FUSION OF MULTI PRECURSORS EARTHQUAKE PARAMETERS TO ESTIMATE THE DATE, MAGNITUDE AND AFFECTED AREA OF THE FORTHCOMING POWERFUL EARTHQUAKES

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ABSTRACT:

Since not any individual precursor can be used as an accurate stand alone means for the earthquake prediction, it is necessary to integrate different kinds of precursors. The precursors selected for analysis in this study include electron and ion density, electron temperature, total electron content (TEC), electric and magnetic fields and land surface temperature (LST) several days before three strong earthquakes which happened in Samoa Islands, Sichuan (China) and Borujerd (Iran). The precursor's variations were monitored using data obtained from experiments onboard DEMETER (IAP, ISL, ICE and IMSC) and Aqua-MODIS satellites. Regarding the ionospheric precursors, the geomagnetic indices D_{st} and K_p were used to distinguish pre-earthquake disturbed states from the other anomalies related to the geomagnetic activities. The inter-quartile range of data was utilized to construct their upper and lower bound to detect disturbed states outsides the bounds which might be associated with impending earthquakes. When the disturbed state associated with impending earthquake is detected, based on the type of precursor, the number of days relative to earthquake day is estimated. Then regarding the deviation value of the precursor from the undisturbed state the magnitude of impending earthquake is estimated. The radius of the affected area is calculated using the estimated magnitude and Dobrovolsky formula. In order to assess final earthquake parameters (which are date, magnitude and radius of the affected area) for each case study, using the median and inter-quartile range of earthquake parameters obtained from different precursors, the approximate bounds of final earthquake parameters are defined. For each studied case, a good agreement was found between the estimated and registered earthquake parameters.

1. INTRODUCTION

Many papers and special monographs have been published on satellite observation of perturbations associated with seismic activity (Hayakawa and Molchanov, 2002; Pulinets and Boyarchuk, 2004, Akhoondzadeh, 2011).
Earthquake is a dynamic phenomenon and usually happens because of crust displacement. When the earthquake happens, an energy transfer due to a break down between source and environment is made. These changes prior to the earthquake or along with it may have different physical and chemical affects on the lithosphere, atmosphere and ionosphere, and accordingly makes it possible to be detected. These variations of lithosphere, atmosphere and ionosphere parameters before the main earthquakes are considered as hint of impending earthquakes (earthquake precursors). Widespread researches on earthquake prediction over the last decades have resulted in the recognition of many earthquake precursors in the lithosphere, atmosphere and ionosphere.
Satellite experiments due to the vast coverage of the seismic zones of the Earth along with other sources of information are regarded as suitable means for earthquake study. They allow performing meaningful statistical studies with a much larger number of recorded events. If it can be shown that earthquake perturbations are real and systematic then they could be considered as short-term precursors, occurring between a few hours and a few days before the earthquakes.

1.1 Ionospheric precursors

The regional but substantially large-scale changes in atmospheric electricity over seismically active areas before the seismic shock are transformed into the ionosphere by means of a large-scale electric field.
Pulinets et al. (2003) have shown that ionospheric anomalies have been observed in 73% of earthquakes with magnitude greater than $5M_s$ and 100% of earthquakes with magnitude greater than $6M_s$ within 5 days before the earthquake events. The ionospheric anomalies usually happen in D-layer, E-layer and F-layer, and they may be observed 1 to 10 days prior to the earthquake and stay until 1 to 2 days after the earthquake (Akhoondzadeh et al., 2011).

1.1.1 TEC Precursor

TEC is the integrated number of the electrons within the block between the satellite and receiver or between two satellites. To study TEC variations, data of GIM (Global Ionospheric Map) provided by NASA Jet Propulsion Laboratory (JPL) were used. The GIM is constructed into 5° × 2.5° (Longitude, Latitude) grid with a time resolution of 2 hours.

