Local time dependence of earthquakes occurrence and its possible connection with geomagnetic diurnal variations

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ABSTRACT
Occurrence of earthquakes is not only controlled by internal processes such as the tectonic processes, but also by external ones as Sun-Earth system processes. The aim of the current study is to examine the distribution of earthquakes occurrence at some active seismic regions in order to determine the dominant period of earthquakes occurrence with respect to local time and its possible connection with geomagnetic diurnal variations. Analyzing long-term datasets from 1986 to 2020 demonstrated that occurrence of earthquakes at the studied regions is strongly depending on local time where earthquakes tend to occur more often during noon local time. This behavior is in somehow similar to the pattern of geomagnetic diurnal variations. Therefore, the study was extended to investigate the probable correlation between both of them. Diurnal variation of North-South geomagnetic component (X-component) was examined and compared with the local time distribution of earthquakes at each region. Data analysis revealed a significant correlation between the geomagnetic diurnal variations and earthquakes occurrence. Thus, the results support the idea of existence a dominating time interval of earthquakes occurrence and also a relationship between local time dependence of earthquakes and geomagnetic diurnal variations that may help in earthquakes prediction in the future.

1. Introduction

Earthquakes are shakings of the Earth’s surface resulting from an abrupt release of energy in the Earth’s crust, which generates seismic waves (Ohnaka 2013). The seismicity of a region is the frequency, kind and magnitude of earthquakes occurred during a period of time. Generally, seismic activities take place along boundaries of tectonic plates, faults in the Earth’s crust, mid-oceanic ridges or in association with volcanic activities (Vassiliou and Kanamori 1982). The majority of world earthquakes occur along the tectonic plate boundaries, specifically around the Pacific Rim (Ring of Fire) where there is a particularly intense tectonic activity. Most of the earthquakes along the west coast of Chile and North America, Japan and Alaska are caused by tectonic activities (Stern and Bloomer 2020). Earthquakes are classified into three categories, which are shallow earthquakes that occur at depths up to 70 km, intermediate earthquakes that occur at depths between 70 km and 300 km, and deep earthquakes that take place at depths range from 300 km to 700 km (Spence et al. 1989). According to the U.S. Geological Survey, most of the earthquakes occur at shallow depths.

The occurrence of such hazardous events can cause a great loss of lives and sever damages in the natural environment such as landslides and tsunami, but most attention is focused on their impact on constructed structures. Shallow earthquakes generally tend to cause more damages than deeper ones because seismic waves generated from deep seismic events have to travel for long distances to the Earth’s surface that causes losing energy through their way (Zheng-Xiang et al. 2005). Earthquakes also can bring heavy economic loss. Therefore, understanding the seismic hazard at a certain seismic region and determining the dominant time interval of earthquakes occurrence can be a helpful step towards earthquake prediction in the future.

A number of studies indicated that the occurrence of seismic events depends on the Local Time (LT). Shimshoni (1971) claimed that seismic activity increases significantly during night-time compared with other hours of the day after analysing seismic events occurred worldwide from 1968 to 1970. In addition, he related such observation to the position of the Sun. Goldman et al. (1997), reported that significant seismic events recorded in California occur more often in the morning hours than any other time of the day. Moreover, Duma and Vilardo (1998) have reported a diurnal variation in the seismic activities with a peak a night-time. In addition, Srivastava and Gupta (2004) reported that the percentage of earthquakes occurring during evening/early mornings is larger than during the daytime. Recently, Mazzarella and Scafetta (2016) have also indicated the presence of a 24-h cycle of seismic
activities occurred at Mt. Vesuvius with maximum values at the night-time. On the other hand, Knopoff and Gardner (1972) and Davies (1972) critiqued Shimshoni, claiming that his result was unreliable due to the poor quality and shortness of the analysed seismic data sets. However, some periodicities have been suspected for seismic activity, but none of them has been substantiated until now and the diurnal seismicity still remains a controversial issue.

