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Subsurface VLF electric field emissions associated with regional earthquakes

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A borehole antenna has been installed at Agra (latitude 27.2^{0}N, longitude 78^{0}E), India since 01 June 2006. The subsurface very low frequency (VLF) electric field emissions (f = 3.042 kHz) data has been recorded round the clock for a period of nineteen months from 01 June 2006 to 31 December 2007. This statistical analysis of data is presented in the paper. The occasional amplitude enhancement is observed in the data and examined in the light of magnetic storms, earthquakes, and lightning activities. It is found that in majority of the cases, amplitude anomalies are correlated with moderate seismic activities occurred during the period in the region. The propagation mechanism of VLF signals from the hypocenters of earthquakes to the observing station is discussed in the paper.

Keywords: Earthquake, VLF electric field emissions, Borehole antenna
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1 Introduction

In the recent past several researchers have reported the observations of electromagnetic emissions related to earthquakes in a wide band of frequency ranging from direct current (DC) to high frequency (HF)[1-10]. The association of these signals with seismic activities has also been confirmed from the laboratory based rock fracturing experiments[11-13]. A detailed account of the recent work done in this field has been given in literature[14-17] and references therein.

Recently, subsurface and simultaneous subsurface and terrestrial measurements of VLF electric field emissions have been carried out at Agra (India) based on analog method and some very interesting results have been obtained[18-20]. It has been shown that VLF seismogenic emissions appear in the form of noise bursts mostly as precursors and the results are more significant in the case of local earthquakes and seismic swarm. In the present paper, the results of recent observations carried out, have been presented. The observations were carried out during 1 June 2006-31 December 2007 employing a digital technique and yield occasional amplitude enhancements which may possibly be due to moderate seismic activities occurred in the region.

2 Experimental set up

The experimental set up employed for monitoring subsurface VLF electric field changes (at 3.042 kHz) is shown in Fig. 1. It includes a borehole antenna of naked copper wire of 100 meter length and 4 mm diameter placed in a water tight PVC pipe of 1.75 cm diameter with its lower end tightly fitted with an insulating cork at the bottom. The antenna is totally inside the ground and is connected to a pre-amplifier through a coaxial cable of 20 m length. Another electrode, connected to the pre-amplifier, is placed 3 m down the earth to provide ground terminal. The amplified signal from the pre-amplifier is filtered first at 10 kHz through a band pass filter and then at 3.042 kHz through a digital filter and then passed through a main amplifier. Finally, the signal (having signal to noise ratio >1) is recorded on a PC through a data logger and MATLAB software. The frequency of digital filter is chosen to be 3.042 kHz as a tradeoff between the unwanted noise at the lower frequencies (caused by power line radiations and their harmonics, atmospherics, etc.) and increasing attenuation with frequency. Observations are taken round the clock at Bichpuri, a rural area, about 12 km west of Agra city where local electric and electromagnetic noises are very low.

3 Sources of earthquake and $\sum K_p$ index data

Earthquake data for the period of observations are obtained from United States Geological Survey (USGS) through their website (http//neic.usgs.gov). The data provide the information about the date and time of occurrence of earthquakes, location, depth and magnitude. The electric field induced in the antenna may be influenced by the magnetospheric electric fields (magnetic storm) also. In order to identify the effect of magnetic storms on the vertical component of VLF electric field emissions, $\sum K_p$ data during June 2006 - December 2007, obtained from the Word Data Centre, Kyoto, Japan through the website (http://swdcdb.kugi.koyotee.ac.jp), is considered.

4 Results and discussions

The subsurface measurements of VLF electric field emissions employing a borehole antenna was started in India first at Agra in 1998 which was based on an analog technique of measurement and analysis that included transistorised amplifiers, active filters, and DC ink chart recorder. The analysis of data has shown occurrence of VLF noise bursts associated with earthquakes[18,21,22]. In order to study the lithosphere atmosphere coupling of seismo-electromagnetic signals, a terrestrial antenna was operated in conjunction with the borehole antenna which provided very interesting results, particularly related to Chamoli swarm of March/April 1999. The results included earthquake precursors about five days before the main shock and occasional coupling of seismogenic signals with the terrestrial antenna[23]. These results are satisfied by null hypothesis also. Another important result emanated from the study showed that the borehole antenna was sensitive to moderate and large magnitude earthquakes nearby. This result has been supported by Y Fujinawa[24].

