Inter-Union Commission on Geodynamics
Scientific Report No. 8

Approaches to Taphrogenesis

Proceedings of an International Rift Symposium held in Karlsruhe April, 13-15, 1972

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J. H. ILLIES and K. FUCHS

Geologisches Institut   Geophysikalisches Institut
Universität Karlsruhe, Germany

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List of Contributors

L. Ahorner, Erdbebenstation der Universität, Bensberg bei Köln, Germany

E. Althaus, Mineralogisches Institut, Universität Karlsruhe, Germany

H.-J. Anderle, Hessisches Landesamt für Bodenforschung, Wiesbaden, Germany

J. Ansorge, Institut für Geophysik, Eidgenössische Technische Hochschule Zürich, Switzerland

E. Backhaus, Geologisch-Paläontologisches Institut, Technische Hochschule Darmstadt, Germany

I. Baranyi, Laboratorium für Geochronologie, Universität Heidelberg, Germany

J. Bartz, Geologisches Landesamt Baden-Württemberg, Freiburg i. Br., Germany

E. Becksmann, Talstr. 60, Freiburg i. Br., Germany

H. Berckhemer, Institut für Meteorologie und Geophysik, Universität Frankfurt/Main, Germany

H. Boigk, Niedersächsisches Landesamt für Bodenforschung, Hannover, Germany

K. P. Bonjer, Geophysikalisches Institut, Universität Karlsruhe, Germany

G. Bozorgzadeh, Geodätisches Institut, Universität Karlsruhe, Germany

G. von der Brelie, Geologisches Landesamt Nordrhein-Westfalen, Krefeld, Germany

F. Breyer, Kettlerweg 5, Hannover, Germany

W. Carlé, Rebmannstr. 2, Korntal, Germany

D. Contini, Laboratoire de Géologie historique et Paléontologie, Université Besançon, France

F. Doebl, Wintershall AG, Landau, Germany

G. Dohr, Preussag AG, Hannover, Germany

B. Edel, Institut de Physique du Globe, Université Strasbourg, France

D. Emter, Institut für Geophysik, Universität Stuttgart, Germany

L. Erlinghagen, Prakla-Seismos GmbH., Hannover, Germany

K. Fuchs, Geophysikalisches Institut, Universität Karlsruhe, Germany

C. Gelbke, Geophysikalisches Institut, Universität Karlsruhe, Germany

G. Greiner, Geologisches Institut, Universität Karlsruhe, Germany

V. Haak, Institut für Angewandte Geophysik, Universität München, Germany

D. Heling, Laboratorium für Sedimentforschung, Heidelberg, Germany

G. Hirlemann, Laboratoire de Géologie et de Paléontologie, Strasbourg, France

A. Hirn, Institut de Physique du Globe, Université Paris, France

W. Homann, Geologisches Landesamt Nordrhein-Westfalen, Krefeld, Germany

P. Horn, Max-Planck-Institut für Kernphysik, Heidelberg, Germany

J. H. Illies, Geologisches Institut, Universität Karlsruhe, Germany

J. Karweil, Bergwerksverband, Essen, Germany

E. Kuntz, Geodätisches Institut, Universität Karlsruhe, Germany

J. P. Lauer, Institut de Physique du Globe, Université Strasbourg, France

H. J. Lippolt, Laboratorium für Geochronologie, Universität Heidelberg, Germany

G. Lögters, Sonderforschungsbereich 77 „Felsmechanik", Universität Karlsruhe, Germany

H. Mälzer, Geodätisches Institut, Universität Karlsruhe, Germany

O. Mäussnest, Tuttlinger Str. 9, Stuttgart, Germany

R. B. McConnell, Streatwick, Streat near Hassocks, Sussex, United Kingdom

R. Meissner, Institut für Geophysik, Universität Kiel, Germany

L. Müller, Institut für Bodenmechanik und Felsmechanik, Universität Karlsruhe, Germany

St. Müller, Institut für Geophysik, Eidgenössische Technische Hochschule Zürich, Switzerland

