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Notes

Sedimentary models for extensional tilt-block/half-graben basins

M.R. Leeder & R.L. Gawthorpe

SUMMARY: Extensional tectonism produces characteristic half-graben/tilt-block systems whose facies mosaics are influenced by tectonically induced slopes resulting from hanging wall downtilting and footwall uplift. The characteristic asymmetrical subsidence vectors that therefore develop across the graben also exert a fundamental control upon facies distributions. A number of predictive tectono-sedimentary facies models are presented in which these various influences are explored. Alluvial fans and cones react to tilting by becoming segmented, those in the hanging wall showing down-dip hanging wall off-lap and those sourced in the footwall showing progradation from the apex. Lake and coastal waters react instantly to tilting, causing transgression and seiche-induced erosion. Axial through-flowing river channels and delta lobes tend to migrate or avulse towards the axis of maximum subsidence but may be constrained by the toes of footwall-sourced fans. Peat accumulation or soil development are accentuated up the hanging wall dip slope away from the locus of maximum deposition. In coastal areas, fan deltas sourced in the footwall pass offshore into small submarine fans whilst axial fans issue from delta fronts where individual fan lobes may migrate under fault control. In carbonate provinces the footwall scarp may become a bypass margin whilst the hanging wall dip slope may undergo a ramp-tormented shelf evolution with time.

It has become apparent in the last few years that the process of lithospheric extension is characterized by a distinctive development of tilt blocks and half-grabens bounded by major normal faults (Morton & Black 1975; McKenzie 1978; Wernicke & Birchfiel 1982; Jackson *et al.* 1982a, b; Brun & Choukroune 1983; Gibbs 1984). These types of basins develop progressively during extension, and we recognize that during this time they exert a profound and logical influence upon geomorphology and sediment-transfer mechanisms in the vicinity. Examples of active basins of this sort occur in the Aegean back-arc (McKenzie 1978; Jackson *et al.* 1982b; Jackson & McKenzie 1983); in the Basin and Range Province of the western United States (Myers & Hamilton 1964; Wernicke & Birchfiel 1982; Anderson *et al.* 1983); in the lower Rhine basin (Illies & Fuchs 1983); in the Gulf of Suez (Sellwood & Netherwood 1984); and in Afar (Hutchinson & Engels 1970; Morton & Black 1975). Extinct fault-bounded extensional basins occur around the margins of almost all Atlantic-type passive continental margins (e.g. Surlyk 1977, 1978) and in continental areas where extension did not proceed to oceanic separation (failed arms) as in the Central African rift system (Browne & Fairhead 1983). These extinct basins usually lie buried beneath the later deposits of the thermal-contraction phase of extensional subsidence. One of the best known examples is the North Sea basin (Christie & Sclater 1980; Barton &

Wood 1984; Ziegler 1982). An increasing number of geologically ancient basins of this type are being recognized, e.g. the early Carboniferous extensional province of the British Isles (Leeder 1982; Dewey 1982; Gawthorpe, in press), and doubtless many others await recognition.

Recently major advances have been made concerning the dynamics and kinematics of normal faulting in areas of active extension (Wernicke & Birchfiel 1982; Jackson *et al.* 1982a, b; Gibbs 1984; Jackson & McKenzie 1983). It is the purpose of this paper to integrate such studies with analysis of sediment transfer and deposition, the resulting three-dimensional tectono-sedimentary-facies models being helpful in the study of ancient basin-fill successions. The models developed herein have been culled from an extensive but scattered geomorphological and sedimentological literature, our unpublished studies in active extensional terrains (Aegean, Basin and Range), our work in the ancient extensional graben-fill successions of the Lower Carboniferous in N Britain (Leeder 1982, 1986; Gawthorpe 1986, in press), and from previous stratigraphic-modelling contributions (Bridge & Leeder 1979).

