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Mechanisms driving basin fill architecture in extensional and transtensional alluvial basins

(Mechanismy řídící geometrii výplně extenzních a transtenzních aluviálních pánví)

Bakalářská práce

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Contents

1 Introduction

This thesis is dedicated to mechanisms driving basin fill architecture in extensional and transtensional alluvial settings. Because of the great diversity of natural background factors a highly simplified approach has to be applied reducing the scope to simple intracontinental extension and strike-slip environments. Following the principle of actualism data from both ancient and modern basins are discussed. After a brief summary of sedimentary basins and their settings a short introduction to both types of the alluvial basins follows. At the end of this thesis an overview of major contemporary concepts and their historical perspectives is presented. Attached case studies and illustrations were selected to further illustrate the notions described. The thesis aims to present a generalised picture of the current state of our understanding in this area.

According to various definitions a sedimentary basin is described as a place of large accumulation of sediments. Some authors add the further requirement of the sediment‘s ability to be preserved for long periods of geological time (Einsele, 1992) or strive to specify basin‘s extent by attaching an area requirement of thousands to millions of square kilometres (Nichols, 1999), other expand the definition by adding lithospheric processes as the main driving mechanism (Allen and Allen, 2005). Somehow distinctive position among those complementary statements is taken by industrial definitions, which also look into the hydrocarbon potential of such accumulations (Glossary of petroleum Industry, 2010). All the cited descriptions are conspicuously vague, accentuating the complexity of this term.

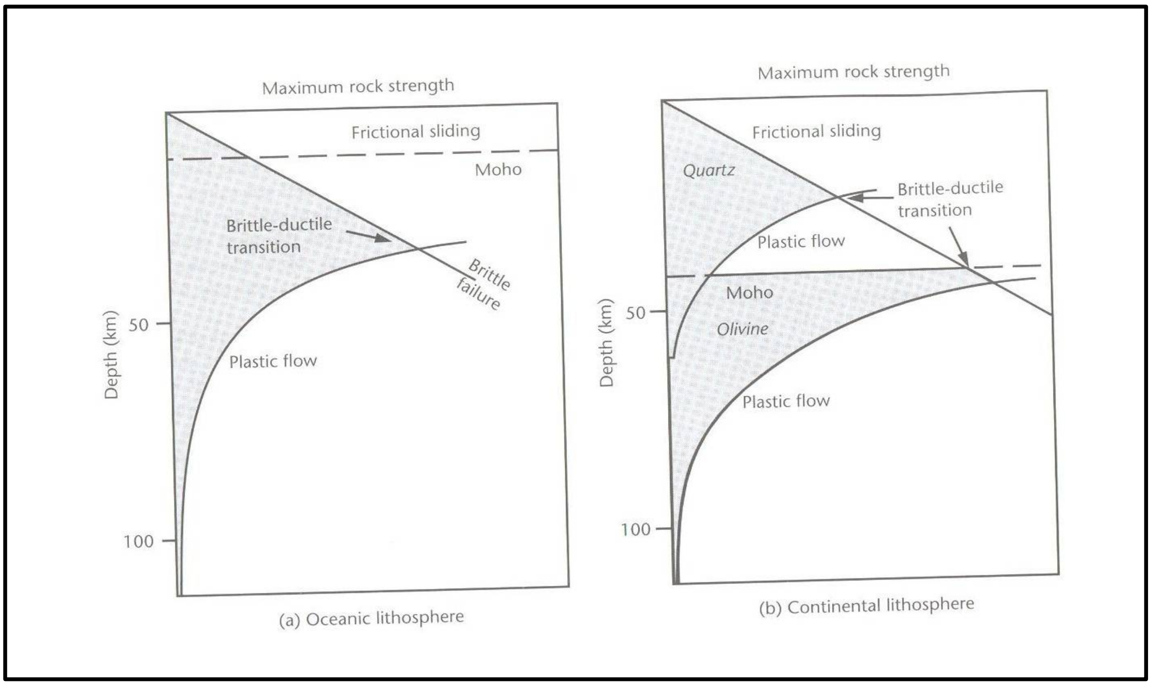
It is a universally acknowledged concept that the majority of observable geological phenomena on the surface of the Earth are the result of plate tectonics. The formation of sedimentary basins is no exception from this rule. In fact, their driving mechanisms are indeed related to the lithosphere (Nichols, 1999). Therefore, it is no surprise that geologic classification of sedimentary basins is more or less derived from the position with respect to the plate boundaries, the type of underlying lithospheric substratum and the lithospheric processes acting closest to the basin (Allen and Allen, 2005). The first typology covers simply the fact, whether the basin lies at the plate margin or is located somewhere in the less active part of the plate, the second typology comprehends types of the crust ranging from oceanic to continental, and the last discerns the ways in which ductile lithospheric behaviour can respond to stress, which is either by stretching or bending. The simplest division could be obtained by ordering basins according to their tectonic settings. Then we get four groups of the settings, i.e. divergent, convergent, transform and indeed hybrid one. Many distinct basin styles can be recognised amid those primary settings. Some authors simplify the situation by naming only nine major types of basins (Nichols, 1999), but some augment it further to twenty-six different basin types by including also the intraplate scenario (Ingersoll and Busby, 1995 in Allen and Allen, 2005). Fundamental lithospheric processes generating the necessary subsidence can be divided into three groups: the isostatic effects, flexural effects, and so called dynamic effects meaning the astenospheric mantle convection (Allen and Allen, 2005). Isostatic effects in reaction to thinning or thickening of the crustal or lithospheric thickness can be observed, for example, on passive margins or in the intracratonic basins, whereas loading of the crust and resultant flexure is the driving mechanism for both types of foreland basins. All three factors usually act upon any basin, and it is important to discern the dominant one. No classification, however, is capable to distinguish the plethora of natural scenarios. The divisions should be therefore considered more of a guideline to help us along the way to describe each basin in its unique entirety.

2 Continental settings in the framework of plate tectonics

For the study of sedimentary basins processes occurring in the lithosphere, the rigid outer shell of the Earth, are essential. Lithosphere, by its definition, constitutes of the crust and the upper part of rigid mantle underneath. Its thermal structure is dominated by conduction, which in turn influences the heat distribution within. Due to its characteristic rheological properties lithosphere can in general accommodate elastic strain over long periods of time, and is studied predominantly by seismology, seismics, and other geophysical methods. Lithospheric plates are flat bodies with their width/thickness ratio much below unity. Therefore they are highly resistant to torsion about steeply inclined axis but are easily deformed by bending about horizontal axis (Allen and Allen, 2005). The resistance to bending of a thin elastic plate overlying a weak fluid, a model commonly used for plate tectonics, is expressed by elastic parameter called the flexural rigidity (Lowrie, 1997). Movements within plates can be observed either by inspecting the subtle change occurring within triangulation networks or with the help of a modern GPS technology.

Many comparisons of the behaviour between oceanic and continental lithosphere have been made, the simplest being that of a brittle-ductile transition for certain major minerals, olivine and quartz respectively (Allen and Allen, 2005; see also Fig. 1). Even the results of such simplifications nevertheless reveal some important properties. While quartz approximated continental lithosphere is less strong than oceanic one and would bend easier given the same thermal gradient, it is also much cooler, which in turn renders it harder to bend. Continental crust and underlying lithosphere have relatively more complex structure when compared to their oceanic counterparts. Continental crust averages 30-40 Km in thickness (Allen and Allen, 2005), which is much more than the mean oceanic crust value, and it is more complexly layered too (Lowrie, 1997). Under continents the lithosphere is poorly defined with estimates of 100 to 250 Km deep boundary (Allen and Allen, 2005). It is rigid, meaning it behaves as a coherent plate, but only the upper parts can retain elastic stresses over geological timescales. The rheological zonation goes from rigid upper crust through middle zone, where creep processes relax elastic stresses near the Moho, to the upper mantle where strength increases again (Lowrie, 1997). The most important result being that the middle aseismic zone is also the level of detachment for major upper crustal faults (Allen and Allen, 2005), which directly affect the near surface conditions. In general the continental crust is weaker when extensional stresses are applied (Allen and Allen, 2005).

Fig. 1. Strength profiles for the oceanic a) and continental b) lithosphere from Allen and Allen (2005). The oceanic lithosphere is modelled with the properties of olivine, whereas the continental is modelled using two-mineral model of quartz and olivine. The yield strength is plotted as a function of depth showing brittle-ductile transitions.



Extensional or transtensional regime within the continental lithosphere is the result of forces acting upon plates. Such forces can be divided into two main categories sorted by the agents of forcing. The first group are forces originating from a viscous upwelling regions in the upper mantle, which act on plates bottom surfaces, whereas the second group results from plate margin processes, such as slab and trench pull or ridge push (Lowrie, 1997). Forces applied on an object cause stress that in turn results in characteristic strains within the lithosphere, depending on material properties. Rheology is moreover strongly influenced by local geothermal gradient and initial thickness as well as by composition of the lithosphere. The way in which a solid object reacts to stress also depends on magnitude of the stress and length of the time applied (Lowrie, 1997). In the case of extension and rifting we recognise two main types corresponding to the previously mentioned two groups of forces. Active rifting, that involves stretching of the continental lithosphere in response to mantle heat circulation, and passive rifting, which is defined by stretching due to distant extensional forces (Allen and Allen, 2005). Transtension domains on the other hand are places of local extension within predominantly strike-slip motion regimes. Strike-slip zones are characterized by simultaneous development of both extensional and compressional tectonics within the same tectonic belt (Reading, 1980). In general transtensional regimes occur on a smaller scale and are more intimately linked to the detailed structural evolution of an area (Allen and Allen, 2005).

3 Continental extensional and transtensional environments

Basin fill architecture is, through various mechanisms, strongly determined by the shape of the sedimentary basin. Sediment can only be accumulated in relative lows, and its spatial distribution is dependent on the original subsidence pattern. There are a number of consequences issuing from the extensional/transtensional settings that specify the style and appearance of those fundamental characteristics. Looking at the general forces and stresses in both settings, one could easily be misled into thinking that both extension and transtension should result in similar sorts of structures, and thereby much the same sedimentary record. While that may be true on a small scale, the large scale image reveals many crucial differences.

The main similarity in both environments is that of a mechanism, where a brittle extension of the crust generates extensional fault arrays resulting in fault-controlled subsidence (Allen and Allen, 2005). Neither of the two environments also evolves as a single, continuous, basin-seized fault structure, but rather as a system of linked fault segments. Tectonics in general tends to concentrate along pre-existing lineaments in the crust (Einsele, 1992). While the main building blocks can in both cases be the planar or listric halfgrabens, their spatial configuration differs considerably. Moreover, every sedimentary basin has its subsidence boosted by the volume of sediment that is already present. Increased seismicity accompanies both settings, yet the focal mechanism solutions as well as the depth of the seismicity vary significantly. The last important analogy concerns a presence of volcanism. The existence of active volcanoes and subsequent oceanic crust creation is generally considered to be a domain of rifting extensional environments, however, igneous activity is also present in the transtensional settings. When the extensional component is very large even ophiolites may be formed at local spreading centres (Reading, 1980).

No matter how great the number of similarities between transtensional and purely extensional provinces is, there are countless more disparities, ranging across the whole spectrum of geophysical and geomorphic properties. For instance, there is the heat flow.

Strike-slip zones are characterized by predominantly low heat flows, unlike the rifts that demonstrate elevated values (Allen and Allen, 2005). This phenomenon is commonly explained by the presence of thermal anomaly underneath the extensional areas caused by thinning of the continental crust, and accompanied by upwelling of the hot mantle, unlike in the transtensional situation, where there is no significant mantle upwelling observed (Allen and Allen, 2005). What is undoubtedly connected to this fact is the presence of a second mechanism of subsidence, apart from the fault-controlled one, in rift basins. The second mechanism being a thermal relaxation following the ductile extension of lithosphere, again we observe no such cooling induced subsidence in majority of strike-slip generated basins. Since the increased heat flow is for most part a direct consequence of decreased crustal thickness, a gravity anomaly induced by the proximity of hot mantle material can be detected around rift basins. Another distinct feature occurring at the sites of active extension is elevated rift flank topography at the sides of the basin. This morphology could be contrasted with the typical linear trough topology specific for strike-slip zones. Conversely, the rifting zones lack geomorphic features derived from lateral displacement along the strike. As well as all those dissimilarities, there exists yet another major characteristic inherent to extensive and transtensive environments that was not yet mentioned, it is the magnitude. Size, once again being of importance, is one of the main differences between both systems, pull-apart basins being the smaller and more complex of the two.

