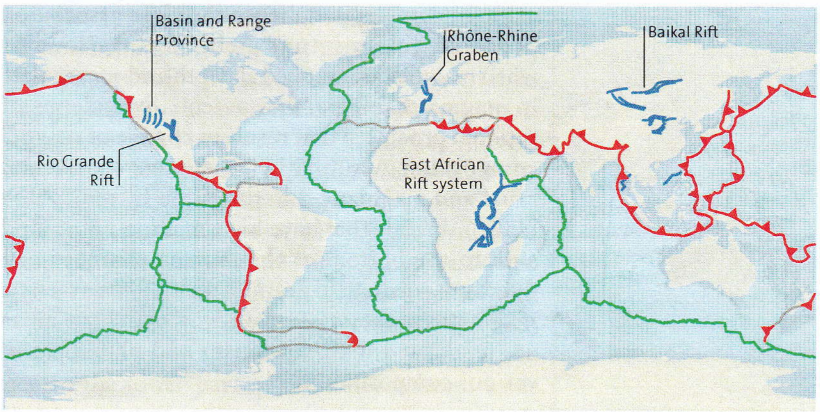
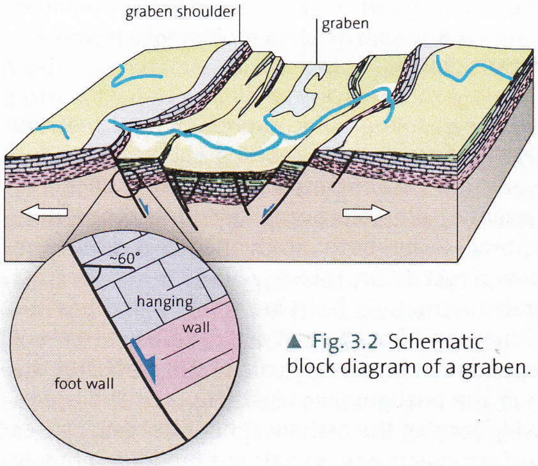
# Continental graben structures

A continental graben structure or rift is a narrow, elongated, fault-bounded structure in the Earth's crust (**Fig. 3.1**). Grabens consist of a central axial depression flanked by steep walls and elevated shoulders that plunge steeply into the rift axis and slope gradually towards the exterior (Fig. 3.2). The most famous example is the East African rift system. Rift systems may be cut and apparently offset by transform faults; examples include the Upper Rhine Graben in Central Europe and its southern continuation in the Bresse and Rhône grabens (see below). Graben structures occur in regions where the crust and lithospheric mantle are extended and thinned (**Fig. 3.3**). Broad regions of extension are typically expressed by numerous grabens and intervening higher horst blocks such as the Basin and Range Province in western North America. Graben systems also occur in oceanic crust along mid-ocean ridge systems and will be discussed in Chapter 5.

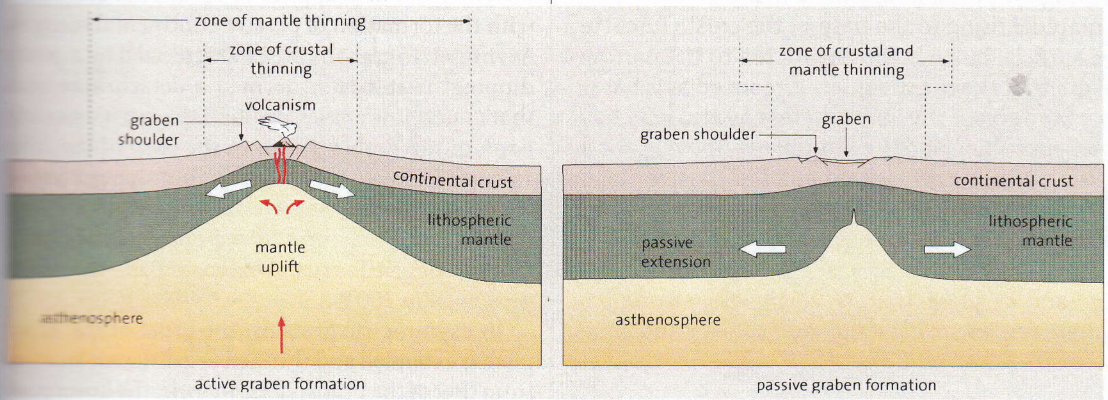
The amount of extension across a graben varies considerably ranging between approximately 5 km across the Upper Rhine Graben to 50 km across the Rio Grande Rift in New Mexico. The brittle extension, generated by fracturing associated with earthquake activity in the upper crust, extends downward to a depth of approximately 15 km. At greater depths, ductile flow occurs without fracturing the rocks; rather, deformation takes place as solid-state plastic flow. Graben subsidence is accommodated along normal faults that dip towards the central graben axis at angles of 60 to 65° (Fig. 3.2): the hanging wall, the block located above any point of the fault plane, moves downwards with respect to the foot wall and causes the subsidence of the graben. Normal faulting is linked to horizontal extension orthogonal to the graben axis.




▲ Fig. 3.1 Tectonic map of Earth showing large, young graben systems.




