Microseismic Monitoring: A Proposed Study in the Upper Rhinegraben and Experiences from the East African Rift System

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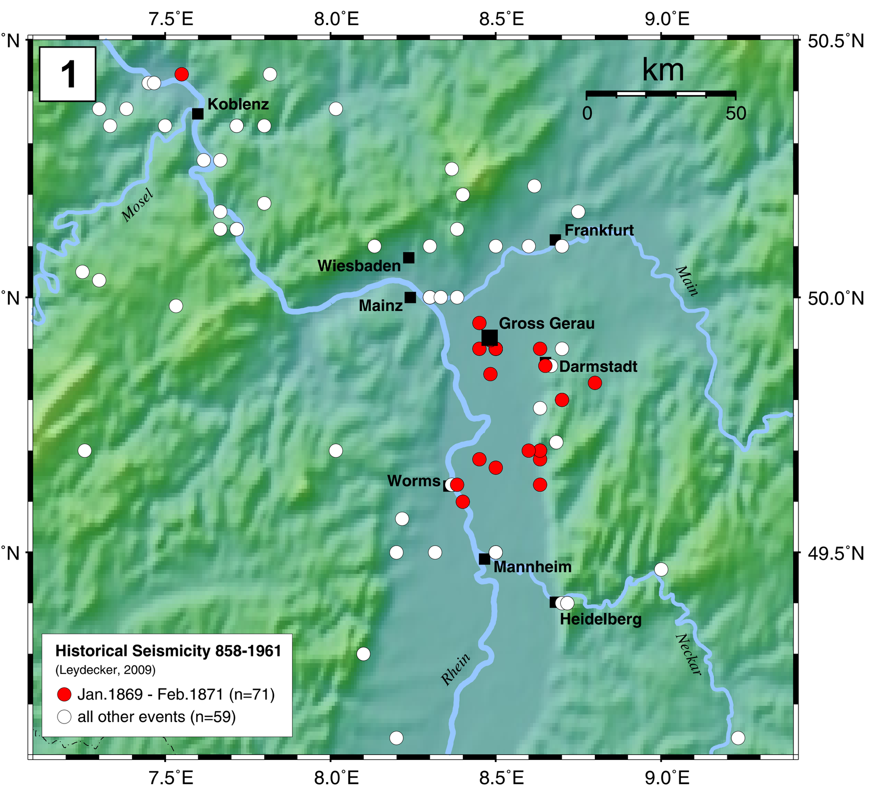


Fig.1: Historical seismicity of the Upper Rhinegraben area from the year 858 to 1962. The data were compiled by Leydecker (2009). There are 130 events on the map. 71 of them occured between Oct. 1869 and Feb. 1871 (red symbols). These are members of an earthquake swarm that consisted of more than 2000 reported shocks (Landsberg, 1931).