The number of discrepancies as described above speaks in the favour of looking at both systems individually, rather attempting to find a common reference frame for both types. For a review of similarities versus differences see Table 1. Where correlation is to be applied, great caution is recommended.

Table 1: A comparison between the number of similar and different features for rift and pull-apart basins

similarities	differences
presence of extensional tectonics	spatial configuration between fault segments
subsidence due to the amount of sediment	thermal relaxation as another reason for subsidence predominantly only in rift valleys
increased seismicity in both environments	different depths and focal mechanism solutions for seismic events
	volcanic activity likelihood
	heat flow magnitude
	the presence of lateral displacement features
	size

4 Alluvial basins in extensional and transtensional regime

4.1 Alluvial basin characteristics

Alluvial basins in extension are predominantly rift basins, whereas transtension ones are commonly known as pull-aparts. Their alluvial nature results from position within the continent and is characterized by an absence of sea sedimentation. As stated by Einsele (1992) the geometry of an ultimate basin fill is controlled mainly by basin-forming tectonic processes but the morphology defined by sedimentation surface is a product of interplay between tectonic movements and sedimentation. Those two significant factors will be further discussed after a summary of rift and pull-apart basin typology.

There are several types of transtensional basins. Their formation mechanism might differ but they have a number of common characteristics. All strike-slip generated basins are relatively small in size, from hundreds to thousands of square km in length and usually less than fifty km wide, they often have a thicker succession than the other basins of similar size, and are characterized by rapid subsidence, namely several km of strata in few millions of years (Nichols, 1999). On a local scale several factors result in zones of extension, the main ones being curvature of a strike-slip fault, braiding, and side-stepping (Reading, 1980 see also Fig. 2). A fault termination can also be a suitable environment to give rise to a sedimentary basin. Overlapping of faults, or side-stepping, results in the most typical pull-apart basins (Nichols, 1999). Some recent examples are the Mesquite Basin in California, GlynnWye Depression on the South Island of New Zealand and the Dead Sea Basin in Israel (Dooley and McClay, 1997). It is a bit more difficult to recognize the ancient strike-slip sedimentary basins, the best approach being probably an attempt to match rock types and sedimentary facies that have been displaced along the fault. It is also helpful to look for a source area of particular kinds of depositional structures (Reading, 1980).

Rift basin structures are in general less varied than pull-aparts. Usually, they form long structural valleys bound by downfaulted blocks. Some modern examples are for instance Rio Grande on SW of North America, Baikal in Russia and Rhine-Bresse Graben in Europe (Allen and Allen, 2005).

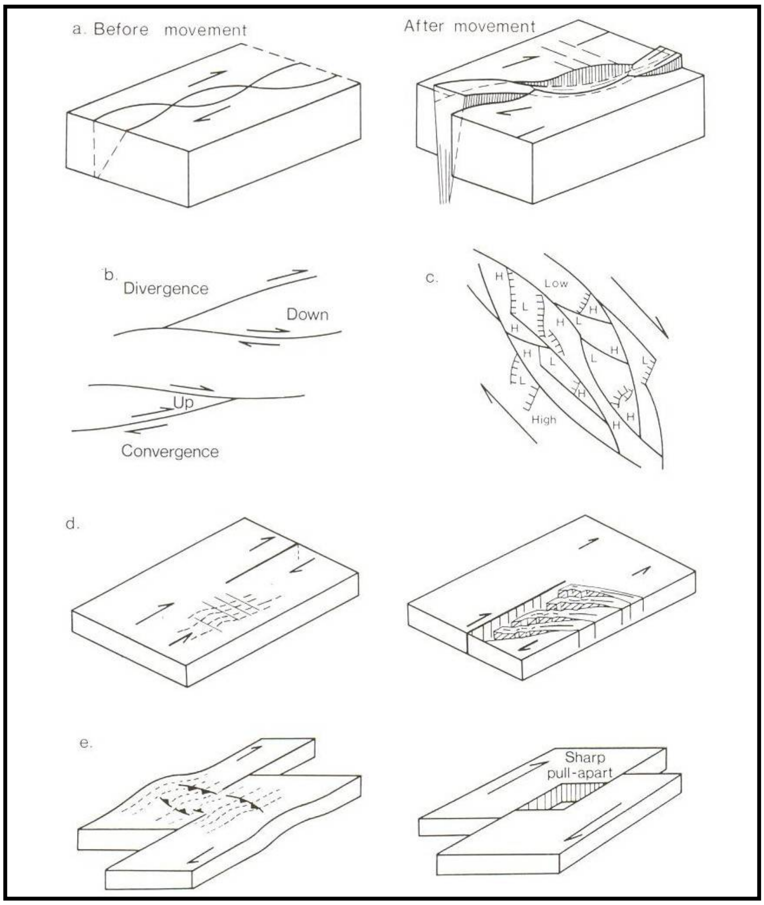


Fig. 2. Types of strike-slip fault pattern that produce extensional subsiding basins and compressional, uplifted blocks: a) curved fault trace, b) divergent and convergent fault patterns, c) anastomosing faults, d) fault termination, e) side-stepping faults. After Kingma (1958), Quenell (1958) and Crowell (1974) in Reading (1980).

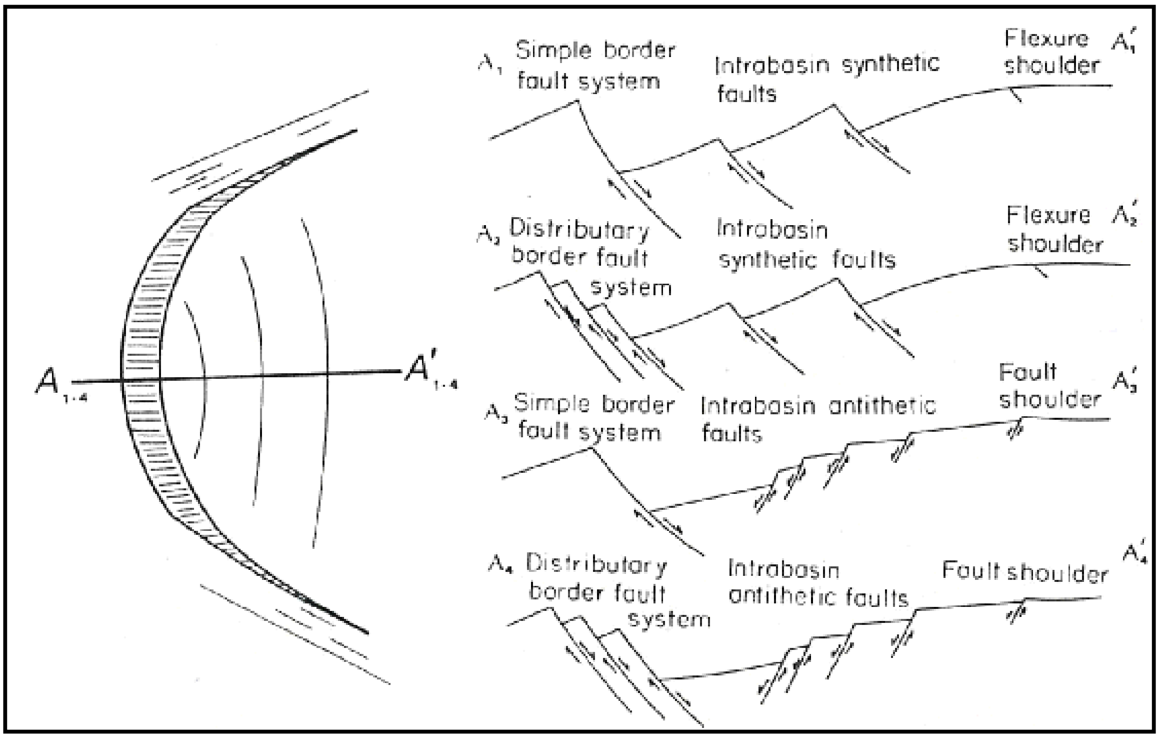
4.2 Tectonic settings

4.2.1 Rift basins

Extensional tectonics that stays behind the creation of a rift-basin produces characteristic half-graben or tilt-block systems bounded by major normal faults (Leeder and Gawthorpe, 1987). The major normal faults are commonly considered to be of a mid-crustal penetration. Extensional basins vary significantly in strain rate, resulting in two end-member groups. First group are discrete continental rifts located on normally thick crust, bounded by steep master faults ranging from forty-five to seventy degrees in dip, and their extension often reaching a mid-crustal level. Second are supradetachment basins that experience very rapid extension over a short period of time. Master faults of such basins are shallow in between ten and thirty degrees of dip (Allen and Allen, 2005). The structures within a rift basin evolve progressively in time, which can lead to several situations, one of them being an abandonment of half graben system and its shift to a nearby location. It can even occur that the new fault develops in the hanging wall of the old system and the old basin fill gets gradually uplifted and eroded (Leeder and Gawthorpe, 1987). When extension ceases and basin goes extinct, there is still some subsidence present due to the thermal contraction.

Fundamental building blocks of rift-basins are the half-graben (Rosendahl *et al.*, 1986; see also Fig. 3) with a round major fault segments that usually dip steeply inwards towards the basin centre (Allen and Allen, 2005). The faults are predominantly planar, even though listric structures also occur. When extension is controlled by planar faults, it is likely to result in a gross rollover structure with new, small-scale faulting planar or antithetic to the master fault. In such cases a minimal rotation towards the master fault occurs (McClay and Ellis, 1987). A different scenario can be seen around listric fault controlled extension. A well developed rollover anticline is present there, together with a highly rotated layering. According to some models, the faults dipping in the same direction as the main fault are also listric, whereas those dipping in opposite direction are planar (McClay and Ellis, 1987). The idea of listric faults is preferred by some authors, pointing out that the real structures are crescent-shaped in plan view (Rosendahl *et al.*, 1986). In both cases, however, a significant asymmetric subsidence occurs with basin progressively developing above the hanging wall (Leeder and Gawthorpe, 1987). In connection with a half-graben development the term fulcrum is sometimes applied. The fulcrum is defined as the point, where a hanging wall displacement tends to zero. Its position in time is a useful tool when describing the chronological evolution of the graben.

Fig. 3. Cross-sections as observed in seismic profiles of Lake Tanganyika area of a single, relatively isolated, fundamental unit. After Rosendahl (1986).

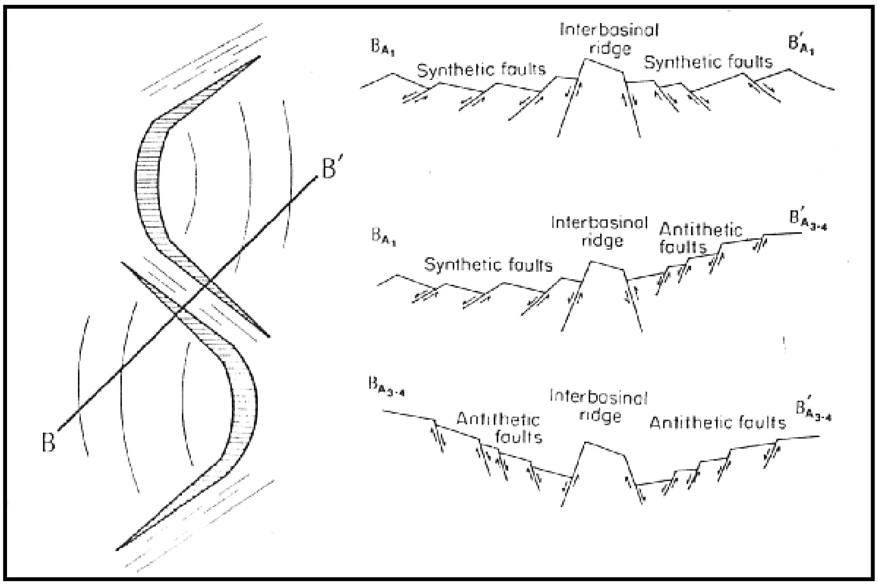


The fundamental units within the rift zone interact with each other in space and time (Rosendahl *et al.*, 1986). The prevalent large-scale structure is that of alternating polarities along the strike of the rift, meaning that two half-grabens next to each other are as a rule dipping in an opposite direction. Those structures have been observed in nature and their relative position is of some importance in shaping the morphological structures within the rift. When fundamental units do not overlap, they are separated by an interbasinal ridge, in other cases linking and interaction occurs (Rosendahl *et al.*, 1986). Sometimes transform faults develop at a high angle to normal faults within the half-graben, those can also be the places of changing polarity between two adjacent fundamental units (Leeder and Gawthorpe, 1987). When neighbouring half-grabens end up side by side, the resultant feature is an interbasinal ridge. On the other hand, when the positions of grabens is opposing and overreaching, hinged highs of different geometries are created. In the second case the amount of overlap, position within the overlap and relative rates of subsidence between the adjacent units plays an essential role (Rosendahl *et al*., 1986).