2. Calculating the local time of earthquakes occurrence

It is known that the Earth rotates around its axis from west to east. As a result of this rotation, the Sun rises in the east and sets in the west. The Earth needs 24 h to make one circle (360° of longitudes) around its axis, where 180° of longitudes are found at both sides of the Prime Meridian. Prime Meridian (0° longitude) is an imaginary line on Earth that passes from north to south through the Greenwich Observatory in London (Howse 1997). Therefore, the Sun needs 12 h to go across the eastern or western hemispheres. In other words, the Sun traverses 15° of longitudes per hour or 1 degree of longitude in every 4 min of time (McCarthy and Pilkington 1979). It may further be noted that the time decreases when we move from west to east and increases with our westward movement. The rate at which the Sun goes across certain degrees of longitudes with respect to the time at the Prime Meridian is used to estimate the LT at that region.

Most earthquake catalogues provide the earthquake data with Universal Time (UT). The exact LT of an earthquake at the origin is simply obtained by adding/subtracting the factor of (± longitude of epicentre /15) to the UT provided in the earthquake catalogue. The value of this factor will be added to the UT if the earthquake occurred at the eastern hemisphere and will be subtracted from it if the earthquake took place at the western hemisphere. Thus, using the given longitude of the epicentre and the UT of seismic events, the LT was computed for each seismic event.

3. Geomagnetic diurnal variations and earthquakes occurrence

The geomagnetic field measured on the Earth’s surface represents a superposition of several components from various sources (Takla et al. 2011). The main component of the geomagnetic field is related to the electric currents generated in the Earth’s core, which produce a geomagnetic field of several tens of thousands of nano teslas on the Earth’s surface (main field). The contribution of other components to the total geomagnetic field is only a fraction of the measured geomagnetic field. Among these components are the electric currents flowing in the ionosphere. These ionospheric currents generate a regular daily variation in the geomagnetic field with magnitude of a few tens of nano teslas, which is known as geomagnetic diurnal variation. Thus, the geomagnetic diurnal variations are fluctuations in the magnetic field of the Earth that are caused by the dynamo processes in the upper part of atmosphere with a periodicity of a day (Chapman 1919). Their shapes and amplitudes are strongly depending on the location (latitude) of observing point (Takla et al. 2018). The intensities vary with LT in a prevailing cycle period of 24 h. They are visible clearly only on quiet solar days since the intensity of geomagnetic disturbances associated with ionospheric turbulences is generally about several hundreds of nano teslas on the Earth’s surface, so in this case they can easily mask the diurnal variation effect (Yamazaki and Maute 2017).

The pattern of geomagnetic diurnal variations in the northward geomagnetic component tends to be symmetric around the geomagnetic equator, where the geomagnetic field is almost horizontal. Meanwhile, the geomagnetic diurnal variations patterns in the eastward and vertical components reverse at the magnetic equator. Moreover, the amplitude of geomagnetic diurnal variations of northward component at station located around the geomagnetic equator (±3°) is about 2–3 times larger than that at low latitude station of the same longitude. The equatorial enhancement of geomagnetic diurnal variations can be observed clearly in the horizontal component (Yamazaki and Maute 2017). In spite of their small amplitudes, research works on geomagnetic diurnal variations are essential for studying the geomagnetic indices (Gjerloev 2012), solar radiation activity (Svalgaard 2016), electrical conductivity of the Earth (Okeke and Obiora 2016) and recently have been linked with seismic activities (Duma and Ruzhin 2003).

