (Ahmed, 2001), one which was taken as a deformation band (Figure 9). The analytical equation is defined as:

$$K_{av} = \frac{L_t}{\frac{L_b}{K_b} + \frac{(L_t - L_b)}{K_h}} \qquad (2)$$

where:
K_{av} - average permeability of the plug with deformation band,
L_t - total length of the plug,

L_b - width of deformation band inside the plug (inferred from CT scans),
K_h - host rock (matrix) permeability (the plug without a deformation band)
K_b - deformation band permeability

Results and Discussion

Processing and subsequent interpretation and analysis of GR logs and DB data yielded that no DB are observed for any bed dips in various locations of Yasamal Valley outcrops, where shale volume exceeded 18% for unconsolidated and 32% for calcite-rich sandstones, respectively (Figure 10, left). When these threshold values are met, mineralogical content becomes dominant over other factors (e.g. structural elements). The increase in the threshold value for calcite-rich sandstones is related to the brittleness of calcite concretions in the pore space. In unconsolidated sandstones reduction in occurrence of DB correlates well with the increase of Vshale. The right graph in Figure 10 shows probability of occurrence of DB based on the field measurements in Yasamal Valley, where the number of DB observations is divided by total number of measurements. The same trends are observed for both facies. As a validation, XRD results from collected outcrop samples of the unconsolidated sandstone layer show no DB for the Vshale values above the cutoff as the statement above.

The trends in Figure 10 are valid for the occurrence of DB, which is the number of times DB were seen in a given Vshale range. The concentration of DB, as mentioned earlier, depends on several parameters. To further investigate the influence of ductile content (in this case quantified through Vshale) on the concentration of DB in the clean sandstones, the dip angle effect was diminished by selecting the batch of samples from unconsolidated and calcite-rich sandstone layers of the Balakhany VIII & VI subunits with minor variation of dip angles (within the range of ~2-3 degrees) in the direction perpendicular to TST.

As can be seen from Figure 11, despite an appreciable scatter in the data, the trends are certainly observed for both facies. Not only the overall increase in concentration of DB in the calcite-rich sandstone facies is observed, but also the shift in Vshale for the presence or absence of DB is confirmed as per previous statement regarding the occurrence of DB with ductile content. The presence of the calcite cement in the pore space of the sandstone rocks does affect the number of DB but also complicates their distribution pattern.

Structural elements of the logged sandstone layers have a larger imprint on DB formation when the shale volume is less than the threshold value. Abrupt changes in the dip angles along the short distance leads to occurrence of either DB or fractures due to dominating shear forces. Complications associated with on-site data acquisition, dip angle measurements sampling rate was not enough for reliable dip gradient calculations. Instead, the absolute values for the dip angles of individual layers were used in the correlations. Figure 12 shows that the relationship between average concentrations of DB in unconsolidated sandstones is less pronounced in the direction parallel to layering compared to the data collected perpendicular to the bed plane. There could be a wide range of explanations regarding the scatter and the behavior of the trends on both plots, but in both cases, there is an increase in the concentration of the bands with steepness of the formations. One of the challenges in the outcrop conditions is to identify the distance of the data points to the hinge zones, which would require the reconstruction, and structural evolution modeling of the plunging anticline. We therefore envisage interdependence between the dip angle, dip gradient and the distance to the hinge zones with the concentration of the DB in the clean sandstone layers. Although this maybe a quick practical solution to predict porosity and permeability reduction of the reservoir rocks, there are other factors that can equally influence the occurrence and distribution of DB such as the migration of the hinges, stress history and presence of faults.

We also introduce another way of relating the lithology effect on the distribution of DB. During the graphical investigation of DB versus "sandwich" NTG (see Eq.1), no DB were observed below a boundary NTG value of 0.32 (Figure 13). Apparently, sandstones bound by thicker beds of mudstone experience decreased compressive load in the horizontal plane. A possible explanation for this phenomenon lies in the concept of residual stress arising due to the contrast in elastic properties of adjacent rocks (Holzhausen and Johnson, 1979).

Although no considerable work has been done in relating occurrence of DB to the effect of residual stress, it was shown that it could introduce tensile stress in sandstones enclosed by softer rocks in the overall compressive regime, thus decreasing the probability of deformation. This idea is supported by multiple investigations, which demonstrate that residual stresses in shale-bound sandstones account for the formation of natural fracture system under external compressive force (Stephen J. Bourne, 2001). Owing to the reduction of compressive load on sandstone in a low NTG "cake", the effect of residual stress might alleviate the evolution of DB.

Relationship between DB occurrence and their influence on rock properties is not trivial. Both aspects are highly dependent on the initial state and dynamical processes applied on the host rock. Alteration of porosity and permeability in deformed areas can also be observed without existence of DB due to slight changes in the pore network arrangement under certain stress conditions. Figure 14 illustrates the exponential trend in reduction of permeability in deformed areas with the increase of the average concentration of DB across the layers.

Relationship shown in the graph above suggests that DB also influence permeability away from the band plane. Relatively large number of DB can be a good indicator for regional deterioration of rock properties. Fossen et al. 2011 observed an opposite relationship for permeability vs. DB concentration, when permeability is higher than 18 Darcy. The authors explain that the higher host rock permeability suggests more "room" for creation of DB. The contrast in these results might be caused by the difference in grain size. Navajo sandstones studied by Fossen et al. are coarse grained, while Yasamal Valley sandstones (Balakhany Suite) are fine to very fine grained, as per Udden-Wentworth classification scheme (Figure 15), therefore no sensitivity analysis was performed with respect to the grain size variation.

From both theoretical considerations and experimental measurements on core plugs, DB have a significant effect on the micro scale porosity and permeability. Figure 16 compares rock properties of Balakhany VIII & VI sister plugs with and without a DB. Since the dimension of the DB contained within the plug and that of a plug are comparable, the existence of the impact on reservoir properties is obvious, however the degree of that impact is subject to several factors. For example, DB has a higher effect on permeability in contrast to porosity. As can be observed from Figure 16, permeability reduction is 33 percent, while for porosity it amounts to 3 percent. Such a behavior is expected due to the nature of DB: the presence of small pore throats prevailing in DB creates a strong capillary pressure barrier within its proximity, which has a stronger effect on permeability, whereas the volume of the pores associated with the DB is very small, hence less effect on porosity of the plug. Measured permeability of the plugs with a single DB shows reduction from one to two orders of magnitude compared to the host rock (Figure 17). This range has been widely observed in various types of sandstones mentioned by Fossen et al. (2017) and Ballas et al. (2015).