With the availability of fast computers and sophisticated signal processing techniques the analog method of recording has been replaced by digital method since 1 June 2006. The paper presents the results of the analysis of data for 19 months (1 June 2006 to 31 December 2007). The terrestrial antenna was not operated during this period, hence data corresponding to borehole antenna are available only. Recording of the data is done at the rate of 1 sample per second. The bulk of the data is block averaged by 500 data points and then running mean of 10 such data is taken. Then from the graphical variation of such data, largest peak of the amplitude per day is considered in the present analysis. The daily variation of such amplitudes is presented in the five panels in Fig. 2. Each panel represents data variation for a period of four months except the last one represents data for three months only. For statistical study of the data, mean (m) and standard deviation around the mean ($m \pm \sigma$) approach has been adopted. The mean (m) and standard deviation around the mean ($m \pm \sigma$) are presented by solid and dotted horizontal lines in each panel respectively. The standard deviation around the mean is adopted to be $\pm 2\sigma$ for a high degree of confidence. Such approach has also been adopted by Molchanov & Hayakawa[25] for VLF studies and Biagi & Hayakawa[26] for LF studies related to earthquakes. The solid curves with open square points represent the variation of the processed amplitude data. Duration of the data is mentioned at the top of each panel. Downward arrows in each panel show the days of occurrence of earthquakes.

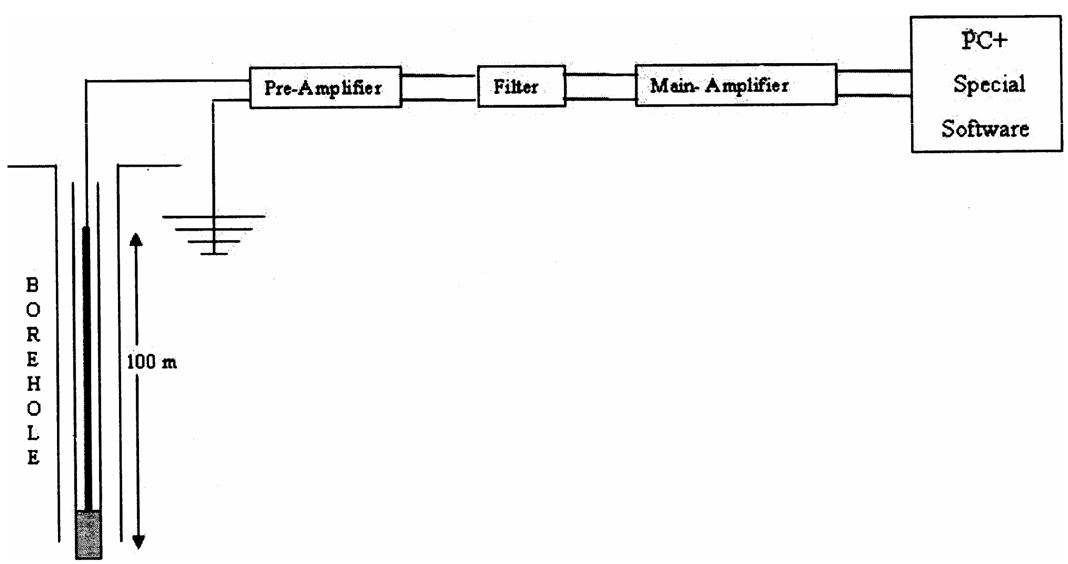

Fig. 1 — Experimental set up at Agra for monitoring vertical component of subsurface VLF electric field emissions

