Geophysical Research Abstracts
Vol. 19, EGU2017-2344-1, 2017
EGU General Assembly 2017

Quantitative Analysis of Piezoelectric and Seismoelectric Anomalies in Subsurface Geophysics

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The piezoelectric and seismo-electrokinetic phenomena are manifested by electrical and electromagnetic processes that occur in rocks under the influence of elastic oscillations triggered by shots or mechanical impacts (hits) (e.g., Neishtadt and Osipov, 1958; Neishtadt, 1961; Parkhomenko, 1971; Neishtadt et al., 1986; Maxwell et al., 1992; Butler et al., 1994; Kepic et al., 1995; Neishtadt et al., 1996; Mikhalov et al., 1997; Boulytchov, 2000; Dupuis et al., 2009; Schakel et al., 2011; Neishtadt and Eppelbaum, 2012; Jouniaux and Zyserman, 2016).

The developed classification divides the above phenomena into the following types: (1) the seismo-electrokinetic (electrokinetic) phenomenon *E*, which occurs in polyphase media due to the mutual displacement of the solid and liquid phases; (2) the piezoelectric phenomenon, which occurs in rocks that contain piezoactive minerals; (3) the shot-triggered phenomenon, which is observed in rocks in the vicinity of a shot or hit point; (4) the seismoelectric phenomenon *I*, manifested by the change of the electric current passing through rocks, and (5) high-frequency impulse electromagnetic radiation, which is generated by massive base-metal bodies. This paper describes the above phenomena in detail, describing their nature, manifestation patterns, and registration techniques. Because the manifestation patterns of the above phenomena are different in different rocks, these phenomena can be used as a basis for geophysical exploration techniques. The piezoelectric method is an example of a successful application of piezoelectric and seismo-electrokinetic phenomena in exploration geophysics. It has been successfully applied in mineral exploration and environmental features research in Russia, USA, Canada, Australia, Belorussia, Azerbaijan, Georgia, Israel and other countries.

This method uses comparatively new geophysical parameter – piezoelectric activity of rocks, ores, and minerals. It enables direct exploration for pegmatite, apatite-nepheline, essentially sphalerite, and ore-quartz deposits of gold, tin, tungsten, molybdenum, zinc, crystal, and other raw materials. This method also enables differentiation of rocks such as bauxites, kimberlites, etc., from the host rocks, by their electrokinetic properties.

Classification of some rocks, ores, and minerals by their piezoactivity is given in Table 1. These objects (targets) transform wave elastic oscillations into electromagnetic ones. It should be taken into account that anomalous bodies may be detected not only by positive, but also by negative anomalies, if low-piezoactive body occurs in the higher piezoactive medium.

The piezoelectric method is an example of successful application of piezoelectric and seismo-electrokinetic phenomena in exploration and environmental geophysics and designed for delineation of targets differing from the host media by piezoelectric properties (Neishtadt et al., 2006, Neishtadt and Eppelbaum, 2012). This method is employed in surface, downhole, and underground modes.

Recent testing of piezoelectric effects of archaeological samples composed from fired clay have shown values of $2.0 - 3.0 \cdot 10^{-14}$ C/N.

However, absence of reliable procedures for solving the direct and inverse problems of piezoelectric anomalies (PEA), drastically hampers further progression of the method. Therefore, it was suggested to adapt the tomography procedure, widely used in the seismic prospecting, to the PEA modeling. Diffraction of seismic waves has been computed for models of circular cylinder, thin inclined bed and thick bed (Alperovich et al., 1997). As a result, spatial-time distribution of the electromagnetic field caused by the seismic wave has been found. The computations have shown that effectiveness and reliability of PEA analysis may be critically enhanced by considering total electro- and magnetograms as differentiated from the conventional approaches. Distribution of the electromagnetic field obtained by solving the direct problem was the basis for an inverse problem, i.e. revealing depth of a body occurrence, its location in a space as well as determining physical properties. At the same time, this method has not received a wide practical application taking into account complexity of real geological media. Careful analysis piezo- and seismoelectric anomalies shows the possibility of application of quantitative analysis of these

effects advanced methodologies developed in magnetic prospecting for complex physical-geological conditions (Eppelbaum et al., 2000, 2001, 2010; Eppelbaum, 2010; 2011, 2015). Employment of these methodologies (improved modifications of tangents, characteristic points areal methods) for obtaining quantitative characteristics of ore bodies, environmental features and archaeological targets (models of horizontal circular cylinder, sphere, thin bed, thick bed and thin horizontal plate were utilized) have demonstrated their effectiveness.

