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Polarization method to detect the co-seismic magnetic oscillations

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Abstract

A method for detecting seismomagnetic signals is considered. These signals are generated during the course of the propagation of surface seismic Love wave from far earthquakes. Magnetic field vector of the seismomagnetic signal rotates counterclockwise and has a circular polarization, which allows us to extract the signal against the background noise. By using the described method of polarization filter the seismomagnetic signals from the earthquake on 4 June 2000 have been detected at two remote magnetic observatories. In the other case, the two signals from the disastrous tsunami 2004 earthquake were detected both for the first arrival of Love wave coming directly from the epicenter along the minor great circle arc, and for the second wave propagating along the major great circle arc.

Keywords: Seismomagnetic signals; Polarization method

1. Introduction

It is common knowledge that observations of the co-seismic magnetic oscillations are impeded by the noise background, such as the microphone effect, seismographic vibrations, and magnetospheric noise (e.g., Eleman, 1966). The presence of strong interferences hampers the accumulation of the experimental data to test existing ideas on the mechano-electromagnetic conversion in the Earth's crust. There are a few observational methods to detect the seismomagnetic signals: the method of modular measurements (Breiner, 1964; Eleman, 1966), the gap-method or the method of the time leading interval, when we use the silent time before the arrival of the seismic wave front (Belov et al., 1974; Iyemori et al., 1996), the so-called gradient method (Gokhberg et al., 1989; Krylov and Levshenko, 1990; Guglielmi and Levshenko, 1994; Kopytenko et al., 2001), and the method of polarization filtering (Tsegmed et al., 2000). In this paper we would like to discuss the polarization method, which suppresses effectively the seismographic and magnetospheric interferences.

2. The polarization method background

Let us introduce the Cartesian coordinate system (x, y, z) in such a way that the Earth's surface coincides with the (x, y) plane and the z-axis is directed upward. We consider a plane monochromatic seismic wave, which travels in the positive direction of the x-axis. It is natural to suppose that the accompanying magnetic field $\mathbf{B}$ in the upper half-space is linearly related to the mechanical variables. Then $\mathbf{B} \propto \exp(\mathrm{i}kx - \mathrm{i}\omega t)$, where $k = \omega/c_s$, ω is the frequency and c_s is the horizontal velocity of seismic wave. On the Earth's surface and above it $\mathbf{B}$ obeys the Laplace law $\nabla^2\mathbf{B} = 0$ and the solenoidality condition $\nabla \cdot \mathbf{B} = 0$. Besides, the magnetic field tends to zero with increasing the height above the Earth's surface because the field sources are located beneath the surface. Altogether these give us the following relation:

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$$\mathbf{B} = \frac{B}{\sqrt{2}}(1, 0, i)\exp[k(\mathrm{i}x - z) - \mathrm{i}\omega t]. \quad (1)$$

This means that on the Earth's surface and above it the modulus $|\mathbf{B}|$ remains constant. The magnetic wave has a circular polarization with counterclockwise rotation. The vector $\mathbf{B}$ rotates with the frequency ω in the vertical plane parallel to the direction of seismic wave propagation. These polarization properties are quite general. In particular, they are independent of the excitation mechanism of co-seismic magnetic oscillations. Besides, these properties are so specific that one can try to use them for the detection of co-seismic magnetic signals. Indeed, the seismographic oscillations are linearly polarized; for the magnetospheric waves, the appearance of intense spectral components with the aforementioned circular counterclockwise polarization is most unlikely.

Various methods can be used to study the polarization properties, beginning with the hodograph technique for tracing out the end point of the polarization vector. A good method to monitor the sense of electromagnetic field polarization is by calculating a Stokes' vector-parameter (Rankin and Kurtz, 1970) along with the application of spectral analysis. By this technique, the cross- and auto-correlation functions of the observed data series are calculated at first, and then Fourier-transformed. We use here another sequence of procedures which describes two orthogonal components of the observed field vector as a complex signal and performs its complex Fourier transform (Turunen and Manninen, 1997).

3. Analysis of seismomagnetic signals

The polarization method was applied to detect magnetic oscillations accompanying the propagation of surface Love wave produced by a strong earthquake. A specific property of the Love waves is that, theoretically, the Tolman–Stewart effect is alone responsible for the magnetic field that penetrates into the Earth's surface.

