ISSN 1028-334X, Doklady Earth Sciences, 2024, Vol. 515, Part 1, pp. 502–506. © Pleiades Publishing, Ltd., 2024.
ISSN 1028-334X, Doklady Earth Sciences, 2024. © Pleiades Publishing, Ltd., 2024.

SEISMOLOGY

Geomagnetic and Ionospheric Effects of Two Consecutive Strong Earthquakes in Morocco on September 8, 2023

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Received October 27, 2023; revised November 28, 2023; accepted December 1, 2023

Abstract—The geophysical effects of a strong seismic event as two earthquakes with magnitudes of 6.8 and 4.9 occurred on September 8, 2023, in Morocco at close times 22:11 and 22:30 UTC with an epicentral distance between the foci of ~4 km were considered. The data of a number of INTERMAGNET observatories and the magnetic recording results obtained at the Mikhnevo Geophysical Observatory of Sadovsky Institute of Geosphere Dynamics of Russian Academy of Sciences, were used. In the absence of considerable global disturbances of the Earth's magnetic field, earthquakes were accompanied by a series of three positive bay-shaped geomagnetic variations with a maximum amplitude from ~1 to ~10 nT, following each other after ~60 min. The maxima of the induced magnetic field variations were observed almost synchronously at a distance from ~800 to ~10000 km. The magnetic effect delay time relative to the main shock of the first earthquake was ~70 min. Taking into account the almost planetary nature and high synchronicity of the magnetic field disturbances caused over a significant range of distances, as well as the time delays corresponding in order of magnitude to the travel time of the seismic signal of a distance multiple of the Earth's dimension, it is suggested that the magnetic effect of the seismic event in question was caused by a global source such as an excited geodynamo. The ionospheric effect of the seismic event under consideration is reported as variations in the critical frequency f_0F2 calculated from the data obtained by the ground-based sounding station of the del Ebre Observatory.

Keywords: earthquake, instrumental observations, magnetic field, variation, critical frequency of the $F2$-layer of the ionosphere

DOI: 10.1134/S1028334X23603395

Magnetic variations are observed along with well-known variations in the magnetic field caused by cosmic factors. They are related to natural and man-made processes and phenomena in both the upper and lower geospheres [1–3]. For example, strong earthquakes accompanied by a number of geophysical effects such as rock deformation and destruction, seismic and atmospheric wave generation, atmospheric electric field variations, changes in a critical frequency of the ionospheric F-layer, etc., also cause variations in the magnetic field, which is relatively sensitive to external disturbances [1, 4–6].

The study of geomagnetic variations is of great interest not only from the standpoint of a comprehensive description of the effects related to earthquakes, but also in terms of understanding their internal processes and development patterns, as well as the environmental impact. It should be noted that the induced magnetic variations contain important information needed to model in detail the Earth's magnetic field and, in general, to clarify the nature and processes of intergeosphere interactions [4].

Despite the available data, the observation material is not sufficient. This material is necessary to represent adequately the complex structure of the magnetic effect of an earthquake in order to develop conceptual, theoretical, and phenomenological models that would fully describe the consequences of strong seismic phenomena.

This report considers the magnetic effect of two strong earthquakes that occurred sequentially on September 8, 2023, in Morocco in a short period of time[1] (Table 1) [7]. The study is focused on the most frequently observed long-period magnetic field variations that made the main energy contribution to the magnetic effect.

The initial data included the results of instrumental observations obtained at a number of INTERMAGNET observatories actively operating during this period of

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[1] According to our estimates, the seismic energy was ~10^{15} and ~10^{12} J, respectively, for the first and second seismic events.