▲ Fig. 3.2 Schematic block diagram of a graben.




◀ Fig. 3.3 Main characteristics of active and passive graben systems (Condie, 1997).

In continental settings, as the lithosphere extends, the asthenosphere tends to rise (**Fig. 3.3**) and heat-flow rate increases; as a consequence, melting in the uppermost asthenosphere or overlying lithospheric mantle may occur. The melts penetrate the crust and feed volcanoes at the surface or form magma chambers at depth. Because the magmas are derived directly from the mantle, they are basaltic in composition, hence the close association of basaltic volcanism and graben rifting. However, when magmas are trapped at depth and accumulate in magma chambers, they potentially undergo additional processes that result in change of magma composition. Assimilation of adjacent continental crust and magmatic differentiation by removal of mafic minerals that have high melting points and sink to the bottom of the magma chamber produce intermediate to granitic melts. These various magmatic processes explain why many rift areas are associated with volcanism and plutonism of various compositions.

### Active and passive graben structures

Based on the relations between topographic expression and method of formation, Condie (1997) defined two classes of grabens, active and passive (**Fig. 3.3**). *Active grabens* are generated by upwelling of the asthenosphere, commonly over hotspots; the overlying mantle lithosphere and crust respond to this process and both are thinned as a result. The mantle lithosphere and lower crust deform plastically and the upper crust is faulted to form the graben structure; both are thinned and basaltic volcanism is generated. Extension of crust at an active graben structure is much wider in the deeper ductilely reacting part of the crust and the lithospheric mantle than in the brittle upper crust (**Fig. 3.3**; Thompson and Gibson, 1994). The wide zone of the asthenospheric doming causes the bulge of the Earth's surface at active rifts to also be broad, commonly several hundred kilometers wide.

At *passive graben structures*, extensional forces are the primary cause. Initially, the extension is limited to the narrow zone of the rift, both in the deeper crust and in the lithospheric mantle (**Fig. 3.3**). This process can result in the complete tearing off of the lithospheric mantle which then leads to asthenospheric material rising to the base of the crust (Turcotte and Emerman, 1983). The surficial bulge is thus restricted to the narrow graben zone and thermal uplift of the rift shoulders is reduced as is basaltic magmatism. However, extension of the lithosphere may also lead to a wider updoming of the asthenosphere and the lithosphere above. Thus a passive rift may change into an active rift system and the passive stage is no longer detectable. Although most present graben systems seem to be active rifts, it is assumed that both processes, updoming and crustal extension, act together. The primary reason for the graben formation is thus an academic chicken-and-egg question. Nevertheless, strong updoming of the asthenosphere causes strong magmatic activity and wide graben shoulders.

## Symmetric and asymmetric crustal extension

Crustal extension is believed to occur in two different modes symmetric (McKenzie, 1978) and asymmetric (Wernicke, 1981); models have been proposed for each. The *symmetric model* is based on many present graben systems (**Fig. 3.4a**). It assumes symmetric, brittle extension of the crust along normal faults in the upper 10 to 15 km, and ductile deformation at depth. Both the crust and lithosphere thin accordingly. Crustal thinning and brittle deformation cause the surface of the Earth to subside and generate the graben morphology.

If a 30 km-wide strip of 30 km-thick crust is stretched by 5 km, the resulting stretched crustal section has thickness of only 25.7 km. Such a situation is approximated in the southern Upper Rhine Graben. Assuming an original thickness of 100 km for the total lithosphere, the initial 30 km-wide tract is reduced in thickness to 85.7 km following stretching. However, the ascent of hot asthenosphere causes the lower part of the lithospheric mantle to be transformed into asthenosphere. The lithosphere-asthenosphere boundary is defined by thermal and state properties of approximately 1300 °C; it is not a material-based boundary. Therefore, lithospheric mantle can be transformed into asthenosphere by an increase in temperature and vice versa.

The original bulge of the surface, caused by a hot, relatively light bulge of asthenospheric mantle material, leads to erosion at the graben shoulders, a process that also results in a reduction of thickness of the crust. Thermal subsidence is developed after the heat source disappears and the mantle bulge cools and increases in density. The area of subsidence broadens because the area of mantle uplift is generally two to three times wider than the graben structure. Therefore, old inactive graben structures may have morphologically unobtrusive shoulders.

The *asymmetric model* of graben formation was initially developed for the Basin and Range Province but also applies to some rifts associated with the formation of passive continental margins. Asymmetric grabens are characterized by a gently dipping master fault, termed a detachment fault, that cuts at low angles through the crust from one flank of the graben down to the base of the lithosphere (**Fig. 3.4b**). The overriding upper plate of the detachment is characterized by steeply inclined normal faults that form in response to the extreme amount of brittle crustal extension, in some cases greater than 200 %.

In asymmetric grabens, the crust of the upper plate is extended and thinned at a different location from that of the lithospheric mantle, the lower plate of the detachment (Fig. 3.4b). This asymmetry gives rise to the following morphology: above the area of crustal thinning, the surface subsides because light crustal material is replaced by denser mantle material; above the area of lithospheric mantle thinning, the surface bulges because lithospheric mantle is replaced by slightly less dense, hotter asthenospheric material. In some cases, the bulge brings lower crustal material rapidly to the surface.