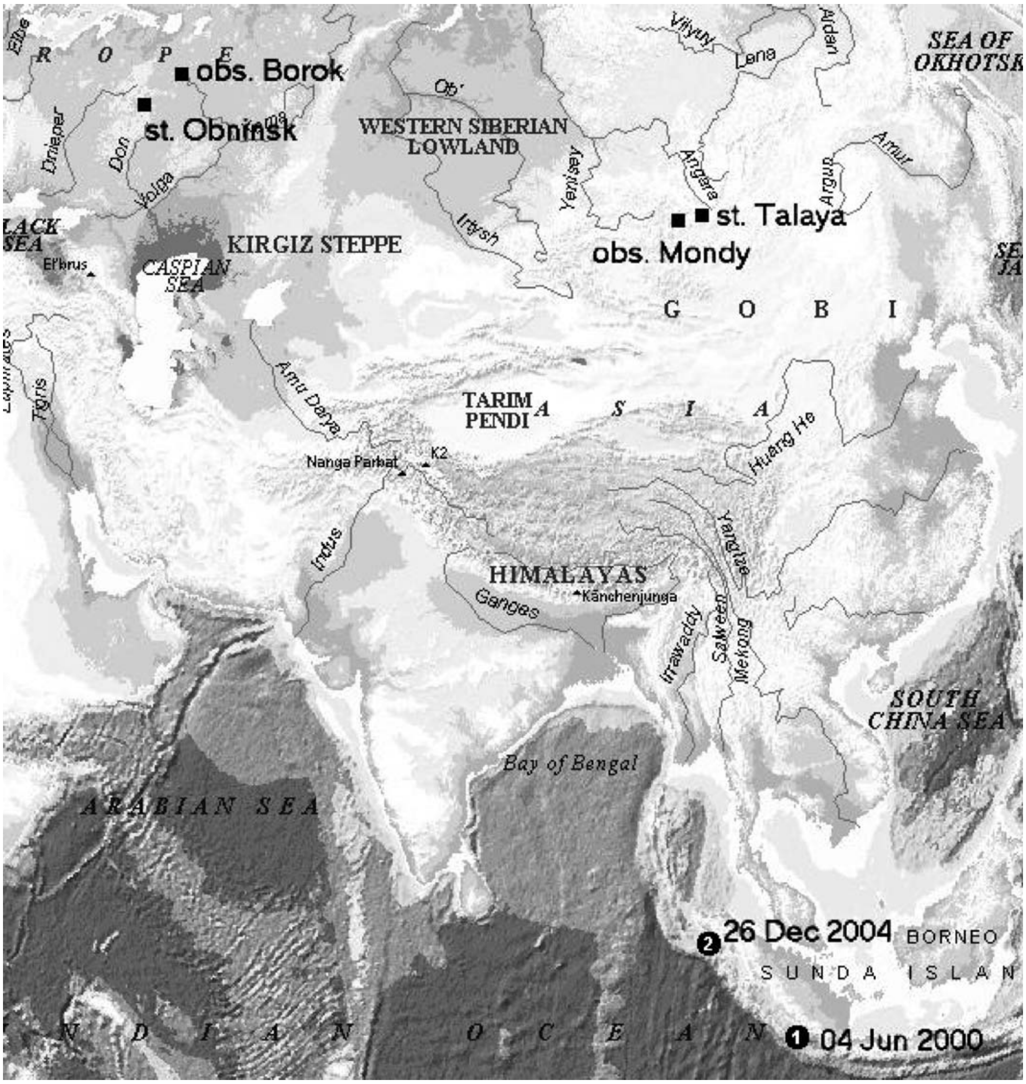

Fig. 1. Map view of location of the seismic stations, magnetic observatories and the epicenters of earthquakes.

To detect seismomagnetic signals we considered a distant earthquake event with magnitude $M > 7$ and examined data from the magnetic observatories at Mondy (51.6°N, 100.9°E) and at Borok (58.0°N, 38.2°E). Digital data on Love waves from the seismic stations at Talaya (51.7°N, 103.6°E) and at Obninsk (55.1°N, 36.6°E) were used to compare with magnetic signals. These stations are the nearest ones to Mondy and Borok, respectively (see Fig. 1). Seismic data were taken from the site of IRIS Consortium.