1.1.2 Ionospheric precursors provided by DEMETER data

The French micro-satellite DEMETER was launched on June 29, 2004. The satellite's altitude is about 680 km and its measurements are made within 65°N to 65°E. One of DEMETER scientific objectives is to detect anomalous variations of electromagnetic waves, particle fluxes and thermal plasma parameters which could be related to seismic activity.
DEMETER has five instruments on board. They are ICE (Instrument Champ Eletrique), IMSC (Instrument Magnetic Search Coil), IDP (Instrument Detecteur de Particules), IAP

(Instrument Analyseur Plasma), and ISL (Instrument Sonde de Langmuir). ICE measures the three components of electric field in a frequency range from DC up to 3.5 MHz, IMSC measures the three components of magnetic field in ELF and VLF frequency ranges, IDP measures ionospheric particles energy (electron and proton), IAP measures temperature, density and velocity of plasma ions, and ISL measures temperature and density of plasma electrons.

1.2 Thermal anomaly precursor

Thermal anomaly is an unusual variation in surface temperature that occurs around 1-13 days prior to the earthquake with abrupt change in the temperature value of the order of 3-7° C or more and disappears a few days after the event. Some remote sensing satellites can measure the radiations coming from the earth in thermal bands and provide useful information prior the earthquakes. Due to their suitable temporal and spatial resolutions, thermal infrared bands of Aqua-MODIS data have been used.

2. APPLIED METHOD FOR ANOMALY DETECTION AND ESTIMATE EARTHQUAKE PARAMETERS

In order to search for earthquake anomaly from precursor variations a reasonable range for precursor regular variations must be determined. The median and the inter-quartile range of data are utilized to construct their upper and lower bound in order to separate seismic anomalies from the background of natural variations (Liu et al., 2004).
The upper and lower bound of the mentioned range can be calculated using the following equations:

$$x_{high} = M + k \times IQR \qquad (1)$$

$$x_{low} = M - k \times IQR \qquad (2)$$

$$x_{low} < x < x_{high} \Rightarrow -k < Dx = \frac{x - M}{IQR} < k \qquad (3)$$

where x , x_{high} , x_{low} , M , IQR and Dx are the parameter value, upper bound, lower bound, median value, inter-quartile range and differential of *x*, respectively. According to this, if the absolute value of *Dx* is greater than *k*, ($|Dx| > k$), the behavior of the relevant parameter (*x*) is regarded as anomalous. According to Eq. (3), $p = \pm 100 \times (|Dx| - k)/k$ indicates the percentage of parameter change from the undisturbed state.
The results from our previous studies indicate that *Dx* value is relatively proportional to the earthquake magnitude (Akhoondzadeh, 2011). For instance, in large earthquakes with a *Dx* value between 2 and 3, the magnitude value (M_W) is estimated to be around between 7 and 8. The earthquake magnitude estimation based on *Dx* value is shown in Table 1.
The radius of affected area can be estimated using the Dobrovolsky formula: $R = 10^{0.414M - 1.696}$, where *R* is the radius of the earthquake preparation zone, and *M* is the earthquake magnitude (Dobrovolsky et al., 1989).

Dx value	Earthquake magnitude
$Dx \le 1$	$M_W < 6$
$1 < Dx \le 2$	$6 < M_W \le 7$
$2 < Dx \le 3$	$7 < M_W \le 8$
$3 < Dx$	$8 < M_W$

Table 1. Estimation of the earthquake magnitude.

Based on previous studies related to anomaly detection before strong earthquakes mentioned in Table 2, the earthquake anomalies may be observed 1 to 13 days prior to the earthquake. If *Dx* value of a given day is greater than a predefined threshold then based on the type of precursor, the earthquake date is estimated according to the relation $\mu + 2.5 \times \sigma$, (i.e. the fourth column) where μ and σ are the mean and standard deviation of values of the anomaly observation day relative to the earthquake day (i.e. the third column) (Akhoondzadeh, 2011).
In order to assess final earthquake parameters (which are date, magnitude and radius of the affected area) for each case study, using the median and inter-quartile range of earthquake parameters obtained from different precursors, the approximate bounds of final earthquake parameters are defined. For instance, the date of impending earthquake is calculated based on $M \pm IQR$, where M and IQR are respectively the median and inter-quartile range of the predicted values of the earthquake date for all precursors (Akhoondzadeh, 2011).

3. OBSERVATIONS AND CASE STUDIES

In order to clear up uncertainty to earthquake anomaly detection, our study is based on a few types of precursors, sensors and case studies. Using visual inspection in seismic databases three earthquakes which happened in Samoa Islands, Sichuan (China) and Boroujerd (Iran) have been incorporated in this analysis. Table 3 indicates some characteristics of these earthquakes.