Tilt-block/half-graben morphology and structure

Originally, Morton & Black (1975) envisaged domino-type fault blocks forming during active

extension, with the further occurrence of progressive fault rotation causing nucleation of higher angle second- or third-generation normal faults which themselves become progressively rotated. Structural studies in the Basin and Range Province have confirmed this model (Proffett 1977) and led to a number of more detailed tectonic models involving basement thrust reactivation, listric-fault fans and extensional analogues to the ramp and flat models of thrust tectonics (Wernicke & Birchfiel 1982; Brun & Choukroune 1983; Anderson *et al.* 1983; Chamberlin 1983; see also the general papers of Gibbs 1983, 1984). These studies serve to stress the great complexities of extensional faulting, especially on an intrabasinal scale.

Whilst American workers in the Basin and Range Province have stressed the importance of shallow, 'domino-style' faulting, workers in the Aegean extensional province (McKenzie 1978; Jackson *et al.* 1982a, b) have shown the importance of major normal faults of mid-crustal penetration which bound 'bouyant' tilt blocks. Some examples of this type of fault also occur in the Basin and Range Province (Anderson *et al.* 1983). These major faults cause instantaneous unloading along the fault plane during fault motion leading to an instantaneous isostatic upwarp of the footwall block (Heiskanen & Vening Meinesz 1958; Savage & Hastie 1966; Bott 1976). Jackson & McKenzie (1983) calculate this footwall uplift to be around 10% of the hanging wall subsidence.

Whether small- or large-scale faulting develops seems to depend upon the extensional strain rate, the geothermal gradient and the

existence of crustal fractures ripe for rejuvenation (Anderson *et al.* 1983; Eaton 1982).

Reduced to their simplest form, tilt-block/half-graben structures can be considered to be bounded by single normal faults which penetrate to mid-crustal levels. As the hanging wall basement detaches from the footwall an asymmetrical basin progressively develops above the hanging wall. The fundamental controls upon geomorphology and sedimentation patterns are as follows (see Figs 1 & 2):

1 Tectonic slopes. These are produced by a combination of footwall uplift and hanging wall subsidence and comprise the steeper footwall scarp slope and the gentler hanging wall dip slope. The footwall area is the main sediment source for the adjacent basin although, due to the asymmetrical nature of the basin, the hanging wall-derived sediment may be spatially more extensive. Recent geomorphological studies (Hanks *et al.* 1984) demonstrate that the gradual decay of the scarp profile with time follows a decay equation of the error-function type. The periodic rejuvenation of the footwall scarp will give rise to important sedimentary consequences in the basin fill (q.v.). In examples where the basin-margin fault has a listric geometry, tilting of the surface during extension is accompanied by rotation and the development of a rollover structure.

2 Asymmetrical subsidence. This is due to the pivot-like motion of the hanging wall after individual extensional episodes. Asymmetrical subsidence following historic earthquakes is best documented for the Hebgen Lake area of Montana, USA. In Fig. 2a we reproduce the

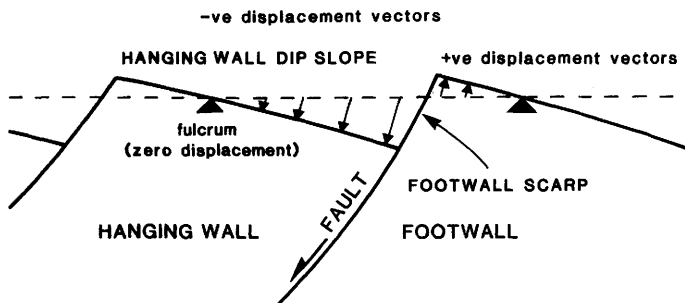


FIG. 1. Nomenclature diagram for tectonic slopes associated with a simple tilt block/half-graben. The main tectonic slopes produced during basin development are the steep, spatially restricted footwall scarp associated with the footwall-to-hanging wall transition, and a broad, gentle slope, the hanging wall dip slope, characteristic of the hanging wall of the basin-forming fault. The fulcrum is the position where displacement of the hanging wall block is zero; either the limit of roll-over in isolate tilt block/half-grabens or the transition from areas of the hanging wall undergoing positive motion due to footwall uplift to areas undergoing negative motion due to hanging wall subsidence. The position of the fulcrum is governed by the relative displacement vectors across the half-graben-bounding fault(s), the presence of antithetic/synthetic intrabasinal structures and the subsurface geometry of the faults.