For subsequent analysis, we transformed the initial dataset of geomagnetic field to a coordinate system rotated about the vertical axis z in such a way as to bring the x-axis into coincidence with the tangent to the arc of the great circle passing through the epicenter and to direct it away from the epicenter. Then the initial data were subjected to broadband filtering with a pass band from 5 to 200 mHz in order to eliminate high-frequency noise and long-period trends. Finally, using the results of the preliminary visual analysis, we chose a frequency-time window containing Love waves and constructed the wave amplitude spectrum, and then we determined more accurately the carrier frequency and the time interval suitable for detecting seismomagnetic oscillations.

4. Two-station observation of seismomagnetic signals for the 4 June 2000 event

An earthquake with magnitude $M = 7.6$ had occurred at depth of 33 km in Southern Sumatra, Indonesia (4.72°S, 102.1°E) (indicated by index "1" in Fig. 1). Seismomagnetic signal of this earthquake was gated out at both magnetic observatories. Fig. 2 shows the result obtained for the observatory at Mondy and Fig. 3 relates to the observatory at Borok. Top four oscillograms of mechanical and magnetic oscillations show the signals after rotation of the coordinate axes and broadband filtering. Here, V_y and V_z are the transverse and vertical components of the velocity,

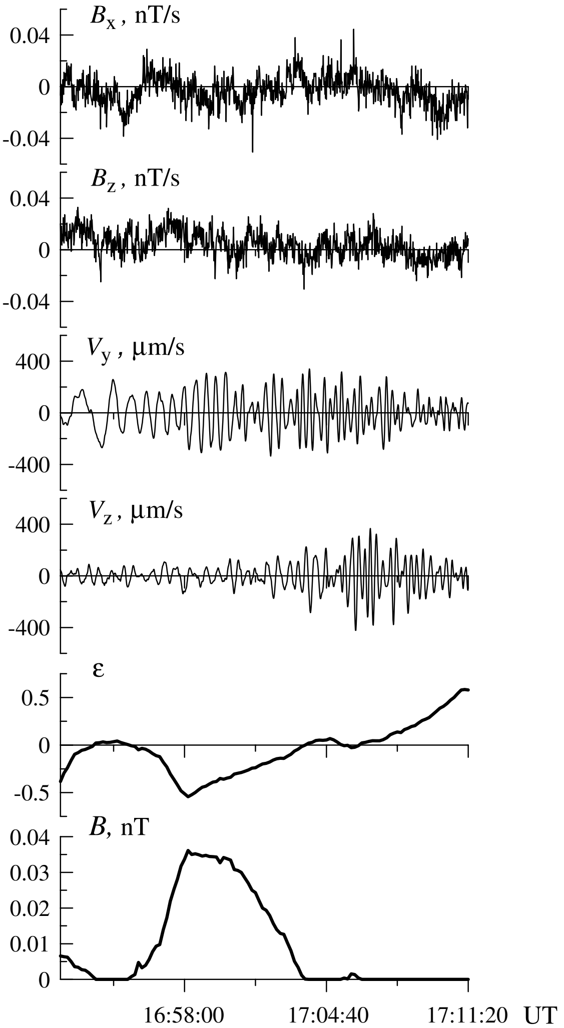

Fig. 2. The oscillograms of magnetic (top two panels) oscillations at Mondy, mechanical (next two panels) oscillations at Talaya, and ellipticity (ε) and amplitude of seismomagnetic signal with a left-hand circular polarization at frequency $f = 33$ mHz (bottom two panels).