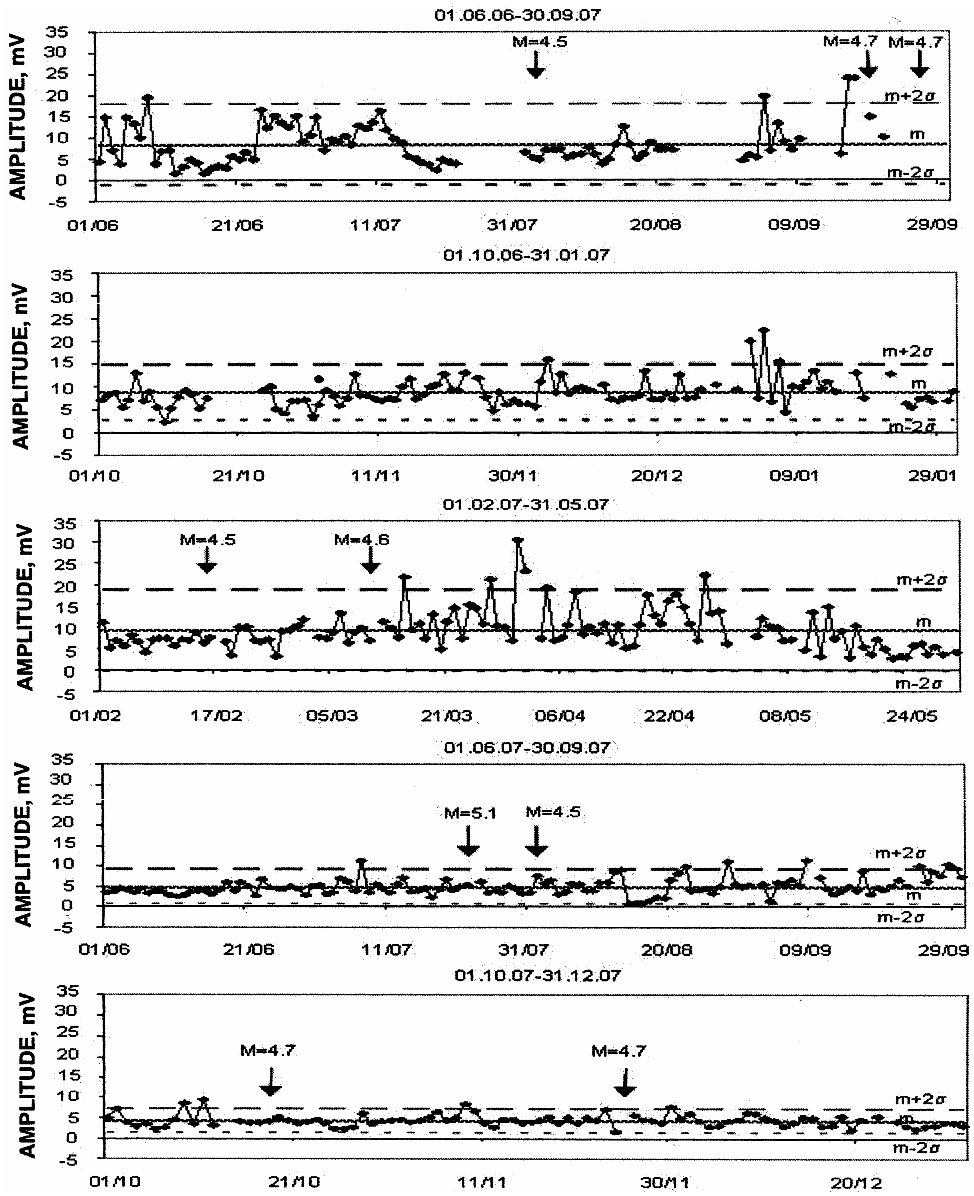

Fig. 2 — Daily variation of vertical component of subsurface electric field changes (shown by solid curve with square points) from 1 June 2006 to 31 December 2007. Each panel represents data variation for a period of four months except the last one which is for three months. Horizontal dashed lines in each panel indicate standard deviation around the mean. Downward arrows show the dates and magnitudes of occurrence of earthquakes

From a glance at the variation of data in each panel, one finds that amplitudes are beyond 2σ lines occasionally which show some kind of anomalous situation as compared to the rest of data. In Table 1, the days are mentioned on which such anomalies have occurred. An attempt has been made to explain these anomalies in the light of magnetic storms, earthquakes, local lightning, and other local noises, etc. The magnetic storm variation during the period of study is shown by $\sum K_p$ histograms in each panel of Fig. 3. It is well known that $\sum K_p > 30$ represents the occurrence of magnetic storm and $\sum K_p < 30$ represents a quiet day. The days of occurrence of magnetic storm under this criterion are also indicated in Table 1. Since the number of anomalies is larger than the number of magnetic storm days, it is possible that some of the anomalies are caused by seismic activities and other sources in the region. As it has been mentioned earlier that the borehole antenna is sensitive to moderate and large magnitude nearby earthquakes, in this study all

