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Diurnal changes of earthquake activity and geomagnetic Sq-variations

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Abstract. Statistic analyses demonstrate that the probability of earthquake occurrence in many earthquake regions strongly depends on the time of day, that is on Local Time (e.g. Conrad, 1909, 1932; Shimshoni, 1971; Duma, 1997; Duma and Vilardo, 1998). This also applies to strong earthquake activity. Moreover, recent observations reveal an involvement of the regular diurnal variations of the Earth's magnetic field, commonly known as Sq-variations, in this geodynamic process of changing earthquake activity with the time of day (Duma, 1996, 1999).

In the article it is attempted to quantify the forces which result from the interaction between the induced Sq-variation currents in the Earth's lithosphere and the regional Earth's magnetic field, in order to assess the influence on the tectonic stress field and on seismic activity. A reliable model is obtained, which indicates a high energy involved in this process.

The effect of Sq-induction is compared with the results of the large scale electromagnetic experiment "Khibiny" (Velikhov, 1989), where a giant artificial current loop was activated in the Barents Sea.

1 Introduction

Studies dealing with changes of the regional geomagnetic field associated with strong earthquakes began intensively in the 1950s. The "tectonomagnetic" effects (Nagata, 1969) have been subject of many theoretical and laboratory investigations (e.g. Kean et al., 1976) since they were expected to open a way to a future earthquake prediction (Rikitake, 1982; Wyss, 1991). Several observations have been convincingly interpreted as a result of changing magnetic rock properties under varying tectonic stress (Nagata, 1976). However, these observations of magnetic anomalies prior to strong earthquake were obtained only in the very vicinity of the rupture zone in each case and the anomalies amounted to a few tens of nT at best.

A six year research programme performed at the Central Institute for Meteorology and Geodynamics (ZAMG), Vienna, has revealed a process of seismic and geomagnetic interaction which differs significantly from the "tectonomagnetic" effects described in many publications so far. Analyses of temporal changes of earthquake activity in many seismic zones around the globe and of geomagnetic variations in two time domains have been carried out: in the diurnal range and in the long term. Only a few typical results can be presented here to illustrate the process, which links the two quantities in a very remarkable way.

2 Analysed seismic zones

Figures 1, 2 and 3 show several of the earthquake zones for which earthquake frequency studies have been performed as well as the geomagnetic observatories, the data of which have been used in the analyses. The regions differ considerably in size and do not delineate specific seismic source regions. Likewise, the observatory sites are situated differently with respect to the seismic regions, in some cases hundreds of km outside.

3 The ionosperic Sq current system

The diurnal magnetic variations, commonly known as Sq variations or "magnetic quiet-day solar daily variations" (Chapman and Bartels, 1940) are generated in the Earth's ionosphere, mainly by solar radiation and tidal forces, which act on the neutral and ionized particles at heights between 70 km and 120 km. Corresponding to the solar position, an electric current system is generated which covers about 1/3 of the northern Earth's hemisphere, corresponding to approximately 08:00 LT (Local Time) in geographic longitude (Fig. 4). The current vortex in the Southern Hemisphere exhibits a current flow in the opposite direction. The day-side

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Fig. 1. Selected seismic regions in Europe and geomagnetic observatories (Wien-Cobenzl WIK, L'Aquila AQU, Kandilli ISK).

Fig. 2. Selected seismic regions in eastern Asia and geomagnetic observatories (Sheshan SSH, Kakioka KAK).

ionospheric currents are of considerable size up to many ten thousands of Amperes close to the centers. The night-side current systems ("regeneration currents") are smaller in amplitude, but extend over a larger area.

The geomagnetic variations resulting from these dynamo systems are safely observed at each magnetic observatory, day by day, with amplitudes of ± some tens of nT maximum in the magnetic components D, H, Z. The shape and amplitude of these diurnal Sq-variations depend strongly on the geographic latitude of the observatory site.

