GEODYNAMICS OF CONTINENTAL RIFTING: INSIGHT FROM COMPARISON OF RIFTS

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Summary

In the frame of Project IGCP 400 "Geodynamics of Continental Rifting", a comparison of the tectonic structure and kinematic evolution of a series of active continental rift systems was made. Both the pre-rift and the syn-rift evolution was considered, to highlight common factors in the processes responsible for the initiation and development of intracontinental rifts. The comparison involves the Baikal, East African, Dead Sea and Rio Grande rifts. They are all active rift systems composed of a narrow chain of deep depressions, formed in a cold and strong crust, in response of a long tectonic history. The comparison shows that the pre-rift history and rifting initiation are of crucial importance for the development of rift systems. Location of rifts is favored by the presence of strong lithospheric contrasts, typically along the margin of old cratons and characterized by elongated shear belts, often weakened by repeated reactivations in lower greenschist conditions. In the course of rifting, the stress field tends to evolve to more extensional conditions, due to the onset of locally generated buoyancy extensional forces related to the development of lateral density heterogeneities in the lithosphere. The typical sequence of stress field evolution with time is: transpressional, transtensional, pure extensional and radial extensional. However, once initiated, the rift system are more sensitive to intraplate stress fluctuations of far-field origin. Rift systems can also become inactive for some periods of time, then reactivated later once the stress conditions become more favorable.

Scope and status of the Project IGCP400

The IGCP 400 project "Geodynamics of Continental Rifting", leaded by D. Delvaux (MRAC, Belgium) and A. Khan (University of Leicester, UK), aims at a better understanding of the geodynamics of rifting and sedimentary basin formation in their complex intraplate environment. It is based on comparative investigation of geophysical, tectonic, kinematic and magmatic processes in active intracontinental rifts, their crustal and upper mantle structure and their global plate tectonic settings. It pays a special attention to the early stages of rifting in continental plates. Five active rift systems were selected: the East African, Afro-Arabian, Baikal, Rio Grande and European rift systems. For a better understanding of the evolution of rifting processes with time, the project also considers rifts at various stages of formation, with examples of the mature failed rift of North Sea and Passive Margins in general. The IGCP 400 project has several links with others IGCP and ILP projects. It considers also environmental and natural hazard risks prediction, paleoclimatic and paleoenvironmental changes, lacustrine environment protection and promotion of multilateral north-south and east-west scientific and technological co-operation.

The IGCP 400 project officially started in July 1996. To launch the project, business meetings were organized at the 21rst EGS General Assembly in The Hague (The Netherlands), in Novosibirsk (Russia), at the 30th IGC in Beijing (China) and at the third annual meeting of IGCP 369 "Comparative Evolution of PeriTethyan Rift Basins", in Cairo (Egypt). The first annual meeting of IGCP 400 was held in Dublin (Ireland), in March, 1997, with three days of interdisciplinary sessions reviewing the state of knowledge on the East African, Afro-Arabian, Baikal, European and Rio Grande rift systems, and on rifted passive margins. The second annual meeting was organized in Gaborone (Botswana), in June 1998, as a separate symposium of International Conference *The Role of a National Survey in Sustainable Development* at the occasion of the 50th Anniversary of the Geological Survey of Botswana. It concentrated on the spatial and temporal control of rifting with emphasis on the East African Rift System. It was followed by a 4-days field excursion to the Okavango alluvial fan where a new rift is developing. During the third year of activity, IGCP 400 also participated and co-sponsored the International Conference on Active Tectonic Continental Basins organized at the University of Gent (Belgium), and a session at the 23rd EGS General Assembly in Nice, (France), on plumes, kinematic conditions and lithospheric inhomogeneities in modern rifts.

The Third Annual Meeting was convened at Irkutsk (Russia), in August 1999, with a field excursion on Lake Baikal and in the Tunka depression. The workshop focused on the origin and development of the Baikal intracontinental rift system, in the middle of the Asian plate, as a combined consequence of plate boundary and intraplate influences. Presentations concentrated on temporal changes and spatial variability of tectonic, magmatic and geophysical processes, and their influence on the development of the Baikal rift basin and on its structure and sedimentation. Comparison with other major rift systems of the world were highlighted.

During the forth year of activity, IGCP 400 also participated and co-sponsored, a Discussion Meeting at the Geological Society, London (UK), on lower crust magmatic processes during continental extension, and a session on geophysical and petrophysical constraints for rifting, hotspots and plumes at the 24th EGS General Assembly, The Hague (The Netherlands).