The asymmetric model has not been identified in a simple graben system (Roberts and Yielding, 1994), but rather has been used to explain wide areas of extension such as the Basin and Range Province in the western USA. Such asymmetric areas of extension are connected to the uplift of metamorphic domes that will be discussed below.

In asymmetric rift zones, the zones of crustal and lithospheric-mantle thinning overlap but are offset whereas in symmetric rift zones they coincide. However, subsidence by crustal thinning is much greater because the difference in density between crust and mantle is much greater than that between lithospheric and asthenospheric mantle.

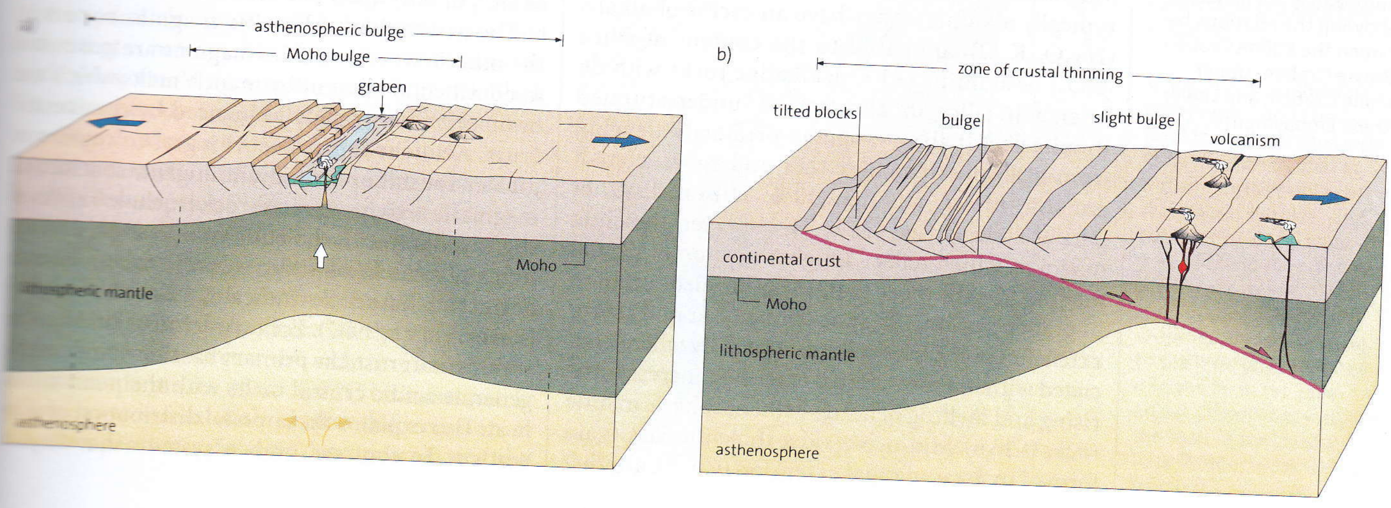
## Sediments and ore deposits in graben structures

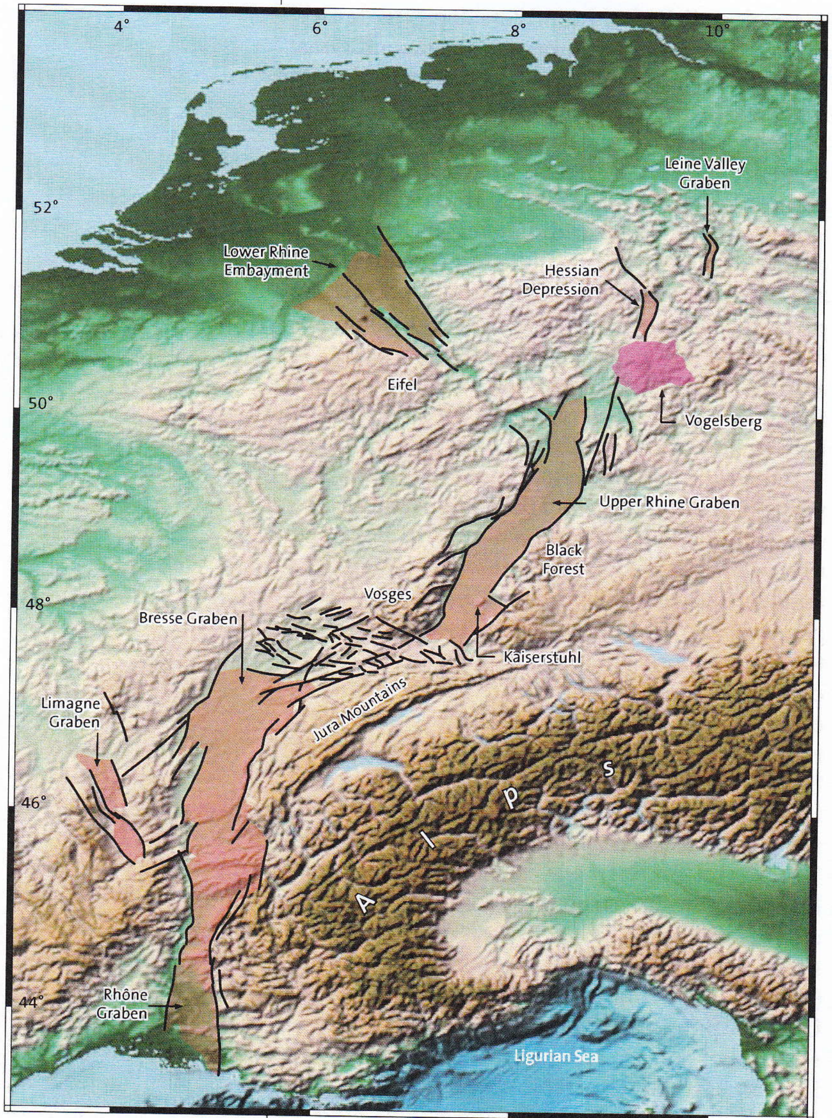
Typically sediments in graben structures are characterized by immature terrestrial deposits that are deposited by rivers that source the steep flank of the graben shoulder. Immature sediments are characterized by an abundance of mineral grains and rock fragments. Normally such minerals are readily weathered prior to reaching the site of deposition but because of the steep topography and short transport distance, they survive the sedimentary cycle in grabens. Many fluviatile sediments in graben structures are mostly composed of conglomerates rich in rock fragments and arkoses (sandstones that contain abundant feldspar) and have a relatively low percentage of quartz. Lacustrine deposits are rich in clays and, under arid or semi-arid conditions, saline sediments. Saline lakes, for instance, occur in the East African graben system.