The intensities vary with Local Time in a prevailing cycle period of 24 h. Other parts of the variation, such as the lunar

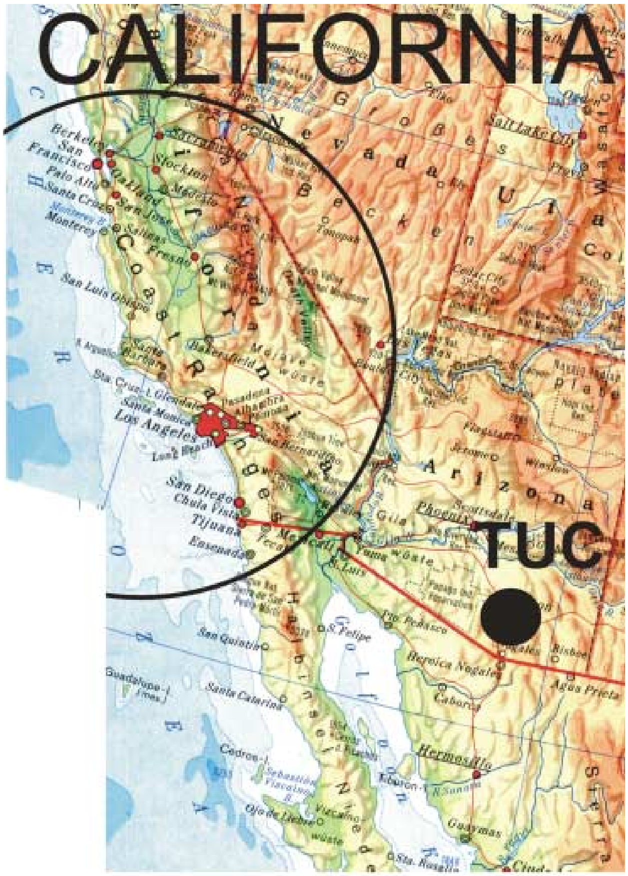

Fig. 3. Seismic region California and geomagnetic observatory (Tucson TUC).

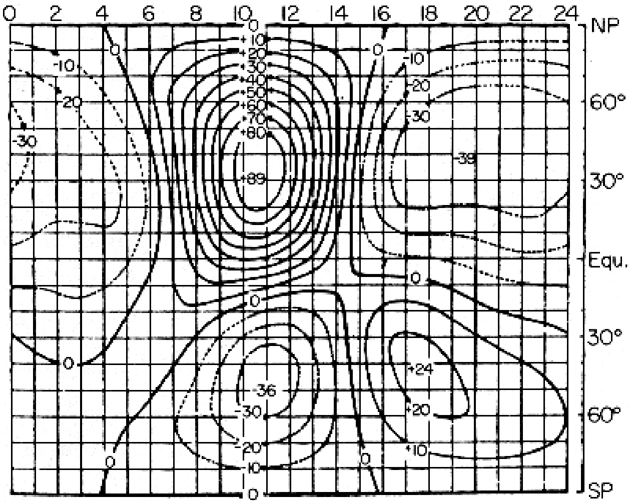

Fig. 4. Ionospheric current system (Chapman and Bartels, 1940) which causes "the magnetic quiet-day solar daily variation"; currents in 10^3 Amperes.

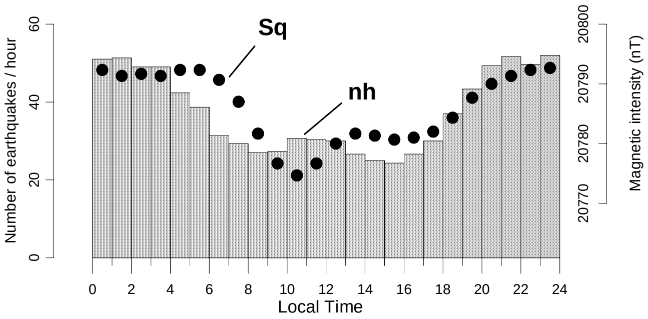

Fig. 5. Region Austria (AUS): Number of earthquakes per hour origin time (nh), period 1901–1990, versus a mean magnetic Sq variation (1986) of the horizontal intensity H, measured at the geomagnetic observatory Wien-Cobenzl (WIK, Austria, geogr. lat. 48° N); earthquake magnitude range $2.5 \leq M \leq 5.0$, 938 events.