Case study at the archaeological site Tel Kara Hadid

Field piezoelectric observations were conducted at the ancient archaeological site Tel Kara Hadid with gold-quartz mineralization in southern Israel within the Precambrian terrain at the northern extension of the Arabian-Nubian Shield (Neishtadt et al., 2006). The area of the archaeological site is located eight kilometers north of the town of Eilat, in an area of strong industrial noise. Ancient river alluvial terraces (extremely heterogeneous at a local scale, varying from boulders to silt) cover the quartz veins and complicate their identification. Piezoelectric measurements conducted over a quartz vein covered by surface sediments (approximately of 0.4 m thickness) produced a sharp (500 μV) piezoelectric anomaly. Values recorded over the host rocks (clays and shales of basic composition) were close to zero. The observed piezoelectric anomaly was successfully interpreted by the use of methodologies developed in magnetic prospecting.

For effective integration of piezo- and seismoelectric interpretation results with other geophysical methods, some schemes developed in theory of information (Eppelbaum, 2014) and wavelet theory (Eppelbaum et al., 2011) can be effectively applied.

Table 1. Classification of some rocks, ores, and minerals by their piezoactivity d (10^{-14} Coulomb/Newton) (after Neishdadt et al., 2006 and Neishtadt and Eppelbaum, 2012, with modifications)

Piezoactivity group	Rock, Ore, Mineral	$d_{min} - d_{max}$	d_{aver}
I	Quartz-tourmaline-cassiterite ore	0.8-28	15.7
	Antimonite-quartz ore	0.2-1.35	0.6
	Apatite-nepheline ore	0-5	0.9
	Galenite-sphalerite ore	0.2-7.7	3.3
	Ijolite	0.1-8	1.2
II	Melteigite	0.2-5	1.6
	Pegmatite	0.1-4.8	1.3
	Skarn with galenite-sphalerite mineralization	0.1-3	0.6
	Sphalerite-galenite ore	0.3-7.7	3.8
	Turjaite	0.9-4.8	2.2
	Urtite	0.1-32.5	3.4
	Juvite	0.2-5.4	1.8
III	Aleurolite silicificated	0-0.5	0.2
	Aplite	0-1.7	0.6
	Breccia aleurolite-quartz	0.1-0.4	0.2
	Gneiss	0-1.4	0.2
	Granite	0-1.6	0.4
	Granodiorite	0-0.2	0.1
	Quartzite	0-3.3	0.6
	Pegmatite ceramic	0-1	0.15
	Sandstone silicificated and tourmalinised	0.1-1.4	0.5
	Feldspars	0-0.4	0.15
	Porphyrite	0-0.3	0.1
	Ristschorrite	0.3-0.9	0.5
	Schist argillaceous	0-0.6	0.2
	Hornfels	0-0.4	0.2
	Skarn sphaleritic-garnet	0-1	0.3
	Skarn pyroxene-garnet	0-0.2	0.1
IV	Aleurolite, amphibolites, andesite, gabbro, greisens, diabase, sandstone	0-0.1	0.05
	Argillite, beresite, dacite, diorite-porphyrite, felsite-liparite, limestone, tuff, fenite	0	0

I – highly active — piezo-activity of samples is greater than $5.0 \cdot 10^{-14}$ C/N

II – moderately active — piezo-activity of samples is $(0.5 - 5.0) \cdot 10^{-14}$ C/N
III – weakly active — piezo-activity of samples is lower than $0.5 \cdot 10^{-14}$ C/N
IV – non-active — piezo-activity of samples are near zero.

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