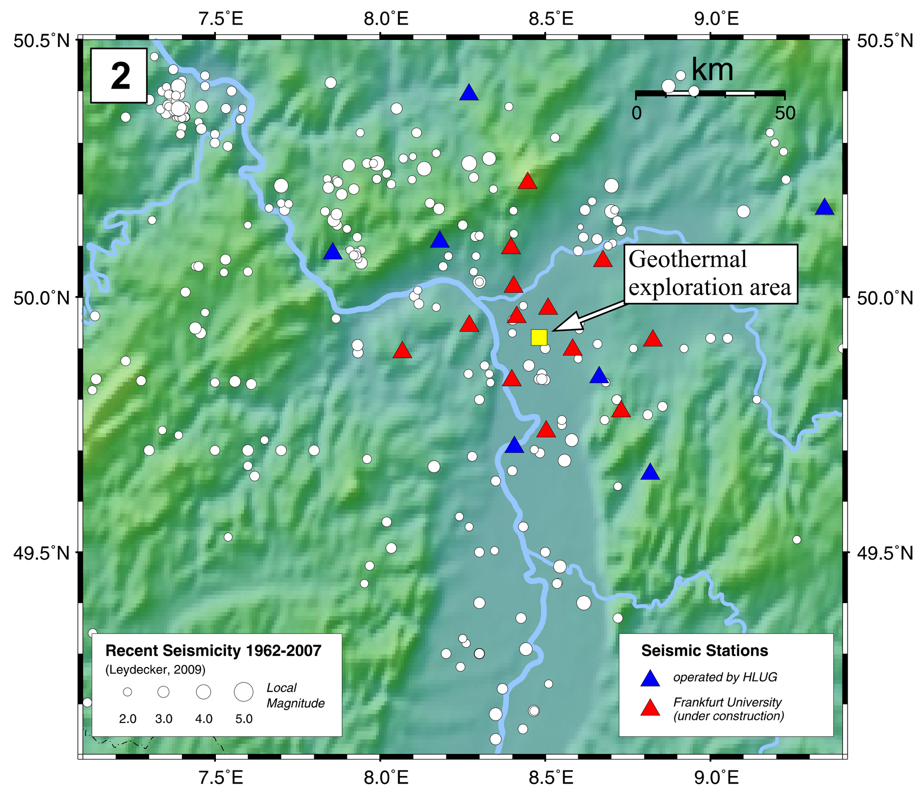


Fig.2: Seismicity of the Rhine-Main area from 1962 to 2007 (Leydecker, 2009). The database comprises 270 events with local magnitudes between 2.0 and 5.5. The permanent seismic network of the HLUG is plottet with blue triangles. Red symbols denote the temporary network that is currently established by the University of Frankfurt. The yellow square marks the area of the projected geothermal drilling.