W. Olbrecht, Ulrich-von-Hutten-Str. 3, Landau, Germany

D. Ortlam, Niedersächsisches Landesamt für Bodenforschung, Hannover, Germany

N. Pavoni, Institut für Geophysik, Eidgenössische Technische Hochschule Zürich, Switzerland

G. Perrier, Institut de Physique du Globe, Université Paris, France

E. Peterschmitt, Institut de Physique du Globe, Université Strasbourg, France

C. Prodehl, Geophysikalisches Institut, Universität Karlsruhe, Germany

A. Rawanpur, Geologisch-Paläontologisches Institut, Technische Hochschule Darmstadt, Germany

H. Reichenbach, Institut für Angewandte Geophysik, Universität München, Germany

G. Reitmayr, Institut für Angewandte Geophysik, Universität München, Germany

G. Richter-Bernburg, Haarstr. 8, Hannover, Germany

M. Ruhland, Institut de Géologie, Université Strasbourg, France

L. Rybach, Institut für Kristallographie und Petrographie, Eidgenössische Technische Hochschule Zürich, Switzerland

K. Schäfer, Geologisches Institut, Universität Karlsruhe, Germany

I. Scheelke, Institut für Geophysik und Meteorologie, Technische Universität Braunschweig, Germany

E. Schenk, Professorenweg 6, Gießen, Germany

O. Schmitt, Hessisches Landesamt für Bodenforschung, Wiesbaden, Germany

G. Schneider, Institut für Geophysik, Universität Stuttgart, Germany

H. Schöneich, Niedersächsisches Landesamt für Bodenforschung, Hannover, Germany

A. Schult, Institut für Angewandte Geophysik, Universität München, Germany

E. Schwarz, Hessisches Landesvermessungsamt, Wiesbaden, Germany

L. Steinmetz, Institut de Physique du Globe, Université Paris, France

P. Streicher, Institut de Physique du Globe, Université Strasbourg, France

K. Strobach, Institut für Geophysik, Universität Stuttgart, Germany

A. Strobel, Landesvermessungsamt Baden-Württemberg, Stuttgart, Germany

J. Strowald, Institut für die Physik des Erdkörpers, Universität Hamburg, Germany

M. Teichmüller, Geologisches Landesamt Nordrhein-Westfalen, Krefeld, Germany

R. Teichmüller, Geologisches Landesamt Nordrhein-Westfalen, Krefeld, Germany

N. Théobald, Laboratoire de Géologie historique et Paléontologie, Université Besançon, France

P. Thiele, Geodätisches Institut, Universität Karlsruhe, Germany

W. Todt, Laboratorium für Geochronologie, Universität Heidelberg, Germany

U. Vetter, Institut für Geophysik, Universität Kiel, Germany

B. VOIGHT. Dept. of Geosciences, Pennsylvania State University, University Park, Pa. 16802. U.S.A.

D. H. WELTE. Lehrstuhl für Geologie, Geochemie und Lagerstätten des Erdöls und der Kohle, Technische Hochschule Aachen, Germany

D. WERNER, Institut für Geophysik, Eidgenössische Technische Hochschule Zürich, Switzerland

R. WINTER, Geophysikalisches Institut, Universität Göttingen, Germany

M. ZIRNGAST, Geologisch-Paläontologisches Institut, Technische Hochschule Darmstadt, Germany

The Geodynamics Project is an international program of research on the dynamics and dynamic history of the earth with emphasis on deep-seated foundations of geological phenomena. This includes investigations related to movements and deformations, past and present, of the lithosphere, and all relevant properties of the earth's interior and especially any evidence for motions at depth. The program is an interdisciplinary one, coordinated by the Inter-Union Commission on Geodynamics (I. C. G.) established by I. C. S. U. at the request of I. U. G. G., and I. U. G. S., with rules providing for the active participation of all interested I. C. S. U. Unions and Committees.