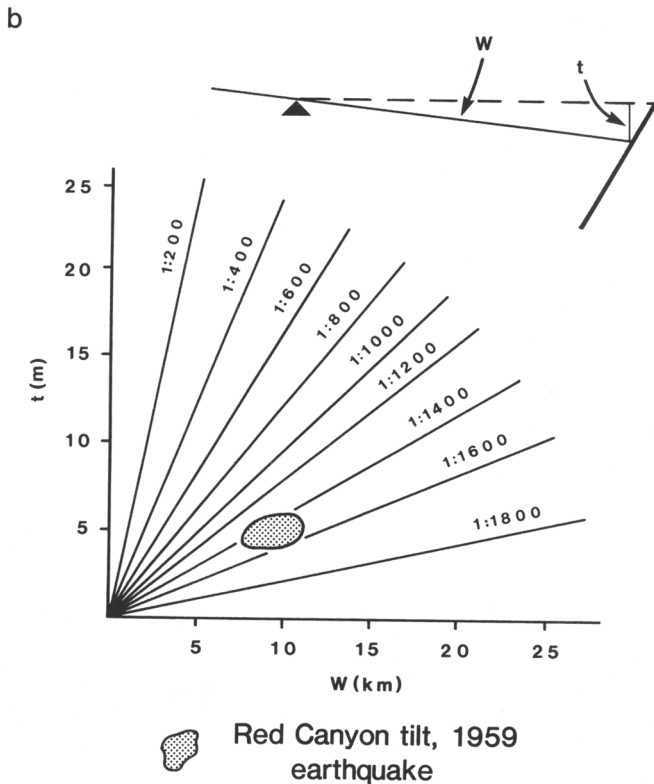
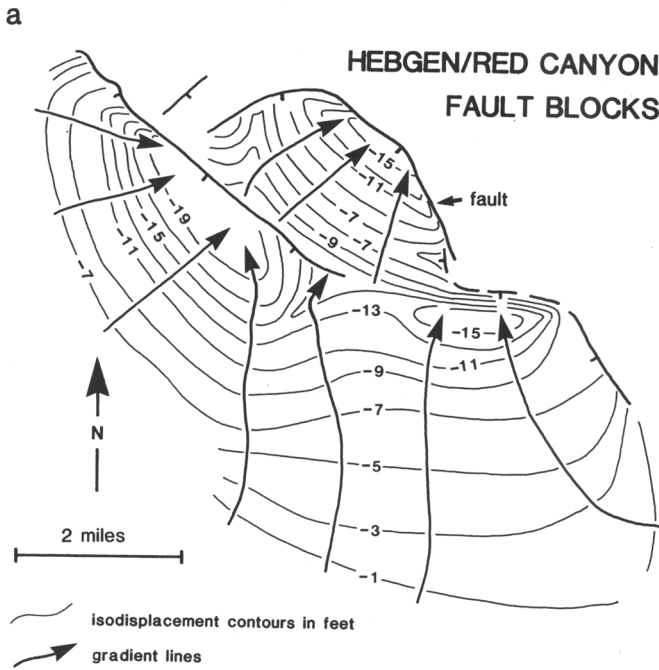


FIG. 2. (a) Example of surface displacement associated with the 1959 earthquake in the Hebgen/Red Canyon tilt block, Montana, USA (after Fraser *et al.* 1964). Contours are of equal ground displacement associated with the earthquake and our arrows represent sketch gradients. (b) Our graph showing the approximate tectonic slopes produced by single motions of vertical magnitude (t) across tilt block of width (W).

isodisplacement contours of Fraser *et al.* (1964) drawn up following the 1959 earthquake, with an indication of the secondary gradients due to tilting. As shown in Fig. 2b, tectonic slopes produced by quite modest fault displacements have a great effect when superimposed on say, typical river gradients. Our fundamental starting point is thus emphasized: all sedimentary processes driven by gravity will be influenced by extensional tilting.