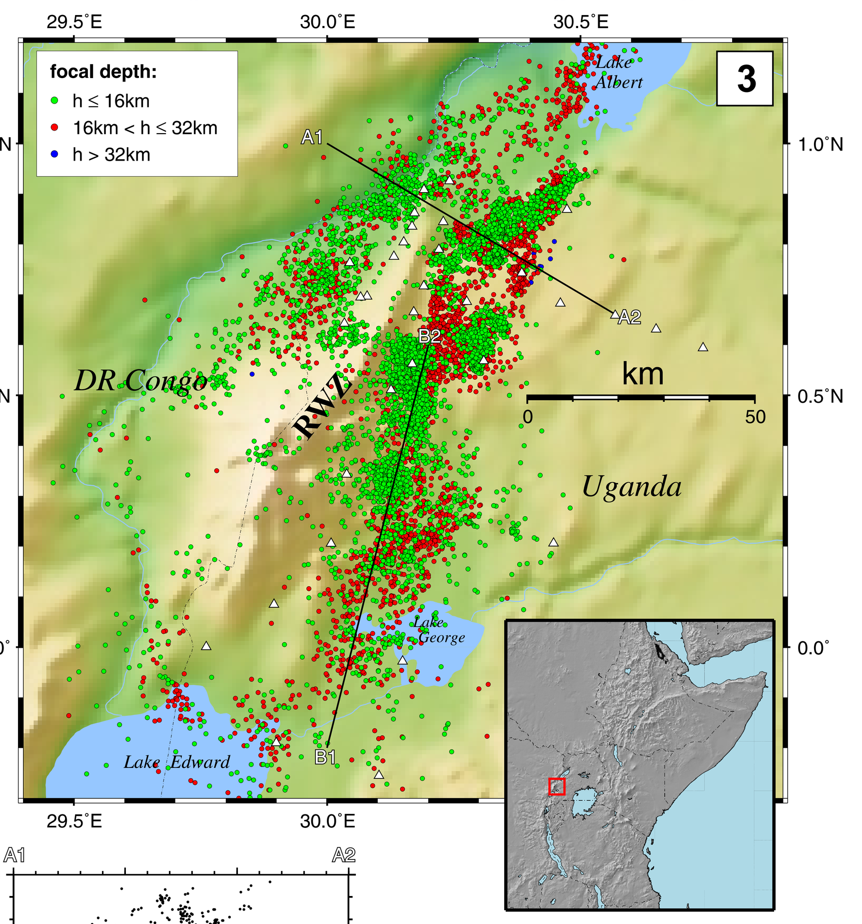
Summary

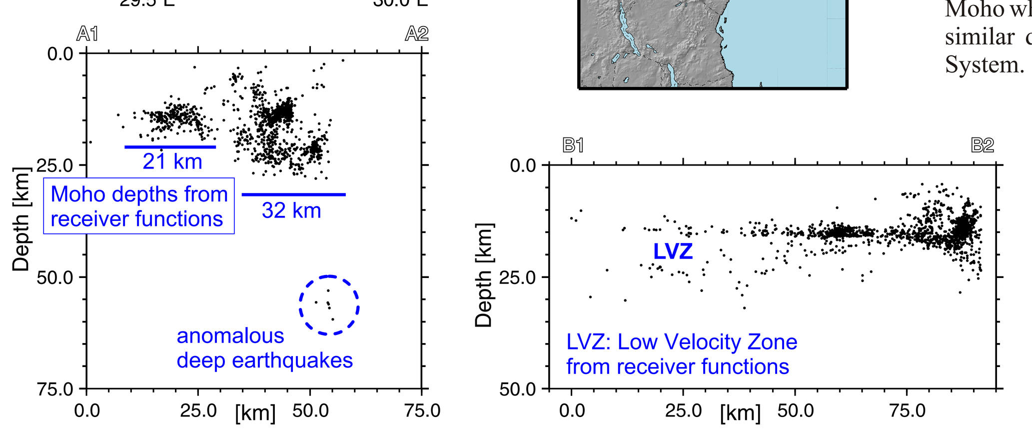
The northern parts of the Upper Rhinegraben exhibit enlarged temperature gradients compared to adjacent areas. Geothermal maps show a maximum with temperatures exceeding 120°C in 2000 m depth in the Rhine-Main area. Several geothermal drilling projects are planned in this region starting within the next years. Seismic monitoring is important to assess the influence of deep-heat mining on earthquake activity. It is well known that the Upper Rhinegraben shows seismic activity. Historic accounts report an earthquake swarm in this area between October 1869 and February 1871 which consisted of more than 2000 felt shocks, 190 of which had intensity IV and more. However, since that time no further macroseismic swarm events have been felt in this area. We intend to install a network of about 12 seismometers to monitor the microseismic activity prior and during the planned drilling activities. With improved localization methods (e.g. double difference algorithm) and determination of source parameters such as magnitude and fault mechanism we want to establish a comprehensive data base of the natural seismicity in the area.

The proposed study will benefit from our previous experience in monitoring microearthquakes of the East African Rift System (EARS). The University of Frankfurt has been operating seismic networks in the western branch of the EARS close to the Border between Uganda and the D.R.Congo for a number of years.

Here, we located more than 800 earthquakes per month with local magnitudes ranging from 0.5 to 5.1. Vertical sections show, that towards the rift valley the focal depths range from 10 to 20 km, whereas the hypocentres go as deep as 30 km at the eastern rift shoulder. This is in good agreement with Moho-depths derived from receiver functions and implies that all of these events are located within the crust. However, we also located a cluster of 7 events that exhibit an anomalous depth of about 60 km. We can confidently locate these earthquakes within the mantle lithosphere beneath the rift. According to our present knowledge these are the deepest events so far observed within the EARS and the African Plate. We think that magmatic impregnation processes associated with dyke propagation into the mantle lithosphere may be a realistic cause for seismic radiation at the observed depth.
P-wave polarities were used to determine fault plane solutions. Nearly all source mechanisms reveal normal faulting with strike directions more or less parallel to the rift axis and extension forces perpendicular to it. Crustal earthquakes northeast of the Rwenzori area are relocated with a double-difference algorithm to improve the spatial resolution of seismicity pattern. Several event clusters in the vicinity of the Fort Portal volcanic field form pipe-like structures with vertical extensions of 3 to 6 km and diameters of 1 to 2 km. In this region the rifting process is probably still in an early stage. The structures possibly indicate magmatic feeding channels through the crust that originate from the heated and impregnated lithospheric mantle.

Seismicity of the Rwenzori region, Uganda





The over 5000 m high Rwenzori Mountains are situated within the western branch of the East African Rift System, at the border between Uganda and the Democratic Republic of Congo. They represent a basement block within the rift valley whose origin and relation to the evolution of the rift are focus of the RiftLink *project.*

Fig.3: Map of the RiftLink seismic station network (white triangles) in Uganda and the recorded local seismicity from February 2006 to September 2007. On average more than 800 events per month with magnitudes ranging from -0.5 to 5.1 could be located.
The figure includes ~10900 events with typical localization errors of 2-3 km. The majority of the epicentres lies within fault zones to the east and west of the Rwenzories with highest seismic activity between Lake Albert and Lake George. The apparent decrease of seismicity in the southwestern region is probably due to the absence of seismic stations in this area.