In parallel, IGCP 400 prepared or participated actively to several publications in international journals: a state of the art in the knowledge of continental rifts, with guidelines for their further studies, published at the *Dublin Institute for Advanced Studies (Jacob et al.,1997),* a special series of articles on the Baikal Rift in the *Bulletin des Centres de Recherches Exploration-Production Elf-Aquitaine* (Logatchev et al., 1993-1999), a special volume of the *Journal of African Earth Sciences* on the East African Rift (Delvaux and Khan, 1998), the proceedings of the Botswana meeting, to be published in a special volume of the *Journal of African Earth Sciences* (1999), two special issues containing selected articles issued from the Active Tectonic Continental Basins in Gent, to be published in *Geologische Rundshau* and in *Tectonophysics*, and a special issue of *Russian Geology and Geophysics* with selected papers from the Irkutsk meeting.

What can be learned from the comparison of continental rift systems ?

The initiation and development of continental rift systems in the middle of continental plates involves a series of processes leading to continental breakup. These processes appear relatively similar in the four rift nearly non-volcanic systems we compare here: the Baikal Rift System (BRS), the Tanganyika-Rukwa-Malawi rift segment (TRM) of the East African Rift System, the Rio Grande Rift (RGR) and the Dead Sea Rift (DSR). The interest of such a comparison is to highlight some common characteristic processes, and emphasize on their order of appearance during rifting, since the rift initiation.

A starting point for this comparison is the frequent occurrence of extensional (rift) basins along continental plate boundaries which acted as transform fault zones, at least during part of the recent geological history (Ben-Avraham, 1992; Ben-Avraham and Zoback, 1992). In addition, these continental transform zones often reactivate persistent crustal weakness zones.

Development of pre-rift persistent crustal weakness

The BRS, TRM and DSR are all issued from continental extension along weakened transcurrent plate boundaries. They develop either between Proterozoic cratons and their surrounding Neoproterozoic-Paleozoic fold belts (BRS and TRM), or also they separate two rigid blocks inside continental plates (DSR). These rifts occur in a relatively strong and cold crust, previously weakened by repeated strike-slip movements, after the final crustal consolidation. Once the crust became strong, reactivation of the existing zone of crustal weakness occur as soon as suitable stress conditions are applied.

Both the margins of the Siberian and Tanzanian cratons have been reactivated in the Late Proterozoic- Early Paleozoic by important lateral movements in retrograde greenschist facies (Theunissen et al., 1993; 1996). This gave rise to major shear zones, which were not sealed by late tectonic magmatism.

The TRM, BRS and DSR represent different modes of rifting along weakened crustal block boundaries. These rifts are all characterized by a single alignment of narrow and relatively deep extensional basins, mostly non-volcanic. Before rifting, the weakness zones were generally reactivated several times, but conditions were not suitable for the development of rift systems. Phases of compression at a high angle to the weakness zone occurred in the Late Neoproterozoic for the TRM, in the Middle Paleozoic and again in the Cretaceous for the BRS, and in the Cretaceous-Paleocene for the DSR. They generated thrusting, reverse faulting, folding and transversal strike-slip faulting, but no extensional basins.

Highly extended belts in warm and weak crust

Extension at a high angle to the lithospheric discontinuity occurred in the BRS during the Jurassic-Cretaceous (Transbaikal area), but in a warm and weak crust. It generated a highly extended belt with metamorphic core complexes, rapid exhumation, dike swarms and small volcanoclastic depressions spread over the whole belt (Ermikov, 1994; van der Beek et al., 1996; Delvaux, 1997; Zorin et al., 1997). This extension was related to the convergence of China and Siberia, with subduction of the Mongol-Okhotsk oceanic crust under the margin of the Siberian plate. The closure of the Mongol-Okhotsk ocean in the Late Mesozoic caused the tectonic inversion of the Transbaikal Mesozoic depression, and affected also the margin of the Angara-Lena plate (Ermikov, 1994; Delvaux et al., 1995).