Conclusion and Further Recommendations

Characterization of rock properties in the structurally deformed areas is complicated by several factors that either counteract or enhance each other. In this study, four quantitative and several qualitative conclusions and observations were made through integration of field and laboratory measurements:

- Occurrence of DB is a function of the amount of ductile content present in the Balakhany sandstone layers of Yasamal Valley outcrops. It was established that DB do not appear in unconsolidated and calcite-rich sandstones for the shale volume fractions above 18% and 32%, respectively
- Permeability reduction between the outcrop samples with and without DB (sister plugs) is around 33%, whereas for porosity this reduction is not significant and averages at about 3%
- Harmonic averaging technique was used to calculate permeability of DB itself. Estimated permeability reduction stayed within 1 to 2 orders of magnitude in comparison to the host rock, which is much less from what was reported elsewhere in the literature

  “Sandwich” net-to-gross (NTG) was introduced to quantify the stress “damping” effect on the occurrence of deformation bands. The empirical observations confirm approximately 32% of “sandwich” NTG is required for DB to occur
- There is no clear correlation between the dip angle of the outcropping beds and concentration of DB. However, no DB are observed in the west flank, dipping at around 40 degrees. The data suggest that to quantify the effect of DB on reservoir rock properties, an empirical relationship between porosity/permeability, dip angle, distance to hinge and dip change rate could be derived for a specific case. Although this exercise becomes challenging for Yasamal Valley outcrops due to unavailable hinge zones (eroded upper and unexposed lower hinge zones), it can be attempted for subsurface data, provided information on dip and dip azimuth from well logs are given along with hinge points from calibrated seismic surfaces
- Although the effect of DB on porosity and permeability of the sandstone samples was measured with a single DB present in the plug, various distribution patterns or amalgamation of DB on a reservoir scale can be investigated only through the fine scale simulation modeling
- To quantify the effect of the proximity to the hinge zones on the concentration of DB and hence the reservoir properties for the outcrops, it would be important to reconstruct the structural evolution of the plunging anticline at Yasamal Valley. For both outcrop and subsurface data, one need to take into account the movement of the hinges and the stress history

Acknowledgements

The authors thank professionals from BP AGT Reservoir Development teams for their invaluable support during execution and various technical discussions throughout the study. We also express our deep gratitude to Azerbaijan International Operating Company (AIOC), all ACG partners and SOCAR for funding the study and the permission to publish the paper.

Selected References

Allen, M.B., S.J. Vincent, G.I. Alsop, A. Ismail-zadeh, and R. Flecker, 2003, Late Cenozoic deformation in the South Caspian region: Effects of a rigid basement block within a collision zone: Tectonophysics, v. 366, p. 223–239.

Alizadeh, A.A., G.A. Akhmedov, A.M. Akhmedov, A.K. Aliyev, and M.M. Zeynalov, 1966, Geology of oil and gas fields of Azerbaijan, Nedra, Moscow: p. 283-288.

Asquith, G., and D. Krygowski, 2004, Basic Well Log Analysis: AAPG Methods in Exploration 16, p. 31-35.

Aydin, A., 1978, Small faults formed as DB in sandstone: Pure and Applied Geophysics, v. 116, p. 913–930.

Aliyeva, E., 2005, Reservoirs of the Lower Pliocene Productive Series at the Western Flank of the South Caspian Basin: Lithology and Mineral Resources, v. 40/3, p. 267–278.

Ballas, G., H. Fossen, and R. Soliva, 2015, Factors controlling permeability of cataclastic DB and faults in porous sandstone reservoirs: Journal of Structural Geology, v. 76, p. 1–21.

Brunet, M.F., M.V. Korotaev, A.V. Ershov, and A.M. Nikishin, 2003, The South Caspian basin: a review of its evolution from subsidence modelling: in Brunet, M.-F., Cloetingh, S. (Eds.), Integrated Peri-Tethyan Basins Studies (Peri-Tethys Programme), Sedimentary Geology, v. 156, p. 119–148.

Bourne, S.J., and E.J.M. Willemse, 2001, Elastic stress control on the pattern of tensile fracturing around a small fault network at Nash Point, UK: Journal of Structural Geology, v. 23, p. 1753-1770.

Devlin, W.J., J.M. Cogswell, G.M. Gaskins, G.H. Isaksen, D.M. Pitcher, D.P. Puls, and K.O. Stanley, 1999, South Caspian Basin: Young, Cool, and Full of Promise.

Fossen, H., R. Soliva, G. Ballas, B. Trzaskos, C. Cavalcante, and R.A. Schultz, 2017, A review of DB in reservoir sandstones: geometries, mechanisms and distribution: Geological Society, London, Special Publications 459, SP459. 4.

Fossen, H., R.A. Schultz, and A. Torabi, 2011, Conditions and implications for compaction band formation in the Navajo Sandstone, Utah: Journal of Structural Geology, v. 33, p. 1477–1490.

Green, T., N. Abdullayev, J. Hossack, G. Riley, and A.M. Roberts, 2009, Sedimentation and subsidence in the South Caspian Basin, Azerbaijan: Geological Society, London, Special Publications, v. 312 p. 241-260.

Gurevich, A.E., and G.V. Chilingar, 1995, Abnormal pressures in Azerbaijan: A brief critical review and recommendations: Journal of Petroleum Science and Engineering, v. 13/2, p. 125-135.
Gilman, J.R., and H. Kazemi, 1988, Improved Calculations for Viscous and Gravity Displacement in Matrix Blocks in Dual-Porosity Simulators: JPT, p. 60-70; Trans., AIME, 285.

Holzhausen, G.R., and A.M. Johnson, 1979, The concept of residual stress in rock: Tectonophysics, v. 58/3, p. 237-267.

Jones, R.W., and M.D. Simmons, 1996, A review of the stratigraphy of Eastern Paratethys (Oligocene-Holocene): Bulletin of the Natural History Museum London (Geology), v. 52, p. 25-49.