Besides the tectonic activities as a main cause of earthquakes, solar activities and their resulting ionospheric turbulences, geomagnetic disturbances (geomagnetic storms) and the geomagnetic diurnal variations have been proposed as external triggers of seismic activities (Sobolev and Zakrzhevskaya 2003; Takla et al. 2012). Duma and Vilardo (1998) proposed a probable relationship linking the solar activity and the variations of the geomagnetic field with the seismic activities at the Mt. Vesuvius. Inspired by the reported results on this controversy issue, the current study examines the seismicity at certain active seismic regions to investigate the LT distribution of earthquakes occurrence and tries to determine the dominant occurrence time interval at these regions and also to detect any possible connection between geomagnetic diurnal variations and local seismic activities.
4. Data analysis and results

In the current study, the global seismicity data with magnitude (M) = 2.5+ on Richter Scale was downloaded from the U.S. Geological Survey (USGS) website (https://www.usgs.gov/natural-hazards/earthquake-hazards/research), while the geomagnetic data was obtained from the International Real-time Magnetic Observatory Network (INTERMAGNET) website (https://www.intermagnet.org/data-donnee/download-eng.php). INTERMAGNET is a worldwide network of digital geomagnetic observatories using ground-based magnetometers. Those geomagnetic observatories use standard specifications for measuring and recording tools and also provide geomagnetic data in near real time (Rasson 2007).

The main target of the present research work is to study the LT distribution of earthquakes occurrence in order to find out whether there is LT dependence of earthquakes occurrence or not at some selected seismic regions. Moreover, the present study attempted to examine the existence of any probable connection between the LT distribution of earthquakes and the geomagnetic diurnal variations. To obtain that goal, large data sets from 1986 to 2020 were analysed.

A number of active seismic regions have been selected for this study. The selection of these regions is mainly dependent on the degree of seismicity and depth of the earthquakes. The selected regions characterised with a high degree of seismicity and shallow depth earthquakes. Seismologists stated that shallow earthquakes (depth <70 km) comprise almost about 85% of the total number of the recorded seismic events (Lobkovskii et al. 2004). The depth of earthquakes is a significant parameter for detecting the influence of external factors on seismic activities since the highest correlation concerning the Sun–Earth relationships is observed with shallow seismic events (Tavares and Azvedo 2011). Moreover, the field experiments carried out by Zeigarnik et al. (2007) indicated that the number of shallow seismic events with depth up to 25 km took place more often after the high power electric current injected into the upper lithosphere. Therefore, the current study focuses on very shallow earthquakes to detect any possible influence on the occurrence of shallow earthquakes by external sources.

For this study, the occurrence of earthquakes at different depths was examined for each region. Figure 1 represents the depth distribution of earthquakes at one of the selected regions. These regions are (1) west of USA–Canada region, (2) Gulf of Alaska region, (3) Kamchatka Peninsula region, (4) north of Japan region, (5) West of Peru–Chile region and (6) South Sandwich Islands region as shown in Figure 2.

The first step was to analyse the cumulative number of seismic events with magnitudes (M) = 2.5+ in the period from 1986 to 2020 in order to determine the dominant period of earthquake occurrence with respect to LT hours at each seismic region. In the second step, the LT distribution of earthquakes occurrence was compared with the geomagnetic diurnal variations recorded on quiet solar days at a geomagnetic observatory located in/or in the vicinity of the studied regions. The selected seismic regions will be discussed as follows.

4.1. West of USA–Canada region [Lat. 35–57 N and Long. 107–139 W]

The Pacific Ring of Fire, which is one of the most active tectonic areas all over the world, is characterised by subduction regions, spreading centres and transform faulting. On the eastern border of the Pacific Ring of Fire, the edge of western North America is located at the boundary between the North American and Pacific

![Figure 1](image_url)  
Figure 1. Distribution of earthquakes (M = 2.5+) occurred at West of USA–Canada region between 1986 and 2020 at depth between 0 and 40 km.
plates. As a part of the Pacific Rim, the high seismicity at this region is related to the presence of several active faults and fractures in the Earth’s crust (Fuis 1998).