Graben structures may also come under marine influence. Marine sediments in graben structures are mostly mudstone, marl (limy mud) or limestone. Strong evaporation in arid climates where partly or completely isolated basins fill with seawater leads to concentration of salt in the water followed by precipitation of salt. In the Upper Rhine Graben, marine ingressions are indicated by salt deposits. If a graben evolves into a narrow ocean like the Red Sea, saline deposits are typically preserved at the base of the marine sedimentary sequence.

Petroleum and natural gas are important deposits in some continental rift systems. Restricted water circulation in a narrow graben sea may lead to benthonic anoxic conditions where free oxygen is sequestered by the bottom fauna. Lack of oxygen in the lower part of the water column leads to oxygen-poor sediment which in turn prevents decomposition of organic matter. This generates an enrichment of organic material in the sediment and results in characteristic dark gray or black colors. Basin subsidence lowers organic-rich sediment into the so-called petroleum window, a temperature range between approximately 80 and 170 °C. Here petroleum forms by complicated reactions involving the organic matter. At temperatures over approximately 150 °C, gas deposits are formed. Oil shales of Messel that originated in a maar funnel (a volcanic penetration tube) within the subsiding Upper Rhine Graben provide a good example of sapropelic (organic-rich) sediments formed in an isolated basin. The incredible fossils preserved at Messel construe a unique deposit of global importance (UNESCO World Heritage Site) concerning the life of the Eocene.

▼ Fig. 3.4 a) Symmetric and b) asymmetric model for the evolution of a graben system. The asymmetric model also explains the early-stage evolution of metamorphic core complexes. The "Moho" (Mohorovičić discontinuity) is the boundary between the crust and mantle.






▲ Fig. 3.5 Map of the European graben system showing the relations between the Rhône Graben, Bresse Graben, Upper Rhine Graben, and Lower Rhine Embayment.

## Volcanism in graben structures

Magmatic rocks that form in graben structures are typically alkaline – they have an excess of alkalis ($Na_2O$, $K_2O$) compared to the content of silica ($SiO_2$) or alumina ($Al_2O_3$); alkaline rocks with deficiency in silica are also termed "undersaturated in silica". Alkaline magmas primarily develop from lithospheric mantle that undergoes a small amount (mostly less than 10%; Wilson, 1989) of partial melting (see Ch. 6, 7). However, tholeiitic magmas, which reflect a higher portion of partial melting (mostly more than 15%), are also common in graben systems. They accompany a rapid rate of extension of the lithosphere, especially where associated with hot spots. Rapid extension increases the rising and melting of hotter asthenospheric mantle rocks (Ch. 6). Mid-ocean ridge tholeiitic basalts are formed in areas of rapid extension (Ch. 5), another indication that tholeiitic basalts are more important in areas that undergo strong extension of the lithosphere accompanied by increased upwelling and melting of asthenospheric material.

In graben systems such as the East African Graben or the Rio Grande Rift, the alkalinity of melts increases outward from the graben axis towards the rift shoulder. This indicates that melt formation is highest below the graben axis where tholeiitic magmatism is favored. Other graben systems such as the Cenozoic Kenya Graben and the Permian Oslo Graben show a decrease of alkalinity with time that indicates increasing rates of extension and melt formation during the evolution of the graben system (Condie, 1997). The East African graben system shows a shift from alkaline basalts and differentiates in the south at Tanzania and Kenya to tholeiitic basalts to the north in Ethiopia. This pattern parallels the increasing rate of extension from south to north (see below).