Juanes, R., J. Samper, and J. Molinero, 2002, A general and efficient formulation of fractures and boundary conditions in the finite element method: Int. J. Numer. Methods Eng., v. 54/12, p. 1751-1774.

Schueller, S., A. Braathen, H. Fossen, and J. Tveranger, 2013, Spatial distribution of DB in damage zones of extensional faults in porous sandstones: statistical analysis of field data: Journal of Structural Geology, v. 52, p. 148–162.

Tarek, A., 2001, Reservoir Engineering Handbook-Ch. 4: Fundamental of rock properties, Second Edition, Gulf Professional Publishing.

Warren, J.E., and P.J. Root, 1963, The behavior of naturally fractured reservoirs: SPE J., v. 3/3, p. 245-255.

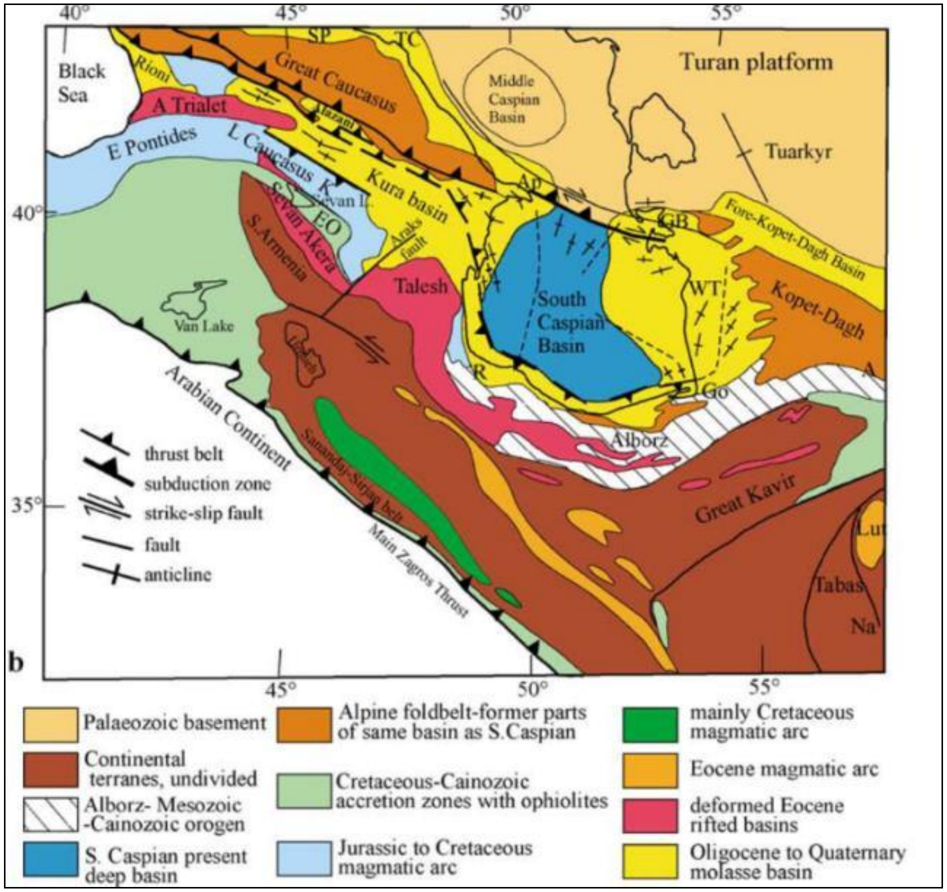

Figure 1. Regional geological map of main tectonic units of the Caspian region (Brunet et al., 2003).

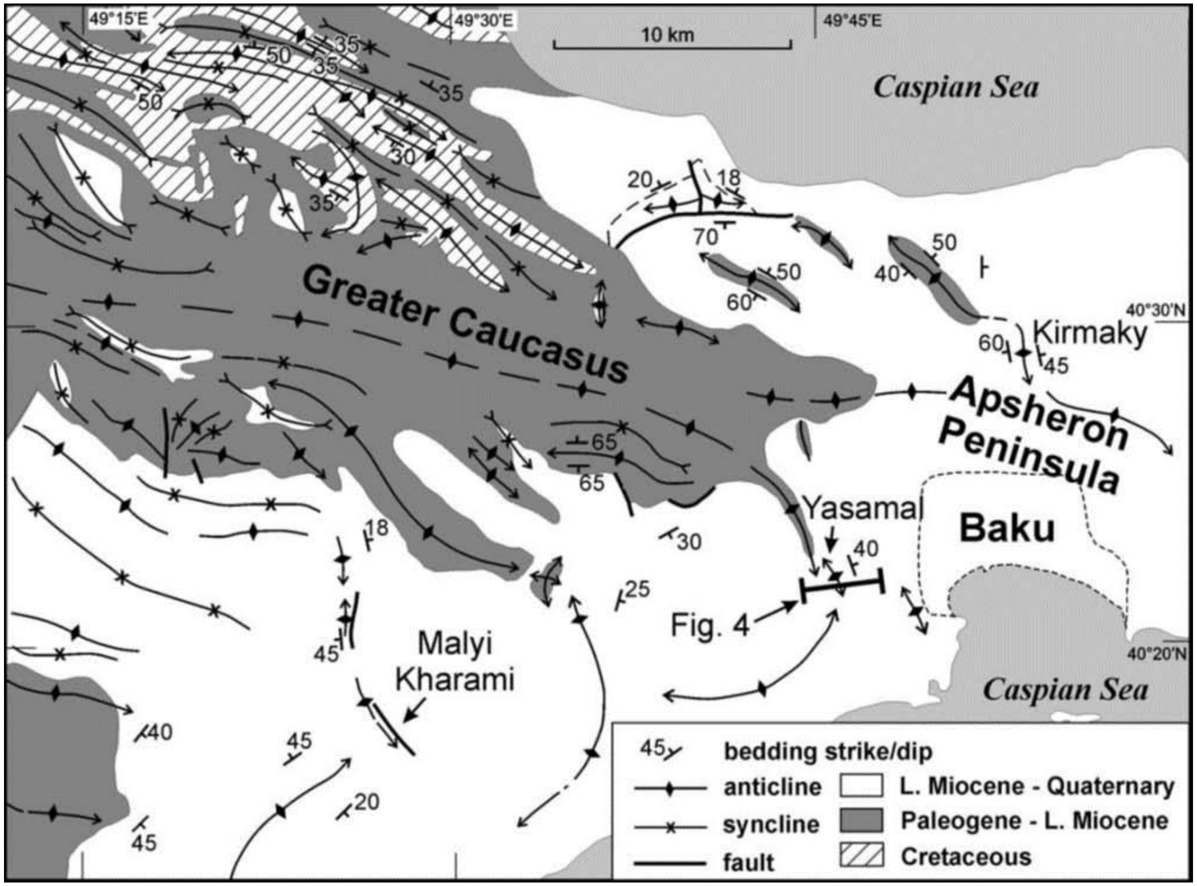

Figure 2. Geology of the eastern Greater Caucasus, the western portion of the Absheron Peninsula and the northeastern Kura basin (modified by Allen et al., 2003).