Table 1 — Details of date of amplitude anomalies and days on which various events such as magnetic storms, earthquakes, local lightning and other local noises, etc. have occurred

S. No.	Days of amplitude anomalies	Days of magnetic storms	Days of earthquakes	Local lightning/local noises
1	08.06.2006			(0) LL
2	04.09.2006		+15	
3	16.09.2006		+3	
4	17.09.2006		+2	
5	04.12.2006			(0) other local noises
6	02.01.2007	-18		
7	04.01.2007	-20		
8	06.01.2007	-22		
9	15.03.2007		-5	
10	27.03.2007		-17	
11	31.03.2007		-21	
12	01.04.2007		-22	
13	04.04.2007	-3		
14	26.04.2007			(0) other local noises
15	07.07.2007		+16	
16	22.08.2007			(0) LL
17	28.08.2007			(0) LL
18	08.09.2007			(0) LL
19	24.09.2007			(0) other local noises
20	28.09.2007			(0) other local noises
21	29.09.2007	-5		
22	09.10.2007		+9	
23	11.10.2007		+7	
24	08.11.2007		+18	
25	30.11.2007		-4	

the earthquakes, having magnitudes 4.5 and above and occurred at distances < 500 km from the observing station at Agra, are considered. In Table 2, the details of these earthquakes including date and time of occurrence, depth, magnitude and distance from the observing station are presented. These earthquakes are also shown by inverted arrows in Fig. 2 and their locations are shown in Fig. 4. Though, lightning activity data is not available, it is possible that some of the enhanced amplitudes are caused by VLF waves (spherics) radiated from the lightning activity, especially during the rainy season (June - August) around the observing station. Some of the days of amplitude anomalies caused possibly by lightning activity are also indicated in Table 1.

In order to explain amplitude anomalies appearing in Fig. 2, taking dates of anomalies in Table 1 as references, the days of possible causative sources, i.e. magnetic storms, earthquakes, and local lightning/local noises such as power line radiations, radio transmissions, local building noises are calculated with the help of Figs 2 and 3. For example, there is neither a magnetic storm nor an earthquake around the first anomaly on 8 June 2006, hence, it may not be correlated with either of them. However, since it occurred in the month of June which is the month of rainy season in the region around Agra, it is likely to be caused by local lightning activity. In that case it may be influenced on the same day, hence, it is shown by 0 (LL). Similarly, the amplitude enhancements on 4, 16 and 17 September 2006 in panel 1 may be caused by an earthquake of magnitude 4.7 occurred on 19 September 2006. In this case, the anomalies occur as precursors 15, 3, 2 days before the earthquake. Since the earthquake occurred after the events, the earthquake days are shown by + sign. The amplitude anomalies on 2, 4, 6 January 2007 may possibly be caused by magnetic storms during 6-15 December 2006. Here, the days of storms are counted from the largest magnetic storm on 15 December 2006. In this case, since the events occurred after the storms, the days are shown by – sign. Since large magnetic storms have delayed effect in the low latitude ionosphere, which may be of the order of 2-3 weeks[27,28], the induced current effect on the VLF amplitude 18-22 days after the occurrence of magnetic storm is quite reasonable. In the same manner, other amplitude anomalies are also interpreted. It may clearly be noted here that there are some earthquakes (for example, those on 5 August and 26 September 2006) corresponding to which no data are available, and there are some other earthquakes (those occurred on 16 February and 1 August 2007) corresponding to which amplitude enhancements are not as large as they could cross 2σ line, hence the effect of such earthquakes are not accounted in the analysis. Similarly, there are some magnetic storms (for example, those which occurred on 7 August and 10 November 2006; 28 April, 23 May and 29 May 2007, $\sum K_p \approx$ 31-34) corresponding to which amplitude enhancements are not significant. Some of the cases of amplitude enhancements which occurred neither in the rainy season, nor they could be correlated with earthquakes and magnetic storms may possibly be caused by local noises (electric and electromagnetic) and such anomalies are also indicated in Table 1.