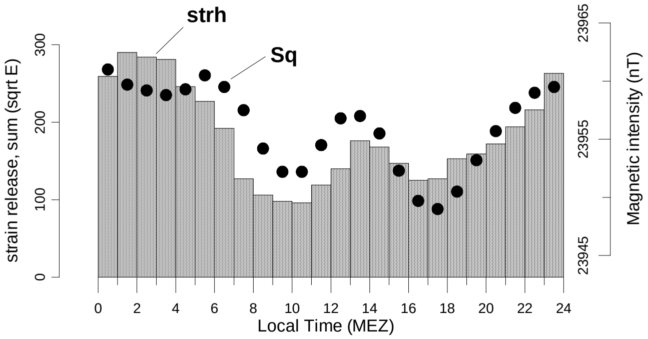

Fig. 6. Region Mt. Vesuvius, Italy (VES): Strain release of earthquakes per hour origin time (strh), period 1972–1996, versus a mean magnetic Sq variation (1986) of the horizontal intensity H, measured at the geomagnetic observatory L'Aquila (AQU, Italy, geogr. lat. 42° N); earthquake magnitude range $1.8 \leq M \leq 3.4$, 1402 events; the region is about 10 km times 10 km surrounding the volcano (Duma and Vilardo, 1997).

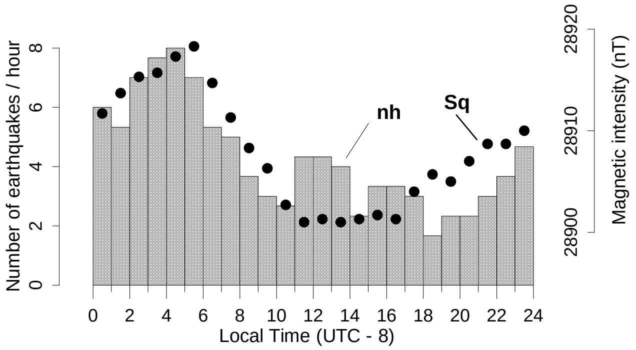

Fig. 7. Region California: Number of earthquakes per hour origin time (nh), period 1800–1990, versus a mean magnetic Sq variation (1920) of the horizontal intensity H, measured at the geomagnetic observatory Tucson (TUC, USA, geogr. lat. 32° N); earthquake magnitude range $M \geq 6.0$; 103 events; circular region $r = 400$ km, center 35° N, 120° W.

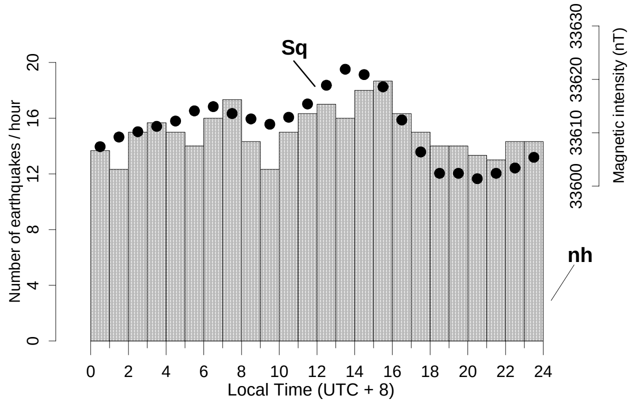

Fig. 8. Region E-China: Number of earthquakes per hour origin time (nh), period 1900–1992, versus a mean magnetic Sq variation (1979) of the horizontal intensity H, measured at the geomagnetic observatory Sheshan (SSH, China, geogr. lat. 31° N); earthquake magnitude range $M \geq 6.0$, 361 events; region 20–40° N, 100–130° E.

component, or induction effects resulting from special conductivity conditions in the Earth's crust or upper mantle are not considered here, as they are of minor relevance for this study.

4 Observational results

In Fig. 5 the earthquake frequency distribution with respect to the hour (LT) of origin time is shown, based on an observation period of 90 years (1901–1990) in Austria. The distribution is compared with an average geomagnetic Sq-variation in the horizontal component H of the Earth's magnetic field, a mean variation 1983–1985, at the Austrian magnetic observatory Wien-Cobenzl. A second example of diurnal changes of earthquake activity and magnetic variation is given in Fig. 6. There, 1400 seismic events in a small area of about 10×10 km around the volcano Mt. Vesuvius, Italy, recorded in the period from 1972 to 1996, have been analysed with respect to their origin time. An average Sq-variation (1986) measured at the geomagnetic observatory L'Aquila is displayed again and a very similar result as in Austria (Fig. 5) is obtained (Duma and Vilardo, 1998).