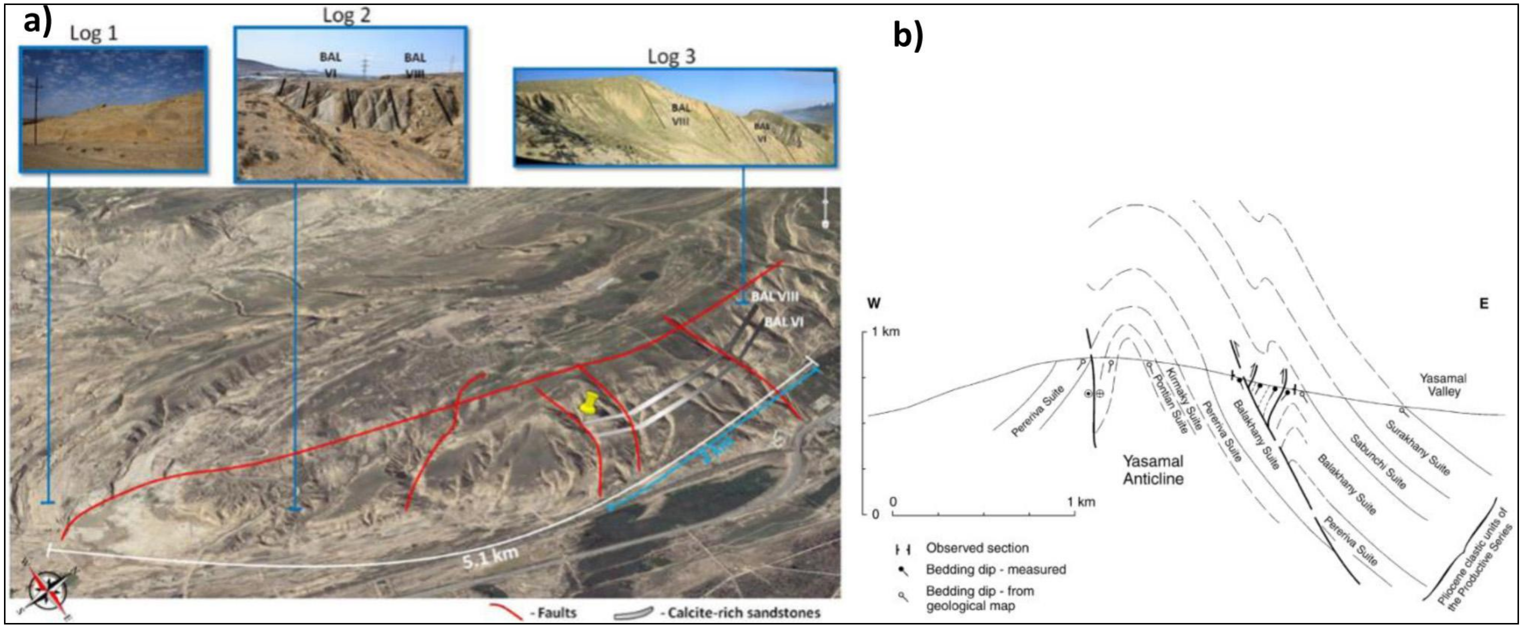

Figure 3. a) Satellite image of Yasamal (Shubany) anticline, showing locations of logs (dark blue), faults (red) and distribution of calcite-rich layers (light-blue); b) Geological cross-section of Yasamal anticline (Allen et al., 2003).

Figure 4. Outcrop of overturned layers in the east limb of Yasamal anticline. Arrows indicate the schematic of measurement path.

Figure 5. DB in unconsolidated (left) and calcite-rich (right) sandstones.