Volcanism in graben systems can be bimodal. In the northern Rio Grande Rift, tholeiitic basalts (basic, $SiO_2$ content of about 50 weight-%) occur beside rhyolites (acidic, $SiO_2$ content of about 70 weight-%). Intermediate rocks with $SiO_2$ contents in between are missing, however. This is not explainable through simple differentiation of an original basaltic magma. The East African Rift is dominated by alkali basalts ($SiO_2$ content less than 50%), phonolites (about 55% $SiO_2$, but very high content of alkalis: $Na_2O$ along with $K_2O$ about 12–14%), and trachytes (about 65% $SiO_2$ alkalis about 10-12%). Phonolites develop by differentiation from alkali basalts that are substantially undersaturated in silica; however, trachytes develop from less strongly undersaturated alkali basalts. Carbonatites also occur in rift systems. These are carbonate rocks that are derived directly from the Earth's mantle and are composed of calcite or dolomite with an accompanying extremely low content of $SiO_2$ of only a few percent.

The generation of basaltic magmas occurs in the mantle whereas acidic magmas are generated in continental crust or by mantle melts which are, in most cases, strongly influenced by continental crust. Acidic magmas occur in graben regions of greater crustal extension and higher, continuous magmatic activity. Igneous rocks include basalts of slightly alkaline or tholeiitic composition, and significant volumes of acidic volcanic rocks; absence of intermediate rocks indicates a clear bimodality (Barberi et al., 1982). Following intrusion into the continental crust, the primary basaltic mantle melts generate acidic crustal melts with their enormous heat. This explains the bimodal distribution of magmatism. In contrast, graben systems that display little crustal extension are characterized by low magma production, interrupted volcanic activity, and strongly silica-undersaturated alkali basalts; intermediate and acidic rocks are rare.

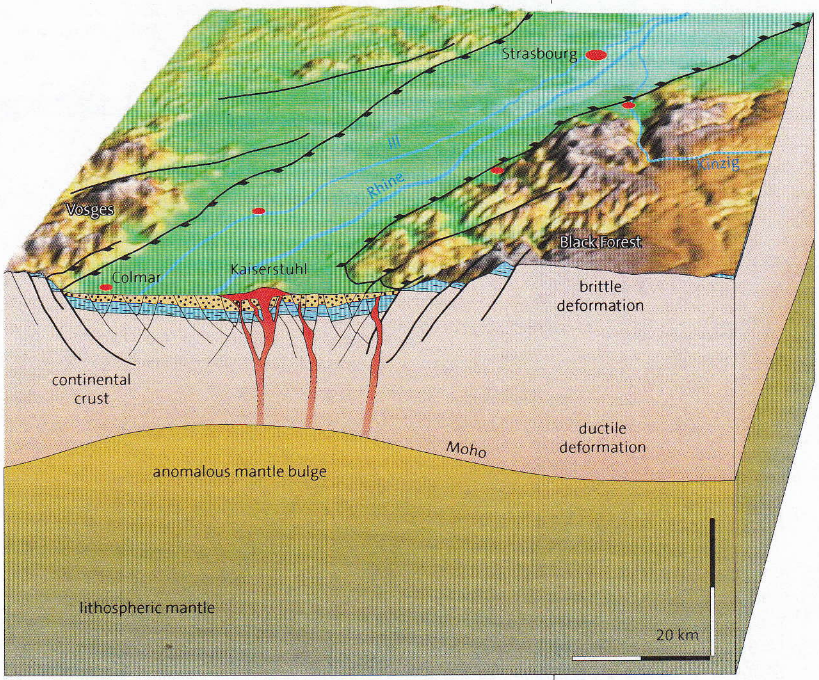
## The Upper Rhine Graben in Germany

Although the Upper Rhine Graben in Germany is not one of the largest nor most active graben systems, it is along with the East African graben system a type locality for the study of graben systems. The term "graben" (*German* ditch) was used by miners for blocks that were dropped down at faults (Pfannenstiel, 1969) and was introduced into the geologic literature by Jordan (1803). Élie de Beaumont (1841) was the first geologist to describe the Rhine Graben. He understood that the facing Vosges and the Black Forest regions were broad, plateau-like uplifts separated from each other by the Upper Rhine River plain (**Fig. 3.5**). He further noted that the Rhine plain was down-dropped and bounded by parallel faults that had dip directions towards each other. This is the classic geometry of a graben system. The acceptance of the term "graben" in scientific literature was solidified by the classic work "Das Antlitz der Erde" ("The Face of the Earth") by Eduard Suess (1885–1909).