Fig. 4. Cross-sections as observed in seismic profiles of the Lake Tanganyika area fitted within the framework of fundamental units and their linkage (after Rosendahl, 1986).

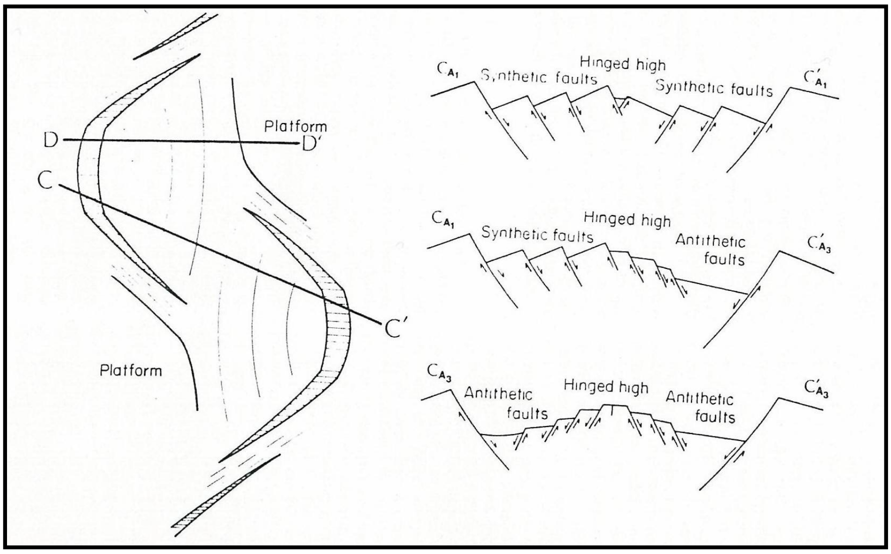
a)

Morphologies observed at the point, where two opposing half-grabens meet without overlap.



b)

Morphologies observed in a cross-section across an overlapping area.



A typical rift-basin would be characterized by a number of dip-slip faults and a variable number of strike-slip faults depending on the orientation of rift axis towards the extension direction (Allen and Allen, 2005). Axis of the rift is, in the simplest case, perpendicular to the direction of the stress. Geomorphologic features of such a basin then are mainly grabens and horsts resulting from fault interaction. Shape of the basin towards the bounding faults is an asymmetric halfgraben (Nichols, 1999) and since on Earth the extensional normal faults do reach only a finite extent a distinctive „scoop“ shape can be observed (Leeder and Gawthorpe, 1987). Flanks of the rift, which have not been thinned by extension, are the areas of uplift.

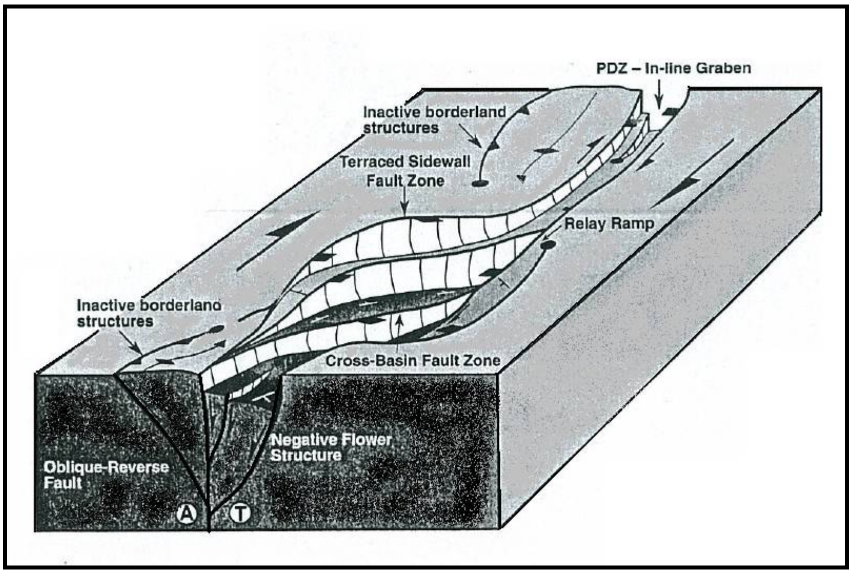
4.2.2 Pull-apart basins

In the following text a brief tectonic situation along strike-slip zones, and especially pull-apart basins, is presented. The case is that zones of localized subsidence along the strike-slip fault system result in topographic depressions where basins are formed (Nichols, 1999). Often there is more than one pull-apart basin created, because the shearing zones are long and the deformation is commonly conducted through collection of uneven faults.

Strike-slip or transform faults are those whose primary motion is horizontal and parallel to the fault trace (Reading, 1980). The movements along the fault do operate at a very high rates of several km of strata in few millions of years (Nichols, 1999), and therefore also the subsidence rate in thus created basins is relatively fast (Einsele, 1992). Majority of the shear strain is conducted through a central principal displacement zone - PDZ, which might be linear or curvilinear in plan view, is generally steeply inclined in cross-section, and commonly branches upwards producing typical flower structures (Allen and Allen, 2005). The PDZ is characteristically segmented, and on the surface can emerge as an en echelon arrangement of faults and folds that are oriented in consistent pattern with respect to the strain ellipse. Strike-slip faults are furthermore linear or curvilinear in plan view (Allen and Allen, 2005). The curvature of such faults gives rise to alternate zones of divergence and convergence along the fault which is one way of creating transtension. Another way is where faults split and rejoin forming an anastomosing pattern. In the location where faults diverge, extension results in sinking. Different type of interaction also producing depression is a side-stepping of closely parallel faults (Reading, 1980). Releasing sidesteps, for example, produce rhombic shaped basins in the overlying sedimentary section.

Shapes and geometries of pull-apart basins are strongly dependent upon the architecture of the underlying basement fault systems (Dooley and McClay, 1997). Basins frequently display extreme structural complexity and evolve from narrow spindle-shaped to lazy-s and lazy-z basins onwards toward rhomboidal ones (Allen and Allen, 2005). The initial narrow graben is bounded by oblique-slip faults, whereas the wider rhombic basins are flanked by terraced basin sidewall fault systems (Dooley and McClay, 1997; see also Fig. 5). Younger and shorter pull-aparts tend to have a comparatively shallow basin floor, and deepen in time. Recent known basin depths vary up to seven or ten km (Einsele, 1992). Types of structures found within pull-apart basins include terraced oblique-slip extensional sidewall fault systems that link the laterally offset principal displacement zones. Sidewall faults may show changes in kinematics from dominantly dip-slip to extensional in the central section and oblique-slip to strike-slip where they merge with the PDZ (Dooley and McClay, 1997). According to Reading (1980) a large and rapid vertical movement is common within pull-apart basins, which causes localized uplift and erosion. Another distinct result is that sedimentary record may be segmented in wedge-shaped bodies with laterally variable facies and thicknesses (Einsele, 1992).

Fig. 5. Synoptic diagram illustrating the three-dimensional geometry of an idealized pull-apart basin (after Dooley and McClay, 1997).



4.3 Sedimentary record

Sedimentary record of alluvial depositional processes is one of the areas, where rifts and pull-apart basins share some of the basic features. Especially fluvial deposits known from both types of environments have comparable facies (Einsele, 1992), but alluvial fans and lake sediments are also present in both types of environments. The sedimentary fill does reflect varied structural histories (Allen and Allen, 2005), yet the small scale depositional environments are comparable. For example, in some works (Blair and Bilodeau, 1988) both rifts and pull-aparts are expected to develop same tectonically generated cyclothems with two main periodically repeating members. In those environments we can observe fine-grained deposits alternating with coarse grained sediments.

Tectonic settings as described above exercise a great influence on the distribution of sedimentary facies. Since the base level is a very important factor in all the sedimentation studies (Einsele, 1992), the rate and nature of tectonic subsidence is also crucial. Combination of footwall uplift and hanging wall subsidence forms a characteristic tectonic slope (Leeder and Gawthorpe, 1987) so basically all sedimentary processes driven by gravity will be influenced. The footwall area is often the main sediment source due to the large drainage area, even though the hanging wall sediments are often more noticeable. The gradual rejuvenation of the footwall scarp caused by subsidence also gives rise to characteristic sedimentary sequences (Leeder and Gawthorpe, 1987). According to Blair and Bilodeau (1988) the onset of fine grained depositional signals point to a renewed tectonic activity. They claim that in the case of a sudden base level change, the lake and large river sedimentation is likely to react instantaneously, or much faster, than coarse grained alluvial fan sedimentation. Such observations are an effect of different hydrologic controls on both types of sedimentation (Blair and Bilodeau, 1988). Fluvial systems have a sediment discharge equivalent to large drainage areas that are thousand times larger than those of alluvial fans. The fan sedimentation is rather infrequent, needing a strong rainfall to act upon the much smaller drainage area, when comparable amount of sediment is needed.

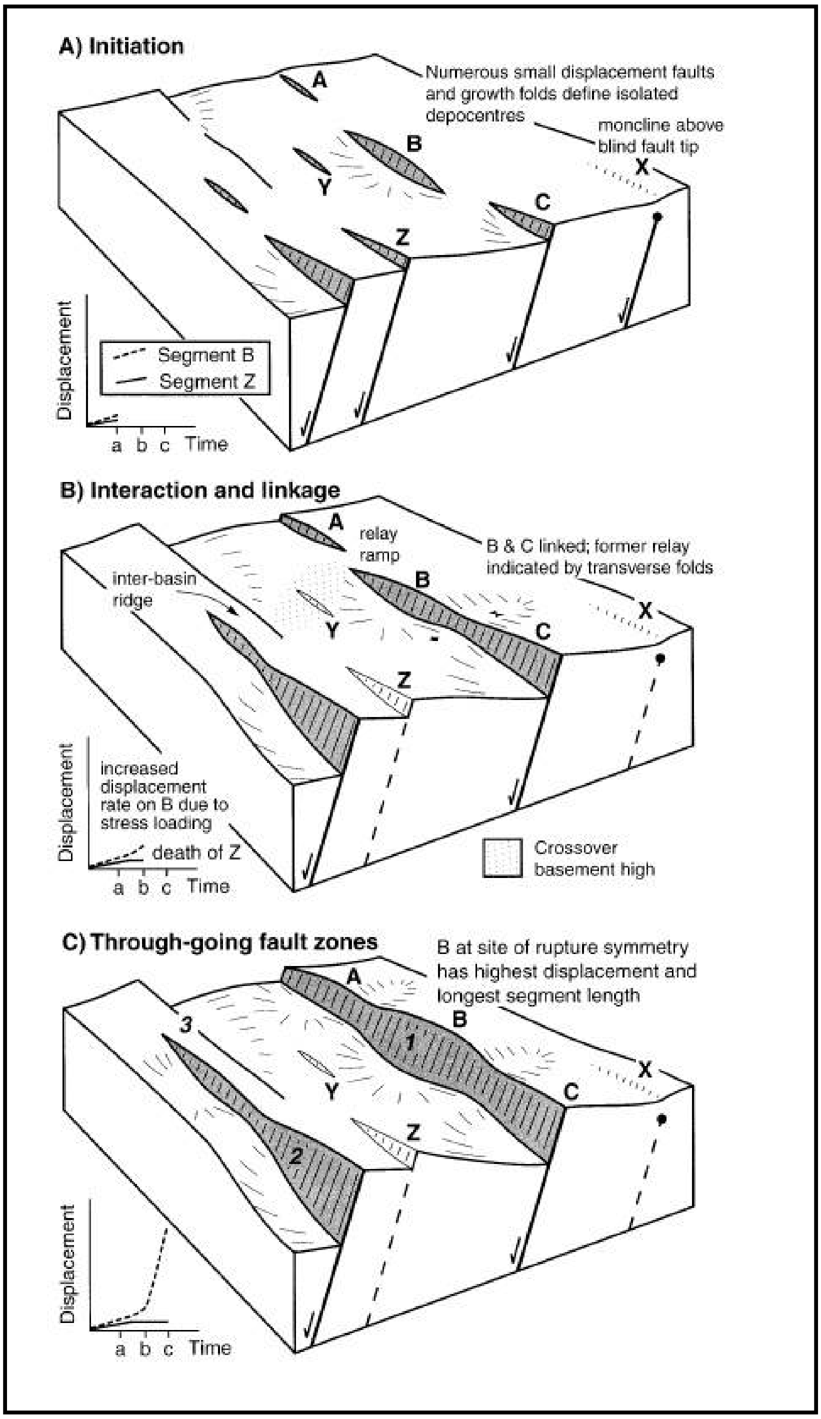
Since the fundamental half-graben structure as a fundamental unit can be cautiously applied to both rift and pull-apart basins, we shall discuss its control upon sedimentary record. When an asymmetric tilt-block structure is fed in a direction perpendicular to its main axis, the high-relief side of the basin has a marginal coarse-grained alluvial fans and debris flows. The opposing, gently steeping, basin margin has by contrast facies consisting of finer materials of alluvial plains building slowly into the basin (Einsele, 1992). If the precipitation conditions are favourable, the place of maximum subsidence might be occupied by a lake. Asymmetric subsidence within the unit is also one of the fundamental controls on geomorphology and sedimentation patterns, because tectonic slopes created by fairly minor fault displacement do have a pronounced effect when superimposed on i.e. typical river gradients (Leeder and Gawthorpe, 1987). Alluvial fans and cones may become segmented after periods of tectonic tilting. Connecting and interaction of the fundamental units, mainly present in the case of rifting, has its important implications since large drainage systems often use the overlap zones as a way into the basin, developing a larger-than average depocentres (Leeder and Gawthorpe, 1987).