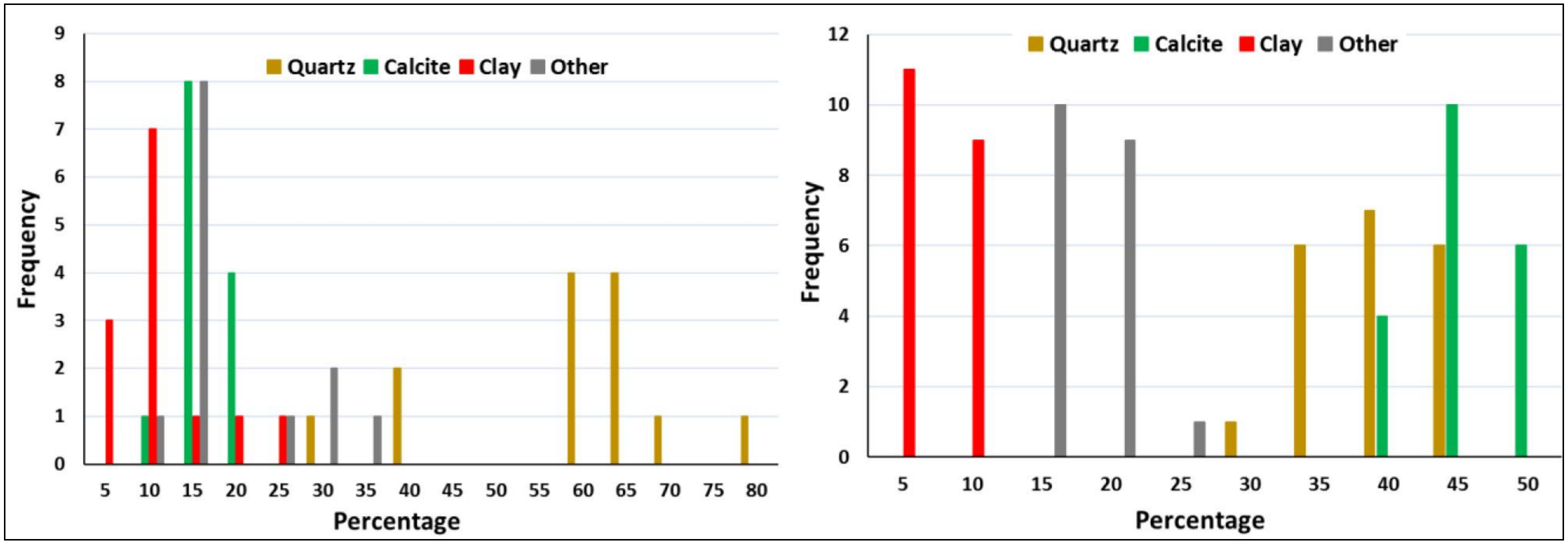

Figure 6. XRD-based distribution of minerals in the unconsolidated, relatively clean (left graph) and consolidated, calcite-rich (right graph) sandstones.

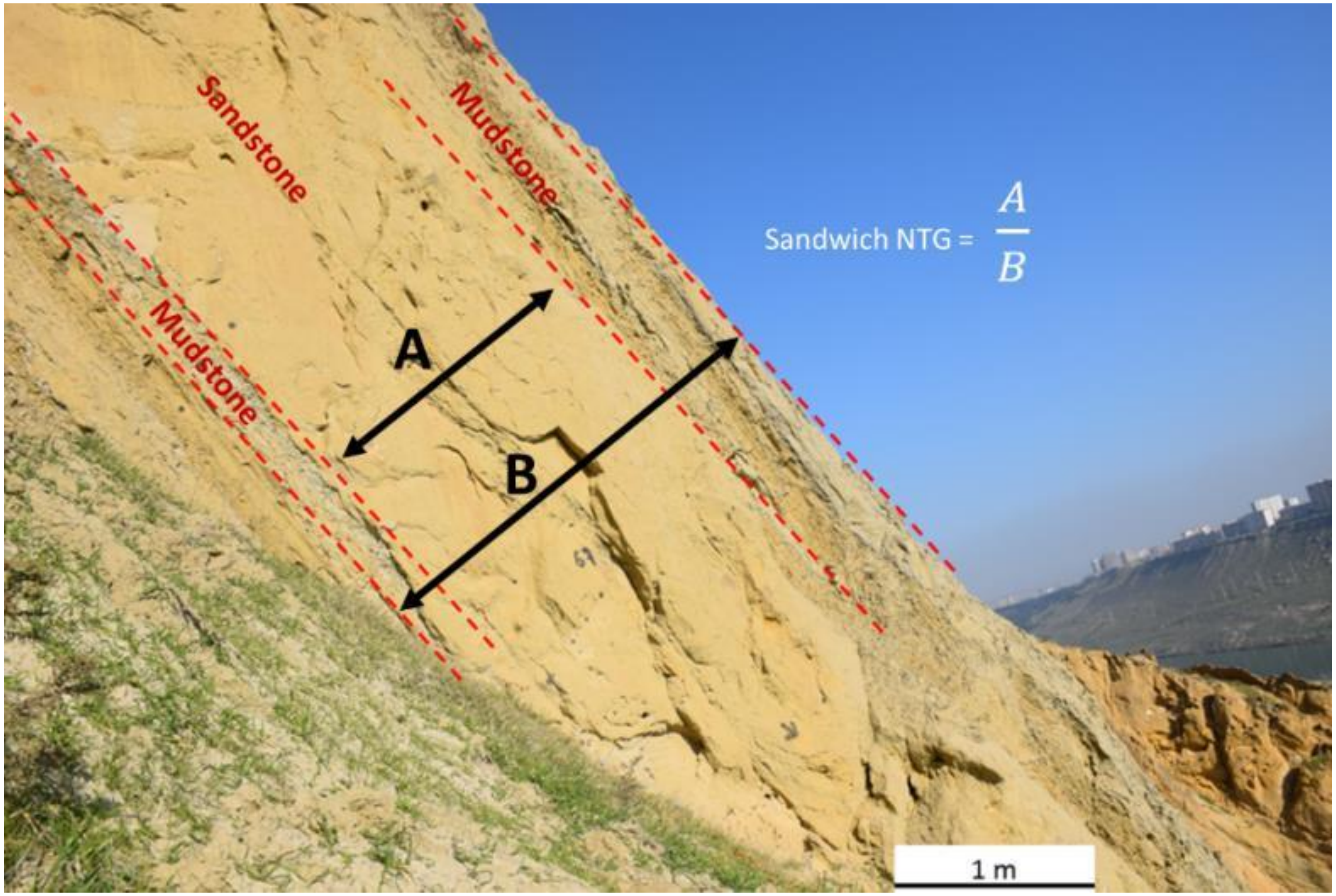

Figure 7. Schematic representation of “sandwich NTG”.

Figure 8. Procedure of sampling sister-plugs in proximity.

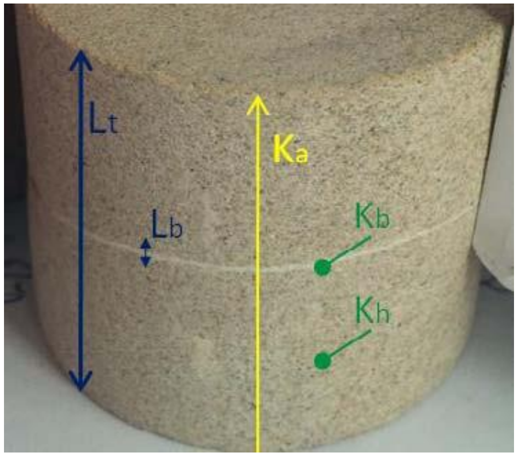

Figure 9. Setting parameters for deformation band permeability calculation (on the example of a calcite-rich plug).