The distribution of the cumulative number of earthquakes occurred at this region at depth up to 50 km and 5 km, as shown in the upper and lower panels of Figure 3, respectively, indicated an increase in the number of shallow earthquakes at noon LT compared with earthquake events occurred at night LT in this region. The increase in the seismic activity occurred between 11:00–16:00 LT with maximum peak at 13:00 LT. The maximum increase was about 30% on considering earthquakes with depth up to 50 km. On the other hand, the peak of the seismic events increased by about 80% at noon LT compared with the night LT for very shallow earthquakes with depth up to 5 km only. This significant observation emphasises that the influence of external factors is more clear in case of very shallow earthquakes than deep ones.

Figure 4 represents the cumulative number of shallow earthquakes (M = 2.5+ and depth up to 5 km) per hour origin time occurred at this region compared with the average geomagnetic diurnal variation of the North–South geomagnetic component (X-component) recorded at Sitka (SIT) geomagnetic observatory, USA [Lat. 57.06 N and Long. 135.33 W], during the quietest geomagnetic days of 2020. It is very clear from Figure 4 that there is a good correlation between the increase in earthquakes number at noon LT and the geomagnetic diurnal variations recorded at this region.

Figure 2. A map shows the location of the selected active seismic regions (R1-6).

Figure 3. Distribution of the cumulative number of earthquakes (M = 2.5+) occurred at west of USA–Canada region between 1986 and 2020 with respect to local hours of day. The upper panel shows earthquakes with depth up to 50 km while the lower panel shows earthquakes with depth up to 5 km.
4.2. Gulf of Alaska region [Lat. 54–64 N and Long. 144–165 W]

The Gulf of Alaska is an arm of the Pacific Ocean, and it is bounded by the Alaska Peninsula, Kodiak Island and Cape Spencer. The Gulf of Alaska is a seismically active region since the boundary between the Pacific and North American plates is located in this region. As a result, Alaska has several types of major faulting systems in addition to the subduction zone (Guptill et al. 1981).

Shallow earthquakes data with depth up to 10 km at this region was analysed to find out the distribution pattern of earthquakes occurrence during local hours. An increase in earthquakes number was also observed around noon LT (10:00–12:00 LT) as shown in Figure 5. There was about 20% increase in the earthquakes number at this period of time compared with night-time earthquakes. In addition, the geomagnetic data of the quietest geomagnetic days that recorded at Shumagin (SHU) geomagnetic observatory, USA [Lat. 55.35 N, Long. 160.46 W], during 2020 was analysed to get the average diurnal geomagnetic variation at this region. The average diurnal variation of X-component was compared with the distribution pattern of earthquakes. As we can see in Figure 5, a good correlation is observed between both of them around noon LT.

4.3. Kamchatka Peninsula region, Russia [Lat. 45–58 N and Long. 150–180 E]

The Kamchatka Peninsula is a peninsula in the Russian Far East. It is located at the northwest corner of the Pacific Ocean at the junction point of two large geological structures, the Aleutian and Kurile–Kamchatka Island. As a result, this region is characterised by the presence of two active seismic zones: the Kurile–Kamchatka subduction zone along the western
margin of the Kurile–Kamchatka Trench, and the Aleutian subduction zone along the northern margin of the Aleutian Trench (Zobin 1998). Figure 6 represents the LT distribution of shallow earthquakes that took place at this region between 1986 and 2020 at depth up to 25 km. Similar to the above-mentioned two seismic regions, an increase in earthquakes number was detected around noon LT at this region. The seismic events tend to occur more often at 14:00 LT with about 40% increase compared with seismic events occurred at night LT in the same region. The average geomagnetic diurnal variation of X-component was obtained by analysing geomagnetic data of the quietest geomagnetic days during 2020 from Paratunka (PET) geomagnetic observatory, Russia [Lat. 52.94 N and Long. 158.25 E]. A clear correlation was also observed between the increase in earthquakes occurrence and the daily geomagnetic variation around noon LT.