Table 1. Description of the strong earthquakes that occurred in Morocco on September 8, 2023, according to the USGS catalog data as of October 4, 2023

No.	Date	Time (UTC)	Magnitude	Geographic coordinates		Depth, km
				Latitude	Longitude	
1	September 8, 2023	22:11:01	6.8	31.055° N	8.389° W	19
2	September 8, 2023	22:30:44	4.9	31.036° N	8.352° W	10

Table 2. Magnetic observatory data

Code	Geographical coordinates		t_1, UTC September 8, 2023	t_2, UTC September 9, 2023	t_3, UTC September 9, 2023	B_1, nT	B_2, nT	B_3, nT	R, km
	Latitude	Longitude							
GUI	28.321° N	343.559° E	23:49	00:41	02:09	~1	~4	~2.5	~830
SPT	39.55° N	4.35° W	23:50	00:50	02:10	~2.5	~9	~4	~1010
DOU	50.1° N	4.6° E	23:50	00:41	02:09	~2.5	~10	~5	~2380
NUR	60.51° N	24.66° E	23:45	01:05	02:07	~3	~8	~10	~4070
ASC	7.95° S	14.38° W	23:49	00:40	02:10	~1	~2.5	~1	~4380
MHV*	54.96° N	37.76° E	23:42	01:05	02:10	~3	~8	~6.5	~4470
TSU	–19.202° N	17.584° E	23:50	00:42	02:10	~1	~6.5	~5	~6240
GAN	0.694° N	73.153° E	23:35	01:05	–	~1.5	~4	–	~7580
TDC	37.067° S	12.316° W	23:49	00:41	02:10	~1.5	~4	~3	~7870
JAI	26.92° N	75.8° E	23:35	01:05	02:15	~1	~1.5	~2.5	~7990
TUC	32.17° N	110.73° W	23:48	01:15	02:08	~4	~2	~1	~9240
VNA	70.683° S	8.283° W	23:50	00:51	01:55	~5	~5	~10	~11310

(*) Not included in INTERMAGNET.

Table 3. Magnetic activity indices *K* (according to the MHV data) and *Kp* (according to the International Service of Geomagnetic Indices (ISGI) data) for September 8, 2023

Index	Time (UTC)							
	0–3	3–6	6–9	9–12	12–15	15–18	18–21	21–24
K	2	1	0	1	1	2	1	1
Kp	3 –	1 +	0	1 –	1 +	2 +	1 +	0 +

time (Table 2; Fig. 1) [8] and at the Mikhnevo Geophysical Observatory of Sadovsky Institute of Geosphere Dynamics of Russian Academy of Sciences (MHV, 54.96° N; 37.76° E) [1]. We analyzed variations in the horizontal component of magnetic induction B_x, the most sensitive to external disturbances, oriented NS. The event under consideration was characterized by calm geomagnetic conditions (Table 3) and made it possible to simplify the identification of the induced magnetic field disturbances.

Examples of geomagnetic variations caused by the September 8, 2023, earthquakes and recorded by the INTERMAGNET observatories located at different epicentral distances R from the event source are shown in Fig. 2. According to this figure, the seismic events under consideration were accompanied by a well-defined magnetic effect as three successive bay-shaped variations in B_x with a duration from ~50 to ~80 min and an amplitude from ~1 to ~10 nT (the characteristics of each bay-shaped disturbance as its maximum amplitude B_i and its arrival time t_i (i = 1, 2, 3) are given in Table 2). Alongside with that, similar induced magnetic field variations were observed almost simultaneously at all epicentral distances R: from 830 to ~10000 km. Disturbances were recorded starting from ~23:23 UTC on September 8, 2023, approximately 70 min after the main shock of event *1* from Table 1. The first maximum of induced variations was recorded ~100 min after the first event; the second and third ones, after ~160 and ~220 min, respectively. The total duration of the disturbed magnetic field period was estimated at ~200 min.

