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Study of the Environment by the Transient Electromagnetic Method Using the Induced Polarization and Superparamagnetic Effects

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Abstract—Detailed magnetic survey and transient measurements were performed with the aim of detection and detailed mapping of an arsenal of unexploded landmines and artillery shells (Sevastopol, Crimea). A high level of anthropogenic background noise made it impossible to reliably locate large deep-seated metallic objects on the basis of magnetic survey. The problem was solved through a combined interpretation of transient data with due regard for the induced polarization and superparamagnetic effects.

INTRODUCTION

In 1941, as the German troops entered Sevastopol, Soviet combat engineers exploded an arsenal of the Black Sea Fleet stored in adits of a limestone massif (the Inkerman adits). However, only about 5% of the ammunition detonated during the explosion; the massif was severely destroyed, and the major portion of the arsenal was buried beneath the debris. According to archival data, the total area of the adits prior to the explosion was about 8 ha; they contained 10000 to 30000 t of ammunition, mainly heavy aircraft bombs, torpedoes, naval artillery shells of large calibers, etc.

Several crevices in the fractured limestone massif were used for penetrating the buried arsenal; as a result, an ammunition area of about 40 m^2 was uncovered. The condition of the ammunition was found to be quite satisfactory, allowing the use of mine-clearing and disposal technologies.

During the explosion, the greatest damage was done to the adit roofs, which subsided by 10 to 20 m. The massif itself was intensely fractured and turned into an accumulation of limestone blocks of 1–2 to 1000–5000 m^3 in volume. The fractures are filled with clayey masses and contain water; the fractured limestone massif is karsted to depths of 15 to 20 m below the surface. Intensely developing karstic processes in the fractured limestones pose the threat of damage to the explosive objects of the arsenal, which is located within the Sevastopol city limits (prior to the explosion, there had been no information on karst zones at this site).

The principal objectives of our study were as follow:

(1) mapping of the ammunition accumulations at depths of 10 to 30 m below the surface;

(2) detailed mapping of sinkholes in the limestone massif; and

(3) testing of traditional and innovative measuring, analytical, and interpretation techniques.

MAGNETIC SURVEY, THE METHOD OF TRANSIENT PROCESSES, AND THE SUPERPARAMAGNETIC EFFECT

To reach our objectives, we conducted the conventional magnetic survey commonly used in such situations and the transient electromagnetic sounding used for solving geological and hydrogeological engineering problems [Vanyan, 1965]. Transient sounding was performed with combined 10 × 10- and 25 × 25-m antennas and the TEM-FAST 48 HPC instrumentation capable of recording impulse responses of the medium in the time interval from 4 μs to 16 ms in both the single-loop and loop-in-loop configurations.

Preliminary *in situ* studies showed that a high electrical conductivity of metallic objects (even as large as a five-ton aircraft bomb) lying at a depth of more than 10 m is virtually unrecognizable due to low resistivities of the karsted limestone zones. However, the superparamagnetic (SPM) effect due to the frequency dependence of the magnetic susceptibility of metals $\chi(\omega)$ is reliably detected even at significantly greater depths, because the induction mode of the field attenuates more rapidly compared to the SPM component [Barsukov and Fainberg, 1997]. When measuring the transient characteristics of the electromagnetic field, the voltage on the receiving antenna $U(t)$ in the presence of the

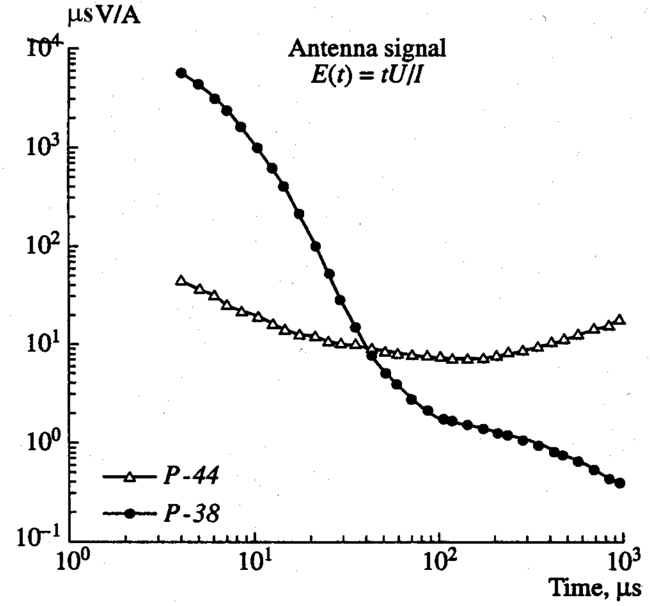

Fig. 1. An example of the SPM effect observed at point *P-44*.

