Domain structure of volcanics' ferromagnetic grains: A case study of the Saatly ultradeep well, Azerbaijan

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Introduction. For the first time magnetometric researches of volcanogenic rock core of the super deep Saatly well have been conducted by the staff of department “Geomagnetism” of the Institute of Geology and Geophysics of Azerbaijan National Academy of Science (ANAS). The necessity in the magnetic researches of a core of the Saatly super deep well has been dictated by need in obtaining the petromagnetic data used at interpretations of results of geophysical activity. The ore minerals’ magnetic research together with microprobe analysis of them [Novruzov, Tselmovich, 2018] revealed that magnetic properties of rocks are bound with magnetite and Ti-poor titanomagnetite.

Environmental conditions of generation of ferromagnetic minerals and changes of them leave traces on magnetic domain structure [Stackey, Banerjee, 1974]. Application of the rock magnetic method for identification of domain structure of magnetic grains is the purpose of the proposed article. For realization of this purpose we used four magnetic criteria. The criteria are based on characteristics of various magnetic parameters of magnetic grains with different magnetic domain structures.

Description of the object. The superdeep well is located near the city of Saatly (λ = 39.91 °N, φ = 48.36 °E), Azerbaijan (Fig. 1). The region of the well location (design depth...
of 15 km) is spaced in the Kur basin placed between the Greater Caucasus and the Lesser Caucasus (the large tectonic constructions). According to deep structure the Kur basin is subdivided into three depressions: upper Kura basin, middle Kura basin and lower Kura basin. The Saatly superdeep well is located within the middle Kura basin.

According to geophysical data interpretation the crystalline basement (around the Saatly local gravitational maximum) possesses a block structure (where there are rocks of persillic and basic composition at a depth of 8 km). Debatable idea of crustal structure within the Saatly local gravitational maximum was formed in two points of view. According to the first — the Earth crust consists of granite and basalt layers, according to the second — the Earth crust is single-layer and it is presented by mafic rocks only. Features of the Earth crust and the reduced thickness of a sedimentary cover at Saatly territory formed a basis for drilling of the super deep well.

Object of our researches are the volcanics located in the depths interval of 3540—8126 m. According to research papers [Abdullaev, Salakhov, 1983; Abdullaev et al., 1984] the development of the low-temperature metamorphism (depth of 3540—7000 m) has been noted in the volcanogenic rocks. But from depths of 7000 m and deeper the development of the low-temperature metasomatism is revealed. The quantities of the studied volcanic rocks were 49. Three duplicate with cubic form (1 cm) were sawn from each sample.

The depth interval of 3540—3900 m is characterized by plagioclase basalts and is mainly presented by volcanogenic facies. Basalts contain the potassium-enriched and sodium-enriched alkalinity.

The depth interval of 3900—4850 m contains porphyritic olivine-pyroxene-plagioclase-basalts and pyroxene-plagioclase-basalts. Basalts are low-alkaline (low-potassium). The depth interval of 4850—5209 m possesses much bigger phases of rocks. Except...
basalts their amphibole-containing phases and andesites are noted. Along with low-potass-
ium basalts potassium-enriched groups ha-
ve been discovered.

In the depth interval of 5209—6100 the double-pyroxene-plagioclase basalts and an-
desite-basalts prevail. These rocks possess
the alkalescence and the strong fracturing.

There are andesites in the depth interval
of 6100—6800 m. The microdolerite sills are
noted as well.

Upper parts of 6800—8000 m depth inter-
val are presented by dacites, dacite-tuffs and
pumiceous breccia. In the middle horizons
and lower ones of the interval dacites are
alternating with plagiolithyolite and andesites.

Thus, the studied columnvolcanics chan-
ge with depth: from the mafics (andesite-ba-
salts, basalts) to intermediate rocks (andesi-
tes) and then to persilicrocks (rhyodacites,
dacites).

Technique of works. During the magne-
tic researches of volcanogenic rocks of the
superdeep Saatly well the following magne-
tic parameters were measured: a natural re-
manent magnetization (NRM) and magne-
tic susceptibility (c). At the laboratory on
each duplicate sample (for each one the NRM
and the c were measured) saturation isother-
mal remanent magnetization (SIRM) and iso-
thermal remanent magnetization (IRM) in the
field of 1.5 T have been created. At the la-
boratory a thermal remanent magnetizati-
on (TRM) was created on each duplicate of
sample by means of cooling from tempera-
tures above the Curie point (more than 600
°C) in the presence of magnetic field equal
to 0.5 • 10-4 T. Partial thermal remanent mag-
netizations (PTRM) were thermally demagnetized by a routine technique
[Kobayashi, Fuller, 1967].