The point where the hanging wall displacement tends to zero may be called the fulcrum. The position of the fulcrum is not fixed but is controlled by the geometry of the basin-margin fault, the presence or absence of antithetic/synthetic intrabasin faults and time. In the simplest case of a tilt block/half-graben bounded by a listric normal fault, progressive extension will lead to the fulcrum moving away from the fault, i.e. up the hanging wall. This effect may be particularly important in the early stages of evolution of tilt blocks/half-grabens, leading to progressive on-lap onto the basement. The seismic section and line drawing across the Fallon basin by Anderson *et al.* (1983, fig. 5) displays such on-lap developed during progressive extension. In a linked series of tilt blocks the fulcrum divides areas undergoing positive motion due to footwall uplift from areas of negative motion arising from hanging wall subsidence. As shown below, we postulate that the location of fulcral lines will have considerable influence upon the sedimentary and geomorphic evolution of a tilt block and should also provide valuable clues concerning crustal dynamics.

In active half-grabens the simple tilt-block concept described above is complicated, to a greater or lesser extent, by the occurrence of both antithetic and synthetic faults which deform both the hanging wall basement and the developing sedimentary fill. Although these various structures have received descriptive attention in seismic studies (e.g. Gibbs 1983, 1984) in ancient basins it is by no means clear how they influenced topography and sedimentation at the depositional surface. Such structures will, however, clearly be of importance in modifying the sub-surface geometry of the sedimentary fill. Major intrabasin normal faults define important 'mini' horsts and grabens in the Rio Grande rift (Velarde graben of Manley 1979; Ladron horst of Brown *et al.* 1979). Analogous structures are deduced for the extensional Carboniferous basins of northern England (Leeder 1986, in press; Gawthorpe 1986, in press).

At the Earth's surface, extensional normal faults are of finite extent and thus the asym-

metrical basins so produced have a distinctive 'scoop' shape, at least in the early stages of extension. This is well seen in the Hebgen Lake area of Montana (Fraser *et al.* 1964, see our Fig. 1) and in the Rio Grande basin system of Colorado/New Mexico where continued extension along a N-S trend has led to the joining up of a series of originally isolated scoops into the present complex linear graben system (Chapin 1979; Bachman & Mehnert 1978).

Another consequence of the finite extent of normal faults at the surface (see Smith & Bruhn 1984) is that overlap zones exist between *en échelon* fault segments. In such zones, where the footwall zone of one fault passes into the hanging wall of an adjacent structure, an oblique monoclinial downbend develops at a high angle to the normal-fault trend. Large drainage systems may exploit the hinterland behind such areas, causing the development of larger-than-average depocentres in the main hanging wall basin (see Fig. 4). We have seen examples in the Greek Aegean, at Karrena Bourla in Locride, and in Montana, USA, along the Madison Front N of 'Quake Lake. Examples have also been described by Crossley (1984) from the East African graben in Malawi. Transform (Bally 1982) or transfer faults (Gibbs 1984) are other structures developed at a high angle to normal faults within half-grabens; indeed, the monoclines described above may be the surface expression of blind transfer faults. These faults separate areas of the basins deforming in different styles or at different rates and, in some instances, the sense of tilting may change polarity across them. Transfer faults also have an important role in sediment transfer, being the sites of major transport of sediment off both the hanging wall and footwall. In the Lower Carboniferous Bowland basin of northern England transfer faults were a major control on the location of coarse-grained carbonate debris-flow deposits that were derived off the hanging wall basin margin (Gawthorpe, in press).

Additional complications also arise because of the occurrence of layers of upwardly mobile partial melts in the shallow crust. These buoyant accumulations cause local areas of minor relative upwarp in an otherwise subsiding regime. Perhaps the most spectacular example occurs beneath the Rio Grande rift at Socorro, New Mexico (Sanford *et al.* 1977; Brown *et al.* 1979). Suspected ancient analogues existed in the Jurassic of the Central North Sea (Leeder 1983) and in the Lower Carboniferous Northumberland graben in the Scottish Borders (Leeder 1976, 1982). Major surface effects will also arise once this magma is erupted, with the

production of lava plateaux, large-scale river damming, and local fan formation. Such effects are seen in the Rio Grande rift (Lipman & Mehnert 1979).