SPM effect is inversely proportional to the time, $U(t) \sim 1/t$, and the normalized response of the medium

$$E(t) = t^*U(t)/I \tag{1}$$

is virtually time-independent at $t > 100$ μs. On the other hand, the induction signal $E(t)$ due to the attenuation of eddy currents in rocks is proportional to $\sim 1/t^n$, where $n = 1$–3.

Transient processes normalized by (1) are illustrated in Fig. 1. Curves *P-38* and *P-44* were obtained with the 25 × 25-m antenna located directly above the karst and accumulation zone of ammunition. Early stages of the processes are due to the conductivity of the surrounding medium; at $t > 60$ μs, either the SPM effect (*P-44*) is activated, or the process associated with the attenuation of the currents induced in ground (*P-38*) persists.

Figure 2 presents three maps showing, respectively, the thickness of near-surface clays filling a sinkhole, anomalies of the magnetic field ΔT, and anomalies of the SPM effect.

The contour map showing the thickness of the near-surface clay layer (Fig. 2a) is based on 1-D inversion of transient data. The electrical conductivity of the clay deposits varies from 8 to 30 Ω m, and their thickness reaches 16.5 m. The scatter in the resistivities appears to be due to the presence of limestone gravel and blocks in the clay.

The ΔT map (Fig. 2b) reveals three anomalies with a magnitude of $|\Delta T| > 500$ nT; the anomaly in the northwestern part has a magnitude of $\Delta T > 1000$ nT. The remaining portion of the map is characterized by randomly distributed anomalies with magnitudes of up to 50–100 nT, apparently related to small shallow metallic objects. This irregular anthropogenic magnetic background precludes the localization of large deep-seated objects.

The right-hand map (Fig. 2c) shows the distribution of the SPM effect $E(t)|_{t = 700\ \mu s}$ and images an accumulation of objects possessing anomalous superparamagnetic properties. The contour of the northwestern anomaly coincides in configuration and position with one of the arsenal adits (according to speleological evidence). The most intense anomaly observed at point *P-44* coincides with the magnetic anomaly $\Delta T = 650$ nT. Comparison between the levels of signals recorded with antennas lying at the surface and raised to a height of 2 m provides a distance to an SPM object of $h_{SPM} = 13$–15 m, which agrees with the depth of the adits.

A vast anomaly in the western part of the map is evidence of the largest adit exploded. The estimated depths to SPM objects there vary from 20 to 30 m. This collapsed adit appears to contain the greatest amount of ammunition. An intense local sign-alternating magnetic anomaly of $\Delta T = 1600$ nT with a gradient of 300 nT/m observed here indicates a metallic object lying at a depth of 2 m or less.

The risk of corrosion is highest in the vicinity of the Moreover, the sinkhole is regarded by experts as the most efficient path of entry for clearing and disposal of the ammunition; therefore, a detailed study was conducted in the vicinity of the sinkhole with regard for the IP effect observed here.

INDUCED POLARIZATION

Figure 3 shows an experimental curve of the apparent electrical resistivity $\rho(t)$ versus time and two 1-D-model curves. Measurements showed that all transient curves in regions affected by karstic processes contain a polarization component (the IP effect). This effect is related to the frequency dependence of the rock resistivity $\rho(\omega)$ and is due (in a kilohertz range) to the pattern of induction currents flowing through double layers in a heterogeneous geophysical medium [Kamenetskii, 1997]. The $\rho(t)$ signature of the IP effect is a marked resistivity increase in the time range $t = 30$–100 μs.

Table 1 presents results of the 1-D inversion of field data with and without regard for the frequency dependence $\rho(\omega)$. The frequency dispersion was calculated with the TEM-RESEARCHER program (AEMR Ltd.) using the generalized Debye formula [King and Smith, 1961] in the form

$$\sigma(\omega) = 1/\rho(\omega) = \sigma_0^*[1 + A_1 j\omega\tau_1/(1 + j\omega\tau_1) + A_2 j\omega\tau_2/(1 + j\omega\tau_2)], \tag{2}$$

where σ_0 is the conductivity at an infinitely small frequency; A_1 and A_2 are the dispersion constants; and τ_1