Preface

In the transition between the International Upper Mantle Project and the Geodynamics Project the Rhinegraben Research Group met to its 5. Symposium on Continental Rift Systems at Karlsruhe on April 13—15, 1972. Results obtained in more than five years of research during the Upper Mantle Project were presented and discussed and are the content of this book. Most of the papers deal with certain aspects of the Rhinegraben rift system in its broader sense but a few also with other continental rift structures. This might be justified not only because of the location where the meeting took place but mainly by the intensity with which the Rhinegraben had been investigated in past and present time in international and interdisciplinary cooperation. When in 1970 the book "Graben Problems", edited by J. H. ILLIES and ST. MÜLLER appeared it found quickly a wide distribution and appreciation. It was, therefore, felt by the Rhinegraben Research Group that the latest results at the end of the Upper Mantle Project should also be made available to a broader public. The title "Approaches to Taphrogenesis" expresses the aim to look at large scale tension features in continental blocks from the viewpoint of the evolution, the appearance at the surface, and the deep seated processes and forces.

Thanks have to be expressed to the Deutsche Forschungsgemeinschaft which sponsored much of this work and supported the symposium.

H. BERCKHEMER

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Taphrogenesis: Rhinegraben, continental rift systems, and Martian rifts

Taphrogenesis, Introductory Remarks

by

J. H. Illies

With 6 textfigures

E. Krenkel (1922) in his classical monograph on the East African rift valleys, after discussing the morphotectonic development and seismicity of these fundamental structures, introduced in the concluding chapter of his work the term *taphrogenesis*. Derived from the Greek word τάφρος for trench and from γένεσις for formation Krenkel understood taphrogenesis as a process of block-faulting on a regional scale. He compared the East African rift structures with the Rhinegraben and defined taphrogenesis as the formation of grabens, induced by tensional forces.

Graben means ditch or trench in German. Pfannenstiel (1969) reviewed the application of this word in the geological nomenclature. He pointed out that already the old miners in Thuringia used this term for downthrown segments and that J. L. Jordan (1803) was the first to mention grabens in the geological literature. The Rhinegraben in Central Europe, a fault trough which extends from Basel to Francfort through which flows the Upper Rhine river, is considered to be the type structure for all grabens. Here, in 1841, the famous French geologist Elie de Beaumont had recognized that Vosges and Black Forest, forming together a wide-spanned vault, are interrupted along the crest of the vault by the downthrown segment of the Upper Rhine plain. In a sketchy cross-section he had outlined the trough as a wedge-block which subsided along two sets of converging step faults. E. Suess in his well-known manual "Das Antlitz der Erde" 1883 (t. 1, p. 166ff) used the term graben for other fault troughs. From there Anglo-Saxon authors adopted the word and since the beginning of this century graben became an international term in the geological nomenclature. But it was a long and hard course from Elie de Beaumont to modern concepts of graben tectonics. One of the most striking milestones along this road is marked by the publication of Hans Cloos "Hebung — Spaltung — Vulkanismus" in 1939. By means of synthesizing field observations as well as experimental data Cloos established an up-to-date hypothesis on taphrogenesis of the Rhinegraben and of continental rifting in general.

The Rhinegraben is neither the largest nor the most active nor the most typical example for continental grabens. But otherwise there are some particularities in this graben that splits apart the very geographical center of Central Europe. Geoscience departments of eight universities like those of Francfort, Freiburg, Heidelberg and Strasburg and offices of five geological surveys belonging to three different nations are established in the Upper Rhine area. Geologists of many generations have mapped this area and year after year the students arrive to study the famous quarries *mente et malleo* (sometimes only *malleo*). Thousands of bore-holes have penetrated the sedimentary fill of the fault trough. Innumerable geophysical campaigns provided much information of the crust and of the upper mantle beneath the graben segment. Hence the Rhinegraben, its sedimentary fill, its internal and external structures, its root (or anti-root) became as transparent as a glass model for the geologist's eyes.