Two vertical sections show the hypocentral depth distribution:

A1-A2: This profile crosses the rift and the northern part of the Rwenzories in NW-SE direction. West of the mountains (towards the rift valley) focal depths range from 10 to 20 km. On the eastern side, where the Rwenzoris are connected to the rift shoulder, seismicity extents from the surface down to 30 km depth. Moho depth determinations from teleseismic receiver functions (Wölbern et al., 2010) confirm, that seismicity is indeed restricted to the crustal part of the lithosphere.
A small group of seven earthquakes is located at depths between 53 and 60 km (dashed circle). The hypocentres are clearly located below the Moho which was found at 32 km depth in this area. We are not aware of similar deep earthquakes in other regions of the East African Rift System.

B1-B2: This profile runs approximately in N-S direction parallel to the rift axis. At its northern end (B2) - near the junction of Rwenzori and rift shoulder - seismicity extends from surface up to 25 km depth, similar to the eastern end of profile A. Further south the hypocentres concentrate at 15 km depth. Then the seismic activity splits up into two horizontal levels at 15 km and 25 km depth, respectively. The upper of these seismicity layers coincides with the upper boundary of a low velocity zone that can be clearly identified with receiver functions in this area..

Local Magnitudes

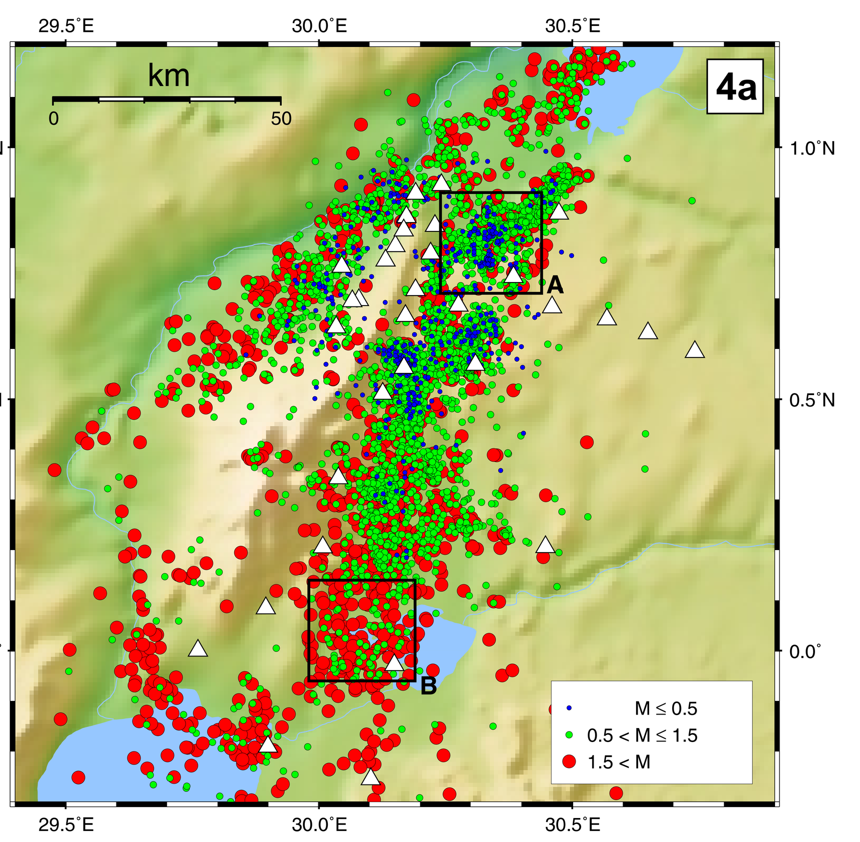
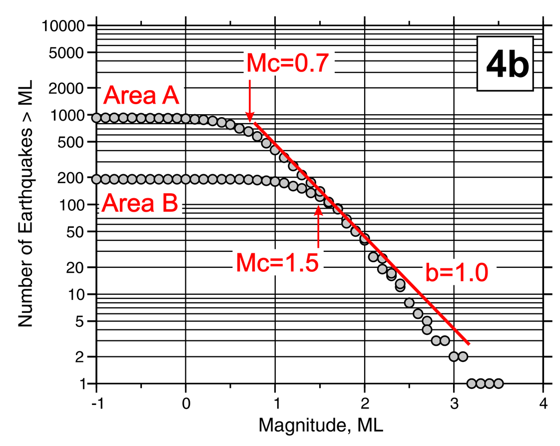
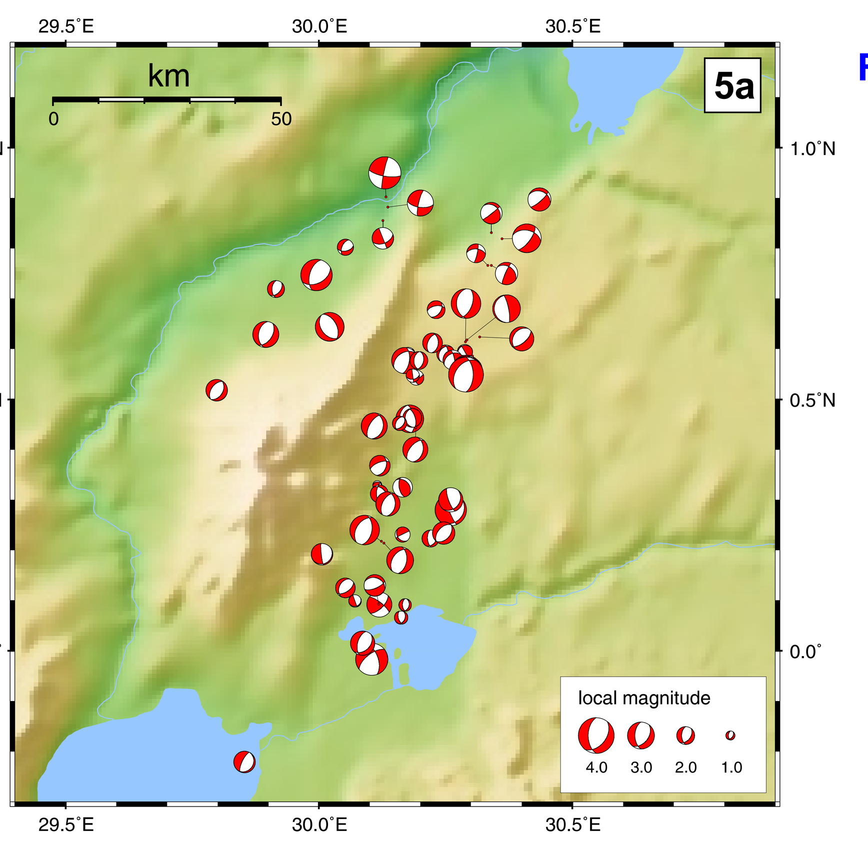