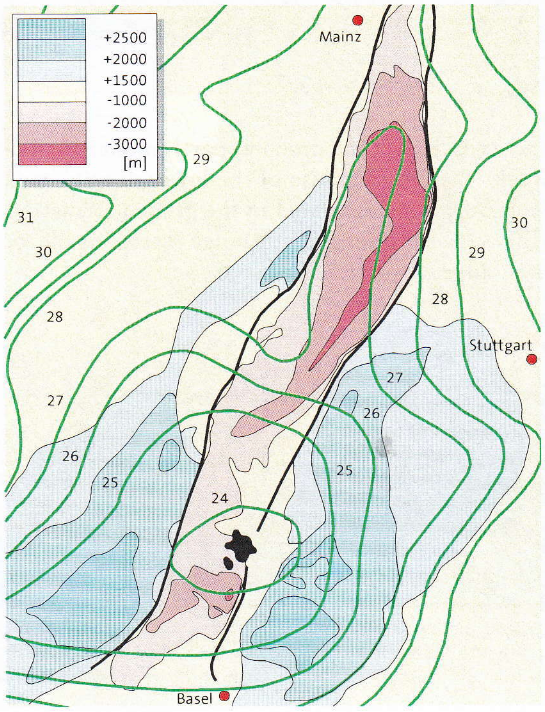
The Upper Rhine Graben extends more than 300 km from Basel (Switzerland) to Frankfurt (Germany) and forms a part of a larger fracture system that runs from the mouth of the Rhône River to the North Sea (**Fig. 3.5**). The bordering faults have dip angles that range from 55 and 85° near the surface; however, a majority of the faults dip between 60 and 65°. The faults at the flanks are parallel and all faults dip towards the center of the graben and decrease in inclination at depth. The graben has a fairly constant width of approximately 36 km with a crustal extension of approximately 5 km (Illies, 1974a). Crustal thinning is 6–7 km maximum and the continental crust in the southern part of the graben is thinned to 24 km (**Figs. 3.6, 3.7**). The graben parallels the axis of an elongated, stretched bulge that is mirrored in the graben shoulders on both sides, the Vosges to the west and the Black Forest to the east. Regionally, the graben shoulders are tilted 2–4° away from the graben.

The presently active earthquake foci occur mostly at a depth of less than 15 km. This indicates that brittle faults disappear at depth, and the crustal rocks below are deformed ductilely and not fractured. Ductile deformation of rocks rich in quartz (most of the rocks of the continental upper and middle crust are rich in quartz) initiates at temperatures of ca. 300 °C because quartz reacts from stress with plastic deformation at these temperatures. Seismic data indicate that the lower crust, dominated by rocks poor in quartz or without quartz, also reacts ductilely because of the higher temperatures; a pervasive horizontal lamination is interpreted to be the result of plastic flow (Illies, 1974a).

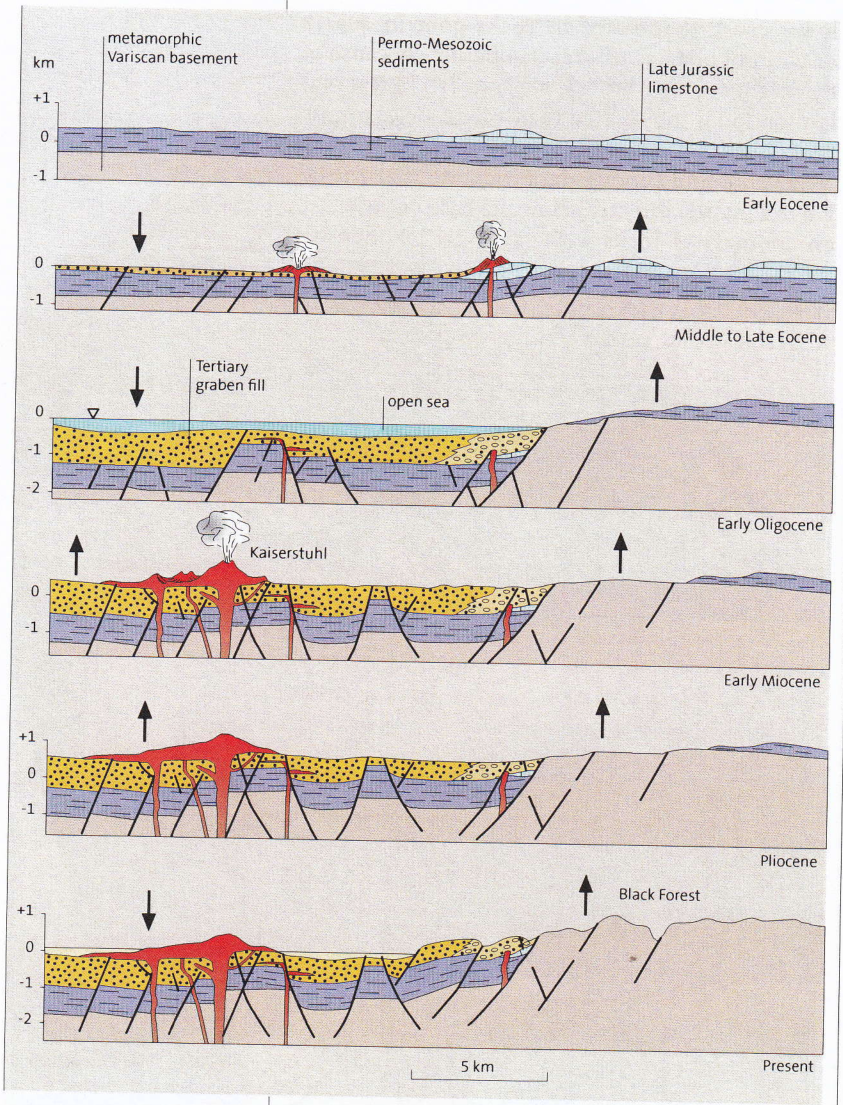
Seismic and gravity data indicate that in the Earth's mantle directly below the base of the crust, an anomaly of rocks with relatively low density