The International Upper Mantle Project and now the Inter-Union Commission on Geodynamics have stirred up the geologists and geophysicists along the Upper Rhine to see if their graben might be a key for a better understanding of the fundamentals of rifting. French, German and Swiss colleagues joined for studying the legion of facts under the scope of modern ideas. New geophysical, geodetic, geological and petrological investigations were started, most generously supported by the *Deutsche Forschungsgemeinschaft*. The Rhinegraben Research Group had just presented two symposia: "The Rhinegraben Progress Report" (1967), and "Graben Problems" (1970). This submitted third part of the Rhinegraben trilogy has been focussed under modern geodynamic concepts like plate tectonics. Primarily, it comprises new data concerning the Western European rift systems, adds new contributions on the mechanics of rifting as derived from observations in that rift belt and also comprises additional studies as required for a better understanding of the continental rifting in general.

The significant physiography of continental grabens is marked by a parallelism of the framing fault scarps. The variation in width ranges from some ten meters of smaller graben splinters to the several hundred kilometers width of the Red Sea rift system. An individual, average width between both master faults seems to be a specific attribute to nearly all graben segments. This regularity is emphasized by sharp curves of the main trend. Thus, a change in the direction of one escarpment is closely followed by a corresponding change on the opposite side, causing the woodcut-like contours of graben systems. The width of the Rhinegraben is 36 km, its length 300 km. The marginal main faults are normal faults. Their dip, measured in numerous outcrops and bore-holes, ranges between 55° and 80°. Near the surface, the most frequent values are 60°—65° (Fig. 1). By means of geophysical observations, a slight, listric configuration with a concave curve downward may be suggested (see ERLINGHAGEN & DOHR, p. 143).

The subsidence of a graben block of the described configuration implies a corresponding lateral dilatation, a yielding of the framing abutments. Such a