4.4. North of Japan region [Lat. 36–46 N and Long. 136–150 E]

Japan, an island country, lies on the east coast of Asia and is located on the boundary of four tectonic plates: the Pacific, North American, Eurasian and Philippines sea plates (Toda et al. 2008). With Japan’s location in the Pacific Rim as a convergent boundary with a subduction zone, Japan is considered as one of the most active seismic regions all over the world (Kagan et al. 2010). According to the Japan Meteorological Agency, one-tenth of global seismic events occur in and around Japan; around 2000 seismic events strike Japan every year. To examine the tendency of earthquakes occurrence with respect to LT at the origin, the number of shallow earthquakes (M = 2.5+ with depth up to 25 km) was calculated for each LT hour as represented in Figure 7. At this region, the earthquakes occur more often between 10:00–13:00 LT. The peak of earthquakes occurrence was at 11:00 LT with an increase of 40% compared with night-time occurrence of earthquakes. Concerning the relationship between the LT distribution of earthquakes and the diurnal geomagnetic field variation, the comparison between the distribution pattern and the average diurnal variation of X-component recorded during the quietest geomagnetic days of 2020 at Memambetsu (MMB) geomagnetic observatory, Japan [Lat. 43.91 N and Long. 144.19 E], showed a remarkable correlation between them as we can see in Figure 7.

4.5. West of Peru–Chile region [Lat. 10–55 S and Long. 66–80 W]

West South America is one of the fewest places where three major tectonic plates meet; the Nazca Plate, the South American Plate and the Antarctic Plate. The Nazca Plate is subducting under the South American Plate, and the Antarctic Plate is subducting under the South American Plate (DeMets et al. 1994). This complex tectonic setting makes West of Peru–Chile region suffer from high seismic activities with very powerful earthquakes (Prezzi and Silbergliet 2015). Figure 8 shows the diurnal seismicity of shallow earthquakes (M = 2.5+ with depth up to 10 km) recorded at this region. The results indicated about 30% increase in the earthquakes number at noon LT compared with nighttime seismic events. Examining the average X-component diurnal geomagnetic variation using data recorded during the quietest geomagnetic days of 2020 from Huancayo (HUA) geomagnetic observatory, Peru [Lat. 12.1 S and Long. 75.4 W], indicted a remarkable association between the increase in earthquakes number and the noon time variation of the geomagnetic field as shown in Figure 8.
South Sandwich Islands are a group of actively volcanic islets in the South Atlantic Ocean. They lie towards the eastern margin of the small Sandwich plate. South Sandwich Plate or Sandwich Plate is a minor tectonic plate bounded by the subducting South American Plate to the east, the Antarctic Plate to the south and the Scotia Plate to the west. The seismic activities occur at this region are mainly resulting from the subduction of the South American plate underneath the young Sandwich plate (Forsyth 1975).

Analysing the shallow earthquakes ($M = 2.5+$ with depth up to 45 km) occurred at this region showed that the LT distribution of earthquakes follows the same pattern observed at other studied regions (see Figure 9). About 30% increase in the earthquakes number at noon LT compared with night-time. The average diurnal variation of X-component recorded at King Edward Point (KEP) geomagnetic observatory, UK [Lat. 54.3 S and Long. 36.5 W], during the quietest geomagnetic days of 2020 showed a clear correlation with the increase in the earthquakes number as shown in Figure 9.

From the above-mentioned cases, the results reveal a LT dependence of earthquakes occurrence where earthquakes tend to occur more often during or around noon LT at the studied regions in correlation with the geomagnetic diurnal variations. This observation suggests a significant connection between both diurnal seismicity and geomagnetic variations.
5. Discussion

The high seismicity at the studied regions provided huge data sets to identify the local time dependence of earthquakes occurrence. To examine the LT dependence of earthquakes occurrence and investigate its possible connection with geomagnetic diurnal variations, only shallow earthquakes were analysed since the external factors for earthquakes triggering tend to influence mainly shallow earthquakes (Sasorova and Levin 2007). Results indicate that earthquakes tend to happen more often during or around noon LT at the studied seismic regions. This observation indicates the presence of a LT dependence of earthquakes occurrence in a way similar to the dependence of geomagnetic diurnal variation on LT. The correlation between the geomagnetic diurnal variations and LT distribution of earthquakes revealed a possible connection between both of them as shown in Figures 4–9.