The results obtained from Table 1 are summerised in Table 3. One can find that about 48% anomalies are

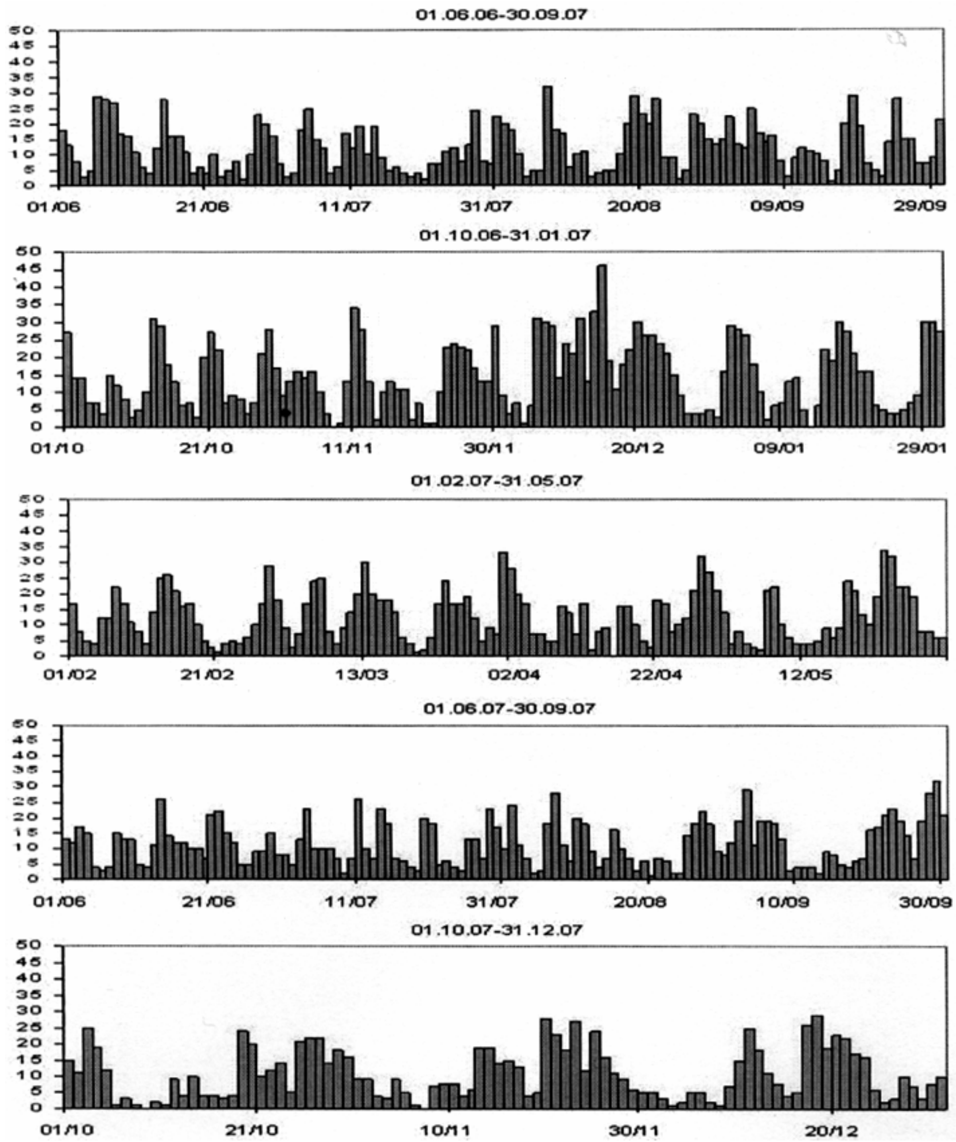

Fig. 3 — Daily variation of $\sum K_p$ (shown by histograms) from 1 June 2006 to 31 December 2007

Table 2 — Details of earthquakes including date and time of occurrence, depth, magnitude and distance from the observing station

Date of Earthquakes	Time, hrs LT	Lat, °N	Long, °E	Depth, km	Magnitude	Distance, km
05.08.2006	13:03:02	29.89	80.1	10	4.5	379
19.09.2006	12:26:46	29.49	81.57	27	4.7	445
26.09.2006	01:34:20	29.76	80.52	6	4.7	392
16.02.2007	00:39:39	29.57	81.45	18	4.5	441
10.03.2007	10:55:47	29.44	81.14	5	4.6	409
23.07.2007	04:32:14	30.88	78.24	19	5.1	430
01.08.2007	20:47:52	29.21	82.2	10	4.5	479
18.10.2007	11:24:42	27.79	77.61	10	4.7	95
26.11.2007	04:42:17	28.56	77.06	10	4.7	195

