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Direction of recent maximal stress and epicenter map of tectonic earthquakes (maps 5 and 6)

Results of IGCP project 346

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1. Introduction

Recent crustal stress and seismicity data can provide valueable information about neotectonic processes within relatively stable continental blocks. For the study area of the IGCP-project "Neogeodynamica Baltica" the maps no. 5 and no. 6 present the state of the art of data compilation of both the direction of maximal horizontal compressive stress S_{Hmax} and the epicenters of earthquakes.

For the stress compilation the well known data base of the World Stress Map (WSM) project, a reinterpretation of the Fennoscandian stress field and a remarkable increase of stress data near and east of the Tornquist-Teisseyre Zone (TTZ) could be used. At first time this data set allows a comparable interpretation of the stress regime of the East European platform with the stress field of western Europe and Fennoscandia.

A homogeneous data set of seismicity is provided basing on earthquake data compiled in the last version of national earthquake catalogues for the study area. The data were collected and made homogeneous in the frame of the Global Seismic Hazard Assessment Program (GSHAP), the IDNDR demonstration project of the International Lithosphere Program ILP. The presented epicentre map seems to be one of the first where detailed data for Fennoscandia, for central Europe, and the scarce data for eastern Europe are combined.

2. Crustal stress data

The only stress parameter which is available with sufficient reliability and quantity is the direction of maximum horizontal stress S_{Hmax}. This parameter is exclusively dealt with for map no. 5. The compiled stress data are based on fault plane solution of earthquakes, in-situ stress measurements in boreholes and mines, geologic fault slip determinations and repeated precise geodetic triangulations as recommended by the WSM project (Zoback & Burke 1993). The methods and constraints of azimut determination of S_{Hmax} have been summerized by Zoback (1992) for the different techniques mentioned.

The presented data for the study area comprise the WSM-data base subset and the new stress indications discussed by Grünthal & Stromeyer (1994). Beyond that the data set for eastern Europe could be extended remarkably. For NE germany high quality breakout and hydrofrac data were recently presented by Palmer & Groß (1999). The breakout interpretations of Jarosinski (1994) for boreholes of the hydrocarbons industries fill a former gap in SE Poland and in the southern Baltic Sea. No stress data were available before the Geogeodynamica Baltica project for the Baltic countries (except one fault plane solution from the Ossmussaer earthquake 1976), NE Poland, Belorussia, and most western part of Russia. This figure could be changed completely by neotectonic stress indications which were derived from Sim et al. (1995) by analysis of secondary disturbances and geological-geomorphological features along recent faults. In a critical review of stress data for Fennoscandia Muir Wood (1993) referred to serious problems connected with fault plane parameters of mostly small earthquakes. Therefore, this map includes only those stress data of Fennoscandia which were recommended to be well-constrained.

To interpret the compiled stress data we have to distinguish between two primary categories of stresses in the upper, elastic part of the Earth's lithosphere. The first, usually called 'tectonic' stress is strongly related to broad-scale forces including plate boundary forces, large-scale flexure of the lithosphere owing to surface and subsurface loads, inhomogeneous density distributions, and thermoelastic forces in cooling oceanic lithosphere. The second category, the local or 'induced' stress, is connected with local effects of topography, anisotropy of strength or elastic properties, effects of erosion and man-made excavation (Zoback, 1992). In the study area there are indications for both, tectonic and induced stresses. The first order or large-scale behaviour of the direction of S_{Hmax} indicates NW-SE trending stress directions in western central Europe and most parts of Fennoscandia. This homogeneous stress field is coincident with a thin to medium lithosphere thickness (50-90 km). Finite element modellings provide clear constraints that Mid-Atlantic seafloor spreading and the northward directed motion of the African plate are compatible with this broad-scale observed stress field (Grünthal & Stromeyer 1992). Therefore, the observed data of this part of the Eurasian plate should mainly be controlled by forces that drive plate motion.

The second order S_{Hmax}-direction in Fennoscandia is not as consistent as in western Europe. Following smaller scaled areas of more or less similar directions can be found: dominating S_{Hmax}-direction NW-SE: offshore of central Norway, Denmark, SE-Norway, in the south of central Sweden as well as Finland; S_{Hmax}-directed N-S: S-Sweden; S_{Hmax}-directed E-W: central Sweden. Generally, one can conclude that the scatter is remarkable. A combination of plate boundary forces at the Mid-Atlantic ridge with flexual stresses from glacial rebound are the mostly discussed sources for the Fennoscandian stress province (Bungum & Lindholm 1996). Possible causes for the scattered tectonic stresses in Fennoscandia could reflect: (1) the shift of the Mid-Atlantic Ridge spreading axis at about 70°N by the Jan Mayen fracture zone, which may indicate an influence of lateral variation of plate boundary forces; (2) a local radial ridge push component due to the Iceland hot spot; and (3) the physical properties of the 110-170 km thick Fennoscandian lithosphere. It contributes to a reduction of the mean stress level of the lithosphere. This might cause local effects on the stress field due to the lateral density or strength inhomogeneities in the crust (Müller et al. 1992, Muir Wood 1993).