In general we can see three most common types of sediment facies. First are the coarse-grained alluvial fan deposits, which abut the geomorphologic highs, second are fine-grained fluvial, mainly river deposits of the lowlands. Third come the lake deposits, which are accommodated in the lowest point of the whole system (Blair and Bilodeau, 1988) sometimes evolving into evaporite playa environments (Einsele, 1992). The lakes seem to be more typical for early phases of the system evolution, and they can be replaced by axial river deposits later on. In most environments migration of facies through time occurs (Einsele, 1992), which can be later tracked within the sedimentary record. However, yet another, often overlooked, factor plays role within both types of sedimentary basins. The existence of upwardly mobile partial melts in the shallow crust, or the volcanic activity in general, can create areas of local relative upwarp in the overall subsidence regime, resulting in local fan formation or large-scale river damming (Leeder and Gawthorpe, 1987).

The terrestrial rift valleys are places containing a wide range of sedimentation processes. Aeolian, fluvial, alluvial and lacustrine sedimentation and their interplays is often discernible (Nichols, 1999). Location of sedimentary bodies often follows the general structure of the rift (see Fig. 6) with alluvial cones fringing the margins, and fluvial or lacustrine running along the centres of the basin. One individual rift depocentre is characterized by a complex interaction between fluvial clastic input, accumulation of boarder-fault conglomerates, and blanket deposition of biogenic ooze (Rosendahl et al., 1986). Any amount of clastic input usually suppresses the biogenic influence. Within one half-graben structure four models of clastic sediment entry can be considered (Rosendahl et al., 1986). The first are classical fan conglomerates at border faults, next the delta systems of axial rivers entering the basin from sides. Third clastic supply mechanism is sediments from platform associated rivers and also some from the shoaling sides of the half-graben. Separate depocentres are theoretically independent, until linkage and spillovers between them occur. Therefore seismoacoustic stratigraphy of adjacent basins initially shows different facies, which can not be easily correlated, followed by overspill sediments and consecutive unified evolution (Rosendahl et al., 1986). In later stages the existence of axial rivers seems to gain dominance over the original lacustrine environments. The sedimentary record is subsequently dominated by interaction between a lateral transport systems like alluvial fans and cones, and axial transport systems, such as the river (Leeder and Gawthorpe, 1987). It can be logically expected, that as in the case of lakes, the river will tend towards the axis of maximum subsidence by the means of migration and preferential avulsion. Peat accumulations and soil development lay commonly away from the places of maximum deposition, usually accentuated up on the hanging wall dip slope (Leeder and Gawthorpe, 1987)

The strike-slip transtensional basins have often much thicker sedimentary successions than rift basins due to the rapid subsidence, and their facies are very variable in sedimentary record (Nichols, 1999). The high rate of subsidence might lead to sediment starvation during the initial stages of basin formation, despite the high sedimentation rate during that stage (Einsele, 1992). Basin margins are normally the sites of coarse facies like alluvial fans and fan deltas that pass laterally into lacustrine sediments. However, the facies are known to typically have a limited lateral extent causing extreme lateral facies diversity (Reading, 1980). Thick coarse grained sedimentation piles are often connected with weathering unconformities of the same age in nearby uplifted catchment areas. Another main diagnostic feature for pull-apart basins is discordance between size and materials of individual fans opposed to their adjacent sources (Reading, 1980).

Fig. 6. Schematic 3D evolution of a normal fault array, with graphs illustrating displacement history of fault segments B and Z (after Gawthorpe and Leeder, 2000). A) Fault initiation stage, where separated lakes are likely to exist. B) Fault interaction and linkage stage. C) Through-going fault zone stage that is supportive of axial river environments.

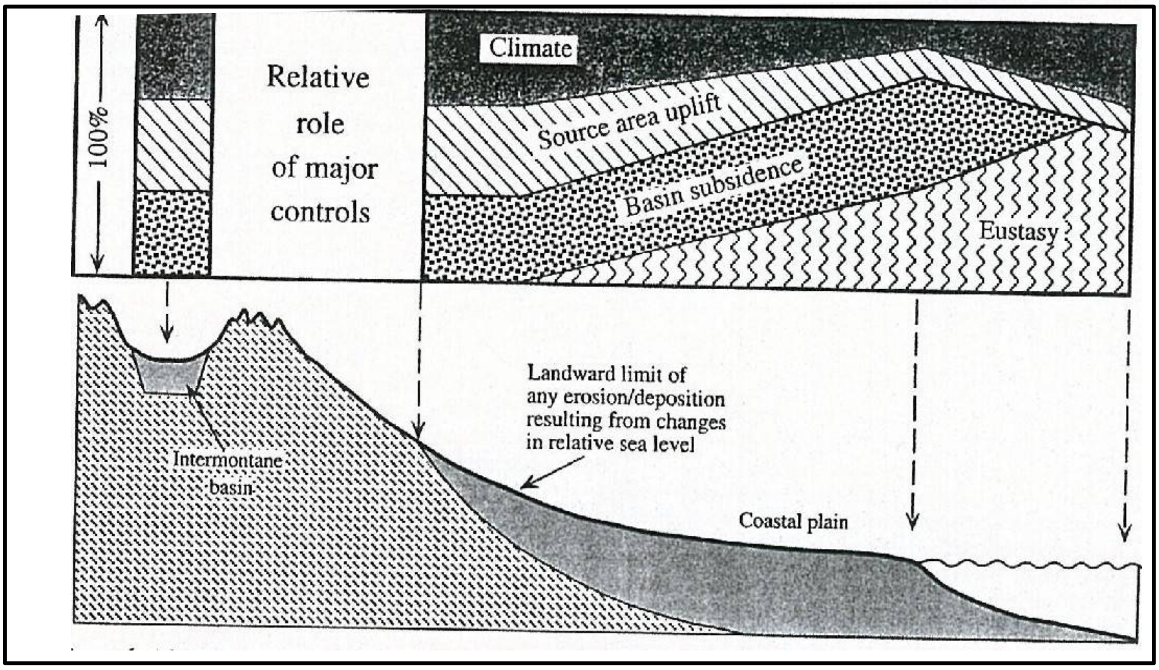


Such discrepancies are often attributed to the fact that a pronounced migration of depocentres is likely to occur along the strike. External drainage existing together with an open lake system in pull-apart might be succeeded by an internal drainage system delivering its total load into the basin (Einsele, 1992). The initial stages are often characteristic by a relative facies stability as strong infilling accompanies strong subsidence. In time when the axial river deltas start to infill the basin, their facies migrate over the older lacustrine sediments causing shallowing. Eventually filling of the basin takes place. Pull-aparts in the humid climate can accumulate some black shales or peat (Einsele, 1992), and therefore small abundant petroleum deposits are commonly present (Reading, 1980). In contrast dry continental conditions might lead to accumulation of evaporites.

5 Mechanisms driving basin fill architecture

The basin fill architecture is a result of temporal evolution of balance set between sediment deposition rate and available sedimentary space (see also Fig. 7). One way of creating such available space is subsidence. Subsidence is governed mainly by tectonics, compaction of sedimentary deposits and endogenous processes such as isostasy. Another way of gaining some space is through raising the relative water level. The amount of sediment is, on the other hand, influenced mainly by the climate. Yet another independent control over the amount of sediment available is the source area geology. In most cases a complex interplay between those factors influences basin fill. It is obvious, that when talking about a global climate change variety of regional responses will be induced. Therefore, while viewing information about for example Milankovitch scale global climate changes, it is important to take the geographic position of studied area into account. Since majority of forcing mechanisms acts repeatedly, from periodic climatic changes to irregular tectonic pulses, cyclicity can be preserved within the sedimentary succession. Then the relative frequencies of all the previously mentioned mechanisms are of some importance, as well as their magnitudes. The question of which mechanism is responsible for a particular order of cycles observed, is the one eventually solving the basin evolution history. Therefore, it is particularly interesting to analyze how each forcing function may be expressed in stratigraphic record (Saparoea and Postma, 2008). An outline of such analysis is presented on the next few pages.

Fig. 7. Main mechanisms driving basin fill architecture are illustrated on the following picture. The controls on reservoir-scale packaging of continental strata are illustrated in terms of the ratios between the effects of climate, eustasy, basin subsidence, and source area uplift (after Shanley and McCabe 1994).