Observations in many other regions reveal distributions of the same type. Moreover, this applies also to strong earthquake activity. Figures 7 and 8 indicate a correlation of Sq variations and seismic activity for earthquakes $M \geq 6$ in the regions CALIFORNIA and E-CHINA, too. A pecularity in the case of E-China is that Sq exhibits a different variation compared to that observed at TUC (USA), obviously because of the observatory position of SSH (China) in the southern part of the ionospheric current system. But again, the earthquake activity distribution follows the Sq variation.

Thus, the observations give a first rise to the idea of a general relation between time dependent earthquake activity and the regional Sq variations.

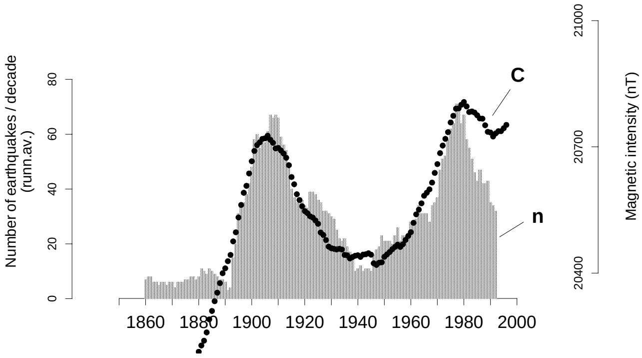

Fig. 9. Region Austria (AUS): Number of earthquakes per decade (n, 10 year runn. av.), versus the horizontal component C of the geomagnetic field, measured at the geomagnetic observatory Wien-Cobenzl (WIK, Austria); C denotes the magnetic horizontal intensity H in this case; earthquake magnitude range $3.1 \leq M \leq 5.0$ (Io $\geq 5°$ EMS-98), 380 events.

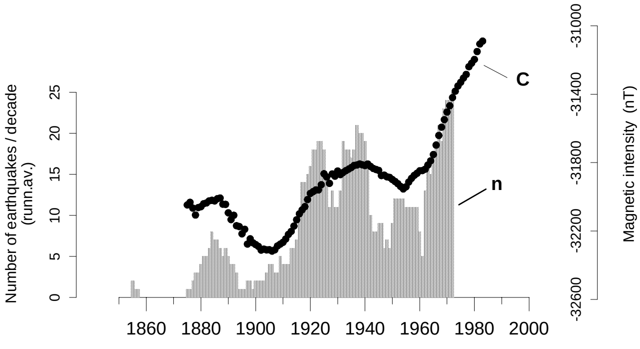

Fig. 10. Region E-China: Number of earthquakes per decade (n, 10 year runn. av.), versus the horizontal component C of the geomagnetic field, measured at the geomagnetic observatory Sheshan (SSH, China); C denotes the magnetic intensity in N-direction (neg. sign) in this case; earthquake magnitude range $M \geq 6.0$, 116 events, region 20–40° N, 100–120° E.

5 Variations of the Earth's magnetic field and earthquake activity in the long term

Another astonishing observation was obtained at the ZAMG in 1996 when comparing the two quantities, earthquake activity and regional geomagnetic intensity, in the long term. A first example is presented in Fig. 9, showing the number of earthquakes per decade in Austria versus the temporal variation of the horizontal magnetic component H in the 20th century. Figures 10 and 11 illustrate the correlation with respect to strong earthquake activity ($M \geq 6$) in the regions E-CHINA and TOKYO.

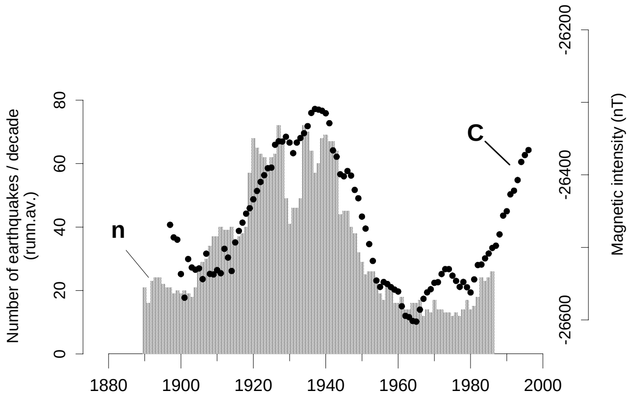

Fig. 11. Region Tokyo: Number of earthquakes per decade (n, 10 year runn. av.), versus the horizontal component C of the geomagnetic field, measured at the geomagnetic observatory Kakioka (KAK, Japan, Tokio); C denotes the magnetic intensity in N22E-direction (negative sign) in this case; earthquake magnitude range $M \geq 6.0$, 347 events, circular region $r = 300$ km (around Tokyo), center 35° N, 140° E.