3.1 Samoa Islands earthquake

In Samoa Islands, the largest earthquake so far, took place at 06:48:11 LT on 29 Sep 2009 with a Magnitude M_w=8.1. Table 4 illustrates the observed earthquake precursors concerning Samoa earthquake.
As shown in Table 4 strong enhancement of TEC anomaly can be seen during several time intervals (Akhoondzadeh et al., 2010a).

Precursor	Reference	Anomaly observation day relative to the earthquake day	Estimated earthquake day relative to the observation day
Ionospheric	Zhao et al., 2008	3	15
	Liu et al., 2004	4	
	Pulinets et al., 2003	5	
	Akhoondzadeh et al., 2010a, 2010b	11	
	Akhoondzadeh and Saradjian, 2010	8	
Thermal	Ouzounov and Freund, 2004	6	16
	Saraf and Choudhury, 2005a	13	
	Choudhury et al., 2006	7	
	Pulinets et al., 2006	7	
	Saraf and Choudhury, 2005b	8	

Table 2. Estimation of the earthquake date.

Case Study	Date	Time (UTC)	Longitude	Latitude	Magnitude (M_W)	Focal depth (km)
Borujerd, Iran	2006/03/31	01:17:01	48.78 N	33.50 E	6.1	7
Sichuan, China	2008/05/12	06:28:01.57	103.32 N	31.0 E	7.9	19
Samoa Islands	2009/09/29	17:48:10.99	172.10 W	15.49 S	8.1	18

Table 3. List of the earthquakes selected in this study (reported by http://earthquake.usgs. gov/)

Anomalous TEC variations of the order of 2.55 began on 24 Sep 2009. Based on proposed method, this anomaly indicates that an earthquake with a magnitude between 7 and 8 would have been happened between 25 Sep and 9 Oct 2009 and the radius of affected area would have been between 15.92 and 41.30 Km. The TEC anomaly on 28 Sep 2009 was expanded and amplified with a maximum value reaching 3.73 at 03:00 LT. For *Dx*=3.73 the magnitude of impending earthquake, which would have been occurred between 29 Sep and 13 Oct 2009, is estimated to be greater than M_w=8.0. Therefore, the radius of affected area is estimated to have been greater than 41.30 km.

Table 4 also illustrates variations of different parameters extracted from DEMETER experiments data over Samoa region. An increase in total ion density is clearly observed at ~10:30 LT on 25 Sep 2009. Variations of total ion density clearly exceed the upper bound of the order of 67% (Akhoondzadeh et al., 2010a). This precursor indicates that an earthquake with a magnitude greater than M_w=8.0 would have been occurred between 26 Sep and 10 Oct 2009. Similar to this, another unusual behavior is seen in electron density variations, when it reaches a maximum value, at ~10:30 LT, and exceeds the upper bound of the order of 67% on 25 Sep 2009. Because of the inverse relation between electron density and electron temperature, observed anomaly in electron density can be acknowledged by the electron temperature variations. Table 4 indicates that electron temperature has reached to its minimum value (*Dx*=-1.82) at ~10:30 LT, on 25 Sep 2009. This anomaly indicates that an earthquake with a magnitude between 6 and 7 would have been happened between 26 Sep and 10 Oct 2009. Irregularities of electron density also occurred at ~22:30 LT, 18, 21, 24 and 26 Sep 2009 that among them, the maximum irregularity intensity (*i.e.* 60.5%) was observed on 24 Sep 2009. According to this anomaly an earthquake with a magnitude between 7 and 8 would have been happened between 25 Sep and 9 Oct 2009 and the radius of affected area to have been between 15.92 and 41.30 km.

Table 4 represents the intense appearance of the NPM transmitter waves in the VLF electric spectrogram on 21 Sep 2009. This strong electromagnetic enhancement of the VLF transmitter wave is due to the broadening of the spectral component at the transmitter frequency. This broadening is enhanced when the VLF wave crosses ionospheric irregularities (Bell and Ngo, 1988). This sharp appearance is also seen in the VLF magnetic spectrogram at the same time (Akhoondzadeh et al., 2010b). These earthquake precursors extracted using ICE and IMSC experiments indicate that an earthquake with a magnitude greater than M_w=7, would have been happened between 22 Sep and 6 Oct 2009. Table 4 also represents the attenuation of the NPM transmitter signals when they crossed the disturbed ionosphere on 24 Sep 2009. This fading of the signal can be associated to an increase of the ionospheric density because during the ionospheric propagation the signal attenuation is directly proportional to the plasma density (Cannon and Bradley, 2003). The analysis of HF electric spectrogram shows the intense appearance of harmonic emissions above NPM transmitter on 28 Sep 2009 (Akhoondzadeh et al., 2010b).