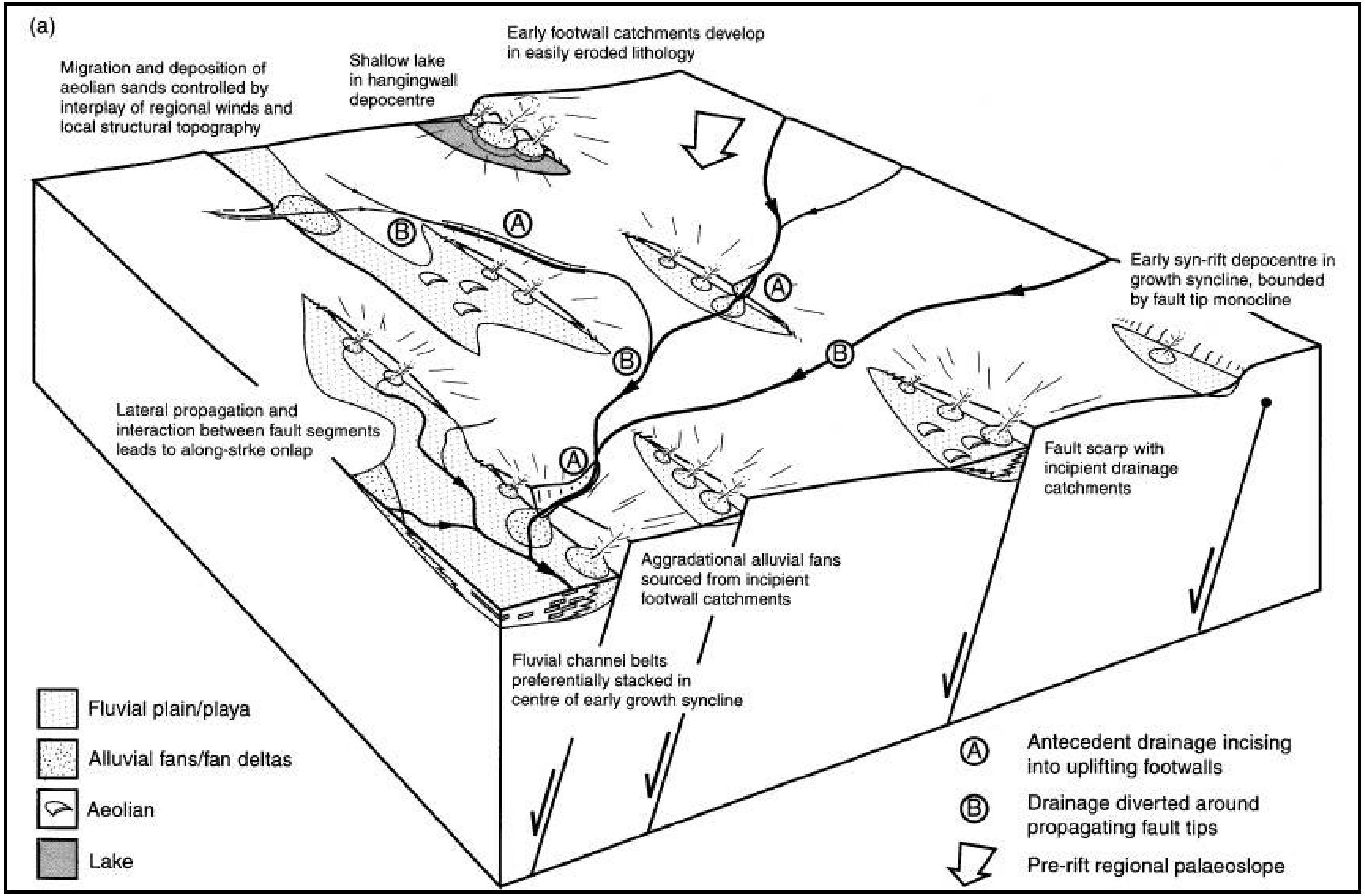


5.1 Tectonics

Tectonics is without any doubt the stronger of the two debated factors especially on the macroscale, as defined by Hickson *et al*. (2005) influencing the evolution of entire basin. Smaller scale tectonic activity then tends to cause rapid and episodic, rather than gradual basin subsidence (Stollhofen *et al*., 1999). Displacement accumulation is intermittent and characterised by earthquake clustering alternating with quieter periods (Gawthorpe and Leeder, 2000). Sometimes the interval of strong tectonism can even be linked to the time of active volcanism (Stollhofen *et al*., 1999). Final structure of a basin is often controlled by the geometries of the basement fault system beneath the sedimentary cover (Dooley and McClay, 1997) as in the earlier mentioned models of McClay and Ellis (1987), where extension controlled by listric and planar faults showed somewhat different properties. The tectonic control on the basin architecture is in particular advocated by a three dimensional evolution of fault propagation, linkage, and death. For example, the stage of fault linkage decides whether the basins is hydrologically closed or open (Gawthorpe and Leeder, 2000).

Tectonic forcing in rifts is mainly indicated by an abrupt migration of facies within the basin, or evidence of syntectonic volcanic activity. Interrelationship between tectonics, volcanic activity and sedimentary facies architecture is vital for the understanding of dominant controls on the sediment formation (Stolhofen *et al*., 1999). On the surface fault growth is often initiated by a ductile deformation that later on remains ahead of the propagating fault tip. The fault segments are in average twenty to twenty-five km long with segment boundaries having characteristically different relief than the central parts (Gawthorpe and Leeder, 2000). Folding parallel to the fault zone is often present, frequently marked by an increase in density of small-displacement faults. Since the fundamental units link as the time goes on, some structures accompanying that change can be expected. It comes to pass, that majority of all the interaction between faults happens subsurface and only one big fault appears on the exterior (Gawthorpe and Leeder, 2000). An equilibrium length of such a single fault is comparable to the thickness of the seismogenic layer (Gawthorpe and Leeder, 2000). However, even if a single fault appearance is not the case, a segmented fault zone acts almost as one fault of the same length. Subsequently during the linkage, many of the pre-existing basement ridges are buried. Faults within the rift zone can also experience the so called „death"(Gawthorpe and Leeder, 2000), which means they are no longer active. The evolution within a rift is quite likely to evolve from initial phase, where many small detached segments exist with hardly any interaction. Later on comes the phase, where segments grow and interact linking together. The last stage then could be such that the deformation restrains into just several major fault zones, and other smaller faults become inactive (see also Fig. 8 and Fig 9.)

Fig. 8. Tectono-sedimentary evolution of a normal fault array in continental environments during the initiation stage (Gawthorpe and Leeder, 2000). There are numerous isolated fluvio-lacustrine subbasins in the hangingwalls of propagating normal fault segments. Major sediment transport pathways are dominated by antecedent drainage networks that are locally modified by surface topography associated with fault breaks and growth folds. Stratigraphic variability between individual basins is high, due to differences in sediment supply and whether surface deformation is associated with growth folds or faults.


(a)
Migration and deposition of aeolian sands controlled by interplay of regional winds and local structural topography
Shallow lake in hangingwall depocentre
Early footwall catchments develop in easily eroded lithology
Early syn-rift depocentre in growth syncline, bounded by fault tip monocline
Lateral propagation and interaction between fault segments leads to along-strke onlap
Fault scarp with incipient drainage catchments
Aggradational alluvial fans sourced from incipient footwall catchments
Fluvial channel belts preferentially stacked in centre of early growth syncline
A
B
Fluvial plain/playa
Alluvial fans/fan deltas
Aeolian
Lake
A Antecedent drainage incising into uplifting footwalls
B Drainage diverted around propagating fault tips
Pre-rift regional palaeoslope

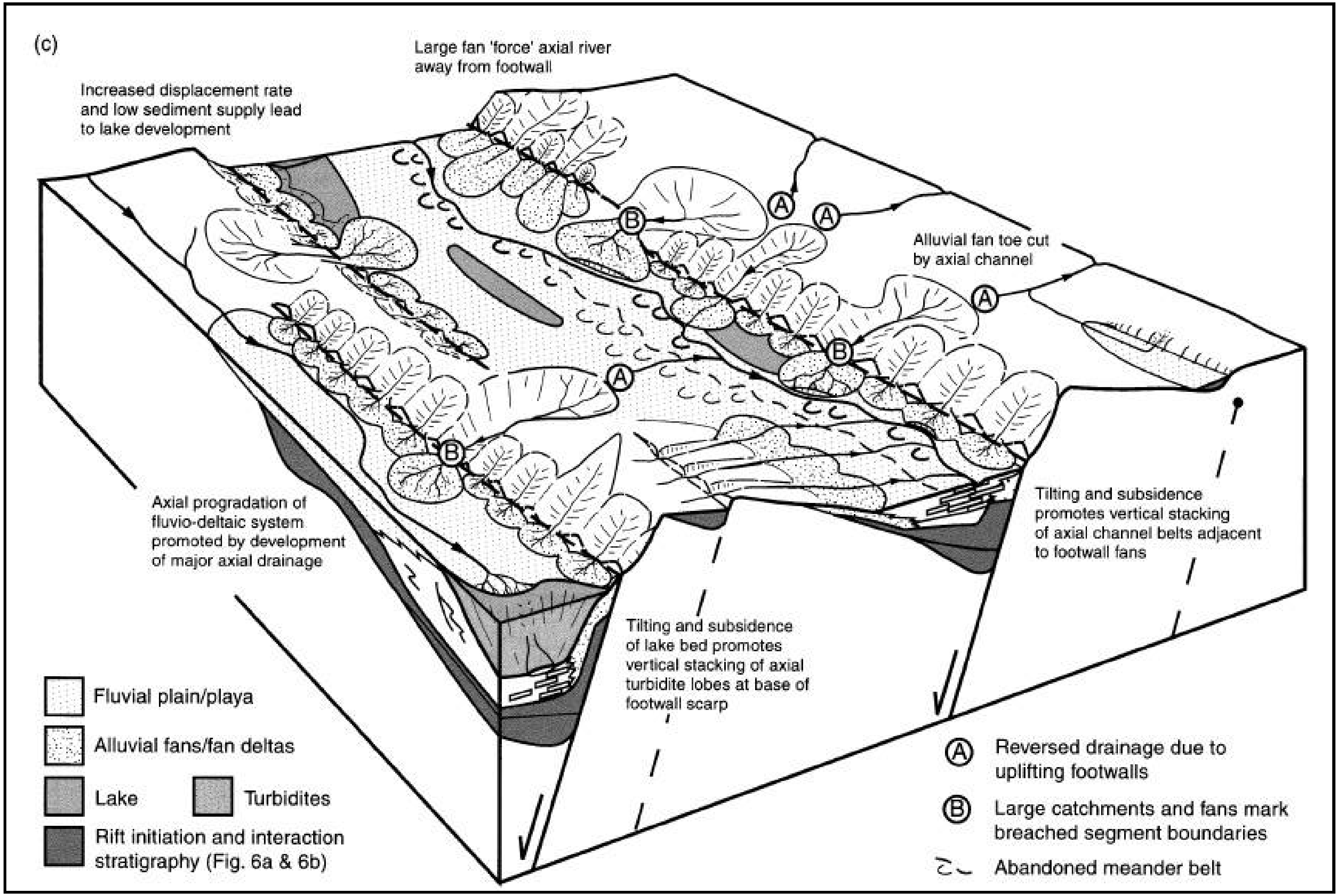
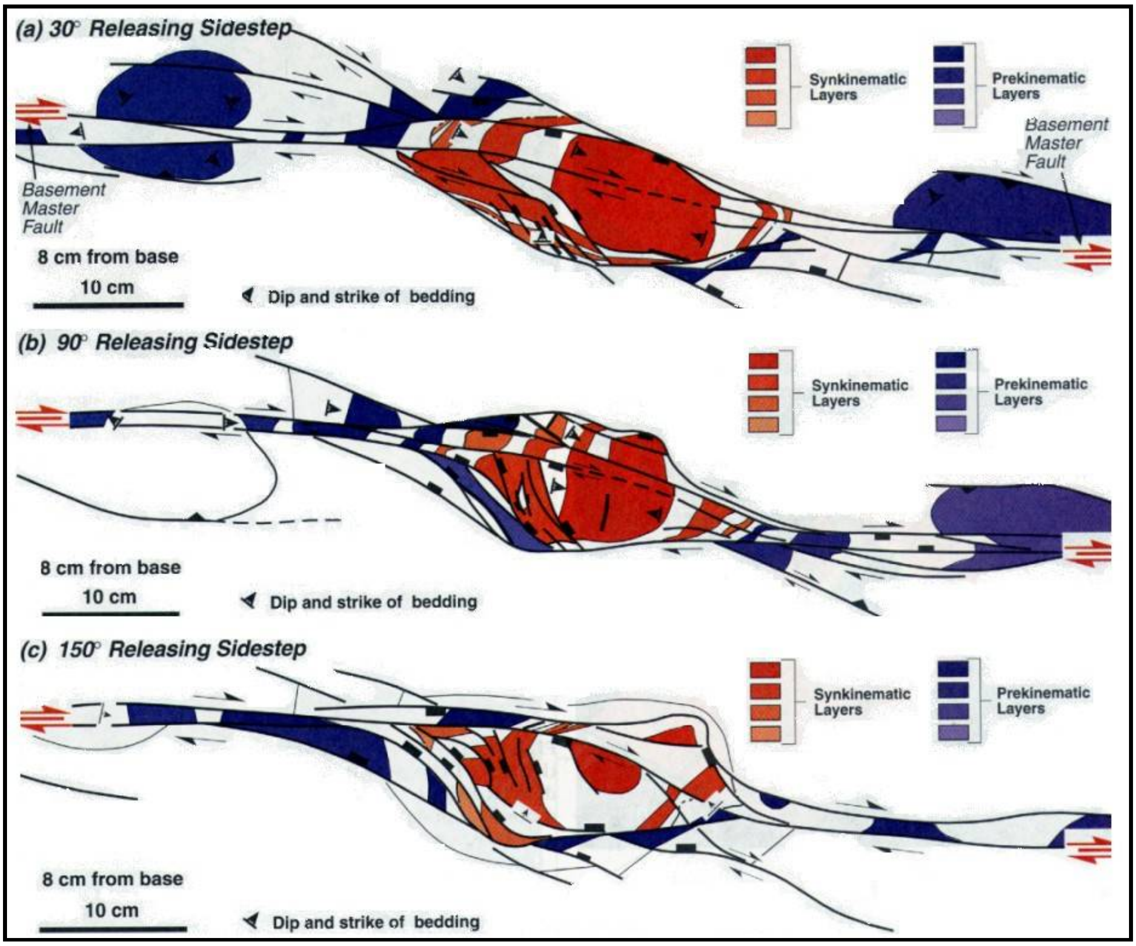

(c)
Large fan 'force' axial river away from footwall
Increased displacement rate and low sediment supply lead to lake development
A
A
B
Alluvial fan toe cut by axial channel
A
B
A
B
Axial progradation of fluvio-deltaic system promoted by development of major axial drainage
Tilting and subsidence promotes vertical stacking of axial channel belts adjacent to footwall fans
Tilting and subsidence of lake bed promotes vertical stacking of axial turbidite lobes at base of footwall scarp
Fluvial plain/playa
Alluvial fans/fan deltas
Lake
Turbidites
Rift initiation and interaction stratigraphy (Fig. 6a & 6b)
A Reversed drainage due to uplifting footwalls
B Large catchments and fans mark breached segment boundaries
Abandoned meander belt

Fig. 9. Tectono-sedimentary evolution of a normal fault array in continental environments during the through-going fault stage (Gawthorpe and Leeder, 2000). Linkage of adjacent fault segments creates major linked fault zones defining half graben basins. Displacement on linked faults reduces topography of former intrabasin highs, allowing axial river to flow between former isolated basin segments. Note asymmetric development of axial meander belt and interaction between meander belt and footwall fans. Localization of displacement causes increased displacement rates on active faults leading to the development of pronounced footwall topography and reversed antecedent drainage.