▲ **Fig. 3.6** Block diagram of the Upper Rhine Graben. Note that the upper crust is characterized by normal faults whereas the deeper crust is ductilely extended (by plastic, fractureless deformation). The Kaiserstuhl is a Miocene volcano.




◀ **Fig. 3.7** Map showing topographic and structural features of the Upper Rhine Graben as well as the amounts of uplift of the graben shoulder and subsidence in the inner part of the graben. Colored areas indicate the present level of the Early Tertiary erosional surface relative to sea level (extrapolated into the air in the blue areas). Green lines indicate the level of the crustal base (Moho) in kilometers below the sea level.




◀ Fig. 3.8 A series of cross sections showing the evolution of the southern Upper Rhine Graben in the area of the Kaiserstuhl volcano (Schreiner, 1977).

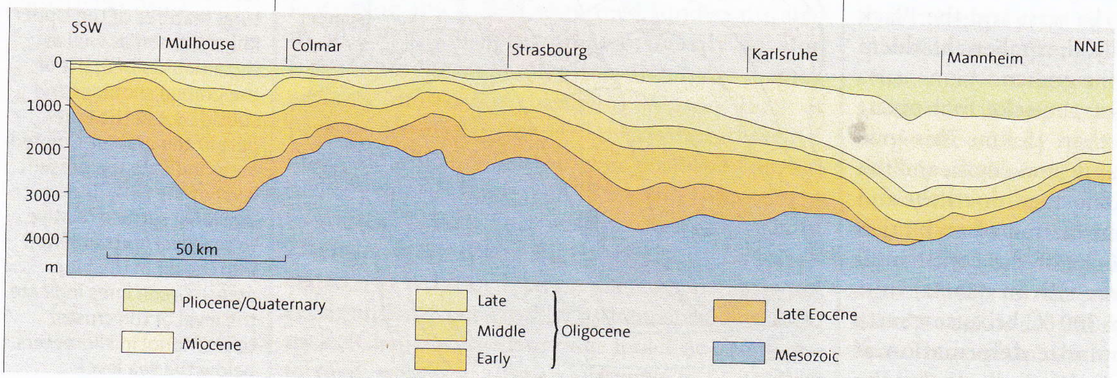
exists. Here, hot and probably partly molten mantle rocks that rise because of the lower density, feed volcanism that is related to the graben formation. This suggests that a mantle bulge is responsible for the bulge of the crust (**Fig. 3.6**).

Formation of the graben, as indicated by initial normal faults, started in the Eocene at ca. 45 Ma. The first sediments were deposited in the downthrown graben block. Extensional forces orthogonal to the graben axis enabled the opening of the graben.

Today, the surface bulge extends more than 200 km orthogonal to the graben axis. Uplift of the graben shoulders varies regionally. More than 2 km of uplift have been documented along the southern end. There, the pre-Tertiary peneplain erosional surface (eroded today) would be more than 2500 m above sea level (**Fig. 3.7**; Illies, 1974b). Total structural displacement across the graben varies from more than 5 km in the south to 4 km in the north. The graben shoulders are not significantly developed in the northern part, although the subsidence of the graben is generally greater and the Tertiary sedimentary fill has a thickness of more than 3 km. The result is a significant topographic gradient parallel to the graben axis. As explained below, subsidence of the northern part occurred distinctly later than that of the southern part.

## The history of the Upper Rhine Graben

The Upper Rhine Graben has been filled with nearly 20,000 km³ of Tertiary sediments (Roll, 1979). Most sedimentary rocks, both pre- and syn-rift, are eroded from the area of the graben shoulders. Along the edges of the graben, coarse-grained clastic sedimentary rocks include conglomerate and immature sandstone. The graben center is dominated by finer-grained clastic sedimentary rocks including siltstone and mudstone; non-clastics include limestone, dolomite, marl, and evaporites (salt rocks). Marine incursions generated saline to brackish conditions. During arid periods, evaporite