The compressional stress regime on the East European Platform (EEP) seem to be significantly different from that in western central Europe and Fennoscandia. The broad-scale S_{Hmax}-orientation rotates to N-S when approaching to TTZ and is stable NE-SW in the southeast of the study area. Generally, stress data on the EEP are obviously subject of stronger fluctuations. This might be the result of the smaller stress magnitudes and/or due to the poor quality of stress information in that part of the study area in comparison with western central Europe. A possible interpretation of the generalized stress regime of the EEP could be a large scale transformation of northward directed push of the Arabian and Indian plate towards to the EEP, while the influence of the Mid-Atlantic spreading decreases.

The stress data for S-Karelia show obviously the same general NW-SE pattern as that in Finland derived from in situ measurements and fault plane solutions. Ridge push can be assumed as the predominat sources for this stress pattern (Bungum & Lindholm 1996).

No uniform stress pattern can be found for the area of the Baltic countries, the region of Kaliningrad and NE Poland. Most stress indications were derived from geological evidences and assessed as quality D. In the north the available data infer an E-W directed compression according to one fault plane solution, while the N-S orientated breakout of quality B dominates the border region of Poland and Lithuania. This Baltic region could be regarded as a transition zone between the stress province of the EEP and the Fennoscandian stress province. It seems to be influenced mainly by the regional effects as they were already discussed for Fennoscandia.

3. Seismicity data

One of the intentions of the IGCP-Project 346 "Neogeodynamica Baltica" is to compare the neotectonic features with the earthquake epicentres in order to derive conclusions which of the neogeodynamic processes have their expression in the occurrence of earthquake phenomena. All known earthquake epicentres have been compiled for this task and made homogeneous especially at the state boundaries. This procedure is described in Grünthal et al. (1999) as a part of the Global Seismic Hazard Assessment Program (GSHAP), the initiative of the ILP (International Lithosphere Program) to the IDNDR (International Decade for Natural Disaster Reduction).

The following, mostly national catalogues or data-files were elaborated to create a joint and homogeneous seismicity-file for the study area of Neogeodynamica Baltica: Austria (Lenhardt 1994) Belorussia and Pribaltica (Boborikin et al. 1993), Belgium and Luxembourg (Verbeiren et al. 1994), Czech Republic (Schenková 1989), Estonia (Nikonov 1991; Nikonov & Sildvee 1992), Fennoscandia (Ahjos & Uski 1992), France (part of the SIRENE data-file, Lambert & Levret 1996), Germany (Leydecker 1986, Grünthal 1988), Hungary and adjacent territories (Zsiros et al. 1991), The Netherlands (Houtgast 1990), Poland (Pagaczewski, 1972 - added by data elaborated by Guterch 1995 as well as own studies), and data of the earthquake catalogue of the former Soviet Union (Kondorskaya & Shebalin 1977).

The earthquake strength parameter depicted in the map no. 6 is the local magnitude ML with values equal or greater 2.5. Most of the catalogues contained several non-instrumental data (i. e. historical earthquakes) given by their intensity (macroseismically felt effects). These data were transformed into ML in the frame of the above mentioned GSHAP activities. It proved to be necessary to elaborate separate empirical relations for each catalogue to convert the epicentral intensity, the felt area and, if available, the focal depth into ML. The seismicity data for the Baltic Republics, for Belorussia and the Ukraine are too scarce to get a reliable separate empirical conversion relation. Because of similarities in the crustal structure and seismicity pattern with those in Finland the relations used there were applied to the large region south of Finland in cases where the original catalogues include solely the intensity as earthquake strength parameter.

For studying the seismicity pattern with respect to tectonic features it is essential to consider different aspects of the data quality. First of all, the localization accuracy of earthquakes has to be taken into account for a detailed analyses. A sufficient high precision of the localization can be guaranteed for these events recorded by dense seismic networks. Large localization errors are frequently typical for historical events. Therefore, the intention of this contribution can solely be to discuss the appearance of seismicity in an areal extent.