The final earthquake parameters including the date, magnitude and radius of affected area are estimated using the earthquake parameters deduced from different precursors. The bounds of the final impending earthquake parameters are calculated using the median and inter-quartile range of earthquake parameters estimated using different precursors. In this case study, it is predicted that an earthquake would have been happened with a magnitude between 7 and 8, on a date between 29 September and 6 Oct 2009, and in an affected area of radius between 15.92 and 41.30 Km. The Samoa earthquake actually happened on 29 September 2009 with a magnitude M_w=8.1.

Precursor	Date of observed anomaly	Prediction of earthquake date	Deviation value (*Dx*)	Prediction of earthquake magnitude	Prediction of the radius of affected area (Km)
TEC	28 Sep	29 Sep – 13 Oct	+2.78	7-8	15.92-41.30
	28 Sep	29 Sep – 13 Oct	+3.73	>8	> 41.30
	28 Sep	29 Sep – 13 Oct	+3.38	>8	>41.30
	28 Sep	29 Sep – 13 Oct	+2.63	7-8	15.92-41.30
	27 Sep	28 Sep – 12 Oct	+2.73	7-8	15.92-41.30
	27 Sep	28 Sep – 12 Oct	+2.54	7-8	15.92-41.30
	26 Sep	27 Sep – 11 Oct	+2.91	7-8	15.92-41.30
	25 Sep	26 Sep – 10 Oct	+2.60	7-8	15.92-41.30
	25 Sep	26 Sep – 10 Oct	+3.07	>8	>41.30
	24 Sep	25 Sep – 09 Oct	+2.55	7-8	15.92-41.30
Electron Temperature	27 Sep	28 Sep – 12 Oct	+3.24	>8	>41.30
O^+ Density	26 Sep	27 Sep – 11 Oct	+2.12	7-8	15.92-41.30
Total Ion Density	26 Sep	27 Sep – 11 Oct	+2.08	7-8	15.92-41.30
Ion Density	26 Sep	27 Sep – 11 Oct	+2.28	7-8	15.92-41.30
Total Ion Density	25 Sep	26 Sep – 10 Oct	+3.0	>8	>41.30
O^+ Density	25 Sep	26 Sep – 10 Oct	+3.18	>8	>41.30
Ion Temperature	25 Sep	26 Sep – 10 Oct	-2.87	7-8	15.92-41.30
Electron Density	25 Sep	26 Sep – 10 Oct	+3.01	>8	>41.30
Electron Temperature	25 Sep	26 Sep – 10 Oct	-1.82	6-7	6.14-51
Electron Density	24 Sep	25 Sep – 09 Oct	+2.89	7-8	15.92-41.30
Ion Density	23 Sep	24 Sep – 08 Oct	+1.96	6-7	6.14-15.92
Total Ion Density	21 Sep	22 Sep – 06 Oct	+1.65	6-7	6.14-15.92
O^+ Density	21 Sep	22 Sep – 06 Oct	+2.24	7-8	15.92-41.30
O^+ Density	21 Sep	22 Sep – 06 Oct	+2.07	7-8	15.92-41.30
Total Ion Density	21 Sep	22 Sep – 06 Oct	+2.04	7-8	15.92-41.30
Electron Density	21 Sep	22 Sep – 06 Oct	+2.8	7-8	15.92-41.30
Ion Density	18 Sep	19 Sep – 03 Oct	+2.07	7-8	15.92-41.30
The intense appearance of NPM transmitter waves in the VLF electric spectrogram	21 Sep	22 Sep – 06 Oct	> 2.2	>7	>15.92
The intense appearance of NPM transmitter waves in the VLF magnetic spectrogram	21 Sep	22 Sep – 06 Oct	> 2.2	>7	>15.92
The attenuation of NPM transmitter waves in the VLF electric spectrogram	24 Sep	25 Sep – 09 Oct	> 2.2	>7	>15.92
The most appearance of harmonic emissions above NPM transmitter in the HF electric spectrogram	27 Sep	28 Sep – 12 Oct	> 2.2	>7	>15.92
The intense appearance of harmonic emissions above NPM transmitter in the HF electric spectrogram	28 Sep	29 Sep – 13 Oct	> 2.2	>7	>15.92
Sea Surface Temperature	26 Sep	27 Sep – 12 Oct	0.79	5-6	2.36-6.14

Table 4. Different precursors concerning Samoa earthquake.