Results of the researches. Magnetic re-
searches of the well volcanogenic rocks shos-
ved that the measured magnetic param-
ters of Mrs and Ms and TRM and Qn are
changing according to depth. Changes of
these parameters reflect variations of grain
size. Magnetic parameters of NRM, χ, SIRM
(Mrs), Ms and TRM were measured for study
of a minerals' magnetic domain state of the
Saatly superdeep well. There are three types
of different magnetic behavior, depending
on the grain size. The defined parameters
allowed calculating Qn factor and magni-
tude of Mrs/Ms.

For use of method-criterion the par-
tial thermal remanent magnetizations (PTRM)
were created. The PTRM were acquired in
the range of temperatures 200—500 °C. For
identification of a magnetic domain state of
volcanic ferromagnetic grains of the Saatly
well the four magnetic criteria were used:
factor Qn, Mrs/Ms, Lauri-Fuller’s criterion
and thermal magnetic criterion.

Short consideration of identification cri-
teria of a magnetic domain state had bro-
tought to light that that any of criteria does
not work completely well, even in case of
ensembles of “pure” grains. The found struc-
tural heterogeneities of grains [Novruzov,
Tselmovich, 2018] and also grains various
by structure and the sizes (magnetic rese-
arches of the structure and concentration)
make impossible to use only one of the men-
tioned criteria. Therefore in this article, the
most often used in rock magnetism the four criteria are applied. At the same time the judgment of a magnetic domain state was based on coincidence of results of identification by the two or the three criteria.

The experimental results of definition of a magnetic domain structure of ferromagnetic grains of volcanogenic rocks of the Saatly well section (interval of 3540—8126 m)

| Type of rock     | Depts, m     | $Q_n$ | Domain state | $M_{rs}/M_s$ | Domain state | Lauri—Fuller | Thermomagnetic | Total |
|-----------------|--------------|-------|--------------|--------------|--------------|--------------|----------------|-------|
| Andesite-basalt | 3540—3546    | 0,15  | MD           | 0,04         | SD           | —            | MD             | MD    |
| Basalt          | 3660—3666    | 2,03  | PSD          | 0,26         | SD (PSD)     | —            | MD (PSD)       | MD (PSD) |
| Basalt          | 3761—3767    | 0,29  | MD           | 0,17         | PSD          | SD           | MD             | MD    |
| Basalt          | 3820—3825    | 0,51  | MD           | 0,13         | PSD          | SD           | —              | MD (PSD) |
| Basalt          | 3975—3981    | 1,71  | PSD          | 0,13         | PSD          | SD           | —              | PSD   |
| Basalt          | 4062—4067    | 0,33  | MD           | 0,10         | PSD          | ?            | —              | MD (PSD) |
| Basalt          | 4165—4171    | 2,55  | PSD          | 0,24         | PSD          | SD           | MD             | PSD   |
| Basalt          | 4250—4255    | 0,41  | MD           | 0,12         | PSD          | SD           | MD             | MD (PSD) |
| Basalt          | 4310—4315    | 0,18  | MD           | 0,04         | MD           | SD           | MD             | MD    |
| Andesite-basalt | 4423—4428    | 0,31  | MD           | 0,07         | MD (PSD)     | SD           | —              | MD    |
| Basalt          | 4516—4522    | 0,83  | MD           | 0,06         | MD (PSD)     | SD           | —              | MD    |
| Basalt          | 4600—4608    | 1,30  | PSD          | 0,03         | MD           | SD           | MD             | MD (PSD) |
| Basalt          | 4634—4640    | 0,68  | MD           | 0,07         | MD (PSD)     | SD           | MD             | MD    |
| Basalt          | 4686—4692    | 0,74  | MD           | 0,08         | MD (PSD)     | SD           | MD             | MD    |
| Dolerite        | 4714—4719    | 0,32  | MD           | 0,07         | MD (PSD)     | SD           | —              | MD    |
| Dolerite        | 4770—4777    | 0,81  | MD           | 0,05         | MD           | SD           | MD             | MD    |
| Andesite-basalt | 4800—4807    | 1,82  | PSD          | 0,04         | MD           | MD           | —              | MD    |
| Andesite-basalt | 4881—4885    | 0,60  | MD           | 0,02         | MD           | SD           | —              | MD    |
| Basalt          | 4915—4922    | 1,39  | PSD          | 0,02         | MD           | SD           | MD             | MD (PSD) |
| Andesine        | 5036—5040    | 0,30  | MD           | 0,04         | MD           | SD           | MD             | MD    |
| Gabbrosnorite   | 5129—5132    | 0,35  | MD           | 0,06         | MD (PSD)     | SD           | MD             | MD    |
| Basalt          | 5185—5190    | 0,69  | MD           | 0,03         | MD           | SD           | MD             | MD    |
| Basalt          | 5270—5273    | 3,00  | PSD          | 0,06         | MD (PSD)     | SD           | MD             | MD (PSD) |
| Basalt          | 5385—5390    | 1,40  | PSD          | 0,04         | MD           | SD           | —              | MD (PSD) |
Fuller’s criterion) are represented. In Fig. 4 typical thermal demagnetization curves of PTRM acquired at different temperatures (thermal magnetic criterion) are presented.