Fig. 4a (left): Spatial distribution of calculated local magnitudes, M_L. Epicentre symbols are colored according to the event magnitude, see legend. There is a clear correlation between magnitude threshold and station density: Small events with $M_L < 0.5$ (blue symbols) are detected exclusively in the northern area where the average distance of neighbouring stations is smaller than about 10 km. In the southwestern region with station spacings of more then 20 km the magnitude threshold rises to $M_L > 1.5$ (red symbols).

Fig. 4b (bottom): Cummulative magnitude-frequency distributions of areas A and B (black squares in Fig. 4a). Both regions show similar b-values (b = 1.0), but different magnitudes of completeness: MC = 0.7 in Area A and MC = 1.5 in Area B. This is due to the inhomogenious spacing of seismic stations.

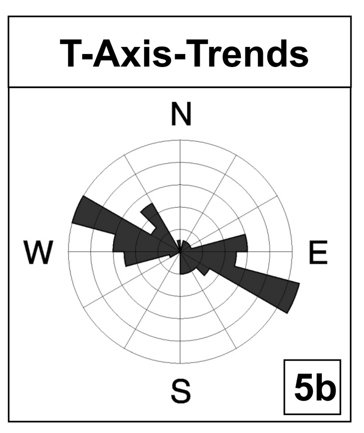




Faultplane Solutions

Fig. 5a (left): Fault plane solutions of numerous events were derived using P-polarities and S- to P-amplitude ratios. 75% of the observations show normal faulting, but there are also several strike-slip and reverse faulting mechanisms.

Fig. 5b (bottom): Distribution of T-axis-trends. The directions of extensional forces are perpendicular to the rift axis.