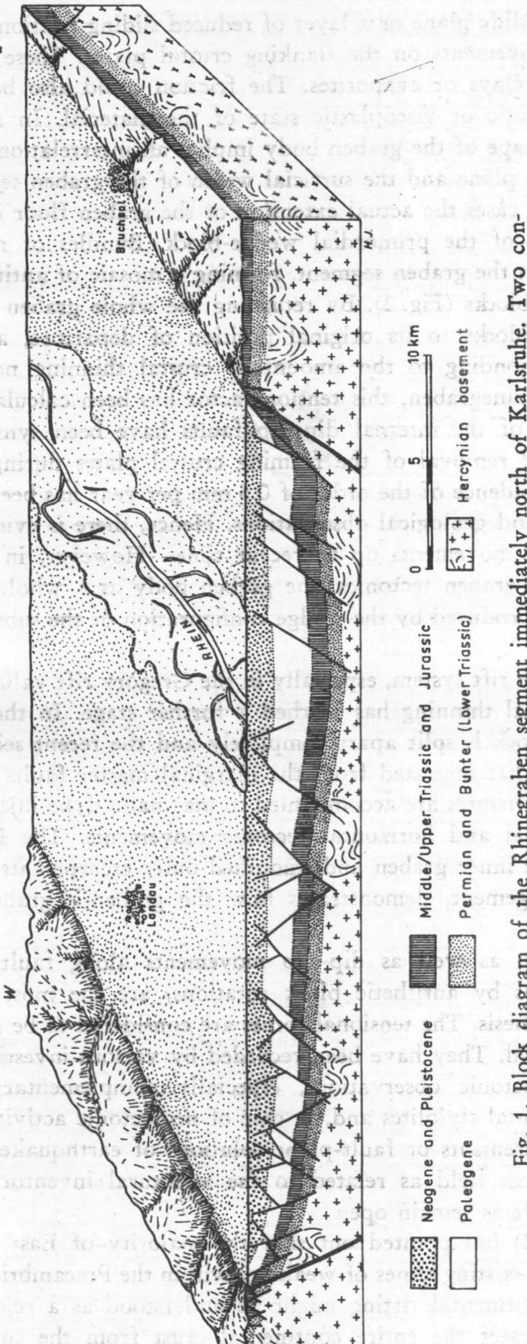

Fig. 1. Block diagram of the Rhinegraben segment immediately north of Karlsruhe. Two converging master faults are bordering the 36 km wide graben area. The graben segment itself is splintered into numerous special blocks, primarily of antithetic character. The graben is framed by elevated shoulders, the Pfälzerwald mountains on the left side and the Kraichgau hills on the right side.

movement requires a slide plane or a layer of reduced sliding friction to take over horizontal gliding movements on the flanking crustal plates. These layers might be sediments such as clays or evaporites. The friction could also be reduced by moisture, or a magmatic or viscoplastic state of the material. In any case, the original, triangular shape of the graben body implies an interrelationship between the depth of the slide plane and the surficial width of the graben segment.

However, in most cases the actual extension of the graben floor is larger than the theoretical width of the primordial wedge-block. Bundles of normal faults generally have splitten the graben segment, forming a mosaic of antithetic or synthetic narrow, tilted blocks (Fig. 2). By returning the whole graben segment and its internal, rotated blocks to its original position of departure, a lateral gap remains open, corresponding to the amount of crustal thinning normal to the graben axis. In the Rhinegraben, this tension factor has been calculated to be of about 4.8 km. Many of the internal dip-slip faults have been synsedimentarily activated by a lateral removal of the framing crustal plates during the graben formation. Active subsidence of the order of 0.5 mm per year has been ascertained by precise levellings and geological observations. Hence, there is evidence for the continuity of dilative movements up to recent times. However, in spite of the tensional character of graben tectonics, the graben body as a whole is subjected to a relative pressure produced by the wedge configuration of the subsiding graben segment.

In the East African rift system, especially in the Gregory rift valley and in the Afar depression, crustal thinning has reached a further stage. In these segments, the primary wedge-block is split apart completely and the recent seismo-tectonic and volcanic activity has migrated from the marginal master faults to the inner graben. There, gaping fissures are accompanied to magmatic dyke injections, steam jets, and rapid vertical and horizontal tectonic movements. The Red Sea rift system, with its active inner graben and smoothed outer escarpments of bilateral, mirror-inverted arrangement, demonstrates how the graben-in-graben evolution proceeds.

Tensional ruptures, as well as dip-slip movements along fault planes and closure of lateral gaps by antithetic block rotations, are the most conspicuous symptoms of taphrogenesis. The tensional forces are considered to be a component of a regional stress field. They have been recorded by various investigations, e. g. by means of microtectonic observations, especially complementary strike-slip movements, by horizontal stylolites and, in case of neotectonic activity, by means of in situ stress measurements or fault-plane solutions of earthquakes. Taking in mind the regional stress field as related to the structural inventory of graben tectonics, several problems remain open.

McConnell (1972) has pointed out that the majority of East African rift segments followed pre-existing zones of weakness within the Precambrian basement. He concluded that continental rifting might be understood as a rejuvenation of lineaments which intersect the entire continental crust from the surface to the upper mantle. Illies (1972) has shown that the Rhinegraben rift system is accom-

Fig. 2. The Rhinegraben escarpment near Baden-Baden, view to the north. In the front is the clay pit of the Hourdis brick field with Pechelbronn beds of Lower Oligocene age. The clay serie which belongs to the basal sequence of the graben fill, is down-warped grabenward and slashed by a bundle of 2nd order faults splintering off the master fault which follows 50 m right of the clay pit (not seen on the picture). The range right in the background marks the elevated graben shoulder and is formed by the Bunter (Lower Triassic). The cross-section along the wall of the clay pit corresponds almost exactly to the vibroseis profile fig. 3 published in the article of ERLINGHAGEN & DOHR (p. 143).
Phot. Nov. 1972.