We can see in the table that in most cases grains of magnetic minerals (carriers of remanent magnetization), are in a multidomain state. For an upper part of a section of volcanogenic rocks (3540—5500 m), especially in the depth interval of 3540—5000 m,

|                |           |        |       |       |       |       |       |
|----------------|-----------|--------|-------|-------|-------|-------|-------|
| Basalt         | 5467—5474 | 0,53   | MD    | 0,05  | MD    | SD    | —     |
| Andesite       | 5544—5550 | 1,89   | PSD   | 0,07  | MD (PSD) | SD | MD | MD (PSD) |
| Basalt         | 5634—5636 | 3,95   | PSD   | 0,08  | MD (PSD) | SD | MD | MD (PSD) |
| Andesite-basalt| 5746—5750 | 2,12   | PSD   | 0,11  | PSD   | SD    | MD    |
| Andesite       | 5828—5830 | 5,48   | PSD   | 0,08  | MD (PSD) | SD | MD | MD (PSD) |
| Andesite       | 6000—6003 | 1,36   | PSD   | 0,07  | MD (PSD) | SD    | —     | MD (PSD) |
| Andesite       | 6174—6178 | 0,68   | MD    | 0,03  | MD    | —     | —     | MD    |
| Andesite-basalt| 6290—6295 | 1,00   | MD    | 0,05  | MD    | —     | —     | MD    |
| Andesite       | 6430—6435 | 1,00   | MD (PSD) | 0,07  | MD (PSD) | SD    | —     | MD (PSD) |
| Andesite       | 6581—6583 | 1,72   | PSD   | 0,08  | MD (PSD) | SD | MD0 | MD (PSD) |
| Andesite-basalt| 6740—6745 | 2,90   | PSD   | 0,03  | MD    | SD    | —     | MD (PSD) |
| Andesite       | 6877—6882 | 1,15   | MD (PSD) | 0,06  | MD (PSD) | SD    | —     | MD (PSD) |
| Dolerite       | 6994—7003 | 1,87   | PSD   | 0,13  | PSD   | SD    | MD    | MD (PSD) |
| Dacite         | 7038—7048 | 0,50   | MD    | 0,07  | MD (PSD) | MD    | —     | MD    |
| Dacite         | 7172—7176 | 2,15   | PSD   | 0,05  | MD (PSD) | SD    | —     | MD (PSD) |
| Rhyodacite     | 7264—7276 | 0,29   | MD    | 0,31  | SD (PSD) | SD    | —     | MD (PSD) |
| Dolerite       | 7332—7343 | 0,49   | MD    | 0,03  | MD    | SD    | —     | MD    |
| Rhyodacite     | 7420—7428 | 0,50   | MD    | 0,04  | MD    | SD    | MD    | MD    |
| Dacite         | 7576—7578 | 0,85   | MD    | 0,06  | MD (PSD) | SD | MD | MD    |
| Dacite         | 7642—7646 | 0,25   | MD    | 0,04  | MD    | —     | —     | MD    |
| Dacite         | 7729—7738 | 1,77   | PSD   | 0,05  | MD (PSD) | SD | MD    | MD    |
| Rhyodacite     | 7874—7878 | 0,21   | MD    | 0,02  | MD    | SD    | MD    | MD    |
| Andesite-dacite| 7991—7993 | 0,65   | MD    | 0,04  | MD    | SD    | MD    | MD    |
| Rhyolite       | 8103—8108 | 0,57   | MD    | 0,03  | MD    | SD    | MD    | MD    |
| Dacite         | 8108—8126 | 0,80   | MD    | 0,05  | MD    | SD    | —     | MD    |