The simplest model, and the one easiest to explore of all the transtensional basins, is the overlap of side-stepping faults (Allen and Allen, 2005). The amount of overlap does influence the resultant basin geometries (Dooley and McClay, 1997; see Fig. 10). In the case of pull-apart basins the terms overstep, or a stepover, is also used. Stepover is a structural discontinuity between two roughly parallel overlapping or underlapping faults, and its width is extremely important in determining the location of subsidence (Allen and Allen, 2005). Initial deformation is, according to analogue model studies, localized above the basement sidestep, and later on the primary displacement zone is formed by strike-slip to oblique-slip faults (Dooley and McClay, 1997). As the master faults grow producing more overlap, the basin lengthens retaining the same width (Allen and Allen, 2005). The two laterally offset PDZ are connected by arcuate, extensional, basin-sidewall fault zones with significant vertical separation (Dooley and McClay, 1997). A more detailed structural situation can be seen on Fig. 10. In the models the intrabasinal deformation is moreover characterized by a cross-basin fault zone, which connects the PDZs (Dooley and McClay, 1997) and a characteristic development of depocentres through time. When the offset across master faults is about the same length as the separation between them, two distinct depocentres begin to develop near the ends of the master faults (Rodgers, 1980). However, such structures are in the nature observed only sometimes. In contrast shallowing of the basin towards each end, and its becoming asymmetric in response to the dominance of one of the fault zones, is something common to both, real-life and model studies.

Fig. 10. Interpretation for 30°, 90°, and 150° releasing sidestep models, taken from analogue model of Dooley and McClay (1997)



Sedimentary record as a witness to tectonic forcing is a matter of an ongoing debate among geologists. It is not as much a question of whether there exists such forcing, as it is an investigation of particular responses to different kinematic settings. For example, even the widely accepted idea that axial rivers react to tectonic tilting by shifting their valley into the place of minimum elevation has its opposers. In a model study by Hickson *et al*. (2005) their experimental channel belts are not attracted to the subsidence maximum. Explanation allegedly lays in the fact, that previous studies have concentrated on Holocene and late Quaternary systems or those developed under semiarid and arid climates. It becomes clear though, that in active system with higher sediment supply, the natural stacking patterns of the river deposits overwhelm any other factors (Hickson *et al*., 2005). The lake level changes are in similar studies considered equal to the sea level changes, in terms of their effect on fluvial equilibrium profile (Stollhofen *et al*., 1999). Such deliberations allow the use of sequence stratigraphy over lake dependent systems. Transgressive lacustrine facies are then often linked to the times of enhanced tectonic activity (Blair and Bilodeau, 1988). Another set of studies strives to uncover the time of basin linkage by searching for evidence of burial and breaching of relay ramps (Gawthorpe and Leeder, 2000). Relay ramps act as topographic barriers limiting free dispersal and mixing of the sediment between individual depocentres, therefore, differences in facies and their thickness are typical for the initial stage (Stollhofen *et al*., 1999). As the rift basin gradually evolves from a hydrologically closed into hydrologically open one, a distinctive sedimentary facies can be observed. Evolution from dominantly lake deposits is expected to be replaced by an axial river system through the set of overspill facies. Once the open system is established, interaction between fluvial and alluvial fan sediments can be studied (Gawthorpe and Leeder, 2000). In pull-apart basins the main attention is given to a typical migration of depocentres (Allen and Allen, 2005) and ways of supplying the basin with sediment (Dooley and McClay, 1997). Even in this case, there are no simple answers at hand. While the model studies clearly indicate a development of two main depocetres as the deformation proceeds, the field based studies are in agreement just rarely (Allen and Allen, 2005). Synkinematic sediments are however in majority of cases more or less horizontal, and show only localized faulting and gentle folding (Dooley and McClay, 1997), similar situation could be anticipated also in the case of rift basins.

As the field research attempts to explain observed phenomena in terms of available theories, a number of discrepancies with the predicted results appear. In an attempt to describe all possible natural outcomes, researchers turn into more complex types of conceptual models, striving to do justice to the whole complexity of the system function. It seems to be of a particular importance, when the final theory is capable of creating some testable predictions. For example, the stratigraphic evidence of theoretical and conceptual growth models can be recognised by features such as occurrence of presurface faulting monoclinal folds, modifications to drainage and sedimentation patterns, or changes of stratal thickness in hanging wall depocentres (Gawthorpe and Leeder, 2000). Predictions like that can be tested, which is the only way of proving their credibility. In case of analogue models, there are two possible approaches as described in Hickson *et al*. (2005).

The first is a classical formal scaling approach, next is just partly scaled modelling relying on scale-independent geometry of the problem. In the second case the modelling itself will generally be the key to scaling up the experimental results (Hickson *et al*., 2005). Positives of modelling studies are many and varied. The controls on the development of certain features can be constrained separately, and slip rates are for once also determined (Gawthorpe and Leeder, 2000). Such variables as subsidence rate, subsidence pattern, rate of water supply or rate of sediment supply can be altered separately, monitoring the contemporary topography as well as an undamaged sedimentary record (Hickson *et al*., 2005). Among the limitations of analogue models is the fact that they can not accurately simulate thermal, flexural or isostatic effects generated by, or associated with, faulting in the upper crust (Dooley and McClay, 1997). Other problems are caused by difficulties surrounding proper scaling down, and simulating some natural processes that require irreducible time scales (Hickson *et al*., 2005).

5.2 Climate

The key issue geologists face when talking about the climatically induced sedimentary record is how to recognize pre-Quaternary responses to climate-change, and disentangle them from tectonic effects or autogenic processes (Blum and Törnquist, 2000). A great caution is advised by a majority of authors when developing models for the basin-fill response to the climate change. Fluvial responses and their sedimentary record seem to be one of the best studied units within the whole source to basin environment. Since axial rivers are especially common in rifts (Leeder *et al*., 1998), and fairly usual in pull-apart basins, studies like that are of some relevance to this thesis. Well-dated and correlated river terraces are of particular importance in such context (Saparoea and Postma, 2008) for which the radiocarbon and other dating techniques are of a great help (Blum and Törnquist, 2000). However, the behaviour of fluvial environments is often confusing and ambiguous. Some studies suggest that the river system attenuates the climate signal, and other imply a direct response to any change (Saparoea and Postma, 2008) meanwhile, both types of studies can be executed on the same river system producing contrasting results. At other times we are witnesses of similar responses being given by different external forcing mechanisms (Blum and Törnquist, 2000). Therefore, to make at least some conclusions one has to consider complexity of the whole internal system dynamics. Spatial and temporal scaling is likely to be of paramount importance to the resultant outcome. For example, the length of climate change has to be compared to the time of equilibration for the river slope. High-frequency changes in discharge control the small-scale stratigraphy, whereas low frequency changes in sediment flux control the large-scale results (Saparoea and Postma, 2008). Only a careful study of mass accumulation through the time and the development of the valley gradient can be used to clarify the situation. Altogether, only a very thorough exploration of the source to sink area can shed some light on how climate worked in that particular region.

The logically expected consequences of both global and local climate change for a studied area are the changes in temperature and precipitation, which are intertwined with a modification of atmospheric circulation. The presence or absence of seasonality is tightly connected to the time alteration of these factors. Nevertheless, temperature and the amount of water in system control a broad spectrum of other variables, such as vegetation growth, chemistry of the area, weathering etc. The lowstand of lake can be accompanied by both lesser or greater sediment supply (Leeder *et al*., 1998; see also Fig. 11) depending on an interplay between those factors. For example, the lakes in the Great Basin area were during the glacials characterised by a cool but wetter climate, high lake levels due to the increased runoff with smaller evaporation, and lowered sediment yields due to the vegetation bloom preventing soil erosion. On the other hand, analogous lakes in Mediterranean experienced an increased winter runoff during the glacial accompanied by high lake levels and enhanced sediment supply because of poorly vegetated source areas. This contrast has been created due to the different position of both areas in respect to the glaciation, and resultant contrasting vegetation bloom. Rivers themselves react to climate in a slightly different manner. Let us consider that a river does receive all water and sediment discharges from its tributary catchments (Leeder *et al*., 1998), since the alluvial channel size reflects the volume of water that must be transmitted on a relatively frequent basis, the changes in atmospheric circulation through time have a direct impact on the magnitude and frequency of floods (Blum and Törnquist, 2000).

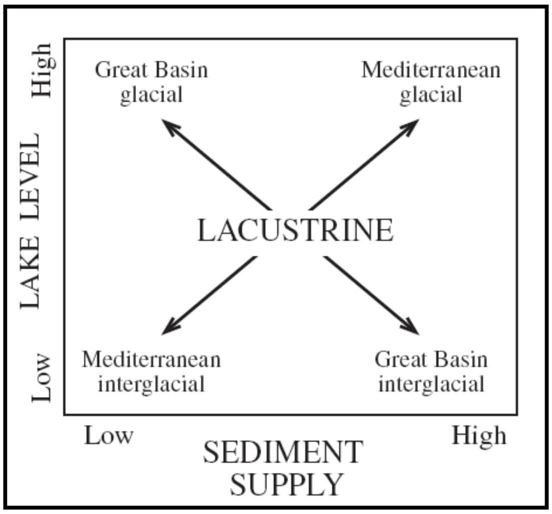


Fig. 11. Relative rates of sediment supply in relation to lake level for Mediterranean and Great Basin Quaternary climatic regimes (after Leeder *et al.*, 1998). The contrast is caused by different types of vegetation controlling the source area.

Climate and its consequences act upon the source area in various ways. Hydrological balance is one of the factors directly influenced by the climate change. The bigger the water discharge into a catchment area the more water is theoretically available for rock erosion and transport. Yet the reality is rather complex and it needs to take vegetation into account (Leeder *et al.*, 1998). Another term is often used in connection with these concepts – the runoff. The runoff can be most plainly described as that portion of rainfall, which runs into streams as surface water, rather than being absorbed into ground water or being evaporated (The Free Dictionary, 2010). The vegetation is known to balance evapotranspiration and runoff accordingly to its type, and moreover it acts like a contributor to bedrock transformation (Leeder *et al.*, 1998). A decrease in precipitation often leads to an overall decline in vegetation growth, tending towards decrease in woodlands and increase of more resistant smaller varieties. Smaller plants such as grass and shrubs, however, do not have the same potential of holding water, and unexpectedly an increased runoff can be observed. For small drainages flood discharge per unit area increases with decreasing precipitation due to the decrease in vegetation cover and corresponding increase in surface runoff (Knox, 1983 in Blum and Törnquist, 2000).

Yet another big process linked with climate within the catchment area, is the weathering. The importance of the climate in production of sediment is nondebatable (Blum and Törnquist, 2000) because it influences erosion rates and resultant volume of sediment entering the basin (Leeder *et al.*, 1998). At least two types of rock can be defined on the weatherability basis, the hard and the soft rocks as described in Leeder *et al.* (1998). Hard rocks are subject to the chemical weathering only, while on the soft rocks physical weathering and direct erosion can take place (Leeder *et al*., 1998). Either of them relies upon the climate conditions, but each in a specific way. It has been proved that slow variations in sediment production strongly influence the basin stratigraphy, and rapid changes show only proximal effects and diminish into the basin (Saparoea and Postma, 2008), therefore, the form of sediment production is also important. Putting some of those variables together, we can conclude that in the catchments where woodland prevails, there is generally a sediment production increase associated with drop in a sediment discharge. The discharge from a soft source in such conditions is higher than from the basement source (Leeder *et al*., 1998). Reversely, where there is dominance of grassland within the catchment areas, the sediment production is usually lower than in the case of woodland (see also Fig. 12).