6 Interpretation

6.1 The model

The observations differ substantially from the tectonomagnetic effects by three reasons:

The described effect does not refer to a single strong earthquake but to the seismic activity in a region. Secondly, the long term changes of magnetic intensity exhibit amplitudes of 100 s of nT within a few decades, thus exeeding the reported magnetic anomalies due to changing magnetization of rock (piezomagnetic effect) by far. Thirdly, the main difference to earlier observed effects is, that the magnetic Sq variations as well as the "magnetic secular variations" (in the long term) undoubtedly have their origins outside the seismogenic zones, i.e. in the ionosphere and in the deep Earth's interior, respectively.

Therefore, the effect described above indicates that the magnetic variations are obviously not a consequence of earthquake activity and of changing stress conditions in the Earth's lithosphere, but they are involved in a process, which significantly influences or even controls seismic activity. In terms of the cause-effect relation, the magnetic variations are on the cause side.

This may also be concluded from another observation: the magnetic variation of Sq type and the secular variation are worldwide phenomena and they cover all aseismic regions in the world, too.

However, serious doubts and questions concerning the effect may remain: How can magnetic variations of small amplitudes – compared to technical magnetic fields – play any role with respect to earthquake activity, a process which involves huge energy rates?

A variety of geophysical effects have been considered in the past years as possible candidates to explain and fit the

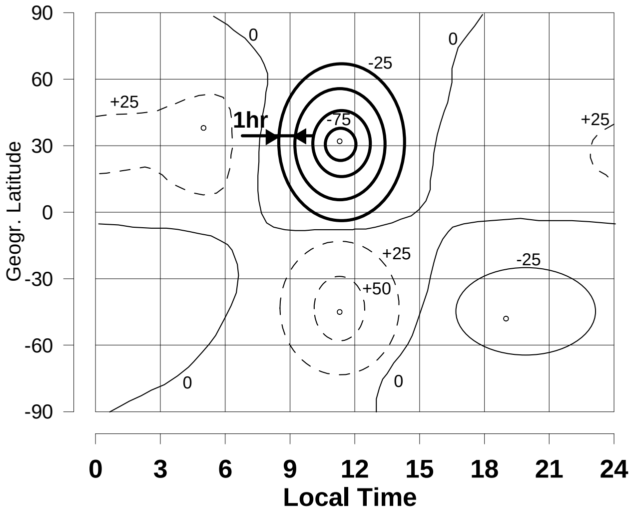

Fig. 12. Schematic sketch of the average induced Sq current system in the Earth's interior after S. Matsushita (1968). Currents are given in 10^3 Amperes. The main day-side current system is splitted into rings of 1 h LT width (15° geogr. longitude) and the contribution of each ring to the total magnetic moment of the current vortex is computed.

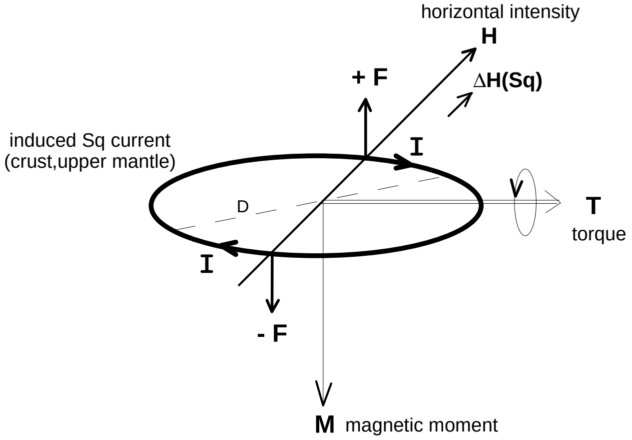

Fig. 13. The magnetic moment, generated by the induced Sq current system, interacts with the horizontal intensity H of the main Earth's magnetic field. A torque results from this process, which acts on the current sheet, i.e. on the lithosphere. The measured magnetic Sq variation is proportional to current I, thus it reflects the changes of torque T with the time of day, as the current vortex moves westwards.

observations, starting from the piezomagnetic effect, evaluating forces acting on remanently magnetized rock, on highly conductive suture zones in an external magnetic field due to the telluric currents (Lorentz forces), and many others. In none of the cases all the observations could be interpreted satisfactorily, nor were the energy conditions met to influence seismic activity.