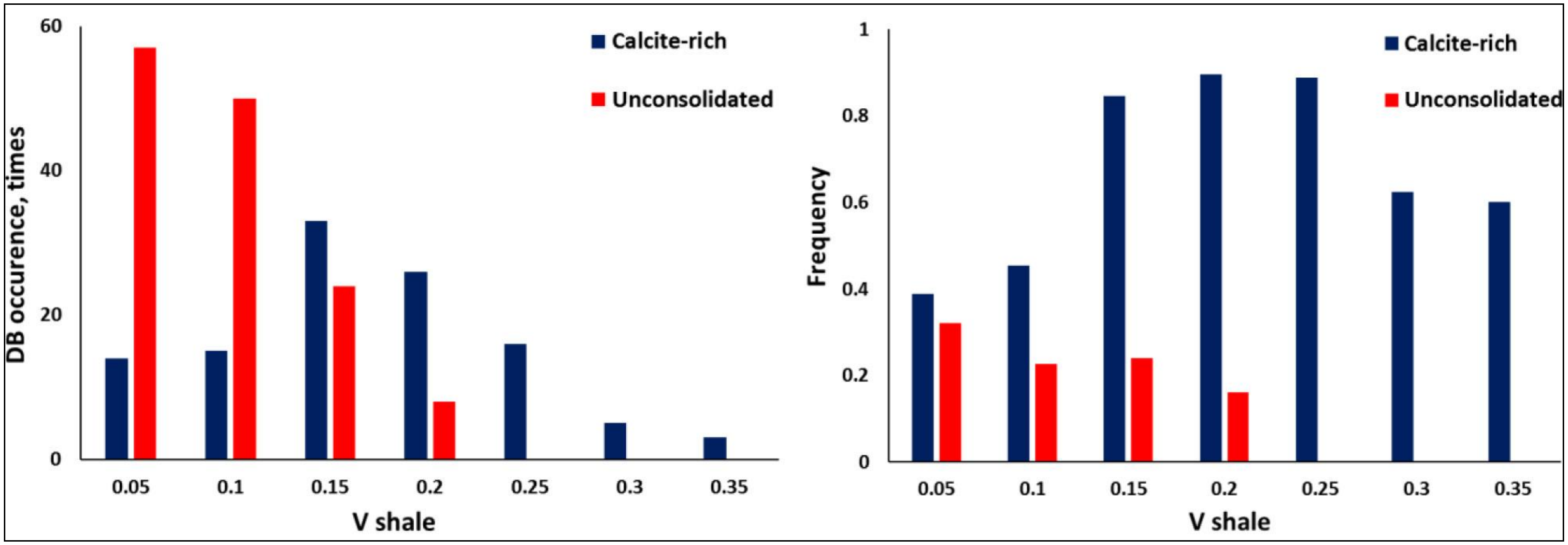

Figure 10. Relationship between deformation bands occurrence and shale volume at Yasamal Valley.

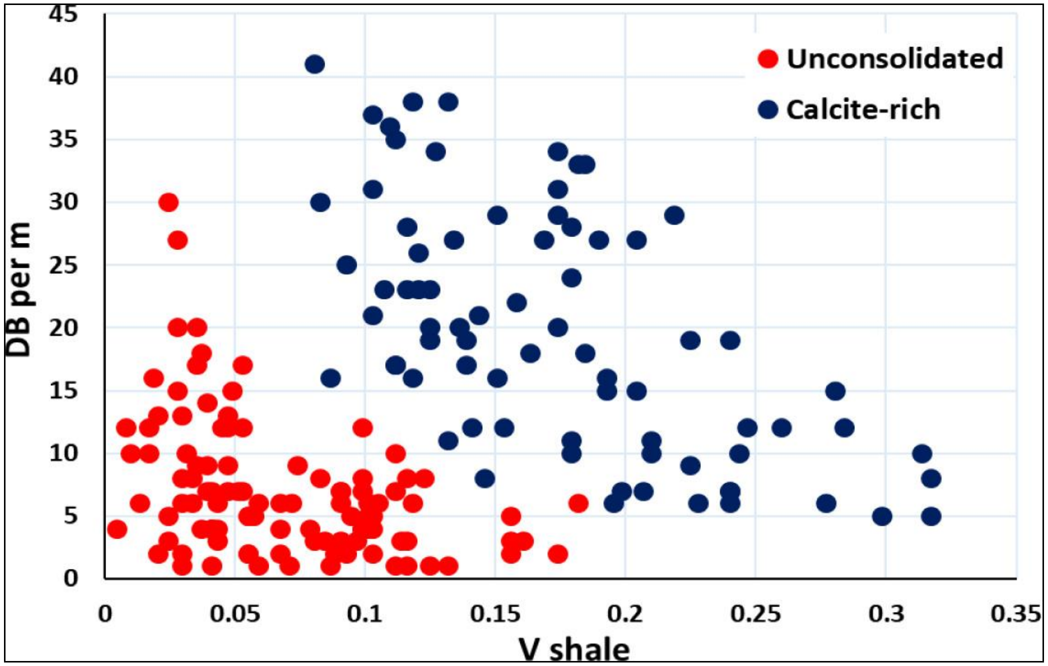

Figure 11. Relation of Vshale to the concentration of DB for unconsolidated (red) and calcite-rich (blue) sandstones.