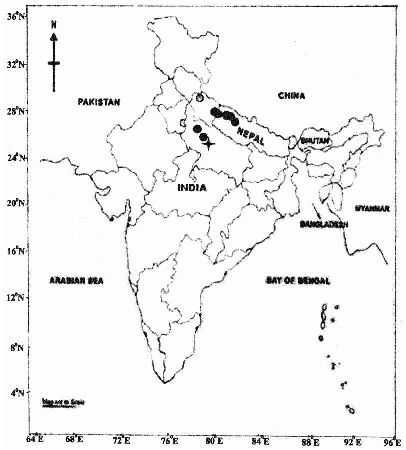

Fig. 4 — Location of earthquakes (shown by solid circles) that have occurred at a distances < 500 km from the observation site during 1 June 2006-31 December 2007

correlated with earthquakes, 20% with magnetic storms, 16% with local lightning, and 16% with other local noises. The results that amplitude enhancements occur as precursors 2-18 days before the occurrence of earthquakes and the effect is continued from 4-22 days after the onset of main shock is consistent with the earlier studies. For example, Fujinawa & Takahashi[29] observed anomalous changes in vertical component of subsurface VLF electric field emissions (f = 1-9 kHz) employing a borehole antenna 15 days before many earthquakes ($M \geq 5$) in central Japan. Hayakawa *et al.*[30] have reported ultra low frequency (ULF) geomagnetic variations 1-2 weeks before the occurrence of several earthquakes in Japan. Uyeda *et al.*[31] have reported slow transient electric potential changes 1-19 days before five seismic events ($M \geq 5$) in Japan, while Tanaka[32] has reported anomalous changes in geoelectric potential difference about two months before the onset of volcanic activity in Izu Island region of Japan. Singh *et al.*[19] have observed abrupt changes in vertical component of VLF electric field emissions (f = 3 kHz) employing a borehole antenna 5 days before the Chamoli earthquakes of March/April 1999 and their effects continued up to about one month.

Now the question arises how the VLF electromagnetic signals are generated in the source region and propagated to such long distances (95-479 km) and cause amplitude enhancements at the observing station. In order to answer this question, it may be mentioned here that four possible mechanisms have been proposed for the propagation of seismo-electromagnetic emissions. Although these mechanisms are not fully established, they include electro-kinetic effect, tribo-electric effect, micro-fracturing and

Table 3 — Percentage correlation of amplitude anomalies with possible causative events
Total number of anomalies = 25

Event	No. of anomalies associated with different event	% correlation
Earthquake	12	48%
Magnetic storm	5	20%
Local lightening	4	16%
Other noises	4	16%

piezoelectric effect. In electro-kinetic effect, electric and magnetic fields are generated due to fluid flow through the crust while in tribo-electric effect electromagnetic emissions are generated due to frictional sliding of rocks. However, both of these mechanisms show only the local influence and the emissions generated through these mechanisms cannot propagate to long distances. In the phenomenon of micro-fracturing, electromagnetic emissions are generated due to acceleration of charges as a result of crack motion when the rocks are under indentation. But this mechanism is found suitable for ULF range of emissions[33]. In piezoelectricity, charges are generated at the opposite faces of the rock or the crystal when the rock or the crystal is under stress. Thus large numbers of elementary dipoles are produced in the middle layer of crust (conductivity $\approx 10^{-4}$-10^{-6} mho). When the stress on the rocks varies, dipoles starts to oscillate and produce electromagnetic radiations. The VLF emissions so generated may propagate long distances through the middle layer of crust acting as waveguide without much attenuation because of low conductivity. It is possible that along the propagation path, they may find "windows" of reduced conductivity formed as a result of some special geological formation through which they can penetrate the upper crust and appear on the ground in the borehole[34]. Similar mechanism for the propagation of VLF/ELF seismogenic emissions from the earth crust has also been proposed by Mognaschi[35].

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