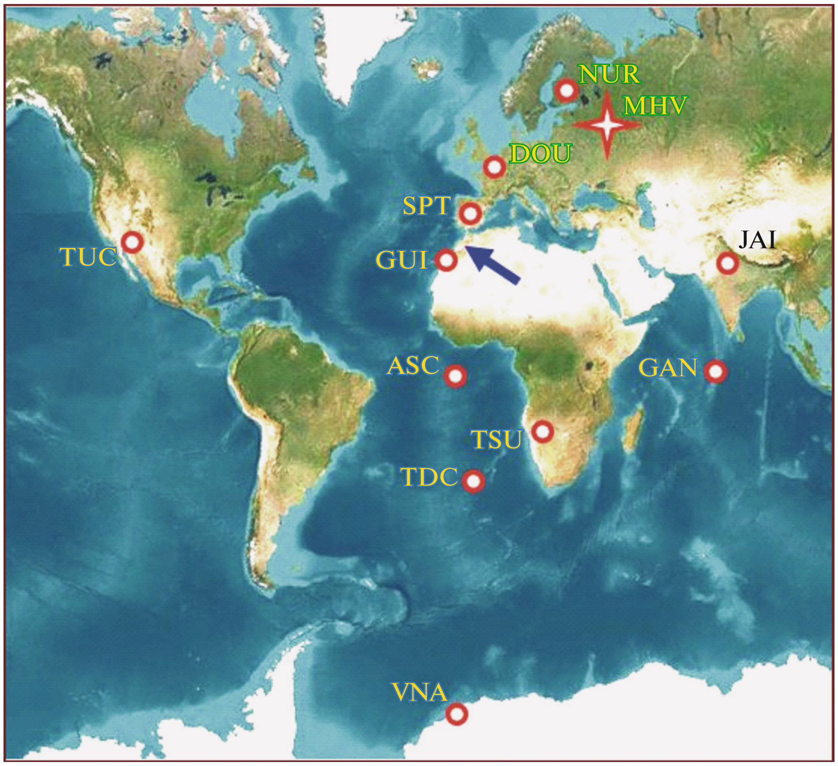

Fig. 1. Layout of the earthquake source (blue arrow) and magnetic observatories: circles indicate the INTERMAGNET observatories (observatory code is given in the figure field); the asterisk indicates the Mikhnevo Geophysical Observatory of Sadovsky Institute of Geosphere Dynamics of Russian Academy of Sciences (MHV).

The synchronous observed magnetic field variations accompanying the seismic event under consideration in a wide range of epicentral distances and a relatively narrow (from a practical point of view) range of amplitudes are indicative of a highly probable single global disturbance source. Taking into account the delays in recorded magnetic disturbances relative to the main shock for the time corresponding in the order of magnitude of the travel time of the seismic signal to a distance that is a multiple of the Earth's dimension, it can be assumed that the source of geomagnetic variations is the geodynamo disturbed by seismic waves that propagated deep into the Earth. The validity of this assumption has already been discussed by [9].

Indeed, it was noted that double earthquakes with foci located in the water area or in the region of transition of the continental crust to the oceanic crust were accompanied in a number of cases by a magnetic effect similar to that considered in this work [6, 10]. Taking into account the multidipole nature of the Earth's magnetic dynamo [11], the relationship between the energy of the main magnetic field of the Earth (~10^{20} J) and that of strong earthquakes (~10^{18}–10^{22} J [7]), as well as a possible trigger effect, it seems very likely that seismic waves caused by strong close-in-time earthquakes, propagating deep into the Earth, and being combined, influence turbulent movements in the liquid core, in the epicentral region of seismic foci and, thus, disturb the magnetic dipoles located in this area, and, in general, the total magnetic dipole of the Earth. Hence, it is possible to suggest a class of earthquakes which, due to the peculiarities of the location of focal zones and conditions of seismic energy release, are capable of influencing the Earth's magnetic dynamo and, as a result, its main magnetic field features.