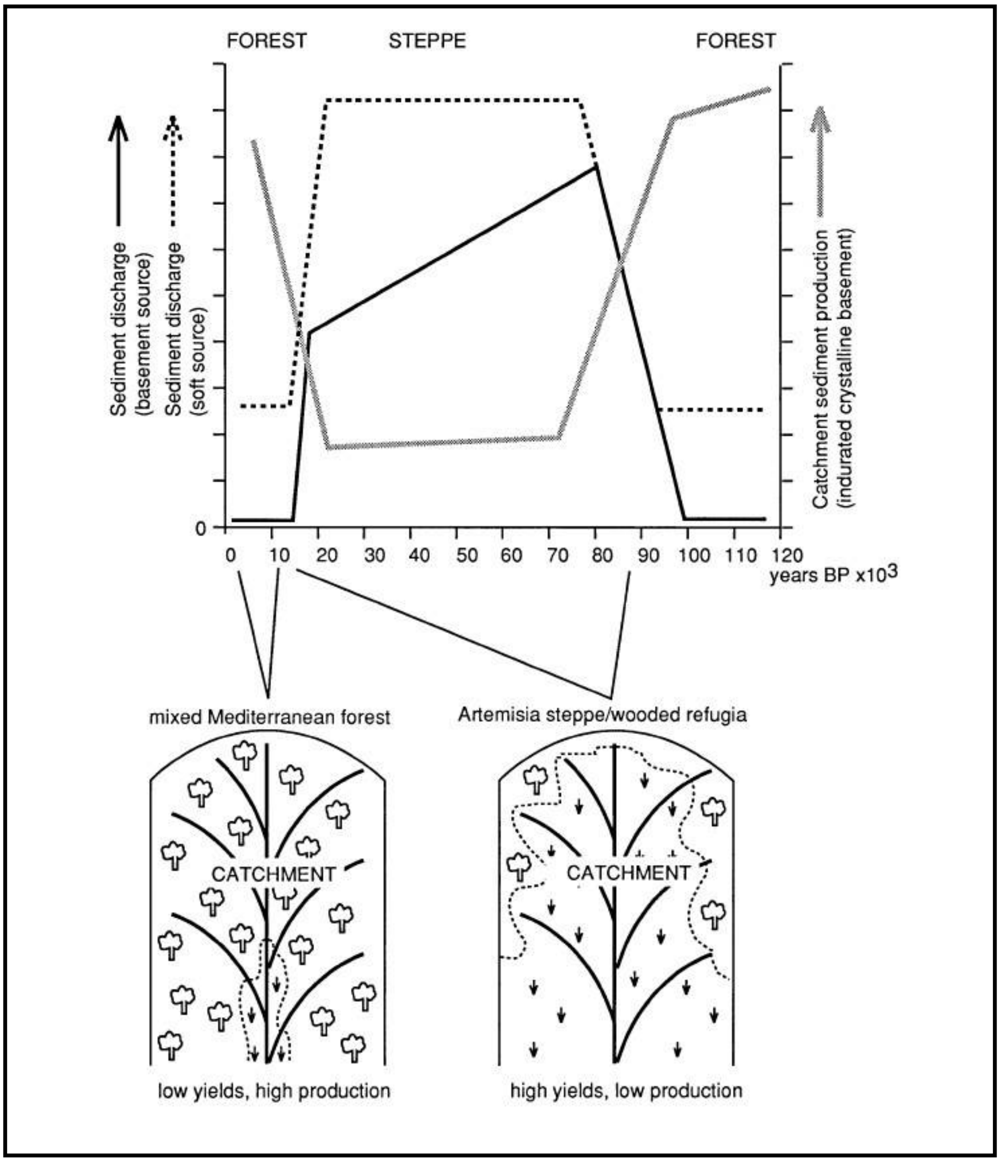


Fig. 12. Cartoon graph to show general trends in vegetation, sediment production and sediment discharge for Mediterranean climates. The graph is indicative only and unscaled (after Leeder *et al*., 1998).

Nevertheless, what is happening in the source area has distinct, but complicated and often unexpected, expressions downstream in the sedimentary basin. When talking about the bulk of sediment delivered into the basin, the term yield of river is used. The yield of a river means the river's output of sediment into the basin. The stream capacity is also one of the dominant factors. It is a feature closely bound to the amount of water going through the system and its speed. When the capacity is increased, more sediment is instantly carried towards the outlet (Saparoea and Postma, 2008). In the case when capacity is already at its maximum, any further sediment supplied is not carried anywhere, and is accumulated until it creates a steep enough slope. Steepening of the slope increases the water speed and capacity creating thusly a dynamic equilibrium (Saparoea and Postma, 2008; see also Fig. 13). The steepness of a slope across which water flows is sometimes also expressed by a gradient of valley floor. The gradient is adjusted to the amount of bedload and water discharge (Saparoea and Postma, 2008) by either stacking of the sediment or valley sediment erosion. The higher the sediment influx, while other conditions stay put, the larger the river gradient. The greater the water discharge, however, the smaller the gradient. Similar changes to the river gradient can be generated through more processes, but at the river mouth the response to discharge change is often very rapid, whereas the response to changes in sediment flux is considerably slower (Saparoea and Postma, 2008).

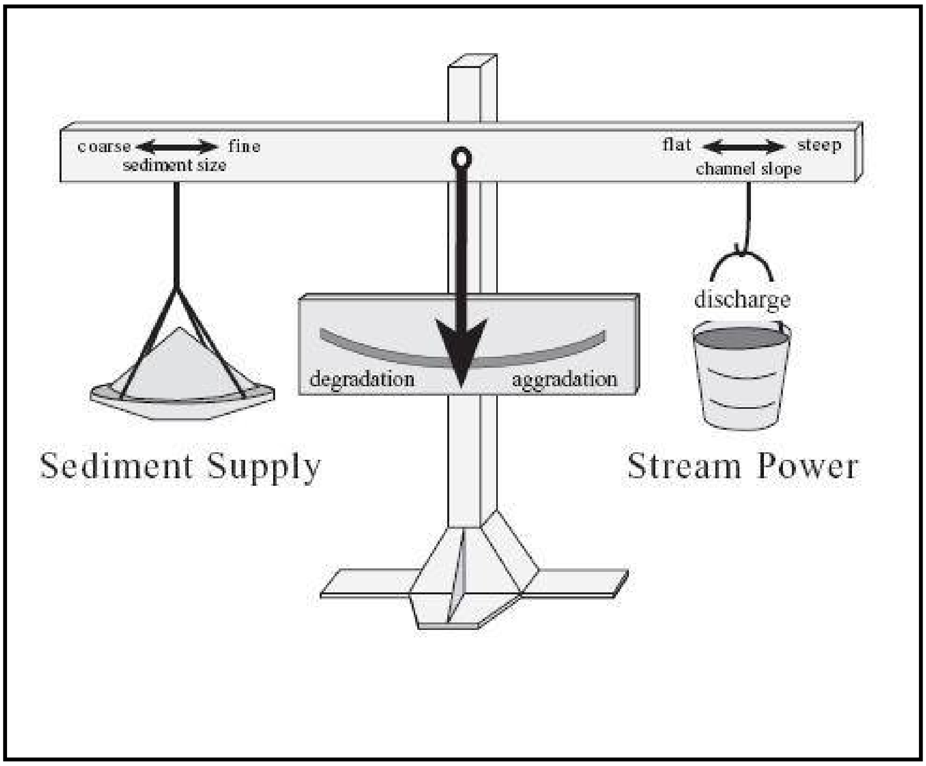


Fig. 13. Balance model for aggradation and degradation of alluvial channels, emphasizing changes in the relationship between discharge and sediment supply (after Blum and Törnqvist, 2000).

Sedimentary record of changing climate is often difficult to discern. Quaternary fluvial landforms and deposits provide one of the most readily studied continental records (Blum and Törnquist, 2000), and together with some model studies they provide a good enough information base for exploring ancient basins. Process-based interpretations of fluvial responses to climate or base-level change can be linked to controls of channel geometry and depositional style (Blum and Törnquist, 2000). Moreover, the rivers are strongly sensitive to how much water and sediment goes into them (Leeder *et al*., 1998). Cross-sectional and plan view geometry of a stream is readily adjusted to prevailing discharge regimes and sediment loads, and it maintains statistically constant size and shape over interval of time, most commonly hundreds to thousands of years (Blum and Törnquist, 2000). Alteration of these variables leads to changes in channel geometry, and in turn the position of depositional environments and facies is shifted. For example, when increased water discharge is accompanied by reduced sediment input, incision takes place together with terrace formation (Leeder *et al*., 1998). Downstream the base-level is likely to be high due to the high water income, with river mouth deltas showing a slow advance due to the lack of sediment supply. If by any chance the base-level stays the same, as e.g. in the case of relatively small water discharge of the river compared to lake size, the progradation would be more pronounced. In the case of a single river, discharge-induced, high-frequency sediment pulses usually cause high-frequency yield pulses at the mouth of the river (Saparoea and Postma, 2008). Rapid variations in discharge are then apt to produce abrupt, asymmetrical progradation cycles (Saparoea and Postma, 2008). Even the river channels are sensitive to shorter term climatic fluctuations (Leeder *et al*., 1998). There are three end-member situations from which channel aggradation can be derived (Blum and Törnquist, 2000). The first is sediment overloading from an upstream source, generating a downstream tapering wedge. The second is sediment overloading from upstream and lateral sources, which results in a constant thickness aggradation, and the last is base-level rise under the conditions of constant sediment supply, slowing the downstream transport rates and capacity (Blum and Törnquist, 2000). A different story can be found in rift valleys due to the interplay of axial rivers and alluvial fans. When great amount sediment is supplied it leads to a lateral fan growth (Leeder *et al*., 1998), the axial river system is then choked and avulsion sediments should be more frequent (Leeder *et al*., 1998).

At present empirical, field-based research on fluvial responses to climate and base-level change lags behind the numerical and physical models (Blum and Törnquist, 2000). Of those existing attempts, many works concentrate on the Quaternary, where the climate changes are quite well known from variety of sources (Leeder *et al*., 1998). However, problem of the most readily performed actualistic studies is the influence of human activity on denudation. There used to be no such things as widespread deforestation, cultivation and river damming as there are now (Leeder *et al*., 1998). In the ancient sedimentary studies, an interpretation of climate from individual features, such as paleosols, within the alluvial successions is the most common (Blum and Törnquist, 2000). A number of workers have also inferred climate change as a control based on transitions between fluvial and other strata (Blum and Törnquist, 2000). Another way of exploring this interesting area is the construction of model experiments. Such models are advantageous, because they allow us to observe the effects of different forcing processes separately and in detail with well defined boundary conditions (Saparoea and Postma, 2008). Experiments like that often reveal the first-order conduct of an arrangement, providing in this way the first step for resolving real-world complexities. However, it is important to bear in mind that models do assume many variables independent of each other, where in reality a clear link exists, and they often tend to disregard the tectonic influences altogether.

6 Interpreting stratigraphic record

There are generally only a few ways of looking at the available information, when trying to understand the larger scale evolution history of a basin infill. Approaches born from sequence stratigraphy for one, are the most modern and least inaccurate of the lot with respect to the depositional processes in the basin. Majority of up-to-date studies apply those ideas in a certain amount, the difference usually being whether they actually use the title and terminology of sequence stratigraphy or not. The key concepts for all such considerations are the terms like *base level, accommodation* and *sediment supply*.

Sediment supply is the most straightforward and easy to understand from between those terms. It can be viewed as the amount of sedimentary material, predominantly weathered rock, entering the system. Rate of sediment supply depends mainly on climate, and tectonics (Leeder *et al*., 1998). Sequence stratigraphic concepts require paying attention to the interaction between sediment supply and accommodation space, however, in general the architecture of inland basins is more heavily influenced by processes responsible for sediment supply (Shanley and McCabe, 1994). Changes in sediment supply over time are sometimes called the unsteadiness (Leeder *et al*., 1998).