SD — single-domain particles; PSD — pseudo-single-domain particles; MD — multi-domain particles.
the pseudo-single-domain state often becomes apparent. It demonstrates that remanent magnetization carriers in this interval of depths are the finest grains. These grains, most probably, belong, to the second generation of grains of magnetite and the Ti-poor titanomagnetite determined on the basis of microprobe analysis [Novruzov, Tselmovich, 2018].

In the bottom of a section (5500—8126 m) is more often, and in the depth interval 7300—8126 m one and all studied rocks contain only multidomain grains of ferromagnetic minerals.

This result presumably can be bound to that circumstance that the low-temperature metamorphism, especially metasomatism, results in partial or complete collapse (replacement) of fine grains of the ferromagnetic minerals in the bottom of a section which are contained in rocks.

At the same time artificial “enrichment” of rocks with more coarse magnetic grains is observed. As shown by means of microprobe [Novruzov, Tselmovich, 2018] of ore grains the fine fraction of the deepest rocks is presented, mainly, by fragments of the crushed large grains.

**Discussion of results.** The done petromagnetic researches showed that in most cases grains of magnetic minerals (carriers of remanent magnetization) represent an ensemble of multidomain particles. In upper part of the section (3540—5500), especially in the depth interval 3540—5000 m, the pseudo-single domain state is often presented. It demonstrates that in this depth interval, except of course (large volume) multidomain grain generation, fine grains of other generation can bear a remanent magnetization.

The results of identification of a domain structure presented in the summary table, in the deeper section (5500—8126 m) are more often, and in the depth interval 7300—8126 m one and all ferrromagnetic minerals are demonstrating only multidomain grains content. This result presumably can be caused by the fact that in the deeper section the generation (rather) of fine ferrromagnetic grains can be partially or entirely destroyed due to occurrence of the low-temperature metamorphism (metasomatism). As a re-
As is obvious from the table the Lauri-Fuller’s criterion is inapplicable for the complex ensemble of ferromagnetic grains. Use of this criterion eventuates in the diametrically opposite data received on the basis of the two or the three other criteria of domain structure identification. The thermal magnetic criterion is sensitive to manifestation of single-domain (pseudo-single-domain) and of multidomain ferromagnetic grains of in the complex ensemble of grains.

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Various magnetic properties of magnetic minerals show strong grain-size dependence. This dependency occurs because these parameters are influenced by the magnetic grain-size (domain state) of the samples. Natural rocks often contain a mixture of different magnetic minerals with different grain-size (domain states). Thus determination of the domain state is important. The Saatly ultradeep well’s volcanics were used as a research material. In the depth intervals of 3540—8126 m the volcanics had been revealed by the borehole. According to data of the petrographic and microprobe analysis the volcanogenic of the ultradeep borehole is conditionally divided into a two parts: 1) the upper part (an interval of depths of 3540—5500 m); 2) the bottom part (an interval of depths of 5500—8126 m). In the upper part of section according to microprobe analysis of volcanogenic rocks ore grains are presented by two generations: 1) large grain of titanomagnetites (Ti-poor), homogeneous or with a decay structures; 2) small-sized usually well faced grain of practically stoichiometric magnetite. So, homogeneous small-sized grains or fragments of decay large grains (which are strongly changed chemically) can have properties of single-domain particles. Here the ferromagnetic grains (especially in the depth interval 3540—5000 m) are often noted as a pseudo-single domain. In the bottom part of the section the presence of multidomain grains of the Ti-poor titanomagnetite is noted. And since depths of 7000 m the oxidized magnetite is also observed. The pseudo-single-domain grains are fixed much less than in the upper section. And, since a depth mark of 7300 m and deeper, they are absent wholly. In the result of research it turned out that the ferromagnetic is presented by basically multidomain grains. It should be noted that Lauri-Fuller’s Criterion is not applicable at identification of a domain structure of the complex ensemble of the ferromagnetic grains.

Key words: indirect magnetic criteria, magnetic domain state, volcanogenic rocks, super deep well.

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