Consideration of the ionospheric effect of strong earthquakes is of special interest. In particular, we analyze variations in the critical frequency of the ionosphere $F2$-layer f_0F2 characterizing the ionosphere trends under external influences. For this purpose, we processed the initial data as altitude–frequency sounding ionograms obtained at the del Ebre Observatory (ionospheric station coordinates 40.8° N, 0.49° E). The ionograms are accessible on the website of the del Ebre Observatory [12]. Each ionogram was subjected to manual processing and interpretation by the URSI method [13]. As a result, a digital series of time variations in the critical frequency f_0F2 was obtained with a sampling time of 5 min.

Figure 3 shows variations in f_0F2 during the earthquakes in Morocco on September 8, 2023. According to this figure, the event under consideration caused pronounced long-term alternating variations at the critical frequency f_0F2 with a period of about 10 min

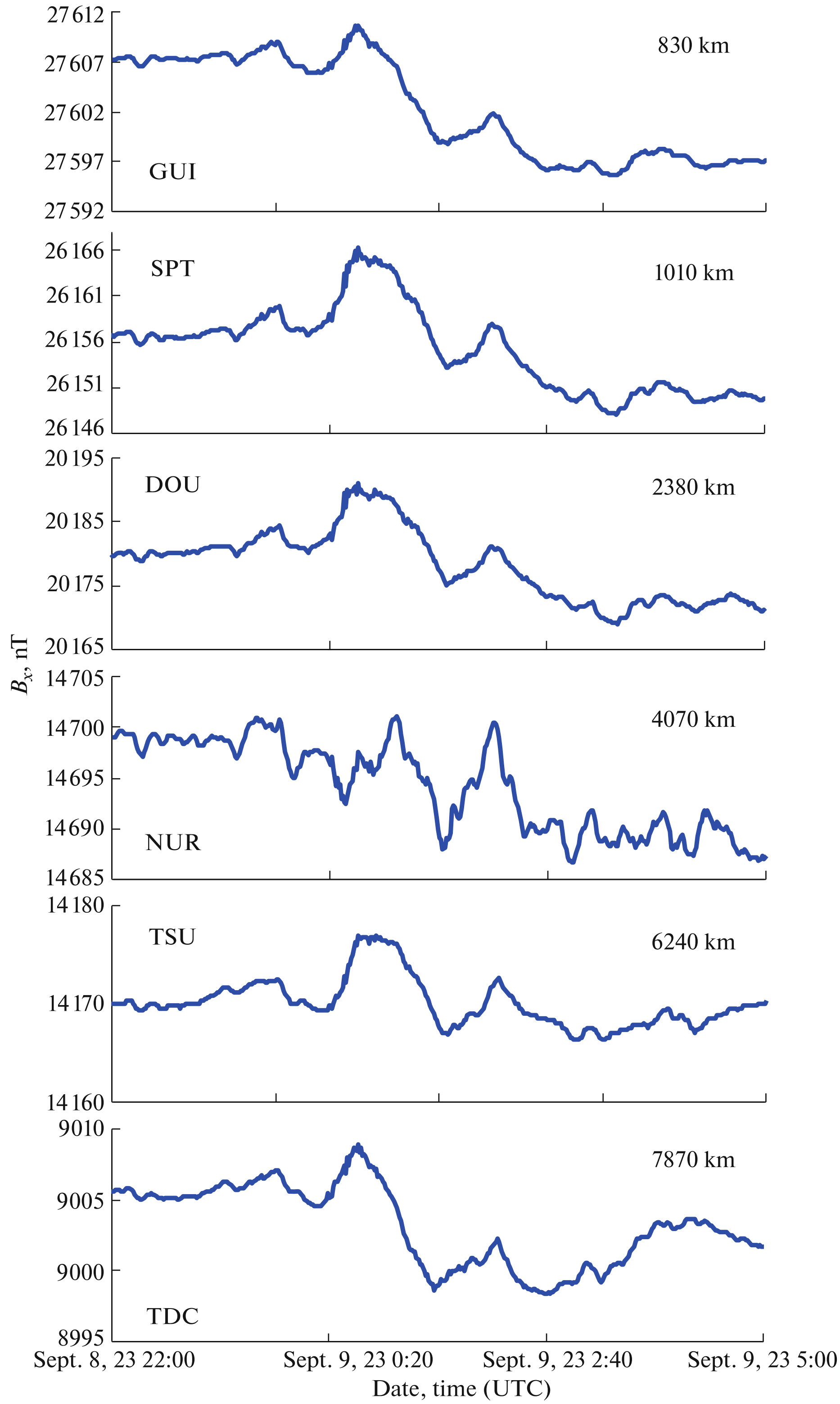

Fig. 2. Variations in the horizontal induction component of the geomagnetic field during the September 8, 2023, earthquake in Morocco (observatory codes and epicentral distances to the earthquake *1* from Table 1 are given in the figure field).

from ~22:40 to ~23:15 UTC on September 8, 2023 (maximum variation amplitude ~0.35 MHz), and from ~00:00 to ~03:10 UTC on September 9, 2023, with a period of ~35–50 min (~0.9 MHz). The total duration of variations in the critical frequency of the $F2$-layer was ~4–5 h. The first disturbance f_0F2 with a