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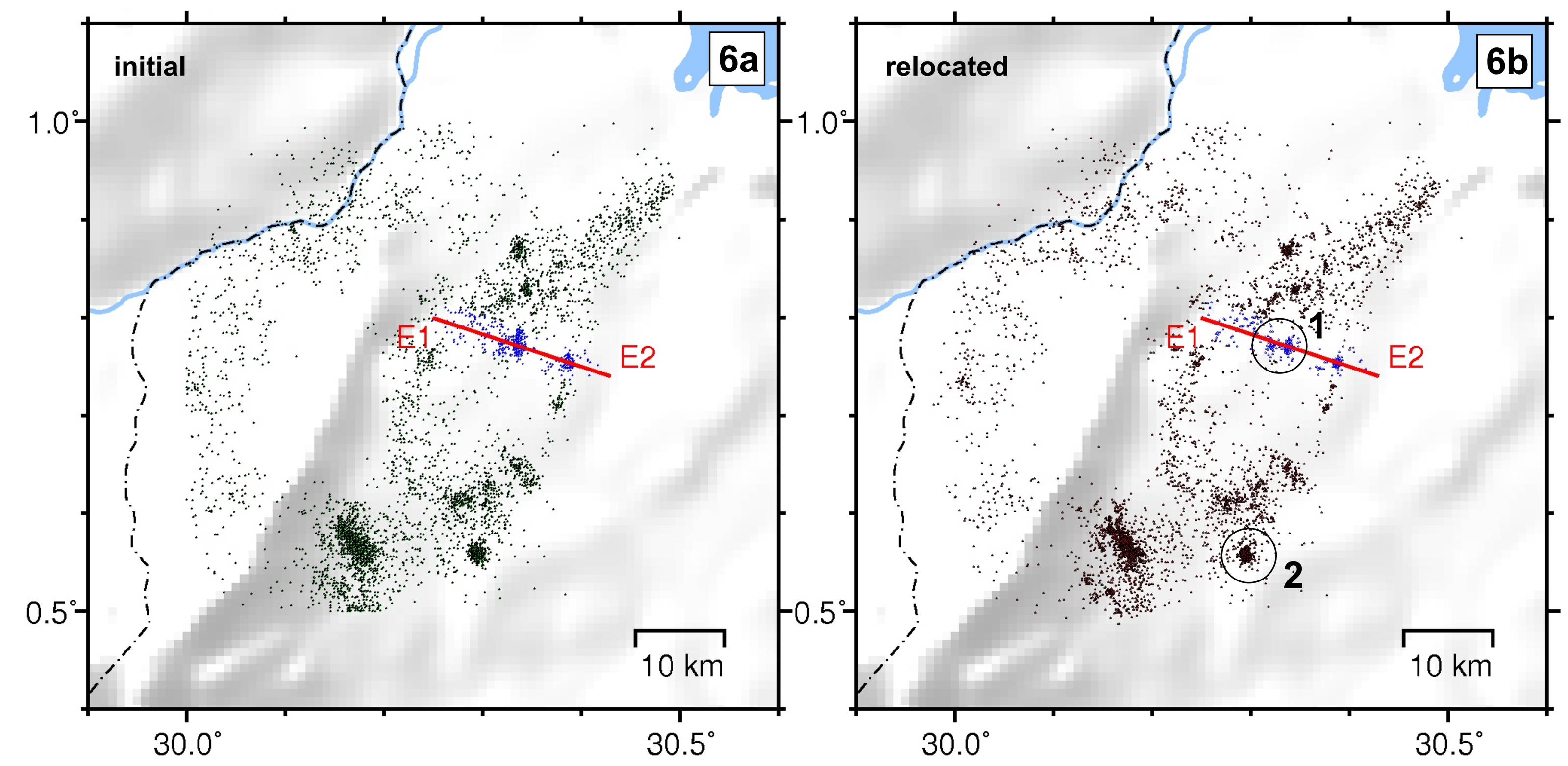