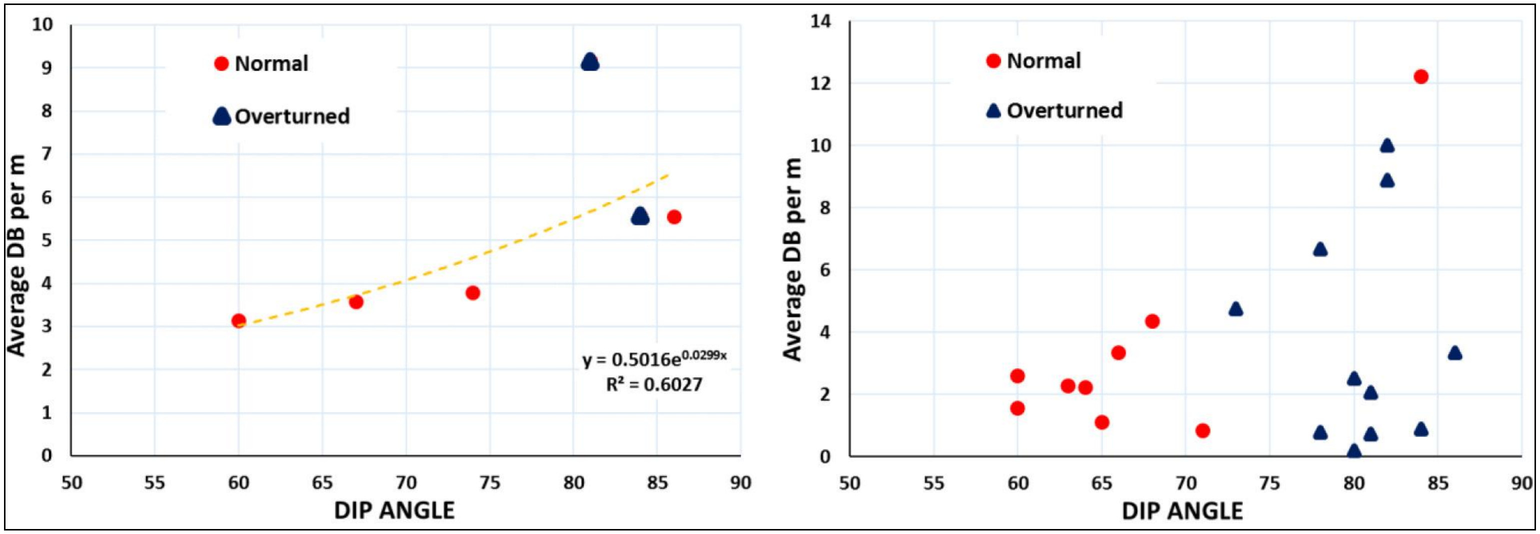

Figure 12. Relationship between average concentration of DB in unconsolidated sandstone layers and bed dip angle parallel (left) and perpendicular (right) to layering.

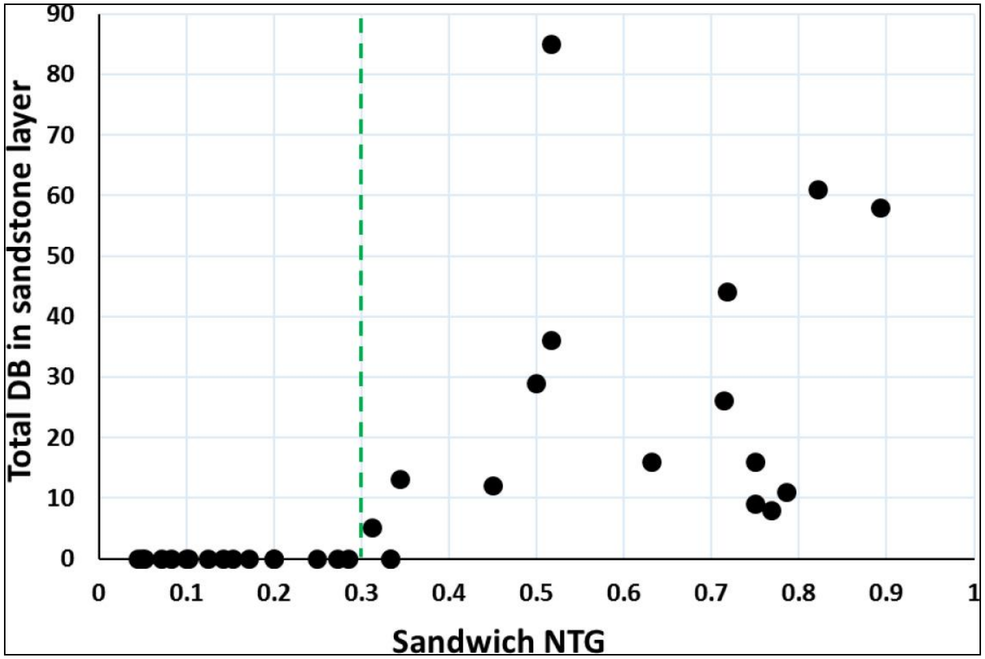

Figure 13. Occurrence of DB vs. “sandwich” NTG of Balakhany subunits.

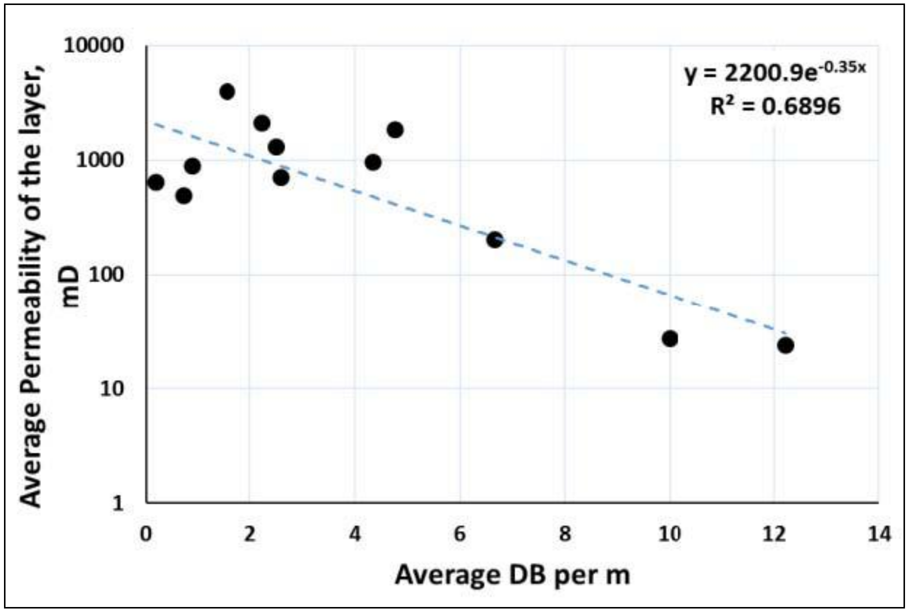

Figure 14. Dependency of permeability on the concentration of DB at the field scale (Yasamal anticline).