Duma (1996; 1999) linked the regional geomagnetic variations with temporal changes of seismic activity where he detected a connection between the regular diurnal geomagnetic field variations and the seismicity. Furthermore, Duma and Ruzhin (2003) tried to estimate the force resulted from the interaction between the induced lithospheric currents and the geomagnetic field to examine its probable effect on the crustal stress field and on seismic activities. In order to connect the solar impact (geomagnetic diurnal variations) with the LT distribution of earthquakes, the electromechanical principle can be considered as one of the possible physical mechanisms. According to the electromechanical principle, the circular electric currents that flow through the conductive lithosphere in the presence of a magnetic field will generate mechanical forces and torques (Lorentz force) into underground of subduction zone that generate conspicuous stress (Duma 2005), which is more or less uniformly distributed all over the Earth’s crust. By this, they do contribute also to the sum of crustal stress that – eventually and in suitable environmental circumstances – can trigger seismic activity.

Mazzarella and Palumbo (1988) have proposed another source of the additional mechanical stress that can be added to the crustal stress. They analysed the seismic and magnetic data recoded in Italy and found that the geomagnetic diurnal variations may induce additional mechanical stress on the stressed crustal rocks by magnetostriction processes, which can change the shape and dimensions of ferromagnetic materials such as iron and nickel when they remained in a magnetic field.

Based on the above-mentioned observations and results, the current study suggests a link between the earthquakes occurrence and the geomagnetic diurnal variations. It is expected that the dominant period of earthquakes may differ from region to another depending on several parameters such as the depth of the earthquakes hypocentre, type and orientation of the fault plane with respect to the direction of the induced lithospheric currents, and the underground conductivity at the fault zone which is an important factor in controlling the electromechanical effect along with the intensity of the geomagnetic diurnal variations. Therefore, we need to accumulate more earthquakes data in future from other regions to determine the dominant period at each region, which could provide more support in discovering more basic rules of earthquakes predication.

Figure 9. Distribution of the cumulative number of earthquakes (M = 2.5+ and depth up to 45 km) occurred at South Sandwich Islands region between 1986 and 2020 with respect to local hours of day. The sold curve represents the average diurnal geomagnetic variations of the X-geomagnetic component recorded at King Edward Point (KEP) geomagnetic observatory.
6. Conclusion

To detect the pattern of earthquakes distribution during local hours of the day (diurnal seismicity) and its possible relationship with the geomagnetic diurnal variations, shallow earthquakes ($M = 2.5+$) data along with geomagnetic data were analysed. Examining the LT dependence of earthquakes occurrence at some selected active seismic regions revealed that the dominant period of earthquakes occurrence is mainly between 10:00 and 14:00 LT. This means that earthquakes tend to occur more often during or around noon LT. This indicates that the extracted dominant period of examined shallow earthquakes is possibly linked with an external factor. The comparison between the LT distribution of earthquakes and the diurnal variation of the geomagnetic field showed a high correlation between both of them as shown in Figures 4–9. Therefore, it is possible to link diurnal seismicity with geomagnetic diurnal variation.

The increase in earthquakes number during the noon LT can be interpreted as a result of the interaction between the induced currents in the Earth’s crust and the regional geomagnetic field. This interaction generates additional stress (The Lorentz force), which added to the tectonic stress and may affect the state of metastable faults and provide enough energy for earthquakes triggering.

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No potential conflict of interest was reported by the author(s).

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