Finally, an evaluation of the Sq induction process in the Earth's lithosphere and its possible geodynamic impact led to a geophysical model, which seems well suited for a far-reaching interpretation of the observations. This model is introduced in the following.

Figure 12 is a simplified presentation of the induced Sq current system in the Earth's interior (Matsushita, 1968), a yearly average. It is very similar to the external current vortex in the ionosphere and the currents reach values up to many tens of thousand Amperes in the central area of the vortex system.

According to the basic electrodynamic principles, circular electric currents generate a magnetic moment M

$$M = \mu_0 \cdot I \cdot (D^2 \cdot \pi/4) \qquad (1)$$

with

$$\mu_0 = 4 \cdot \pi \cdot 10^{-7}\ \mathrm{Vs/Am} \qquad (2)$$

M ... magnetic moment, Am^2
μ_0 ... permeability of free space
I ... electric current, A
D ... diameter of enclosed area, m.

The vector of M is orientated at right angles to the horizontal plane of the ring current. This magnetic moment could also be considered as the equivalent for a magnetic stick positioned perpendicular to the Earth's surface.

On the other hand, this current system with vertical magnetic moment M is exposed to the main Earth's magnetic field, which is of internal origin. In particular, the horizontal component H of the main field is of interest in this regard, because it is directed at an angle of 90° to the magnetic moment vector $\boldsymbol{M}$. Figure 13 illustrates this electromagnetic model.

Thus, a torque acts on the conductive layer in which the ring currents flow. This torque T is given by the vector product

$$\boldsymbol{T} = \boldsymbol{M} \times \boldsymbol{H} \qquad (3)$$

$\boldsymbol{T}$ ... torque, Joule or VAs
$\boldsymbol{H}$ ... geomagnetic horizontal intensity, A/m.

From Eqs. (1) and (3) it becomes evident that the torque and the resulting forces are the product of I and H, and this relation may be considered a key to the interpretation of the observational results of magnetic variations and seismic activity in the diurnal range as well as in the long term: the regional slow changes in H (in the course of years or decades, i.e. the "magnetic secular variation") cause an increase or decrease of torque T, thus possibly explaining the long term influence on seismic activity. On the other hand, the diurnal magnetic variation of H (Sq variation), observed at any observatory site in the Northern Hemisphere, is proportional to I. That is, the observed Sq variation reflects the changes of I with the time of day (LT) in the region, and therefore the changes of the torque, accordingly.

Table 1. Contribution of each current ring to the total magnetic moment of the current vortex (Fig. 12) and torques, generated by an average horizontal intensity of 30 000 nT of the Earth's magnetic field. The results reveal that even in a smaller circular area surrounding the center of the current system (which is at 32° geogr. latitude) considerable torques are generated, equivalent to the energy of a $M4.7$ or $M5.5$ earthquake (bold values)

Ring radius to vortex center (km)	Current (10^3 Amp)	Magnetic moment (10^{11} Am^2)	Torque (10^{12} Joule)	Equivalent magnitude (lgE = 4.8 + 1.5M)
3217	−15.9	6.5	19.4	5.7
2242	−36.5	7.2	21.7	5.7
1267	−53.0	3.4	10.1	**5.5**
292	−62.2	0.2	0.6	**4.7**
	total current system	17.3	51.9	5.9

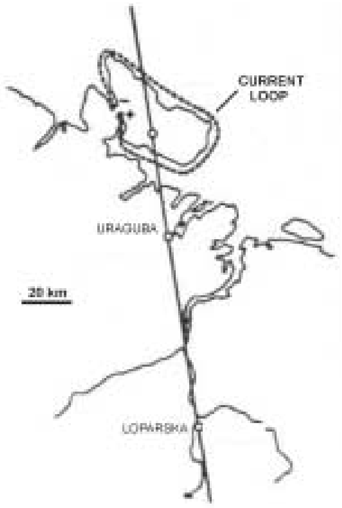

Fig. 14. Current loop arrangement and the profile for magnetic measurements of the "KHIBINY-Experiments", performed at the coast of the Barents Sea in the period 1976 to 1987 (Velikhov, 1989).