Many similarities in the tectonic evolution of the Baikal and Transbaikal areas since the Paleozoic exist with the evolution of the Basin-and-Range Province and the Rio Grande Rift in the western USA. The succession tectonic events in the Basin-and-Range Province (Baldridge et al., 1995; Parson, 1995), is very similar as in the Baikal and Transbaikal areas, but with a shorter timing (Logatchev, 1993; Melnikov et al., 1994; Delvaux et al., 1995; 1997). The Basin-and-Range was in a back-arc setting at the early stage of extension, subsequent lithospheric thickening was caused by long-term subduction of hot oceanic lithosphere and extensional spreading occurred after orogenic thickening. In that context, mantle plume triggered extension by thermal weakening of the lithosphere, causing broad uplifting and generation of buoyancy extensional deviatoric stresses, responsible for the development of the Rio Grande Rift.

A broad zone of extension is predicted in a thermally weakened lithosphere with shallow brittle-ductile transition, while narrow and deep rifts is likely to form in a cold and strong lithosphere with relatively deep brittle-ductile transition (Baldridge et al., 1995; Parson, 1995). In Transbaikal, the lithosphere was thermally weakened during the Mesozoic, while the Cenozoic extension occurred in a strong and cold crust. This might explain why no true narrow and deep rift developed in this region during the Mesozoic.

Transpressional breakup and transition towards rifting

Successful breakup occurred only after an initial reactivation of the lithospheric weakness under oblique compression. This initial stage occurred during the Permian-Triassic in the TRM (Karoo stage: Mbede, 1993; Klerkx et al., 1998), during the Late Oligocene-Miocene in the BRS (slow rifting or proto-rift stage: Logatchev, 1993; Delvaux et al., 1997) and since the Miocene in the DSR (Dear Sea Stress stage: Eyal, 1996). The stress field was generally compressional to transpressional, but with horizontal principal compression (SHmax) oblique to the weakness zone, which was reactivated as a transcurrent fault zone. Extension started when the stress axes rotated towards a parallelism of SHmax with the transcurrent zone and towards a high angle between the principal extension (Shmin) and the transcurrent zone. Extension was also triggered by additional extensional forces generated under the new rift zone as buoyancy forces related to lithospheric destabilization (BRS, and DSR ?) or to the rising of a mantle plume (TRM). Pure extension and rift basin formation occurred during the Tertiary in the TRM (after a long period of quietness since the Karoo event), since the Late Pliocene in the BRS (fast rifting or active rift stage), and during the Pleistocene in the DSR. During the rifting stage, extensional stresses generally dominate far-field compressional stresses, but the latter are still acting on the system, as shown by recent strike-slip movements in the central part of the Rukwa and Dead Sea depressions, and at the southwestern part of the Baikal depression (Petit et al., 1996).

Influence of intraplate stress field fluctuation on rifting

Once rifting is initiated, the rifts became more sensitive to the fluctuation of external far-field stresses, generated at the plate boundary. These can trigger rifting, or even interrupt the rifting process for a while. However, rifting continues as soon as the conditions became again favorable. This is well illustrate by the stepwise rifting in the western branch of the TRM rift zone, with the successive Late Paleozoic-Early Triassic (Karoo), Late Triassic-Early Cretaceous, Early Tertiary and Late Cenozoic rifting periods, separated by tectonically quiet periods (Mbede, 1993; van der Beek et al., 1998; Delvaux et al., 1998; Delvaux, 1999).

The interaction of plate-scale and local stress fields is also an important factor which can modify the kinematics of faulting during rifting. In the TRM zone, the Late Quaternary rotation of horizontal stress axes (e.g. Delvaux et al., 1992; Ring et al., 1992) can be related to a plate-scale event, triggered by plate-tectonic modifications at Red Sea - Gulf of Aden spreading centers (Bosworth and Strecker, 1997). In the BRS, Late Quaternary tectonic intensification was also caused by a plate-scale change in the stress field (Delvaux et al., 1997). In the DSR, a clockwise rotation horizontal stress axes also occurred in the course of rifting (Eyal, 1999; Zain-Eldeen, work in progress).

Conclusion

Comparison of the tectonic setting, geological evolution, fault kinematics and stress field fluctuation in these four rift systems developing along intracontinental transcurrent zones highlight general mechanisms of their formation, all involving the interplay between strike-slip and extension. This complex interaction is reflected in the long debates on the transcurrent or extensional nature of these rift zones.

The comparison shows that the pre-rift history and the rifting initiation process are more important than the rifting itself. Once rifting is initiated, the rift system is more sensitive to plate-scale tectonic stress fluctuations. An important prerequisite is the presence of a zone of crustal weakness, which is maintained week by repeated reactivations.

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