In contrast, *base level* is probably the most abstract of the three terms. Currently there exist two somewhat different interpretations of it. The original definition is nowadays characterised by the adjective geomorphic and states that the *geomorphic* base level is the lowest level toward which erosion constantly progresses (Shanley and McCabe, 1994). Most commonly it is perceived to be the sea level height. Nevertheless, this definition proved to be insufficient for some environments. A *stratigraphic* base level was introduced, stating that it is an undulating surface of equilibrium between erosion and sedimentation that intersects the earth's surface, and which fluctuates in response to forcing functions (Shanley and McCabe, 1994). Such forcing mechanisms can be for example eustatic, tectonic or climatic (Gawthorpe and Leeder, 2000). The nature of relative base level changes in time is quite important in determining whether sedimentation or erosion takes place. While the base level fluctuations have fairly direct and logical consequences within marine and lacustrine environments, the situation and reactions of fluvial systems seem to be less direct. Nowhere is the confusion more apparent than in sequence-stratigraphic models for incised valleys (Blum and Törnquist, 2000), where both geographic and stratigraphic base levels are used and confused. It is the stratigraphic type of base level that, in general, extends its control over creation of accommodation space (Shanley and McCabe, 1994).

Accommodation space is the room made available for potential sediment accumulation (Shanley and McCabe, 1994). If the sediment is to be preserved, there must be a space available for its deposition under the base level. Therefore, the controls of accommodation space are the base level change and tectonic subsidence or uplift (Gawthorpe and Leeder, 2000) the climate is also a factor to be taken into account (Martinsen *et al*., 1999). Where accommodation equals zero, sedimentary bypass takes place, and where it is negative, erosion occurs (Shanley and McCabe, 1994). The accommodation space is a dynamic variable constantly modified throughout geologic time (Shanley and McCabe, 1994) with the rate of such changes being important as well (Gawthorpe and Leeder, 2000). The stratigraphic architecture at a depositional sequences scale is governed by the rates at which accommodation space varies as well as by the sedimentary processes inherent to the depositional environment (Shanley and McCabe, 1994). It is notable that for areas that are far away from the sea, changes of sea level do not seem to affect accommodation space in any observable manner.

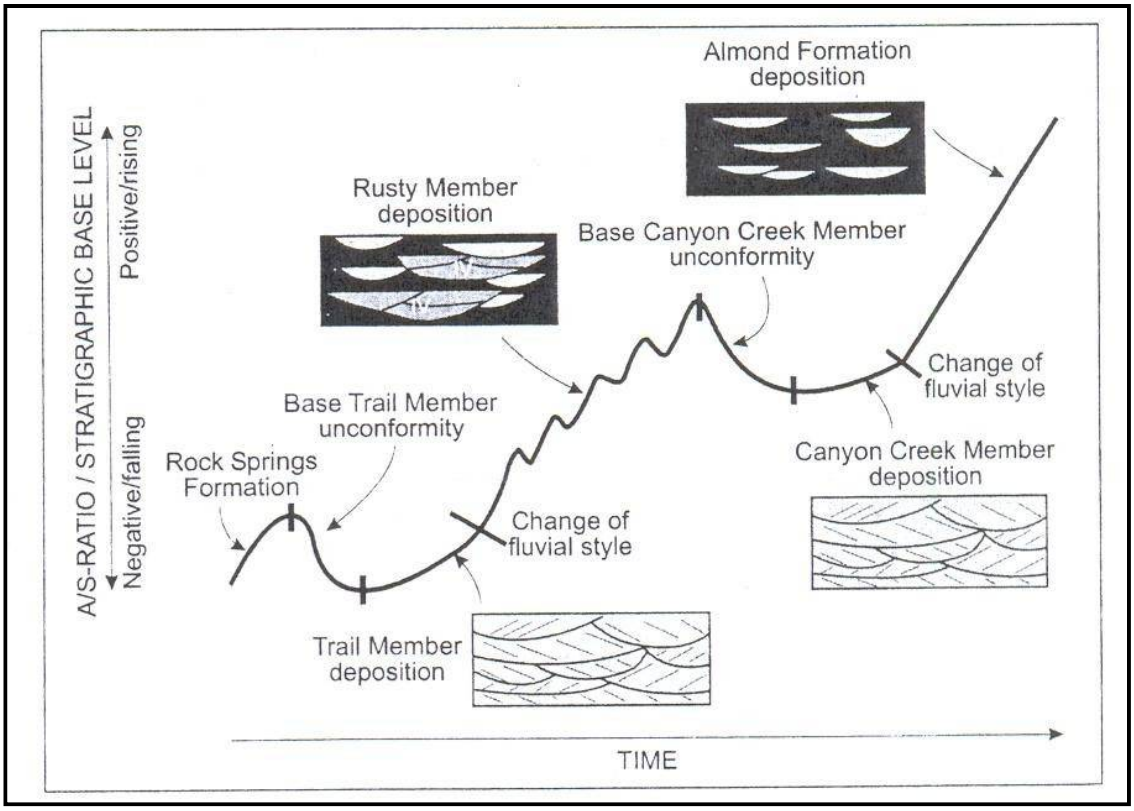
6.1 Sequence stratigraphy

Sequence stratigraphy is one of the principal ways in deciphering evolution of marine and coastal environments, but it is derived mainly from the base level variations. Therefore, it is debatable how similar concepts can, or should, be used to judge continental strata, especially where there are no correlations with sea level (Shanley and McCabe, 1994). While it is true that sedimentary features such as onlap surfaces, thinning upwards patterns, truncations, incised valleys or lowstand sedimentary wedges can be observed even in continental basin record (Contreras and Scholz, 2001), some authors tend to point out that a majority of these is dominantly driven by tectonics or climate (Martinsen *et al*., 1999). However, a respectable number of authors believe that sequence stratigraphy principles and concepts can be successfully applied to continental strata. When well practiced, sequence stratigraphy strives to explain the formation of sequences and sequence boundaries, using the understanding of all controls on sedimentation (Shanley and McCabe, 1994), which is in no conflict with what the continental basin research is about. Especially basins governed by the presence of lacustrine facies are, on the mesoscale, known to develop similar patterns as the coastal environments (Shanley and McCabe, 1994). A careful consideration of all the forcing factors is essential for a correct sequence-stratigraphic interpretation. One of the first examples of sequence stratigraphy usage on a lacustrine set of strata comes from 1993, when Louis Liro used the ideas on the Wind River Basin. In his work he defines sequences and system tracts on seismic profiles, deriving them from the presence of sequence boundaries and downlap surfaces. The initial increase in subsidence is recorded in a thin marker bed below the base of the first lacustrine shale (Liro, 1993). The base of the overlying lacustrine shale then represents a maximum transgression of the lake, or the maximum flooding surface (Liro, 1993). The regressive deltaic interval progrades into the lake in a similar fashion as it would in the marine environments.

6.2 A/S ratio

A parallel way of looking at the base level, accommodation and sediment supply is through using a parameter called A/S ratio. The A/S formula stands for accommodation versus sediment supply. This idea was first introduced by Martinsen *et al*. (1999) as a method to be used on an inland stratigraphic record. The authors claim that using sequence stratigraphy terminology can be misleading in areas, where correlation with equivalent shoreline strata is ambiguous. In continental succession situated at some distance from seashore, sequence boundaries are more controlled by climatic and tectonic processes in the source area, and not the relative level rise and fall of sea (Shanley and McCabe, 1994). Those are exactly the reasons, why Martinsen *et al*. (1999) propose to use a different terminology. Moreover, fewer boundary surfaces are expected in non-marine settings, justifying a simpler approach (Martinsen *et al*., 1999). Additionally, in many continental data sets, especially those subsurface, the maximum flooding surface is more readily identified than any sequence boundary unconformity (Shanley and McCabe, 1994). Therefore, a ratio between accommodation and sediment supply was introduced. When accommodation is larger than sediment supply the sediment is accumulated, however, if the ratio is higher than one, flooding of the observed area is likely (Martinsen *et al*., 1999; see also Fig. 14). In the theoretical case of A/S ratio being equal to one, the resultant state of such system is dynamic equilibrium. When A/S ratio is lower than zero, no accumulation occurs and sedimentary record is characteristic by a presence of erosion surfaces. Hypothesizing from those ideas and field based observations two types of tracts were defined (Martinsen *et al*., 1999). The low accommodation system tract, which is characterised by sequence boundary at the bottom and expansion surface on the top, and the high accommodation system tract that has those boundaries reversed (Martinsen *et al*., 1999). Such practices lead to similar conclusions as the sequence stratigraphy research, but they effectively avoid some of the confusion inherent in the previous approach, especially the problem of base level identification.

Fig. 14. An example of a case study working with the A/S ratio depicts the stratigraphic base level curve for the Ericson Sandstone of the Rock Springs Uplift (after Martinsen *et al.*, 1999).



7 Discussion

I do not presume to solve the question of which mechanism could be dominant in forming the basin fill architecture in a rift or transtensional basins, nor anywhere else. If my study of this subject taught me something, it is the fact that attempting any generally valid statements is close to impossible. However, there are some rules to follow and factors to be observed when looking at a particular set of strata, which help us to discern individual factors acting upon a basin. When the research is thorough, some questions at least can be answered.

It is definitely a good approach to bear in mind all the possible influencing factors, when looking at the sedimentary record of rift or pull-apart basins. Models and model situations help us to keep majority of those factors in mind, which can prove rather helpful. Before starting data processing, it is good to find out all previous studies concerning the certain subject, then hypothesize some results based on general studies, and then look for the signs within the record which either prove or contradict those expected results. It is not our goal to make the researched area match some model, but find a set of correct processes that could have shaped what we see recorded.

The state of published, up-to-date, basin research is characterised by a large number of modelling studies. Since the boom of computer technologies, even relatively complicated processes can be simulated successfully. One, for science rather beneficial, feature of such computer simulations is the need to program the essential driving mechanisms in order to use them in the model. Such mathematical and logical formulas issue from a thorough knowledge of the described system, and when correctly specified, can even lead to some unexpected new discoveries about its internal dynamics. A plenitude of analogue models is still flourishing in spite of the computer model ascent. Such models might not be as precise as formulas and numbers, yet they lead to some very instructive and enlightening results. Strangely enough, the analogue models are probably the best way of confirming a computer models applicability and accuracy. It is because the analogue models are an effective step from the strict bonds of determinism towards the nature's diversity. Analogue models seem to contain both functions known and those merely noted through their results, in nature on the other hand we often know only the results, which can lend base to some incorrect interpretations. It is my opinion, that any computer model should be tested against its analogue counterpart in order to ascertain the measure of its accuracy. Only then a wider discussion with connection to a real basin should follow. It could save the geologic community some time in exploring dead ends of science.

However, models of any kind should only be a tool to help us understand the real world, and definitely not the final product of any science. An unbiased field research should be at the core of any effort to really understand the Earth's processes.

8 Conclusions

The study of extensional and transtensional sedimentary basins is currently characterized by the presence of three complementary fields of research. First are the analogue models, second the computer models and last come the field research case studies.

The information for interpretations are gathered from various sources, mainly outcrops, well logs and seismic studies. Various geophysical and geochemical methods, such as magnetometry or detrital mineral dating are applied in addition to traditional geological and petrological analyses.

Plate tectonic processes are the major factors determining the final basin shape on the macroscale. For example, extensional rifts form long structural valleys that are much larger than the relatively smaller, usually rhomboidal-shaped transtensional basins.

On the mesoscale, extensional halfgrabens are the fundamental building blocks for both types of the environments. However, even though rift and pull-apart basins share some similarities, a much higher number of differences set them apart.

Sedimentary facies within alluvial basins are characterized by the presence of some or all of the following environments. In dry climate conditions eolian and evaporite sediments, as well as alluvial fans are deposited. When there is more precipitation, river and lake environments are present sometimes allowing coal and black shale deposits to develop.

The main mechanisms forming the mesoscale alluvial basin architecture are tectonics and climate. While the tectonic forcing is often rapid and episodic, producing abrupt migration of facies, the climatic influences are commonly periodic, and they act upon many variables such as temperature, precipitation, vegetation growth and weathering.

To be able to read stratigraphic record and recognise tectonic forcing from the climate change, geologists introduced concepts such as the sediment supply, the accommodation and the stratigraphic base level. Sequence stratigraphy and the A/S ratio then work with those ideas, allowing us to decipher some of the basin’s history.

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Prohlašuji, že jsem svou bakalářskou práci vypracovala samostatně a pouze s využitím citované literatury.

V Praze, Dne

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