6.2 Quantification of involved energy

In order to determine the size of the torque T it seemed appropriate to split the main day-side current vortex into rings of equal width, namely of 15° in geographic longitude, i.e. 1 h of solar movement.

According to Eq. (1) the contribution of each current ring to the total magnetic moment of the vortex can be computed. The results are listed in Table 1.

The total magnetic moment of the current vortex, which covers an area of 3200 km radius, amounts to about $17 \cdot 10^{11}$ Am^2, which results in a torque energy equivalent to a $M5.9$ earthquake. But even more surprising is the result obtained for the smaller circular currents, i.e. for smaller areas at medium geographic latitudes. The energy provided to a region of 500 km to 1500 km radius is still big, amounting to a $M5.0$ to $M5.6$ event. And close to the vortex center, a torque equivalent to $M4.7$ is acting on an area of about 300 km radius only, due to the strong currents. A horizontal intensity H of 30 A/m (30 000 nT) was assumed in the computations.

In order to evaluate these energy rates with respect to their possible impact on the seismicity of a region, the following consideration on mean recurrence periods of eartquakes may be helpful:

In Austria for instance, which encloses an area of about 600 km times 300 km (geographic latitude ∼ 46° N–49° N), the mean return period of an $M4$ earthquake (Intensity 6° MSK-98) is about 2 years. That is, on average such a period is required to accumulate the necessary deformation energy for an event of this size in the area considered. Comparing this loading rate with the temporarily generated torque energy due to the induction process indicated above, which is of similar order of magnitude and which acts on that area day by day, a triggering effect may not be excluded. This may be even more true for seismic regions at lower geographic latitudes, e.g. between 20° N to 40° N, closer to the current vortex center.

A quantitative analysis of the effect in Austria indicates an average increase of seismic activity of 1.3 events ($M3.0$) in 10 years associated with an increase of 10 nT in magnetic intensity. In the diurnal range, there occur 1.7 events ($M2.5$) more in a hour in which the Sq variation is 10 nT higher on average, in an observation period of 10 years.

7 Experiments with large scale current loops ("Khibiny-Experiments")

Experiments with giant current loops have been conducted on the Kola Peninsula, Barents Sea, near Murmansk in the time 1976 to 1987. The experiments were aimed at the investigation of the deep geoelectrical structure of the Kola Peninsula by applying a powerful electromagnetic excitation, i.e. a pulse MHD generator (Velikhov, 1989; Oraevsky, et al., 1992). In Figure 14 a geographic sketch of the current loop and the magnetic profile for magnetic measurements is given.

The current was led into the sea water at the two sides of a land bridge to the small Ribachiy peninsula, which is 50 km in diameter. Thus, a circular current flow developed along the peninsola coast with an intensity of about 20 kA.

With this experiment arrangement, a magnetic moment of about 10^{14} Am^2 was produced, which is by factor 10^2 or 10^3 stronger than the moment of the induced Sq current vortex, but it is constrained to a small area only. Nevertheless, similar experiments are planned in the near future, to study a possible impact on tectonic and seismic conditions in the Earth's crust, based on the previously presented results on electromagnetic and seismic interactions.

8 Conclusions

Numerous observational results acquired in the past 6 years indicate an intense interaction between the Sq variations and changing earthquake activity in the diurnal range. The same applies to the regional magnetic secular variations and seismic activity in the long term. The effect appears in many of the main earthquake zones of the world. In particular, by providing a geophysical model which fits the variety of observations qualitatively and which includes a surprisingly high amount of energy transferred to the lithosphere, the thesis of a significant and general triggering mechanism due to the induced magnetic moment and the resulting torque gains much credibility. A detailed study on the additional stresses that are generated by this electromagnetic process and which overlay the specific regional stress field has not been performed yet.

Obviously, the described mechanism also applies to strong earthquake activity, thus being of importance for seismic risk considerations.

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