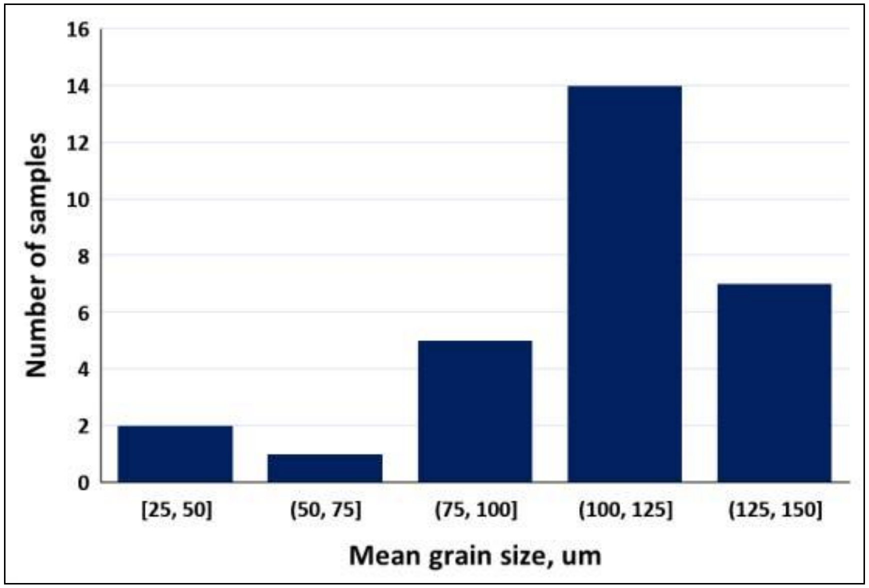

Figure 15. Mean grain sizes of Yasamal Valley sandstones derived from SEM images and thin sections.

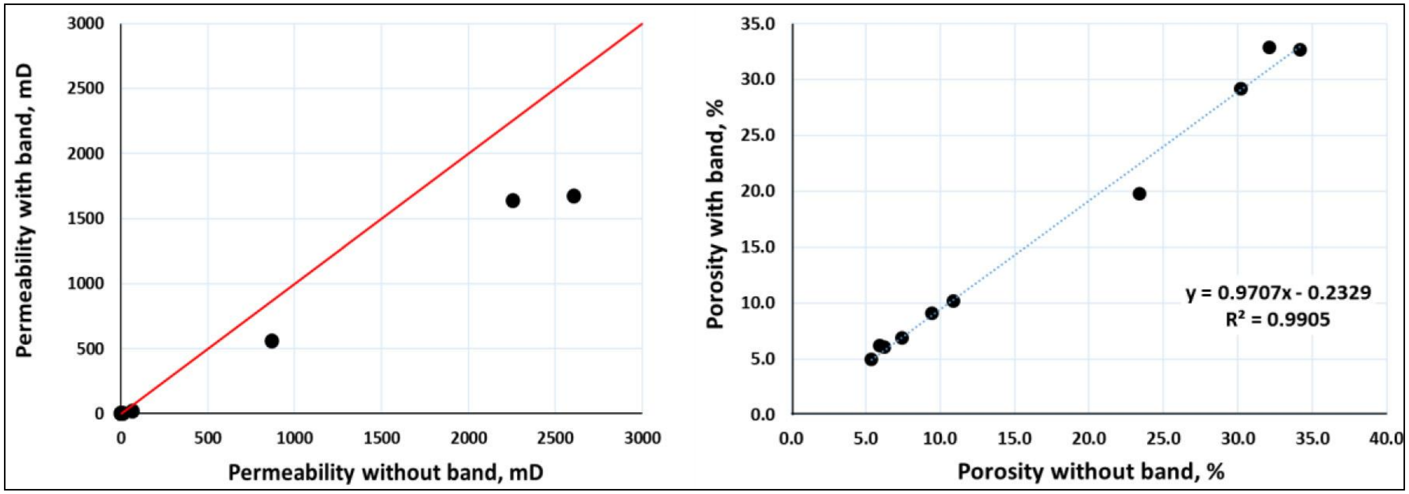

Figure 16. Comparison of permeability (left) and porosity (right) values for sister plugs with and without a deformation band.

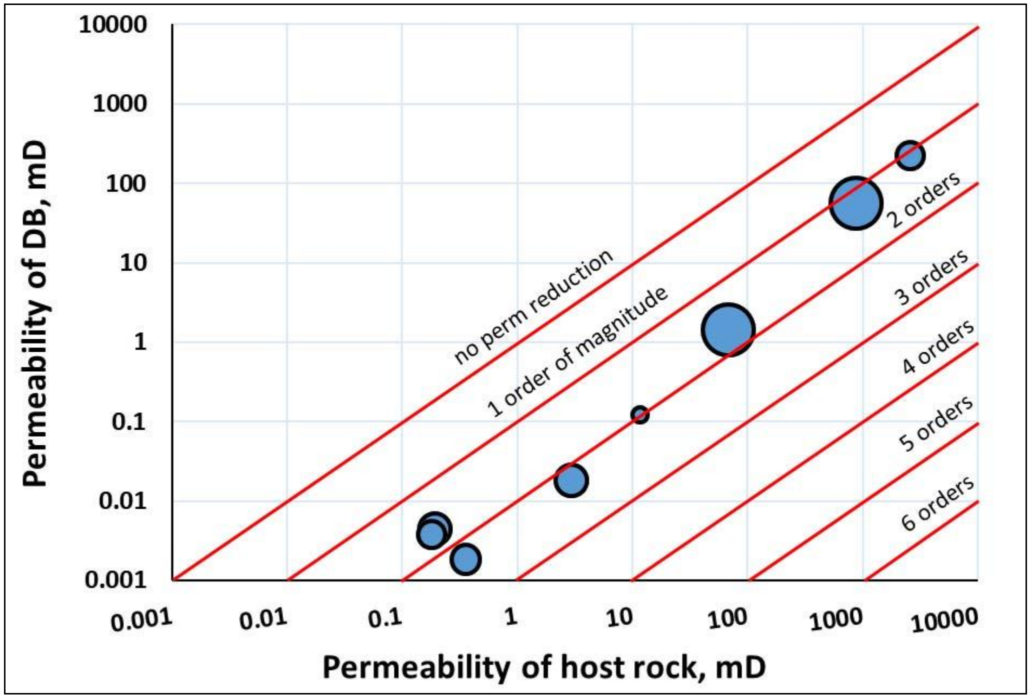

Figure 17. Estimated (harmonic average technique) permeability of the deformation band vs. its host rock. Bubbles sized by XRD-derived clay content.