3.2 Sichuan, China earthquake

On 12 May 2008 at 14:28:01.57 LT a strong earthquake of magnitude M_w=7.9 occurred in southwest China (see Table 3). Some strong anomalies have been observed on 2 May (6:00 LT), 8 May (2, 4, 6 LTs), 9 May (12, 14, 24 LTs), 10 May (12, 14 LTs) and 11 May (12 LT) 2009. Among all above pre-earthquake anomalies, the anomalies observed on 9 and 10 May at 12:00 LT, were the strongest (the observed TEC exceeds the lower bound by -24%) (Akhoondzadeh et al., 2010a). These strong anomalies indicate that an earthquake with a magnitude greater than 8 would have been happened between 10 and 24 May 2009. The corresponding data with total ion and electron density changes recorded by DEMETER IAP and ISL sensors are shown in Table 5. The transition in electron density value from lower bound occurs at ~10:30 LT, on 9 May 2009 and is of the order of -24%. It reaches its minimum value of -37%, 2 days before the earthquake (Table 5). It means that an earthquake with a magnitude greater than 8 would have been happened between 10 and 24 May 2009. Such anomalies are also observed in electron temperature variations, when the magnitude of changes from the undisturbed state

Precursor	Date of observed anomaly	Prediction of earthquake date	Deviation value (*Dx*)	Prediction of earthquake magnitude	Prediction of the radius of affected area (Km)
TEC	11 May	12 May – 26 May	-2.59	7-8	15.92-41.30
	10 May	11 May – 25 May	-03.10	>8	>41.30
	10 May	11 May – 25 May	-03.07	>8	>41.30
	9 May	10 May – 24 May	-03.10	>8	>41.30
	9 May	10 May – 24 May	-2.92	7-8	15.92-41.30
	9 May	10 May – 24 May	-2.50	7-8	15.92-41.30
	8 May	9 May – 23 May	-2.69	7-8	15.92-41.30
	8 May	9 May – 23 May	-2.87	7-8	15.92-41.30
	8 May	9 May – 23 May	-2.68	7-8	15.92-41.30
	2 May	3 May – 17 May	-2.55	7-8	15.92-41.30
O^+ Density	10 May	11 May – 25 May	-2.18	7-8	15.92-41.30
Total Ion Density	10 May	11 May – 25 May	-2.28	7-8	15.92-41.30
Ion Density	10 May	11 May – 25 May	-2.05	7-8	15.92-41.30
Electron Temperature	10 May	11 May – 25 May	+1.98	6-7	6.14-15.92
Electron Temperature	9 May	10 May – 24 May	+1.73	6-7	6.14-15.92
Electron Density	9 May	10 May – 24 May	-1.86	6-7	6.14-15.92
O^+ Density	9 May	10 May – 24 May	-2.40	7-8	15.92-41.30
Total Ion Density	10 May	11 May – 25 May	-2.26	7-8	15.92-41.30
Electron Density	10 May	11 May – 25 May	-1.70	6-7	6.14-15.92
Electron Density	3 May	4 May – 18 May	+2.09	7-8	15.92-41.30
O^+ Density	2 May	3 May – 17 May	+2.37	7-8	15.92-41.30
Total Ion Density	2 May	3 May – 17 May	+2.13	7-8	15.92-41.30
Electron Temperature	2 May	3 May – 17 May	-3.22	>8	>41.30
Electron Temperature	1 May	2 May – 16 May	+2.5	7-8	15.92-41.30

Table 5. Different precursors concerning Sichuan earthquake (Akhoondzadeh, 2011).