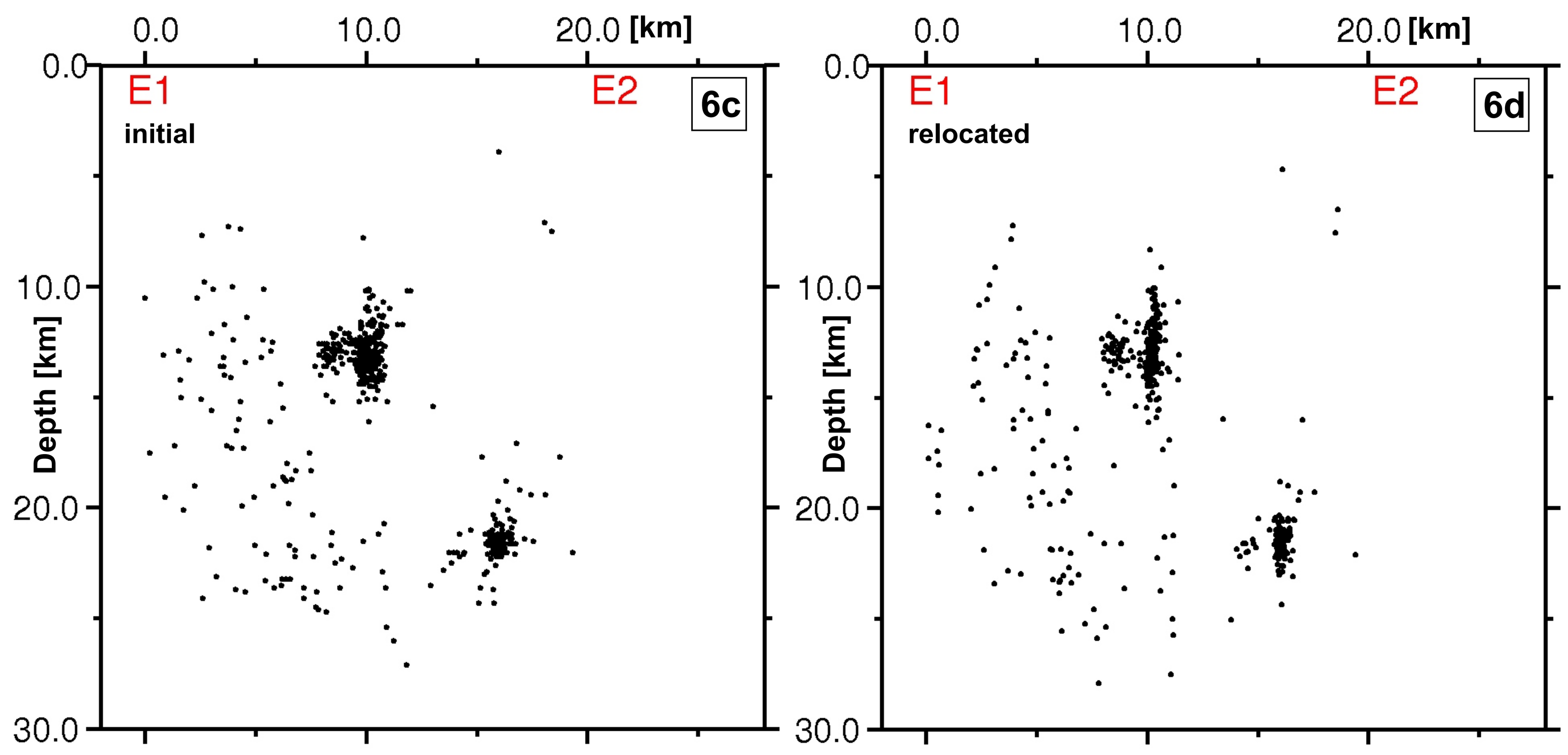
Relative hyocentre relocation