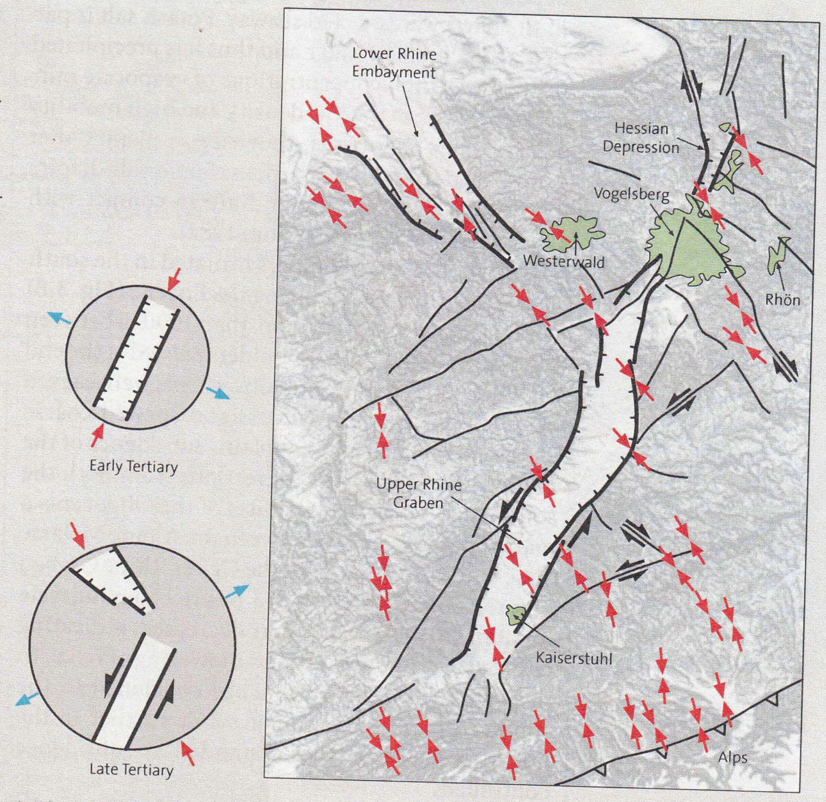

◀ Fig. 3.9 Thickness of sediments in the Upper Rhine Graben in a profile parallel to the graben axis (Pflug, 1982). Differences in the sedimentary thickness indicate that graben formation initiated in the southern area during the Early Tertiary, and that subsidence migrated to the north during the Late Tertiary.

### The Upper Rhine Graben in the Middle European stress field

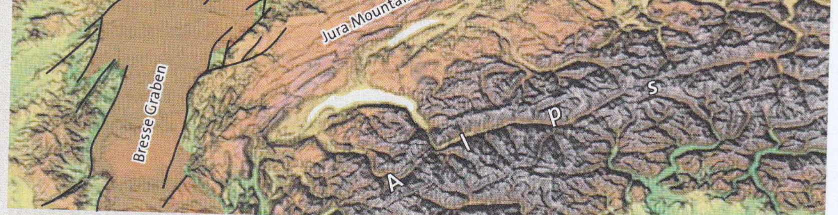
Presently the extensional forces in the Upper Rhine Graben are oblique (SW-NE, with an azimuth of 050–060°) and not orthogonal to the graben axis. Consequently, the principal axis of compression is not parallel but oblique to the graben axis (NW-SE or 140–150°; **Fig. 3.10**). However, when the graben formed, the extensional forces acted orthogonal to the graben. An anticlockwise rotation of the stress field occurred during the evolution of the graben system during the Late Tertiary and caused a left-lateral component to develop that overprinted the normal faults. Therefore, as the Vosges and Black Forest diverged, the Vosges also moved parallel to the graben, southward in relation to the Black Forest (**Fig. 3.10**).

The northern continuation of the Upper Rhine Graben trends along the Lower Rhine Embayment (Fig. 3.10). Neither a mantle bulge nor graben shoulders occur in this region. The graben system varies in width and opens towards the NW. Throughout its development, the extensional stress has been orthogonal to the Lower Rhine Embayment since the Early Miocene. The missing mantle bulge indicates that it is a passive rift structure and that extensional forces are the primary cause for the graben development.

The southern continuation of the Upper Rhine Graben, the Bresse Graben occurs approximately 120 km to the west (**Fig. 3.11**). As in the Upper Rhine Graben, subsidence in the Bresse Graben ceased during the Early Miocene. Offset between the Upper Rhine Graben and Bresse Graben is only apparent; in fact, the distance between the two graben segments remained unchanged since their formation. The situation is that of a transform fault, although such a fault is not developed as one distinct fracture. Rather, the rift structure is transformed by a complex system of mostly W-E trending minor faults linking the Upper Rhine Graben and the Bresse Graben (**Fig. 3.11**). The individual faults in the transformation zone carry out left-lateral (sinistral) offset (see box in Fig. 3.11).




▲ Fig. 3.10 Directions of the present maximum horizontal stress (red arrows) in the Upper Rhine Graben and Lower Rhine Embayment (Blundell et al., 1992). The change in the orientation of the stress field is shown in the two schematic diagrams. The older stress field caused the formation of the Upper Rhine Graben, the younger one led to the formation of the Lower Rhine Embayment and to left-lateral movements in the Upper Rhine Graben. Volcanoes related to the graben formation are shown in green.




▲ Fig.3.11 Map showing the transition zone from the Upper Rhine Graben into the Bresse Graben. The transition is accomplished by a bundle of faults that in total mark the locus of a transform fault. A simplistic representation of the connection between the two graben structures is shown in the insert. The distance between the two graben axes remained unchanged through the course of time.