panied by old shear zones in the Hercynian basement which had facilitated and locally attracted the Cenozoic graben faulting. In some parts the rifting carefully followed the tracks of crustal instability. The functional interdependence between old lineaments and its revived opening under the changed realm of neotectonics is evident. This is predominantly the case when pre-existent zones of weakness are congruent to the potential fault components of the taphrogenic stress field. But the question, whether or not the lineaments have caused the rift process, cannot yet be answered. We still have to consider the grossly different tectonic realm under which the renewed tectonism was initiated.

The Rhinegraben is the central segment of a meridional rift belt which traverses the Western European continent. In addition, this system is part of an extended rift system that intersects the whole Old World from the North Sea to Southeast Africa. The total length of this intercontinental rift belt amounts to more than 9000 km. In spite of the different lithological composition, the different geological pre-history, the different tectonic framework of the crust slashed through by rifting, all graben segments in Western Europe, Near East and East Africa appear very similar in their physiographic features, structural patterns, geophysical properties, seismic activities, and volcanic extrusions. Taphrogenesis has been governed by the same construction formula throughout the entire rift belt. Even the predominant strike of the rift segments and transform elements followed a superordinated trend, and a phasic consonance or contemporaneity in geologic time of subsidence activities seems evident. A global control and an interdependent tectonic realm must be assumed. This realm used the old fracture pattern within the continental plates and revived the weakness zones to new sub-plate boundaries.

The question, whether action or reaction initiated the formation of grabens, is based upon the explanation of the origin of the "basaltic swells" or "cushions" of mantle-derived material underneath some continental graben segments. In several chapters of this book new seismic refraction data concerning the rift "cushion", which accompanies the Rhinegraben and the Limagne graben are presented. It has been suggested that a swell of upsurging substratum below the crust split the overlying sialic shell, uplifted the graben shoulders and induced the graben volcanism. The Cenozoic Rhinegraben volcanism is predominantly an olivine-nephelinitic realm, locally of melilite-ankaratritic character and derives primarily from a depth of about 80—100 km. Thus, it seems conclusive that upwelling material of the upper mantle has induced the taphrogenic cycle. On the other hand, it had been discussed that the old weakness zones have induced the ascent of the magmatic substratum. No doubt, an interplay between the beaten tracks of lineaments within the rigid lithosphere and the ascending tendencies within a plastic layer of the upper mantle, the asthenosphere, have influenced this kind of rifting. Potassium-argon ages of volcanic rocks of the Rhinegraben area, published by LIPPOLT et al. (p. 213), reveal evidence that the mantle-derived magmatic activity started considerably earlier than the surficial graben tectonism. Under this aspect, the taphrogenic action started from the upper mantle, but it was related to inequalities and anisotropies of the crustal rigidity.

The development of a graben tectogene within a crustal plate overlying an upwelling magma cushion may be explained by dilatation as a result of arching along the crest of the rising crustal dome. This single mechanism cannot explain a horizontal displacement of the graben's lateral abutments of about 5 km. To explain the observed dilatation, an additional criterion must be required. According to the interpretation of the anomalous heat flow values in the Rhinegraben area and the P-wave velocities in the lower crust, it is suggested that basal crustal layers of a non-rigid state overlie the swell of mantle material. A mechanical decoupling of the crust from the mantle by a separation along a glide-surface can be concluded. This glide plane follows the "cushion" surface and dips with a gradient increasing to 10° normal to the graben axis. Seismic reflection data has revealed a zone of laminated texture in the lower crust indicating a state of laminar plastic flow. From these observations, one may conclude that the crustal plates upwarped at both marginal faults of the Rhinegraben drifted apart by gravity sliding. Hence, it follows that the tectonic style of block faulting along both graben rims and the internal dip-slip faults reveal remarkable similarities to downslope creep structures in large slump areas, both with the typical, listric