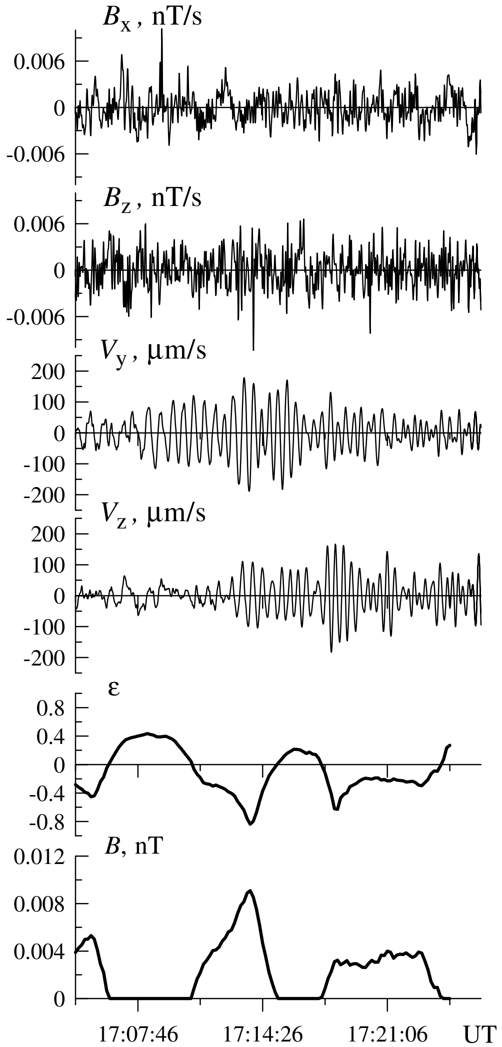

Fig. 3. The oscillograms of magnetic (top two panels) oscillations at Borok, mechanical (next two panels) oscillations at Obninsk, and ellipticity (ε) and amplitude of seismomagnetic signal with a left-hand circular polarization at frequency $f = 29$ mHz (bottom two panels).

and $\dot{B}_x$ and $\dot{B}_z$ are time derivatives of the horizontal and vertical components of the magnetic field, respectively. The seismogram displays quasi-harmonic oscillations typical of Love waves in the far-field zone. On the other hand, the record of the magnetic field is severely complicated by noise. Against the background of this noise, the seismomagnetic signal cannot be detected by a simple comparison of the oscillograms. The power spectral density of mechanical oscillation has its maximum at frequency $f = 33$ mHz at Talaya and $f = 29$ mHz at Obninsk. However, these spectral maximums are not observed in the spectra of magnetic field components at both magnetic observatories.

Therefore, based on the above-mentioned theoretical ideas we applied the method of spectral polarization filtering. Variations in the ellipticity ($\varepsilon < 0$) of magnetic oscillations in the vertical plane at the frequencies $f = 33$ mHz and $f = 29$ mHz are shown in the lower parts of Figs. 2 and 3. The bottom plot shows variation in amplitude B of the circular component of oscillations with a left-hand rotation of the magnetic vector at the same frequencies. As expected, the lowest values of the ellipticity and the highest amplitudes of magnetic oscillations with the left-hand circular polarization are observed during the passage of Love wave train. This leads to the assumption that we have detected seismomagnetic oscillations with the amplitude $B \approx 0.04$ nT at Mondy and $B \approx 0.01$ nT at Borok.

5. Seismomagnetic signals from the tsunami earthquake on 26 December 2004

At 00:58:47 UT on 26 December 2004 first shock of the largest earthquake since 1960 Chilean event happened. The focus of this $M = 9.0$ earthquake was located at the depth of 30 km in Northern Sumatra, Indonesia (3.30°S, 95.78°E) (indicated by index “2” in Fig. 1). The rupture was extending for 1200 km to the Andaman Islands. The quake produced the disastrous tsunami in Southern Asia.

To investigate seismomagnetic signal produced by the surface seismic waves propagating from the focus we have performed time-frequency analysis of both seismic and magnetic oscillations. It shows that the first Love seismic waves which came to Talaya have two spectral maxima peaked at frequencies $f = 20$ mHz at 01:25:00 UT and $f = 39$ mHz at 01:29:50 UT. We could not find these spectral peaks in magnetic variation data from the magnetic observatory at Mondy during Love seismic wave observations at Talaya. However, spectral polarization filter method has allowed us to detect seismomagnetic signals just at these frequencies (as shown in Fig. 4). Surprisingly, amplitudes of the seismomagnetic response to the disastrous seismic event turned out to be very moderate: about 0.02 nT for 20 mHz oscillations and approximately 0.04 nT for 39 mHz wave.