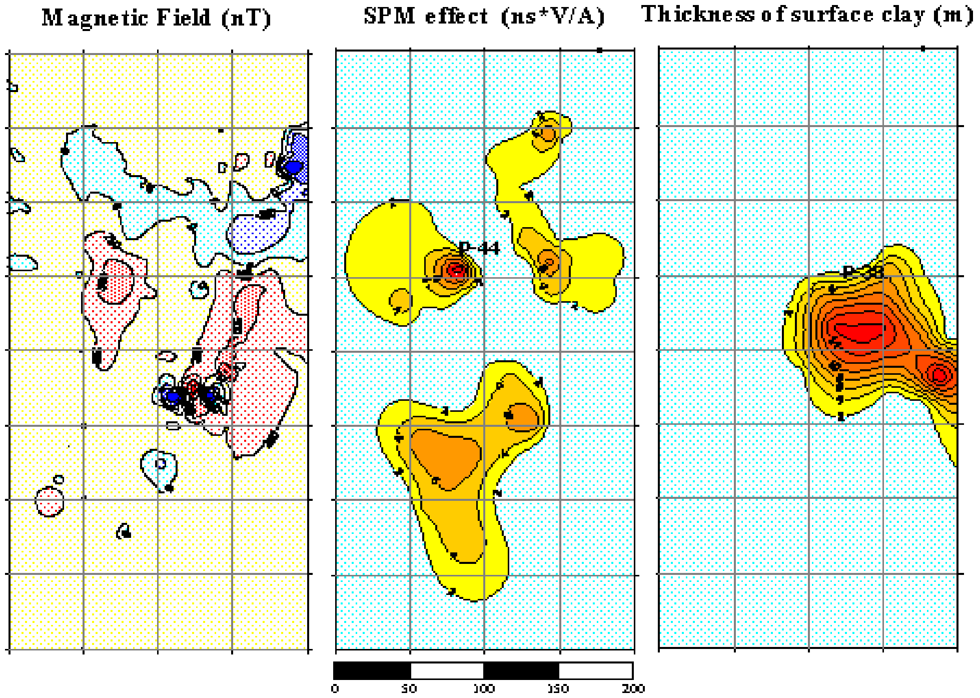

Fig. 2. Results of three different techniques applied to the recognition of the arsenal: (a) transient sounding; (b) magnetic and (3) measurements of the SPM effect. Dots are observation points.

and τ_2 are the IP relaxation constants. Model 2 is derived from a three-layer model section best fitting field data without regard for the IP effect.

One can see that the results of the inversion without regard for polarization, first, do not show any acceptable similarity between the model and observed data and, second, give obviously false parameters of the medium (the value $\rho = 4000\ \Omega$ m is too high for fractured water-saturated limestones!). Moreover, a nearly fourfold error in determining the thickness of the cover clay (layer 1) precludes correct mapping of the karst clay. Given these geoelectric conditions, a negligibly small (close to the background) dispersion of the clay conductivity ($A_1 + A_2 \sim 5\%$) substantially distorts the observed transient characteristics of the field consequence, gives rise to inadmissible error preting the results.

Note also that the commonly observed low ities in the bottom layer of the study section of 50 to 120 m (depending on the altitude of t ing point) are typical of limestones saturated water (the coastline lies at a distance of 500 m study area). Thus, despite the unfavorable g conditions of our study, the presence of the IP effects, which complicate the application of tional interpretation methods, and a high level trial noise, the combined use of various t makes it possible to conduct the transient sou

Table

Model 1							Model 2
No.	ρ, ω m	H, m	A_1	τ_1, μs	A_2	τ_2, μs	ρ, ω m
1	10	3.5	0.03	10	0.02	27	3
2	150	115					4000
3	3						3

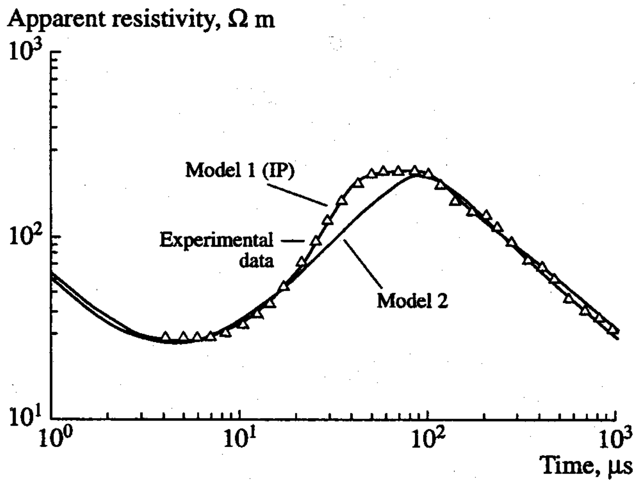

Fig. 3. Inversion of transient data (triangles) with (model 1) and without (model 2) regard for the interpretation effect.

geological medium at depths ranging from 0.5 to 100–130 m.

CONCLUSIONS

Given a high level of anthropogenic noise, the conventional magnetic survey is inadequate in locating large deep-seated metallic objects. These objects can be localized at depths of up to 20–30 m by means of the transient electromagnetic method including the analysis of the SPM effect. The use of combined small antennas enables detailed mapping of karst zones.

A correct interpretation of transient electromagnetic soundings is possible only if the IP effects are taken into account. The description of the interpretation effects by a multicomponent discrete series of elementary Debye relaxation processes markedly raises the inversion efficiency of transient data involving the interpretation effects.

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