reaches 15% and 29%, on 9 and 10 May 2009, respectively (Table 5). The variations of electron density also indicate an increase of the order of 39%, from the normal state on 3 May 2009 which is acknowledged by an anomaly in the total ion density of the order of 42%, at ~22:30 LT, on 2 May 2009 (Table 5). According to this anomaly an earthquake with a magnitude between 7 and 8 would have been happened between 3 and 17 May 2009 and the radius of affected area varies between 15.92 and 41.30 Km. The characteristics of other detected anomalies can be found in Table 5. The integration of earthquake parameters retrieved from different precursors indicates that an earthquake with a magnitude between 7 and 8 would have been happened between 12 and 20 May 2009. The radius of affected area is estimated to be between 15.92 and 41.30 Km.

3.3 Borujerd, Iran earthquake

Occurrence of more than 130 strong earthquakes ($M_w > 7.5$) in the past centuries and almost daily earthquakes of magnitude 3.0 in Iran makes it as a severe earthquake prone region. In Borujerd, an earthquake with a magnitude M_w=6.1 took place at 01:17:01 LT on 31 Mar 2006 (see Table 3). The LST variations exceed the predefind bounds on 25 March 2006 (Saradjian and Akhoondzadeh, 2010). These anomaly indicates that an earthquake of magnitude around 6 would have been happened between 26 Mar and 10 Apr 2005. The IAP experiement measurements indicate that total ion density reaches to its maximum value on 30 Mar 2006 and that ion temperature exceeds the lower bound on 29 Mar 2006 (Table 6) (Akhoondzadeh, 2011). By inspection of predicted parameters obtained from different precursors, it is predicted that an earthquake of magnitude between 6 and 7 would have been happened between 01 and 08 Apr 2006.

4. CONCLUSIONS

In order to detect disturbed states that might be associated to impending earthquake, the variations of different earthquake precursors regarding the three earthquakes have been analyzed in this study. It should be pointed out that one of the aims of this study is to integrate capabilities of the different earthquake precursors in appropriately detection of actual earthquake anomalies. For each precursor the date, magnitude and radius of affected area parameters concerning the impending earthquake were estimated. By integrating the earthquake parameters resulted from all precursors the final earthquake parameters were estimated. In Samoa and Sichuan earthquakes the estimated date of impending earthquake coincides exactly with registered date of earthquake (Table 7). It can be related to the different precursors (i.e. 14 and 6 precursors for Samoa and Sichuan cases, respectively) analyzed in these studied cases. It means that the number and diversity of earthquake precursors can be leaded to precise estimation of earthquake parameters. The low number of precursors in case of Bourujerd has been resulted to low precise estimation of earthquake parameters (Table 7). It should be point out that earthquake anomaly can be hidden in the high magnetic activity periods. Therefore only the pre-seismic plasma anomalies in geomagnetic quiet periods have been investigated in this study. However, it is necessary to take into account that the ionosphere has complicated behavior even under quiet geomagnetic condition and the measured parameters sometimes display variations in quiet seismic condition that can be associated to other unknown factors. The seismic anomalies represented in this paper are promising for the short term prediction but attention has to be paid that further investigation is required to obtain a very accurate regional model of quiet time for lithosphere, atmosphere and ionosphere to discriminate seismic precursors from the background of daily variations.

Precursor	Date of observed anomaly	Prediction of earthquake date	Deviation value (*Dx*)	Prediction of earthquake magnitude	Prediction of the radius of affected area (Km)
LST	25 Mar	26 Mar – 10 Apr	1.31	6-7	6.14-15.92
Total Ion Density	30 Mar	31 Mar – 14 Apr	+1.54	6-7	6.14-15.92
Ion Temperature	29 Mar	30 Mar – 13 Apr	+1.25	6-7	6.14-15.92

Table 6. Different precursors concerning Borujerd earthquake.

Case Study	Date		Magnitude (M_W)	
	Registered	Estimated	Registered	Estimated
Borujerd	31 Mar 2005	01 - 08 Apr 2006	6.1	6 - 7
Sichuan, China	12 May 2008	12 - 20 May 2008	7.9	7 - 8
Samoa Islands	29 Sep 2009	29 Sep – 06 Oct 2009	8.1	7 - 8

Table 7. Case studies accompanied by the registered and estimated earthquake parameters (Akhoondzadeh, 2011).

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