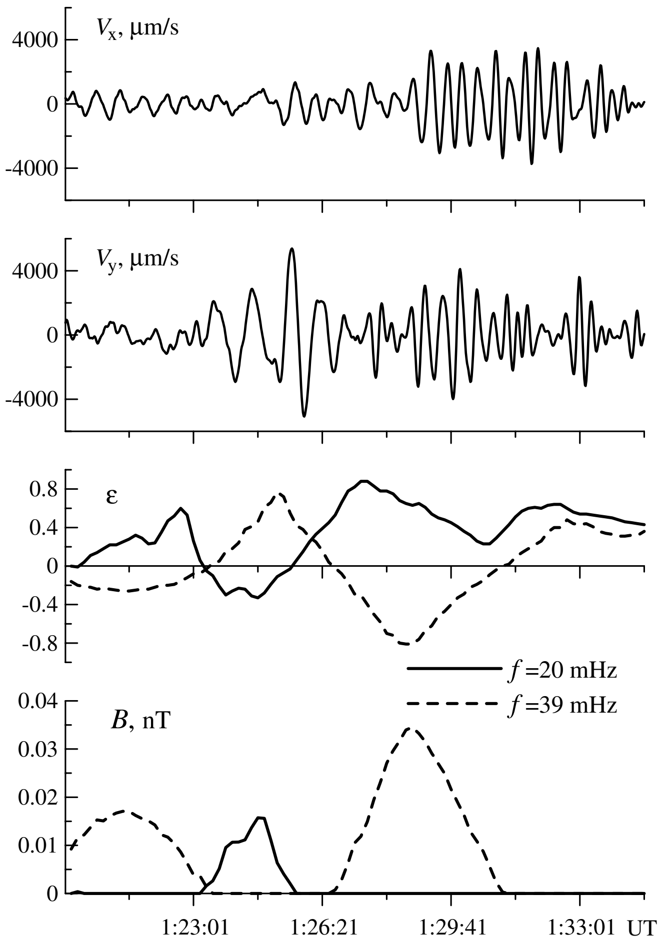

Fig. 4. The oscillograms of mechanical (top two panels) oscillations at Talaya and ellipticity and amplitude of seismomagnetic signal with a left-hand circular polarization at frequency corresponding $f = 20$ mHz (solid line) and $f = 39$ mHz (dashed line).

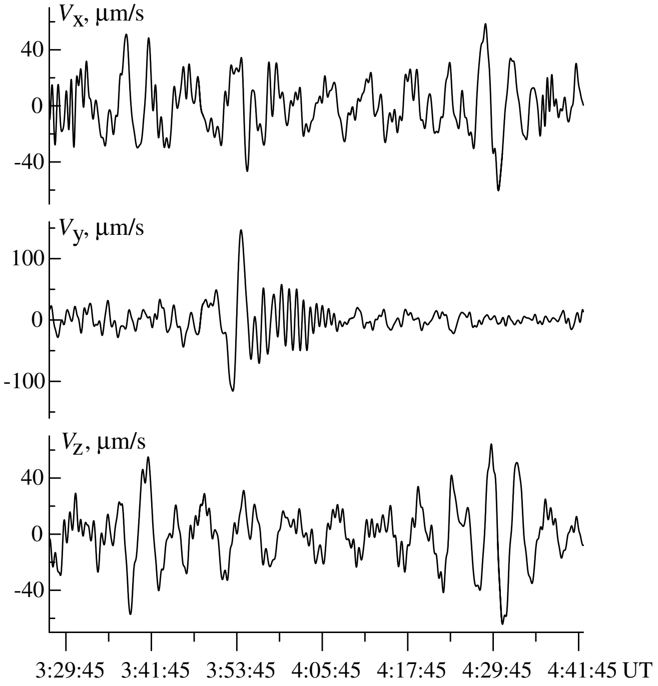

Fig. 5. The oscillograms of Rayleigh waves that travel along major great circle arc (R_2) and additional global circuit to traveling wave along minor great circle arc (R_3).

Long-period seismic waves from a large earthquake are observed repeatedly at one seismic station, because they can propagate around the Earth several times. Park et al. (2005) presented a map of station locations for the Global Seismograph Network (GSN) data from the Sumatra–Andaman earthquake. In their Fig. 1, Park et al. showed a map of the GSN stations and 6-h spans of *z*-component seismograms from all stations with evidences of multiple arrivals of Rayleigh waves to every station: the first and strongest wave R_1 travels along the minor great circle arc, it is followed by the second wave R_2, which travels along the major great circle arc, then the third wave R_3 arrives traveling along the minor great circle arc, but with an additional global circuit, and so on.