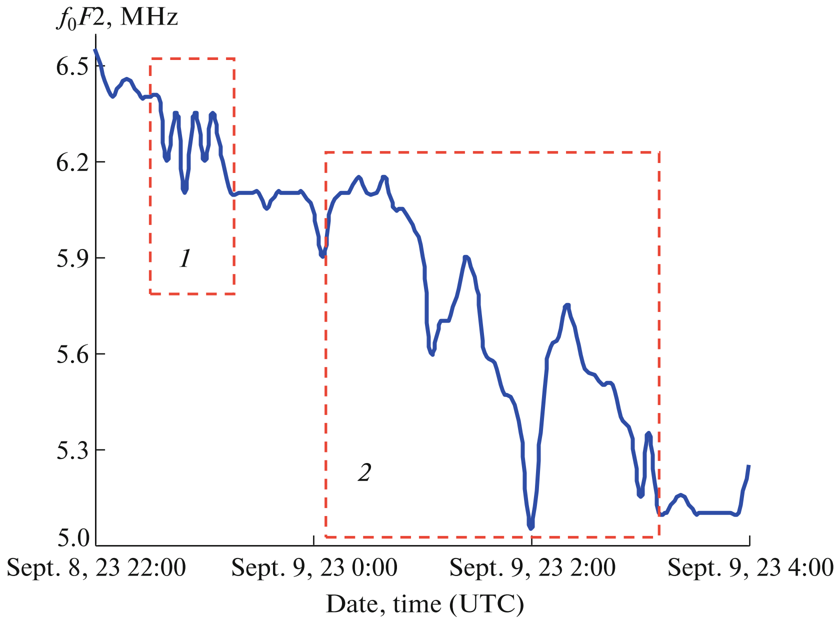

Fig. 3. Variations in the critical frequency of the ionosphere $F2$-layer during the September 8, 2023, earthquakes according to the del Ebre Observatory data (red shading indicates the (*1*) first and (*2*) second disturbance periods f_0F2).

period of ~10 min was related to the influence of earthquake-generated Rayleigh waves on the ionosphere [14]. The second disturbance f_0F2 as a longer-period signal was most likely due to the propagation of internal gravity waves [15].

In our opinion, the data reported in this paper complement the current understanding of the geophysical consequences of strong earthquakes and can be used in the development and verification of analytical and numerical models that would comprehensively describe the energy exchange processes in the course of seismic events, as well as their impact on the external geosphere.

FUNDING

This study was carried out under the State Assignment "Natural and Man-Made Processes in Geophysical Fields," project no. 122032900185-5.

CONFLICT OF INTEREST

The authors of this work declare that they have no conflicts of interest.

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Translated by E. Maslennikova

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