The knowledge of the temporal completeness of data is essential for any further conclusion. It is obvious that the temporal completeness shows large differences in the study area. While southwestern parts show rather long lasting data completeness back into history, the data are less complete when approaching to the east (Grünthal et al. 1999). The clusters of events in the southwestern part of the study area belong to the well known areas of increased seismic activity of the Upper Rhine graben, the middle Rhine zone and the Lower Rhine embayment (Ahorner 1975), the Hohenzollerngraben (Schneider 1980, 1992) and to the saxothuringian seismotectonic province with the prominent swarm quake region of

the Vogtland. The seismotectonics of this region is described by GRÜNTHAL et al. (1990).
Another concentration of seismic activity is connected with the northern rim of the Carpathians as well as with the northern border of the Bohemian massif (border region of Czech Republic and Poland). The seismotectonic provinces of the eastern part of the West European Platform were derived and at least tentatively connected with tectonic elements by GRÜNTHAL et al. (1985).
The seismicity of the Lower Rhine embayment is in most cases connected with normal faulting, while the seismic activity of the Upper Rhine, of the Hohenzollerngraben and of the Vogtland is the result of dominant strike slip movements, the latter two along nearly N-S directed faults, which are at the surface of secondary order. The first order, mostly NW-SE directed faults, are obviously aseismic. But in seismically active regions they can obviously provide zones of weakness. In general, they are not the localizations of the earthquake hypocentres itself. For the other regions mentioned above, there are not so clear constraints and the seismotectonic interpretations can be tentative only.
The seismicity of Fennoscandia (as it is part of the study area) concentrates mainly in three areas: (1) at the coast of western Norway, (2) in a region between the Oslo-graben, the lake Vänern and the lake Vättern as well as (3) at the Swedish coast of the Gulf of Bothnia. The remaining parts of Norway, Sweden, Finland and northern Denmark, including the Skagerak, show a certain level of background activity except the Baltic Sea, where the seismicity is almost lacking. This cannot simply be explained by missing recordings due to sparse instrumention or lacking macroseismic observations (WAHLSTRÖM & GRÜNTHAL 1994).
The origin of Fennoscandian earthquakes is obviously due to both, plate tectonic ridge push and isostatic postglacial rebound. According to MUIR WOOD (1993) the isostasy due to the latest era of glaciation-deglaciation should practically be the only contribution to the seismicity. But his conclusions are controversial and were the matter of several criticism (e.g. WAHLSTRÖM 1993). EKMAN (1985) as well as SKORDAS & KULHANEK (1992) conclude, by using different arguments, that the seismicity in northern Fennoscandia is predominantly the result of the uplift while the plate tectonic ridge push, mainly generated from the North Atlantic, generates the seismicity of southern Fennoscandia. ANDERSON (1980) explained the increased seismic activity along the Swedish coastline of the Gulf of Bothnia as a result of differential strain built up along the coastline due to long-term isostasy.
The origin of the seismicity of Estonia and Latvia can probably be compared with that of Finland. Lithuania, Belorussia, Russia and the parts of Poland and of the Ukraine east of the TTZ, are, at least according to the available data sources, almost free of any seismicity. Another point which has to taken into account for such a conclusion is the fact that the data-file for this region has a rather limited extent into history only.
One fact has clearly to be stressed that one of the most prominent tectonic feature in the centre of the study area, the Tornquist-Teisseyre Zone, is not manifested by seismic activity. If the NW prolongation of the TTZ, the Tornquist-Sorgenfrei Zone, is correlated with the seismic activity in Skåne, northern Sjaelland and nearby Kattegat, is not obvious.
According to A. A. NIKONOV (pers. communication 1995) the aseismic nature of some of the events in Belorussia cannot be excluded. Some of the events could in reality be non-tectonic earthquake-like phenomena associated with exhaustion processes of salt-dome tops.

Summary

An up to date compilation and interpretation of the maximal horizontal compressive crustal stress (map no. 5) and the epicentres of earthquakes (map no 6) are given for the study area of the IGCP-project "Neogeodynamica Baltica". At first time new stress data of the East European Platform are presented in comparision with the stress field of western Europe and Fennoscandia. The epicentre map shows the actual data set collected and made homogeneous in the frame of the Global Seismic Hazard Assessment Program (GSHAP).

Zusammenfassung

Für das Untersuchungsgebiet des IGCP-Projekts „Neogeodynamica Baltica" wurden die aktuellen Daten der maximalen horizontalen krustalen Kompressionsspannung (Karte Nr. 5) und die Epizentren von Erdbeben (Karte Nr. 6) zusammengestellt und diskutiert. Erstmals werden neue Spannungsdaten für die Osteuropäische Plattform im Vergleich mit dem Spannungsfeld Westeuropas und Fennoskandiens präsentiert. Die Karte der Epizentren zeigt den derzeitig katalogisierten Datenbestand, welcher im Rahmen des Globalen Programms zur Einschätzung der Erdbebengefährdung (GSHAP) erfaßt und homogenisiert wurde.

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