We are interested in transverse seismic oscillations, which bear a relation to the Tolman–Stewart effect. Therefore we searched for additional arrivals of Love waves. Scanning Talaya seismograms we found a train of transverse *y*-component oscillations observed between R_2 and R_3 Rayleigh waves in Fig. 5. We suppose that it is the Love wave L_2. When we applied our method of polarization filter to magnetic oscillations recorded simultaneously with L_2 at the Mondy magnetic station, a signal emerged at the frequency $f = 18$ mHz with amplitude of 0.1 nT in Fig. 6. The period, polarization, onset time, and duration of the detected magnetic oscillations lead us to the assumption that we have detected a seismomagnetic signal generated by the transverse seismic wave observed at Talaya between two Rayleigh waves R_2 and R_3.

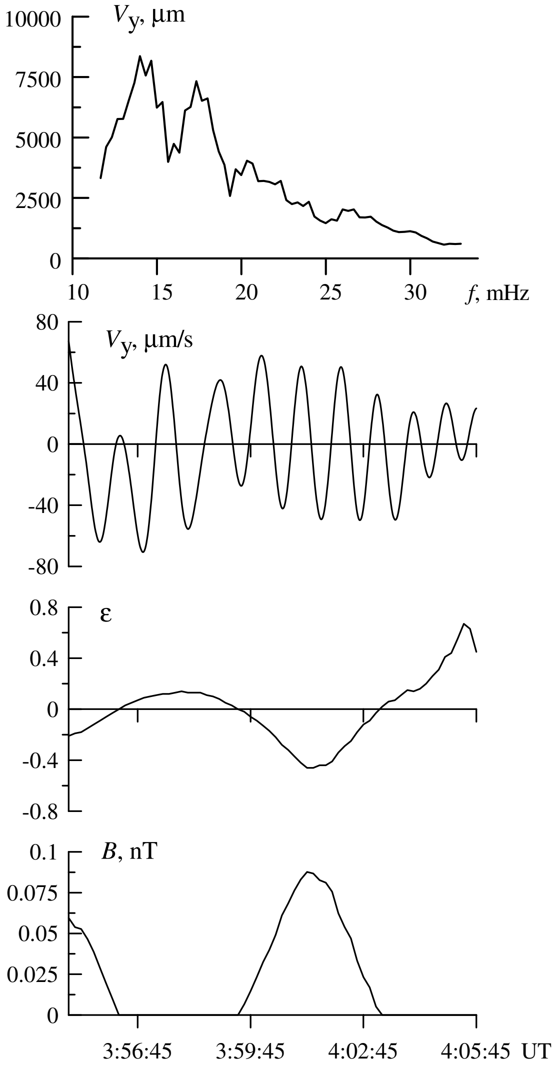

Fig. 6. The power spectrum (top panel) of transverse seismic oscillations (second panel) at Talaya; ellipticity and amplitude of seismomagnetic signal with a left-hand circular polarization at frequency $f = 18$ mHz at the observatory of Mondy (bottom two panels).

6. Conclusion

In principle, there is no problem that seismomagnetic signals should exist because an arbitrary nontrivial motion of any body is accompanied by the excitation of an electromagnetic field. However, the problem of signal detection against the background noise is practically very difficult. We considered the polarization method of a seismomagnetic signal acquisition and demonstrated its capability by the analysis of two particular events observed at two magnetic observatories from a strong earthquake with $M = 7.6$ and from the great Sumatra–Andaman earthquake with $M = 9.0$.

We believe that the development of a Seismomagnetic Research Area (SRA) will be an important further stage in the solution of the problem of recognition and interpretation of seismomagnetic signals. Such an area should be designed to conduct long-term methodological experiments for observation of seismomagnetic signals and measurements of rock parameters that presumably control the mechanic-to-magnetic energy conversion efficiency. The field measurements in the vicinity of the seismomagnetic wave observation point and laboratory experiments with the rock samples from the SRA should considerably reduce uncertainties in the mechano-magnetic conversion parameters. However, a detailed description of the SRA project is beyond the scope of this report.

Acknowledgement

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