Precise hypocentre locations were obtained by using the double-difference algorithm (hypoDD) of Waldhauser and Ellsworth (2000). We relocated earthquakes in an area between 30.0°E - 30.5°E and 0.5°N - 1.0°N. This region is characterised by the highest seismicity and an adequate station coverage, see Fig. 4a.

Fig.6a (top, left) shows the initial epicenter distribution in the area calculated with a standard location algorithm. **Fig.6b (top, right)** shows the double-difference locations. Obviously many events are concentrated in earthquake clusters. But while the inital distribution is more diffuse, the hypoDD locations exhibit sharper structural details. The improvement of the double-difference locations can also be seen in vertical sections. **Fig.6c (bottom, left)** and **Fig.6d (bottom, right)** show initial and relocated hypocetres along profile E1-E2, respectively. The two earthquake clusters that are intersected by the profile form pipe-like structures with vertical extensions of 3 to 6 km and diameters of 1 to 2 km. It is even possible now to discriminate a small cluster in the vicinity of the larger earthquake cluster.

Hypocentre migration

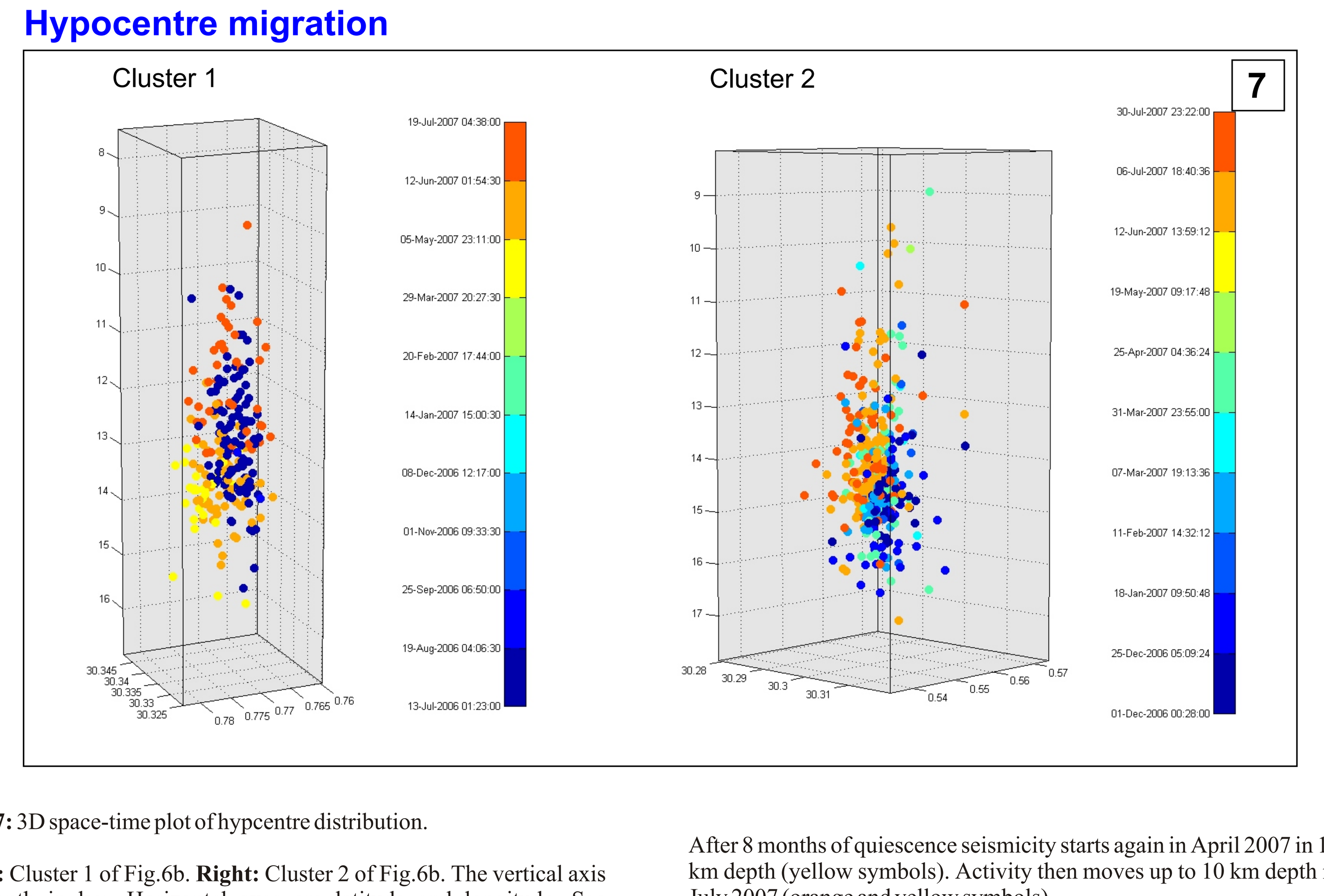


Fig.7: 3D space-time plot of hypcentre distribution.

Left: Cluster 1 of Fig.6b. **Right:** Cluster 2 of Fig.6b. The vertical axis is depth in km. Horizontal axes are latitude and longitude. See colorbars for time information. Both clusters show systematic upward migration of hypocenters with time. Seismic activity in cluster 1 begins in July 2006 and covers the whole depth range (dark blue symbols).

After 8 months of quiescence seismicity starts again in April 2007 in 14 km depth (yellow symbols). Activity then moves up to 10 km depth in July 2007 (orange and yellow symbols).
Similar hypocenter migration exists in cluster 2 (right). Activity begins in Dec. 2006 in 15 km depth (dark blue symbols). Then is ascends up to 10 km depth in July 2007 (light blue, green, orange, red).

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