A dynamic feature of major importance in extensional basin evolution is the abandonment of one tilt-block/half-graben system because of the abandonment of one crustal-scale normal fault and the development of another (Jackson & McKenzie 1983). If the new fault develops on the hanging wall side of the now-extinct fault then the basin-fill is gradually uplifted in the footwall of the new fault. Examples occur in the Greek Aegean, particularly on the S side of the Gulf of Corinth and in Locride (Jackson *et al.* 1982a; Jackson & McKenzie 1983).

Stratigraphic and sedimentary consequences of extension— general remarks

As noted previously the occurrence of movement on an extensional normal fault causes surface tilting. Thus a tectonic gravity slope arises which will be superimposed upon the existing geomorphic slope. Since many sedimentary processes are gravity controlled it follows *a priori* that erosion, sediment transfer, deposition and soft-sediment deformation (see Leeder (in press) for a full discussion of this latter feature) will then have a tectonic influence, if not control. Once sedimentary systems become established in extensional basins then each slope component will contribute to the basin infill in a distinctive and, to some extent, predictable way. Of major importance are (i) *lateral-transport systems* that deposit sediment in high-gradient fans and low-gradient cones down the footwall and hanging wall slopes respectively, normal to the strike of the main bounding fault, and (ii) low seeking *axial-transport systems* that transfer sediment parallel to the strike of the main bounding faults. The effects of surface tilting on those lateral and axial systems give rise to marked basin-wide variations in lithology, facies and thickness. In the following sections the implications of these various general considerations are applied to particular sedimentary facies associations so that general and predictive basin-fill sequences may be proposed.

Before proceeding to the models it is essential at the outset to stress that there are many other variables (other than tectono-sedimentary, that is) which can affect the details of facies distributions. Thus climate and hinterland geology will also exert profound influences upon facies

associations in particular tectonic settings. These two variables will combine to determine the magnitude of clastic-sediment flux into an extensional basin. Clearly, a balance will then be set up between sediment deposition rate and subsidence rate as ultimately determined by the rate of extension. The relative position of sea-level with respect to the basin floor is also of obvious importance. Tilting is expected to have instantaneous and catastrophic effects upon both lake and marine shorelines. Such effects will give rise to a distinctive 'signal' in the basin-fill successions and may cause the production of distinctive sedimentary cycles. Such effects are of major importance to the geologist examining the fills of ancient basins. Here, in the absence of direct evidence for active extensional tectonics, it is essential to integrate the study of observed facies changes with structural information. The following models are proposed as basic templates for such studies.

Tectono-sedimentary facies model A— continental basin with interior drainage (Fig. 3)

This style of basin is a very characteristic one in the Basin and Range Province of the western USA where isolated fault-bounded depressions form local interior-drainage basins with no outlet to adjacent structures. The fundamental slopes are the relatively low-gradient hanging wall dip slope with broad alluvial cones and the relatively high-gradient footwall scarp slope which sources small alluvial fans whose depositional loci occur at the foot of the scarp on the lower hanging wall dip slope. As noted previously, large drainage systems frequently take advantage of transfer-fault zones and areas between *en échelon* fault terminations so that larger-than-average cones may preferentially form in such locations (Fig. 4). Should local climatic conditions allow, permanent or playa lake bodies will form in the basin as close to the locus of maximum subsidence as the footwall-sourced fans will allow. Such triplet cone-lake-fan systems have particularly dynamic interactions at their internal boundaries.

Perhaps the most studied example is Death Valley, California where the meticulous work of Hooke (1972), following on from the studies of Hunt & Mabey (1966), led to the first recognition of the effects of tilt movements on fan evolution and sedimentation. Hooke established beyond reasonable doubt that fan segmentation results from surface tilting and that characteristic off-lap sequences result if the tilting process is carried on periodically. These effects are

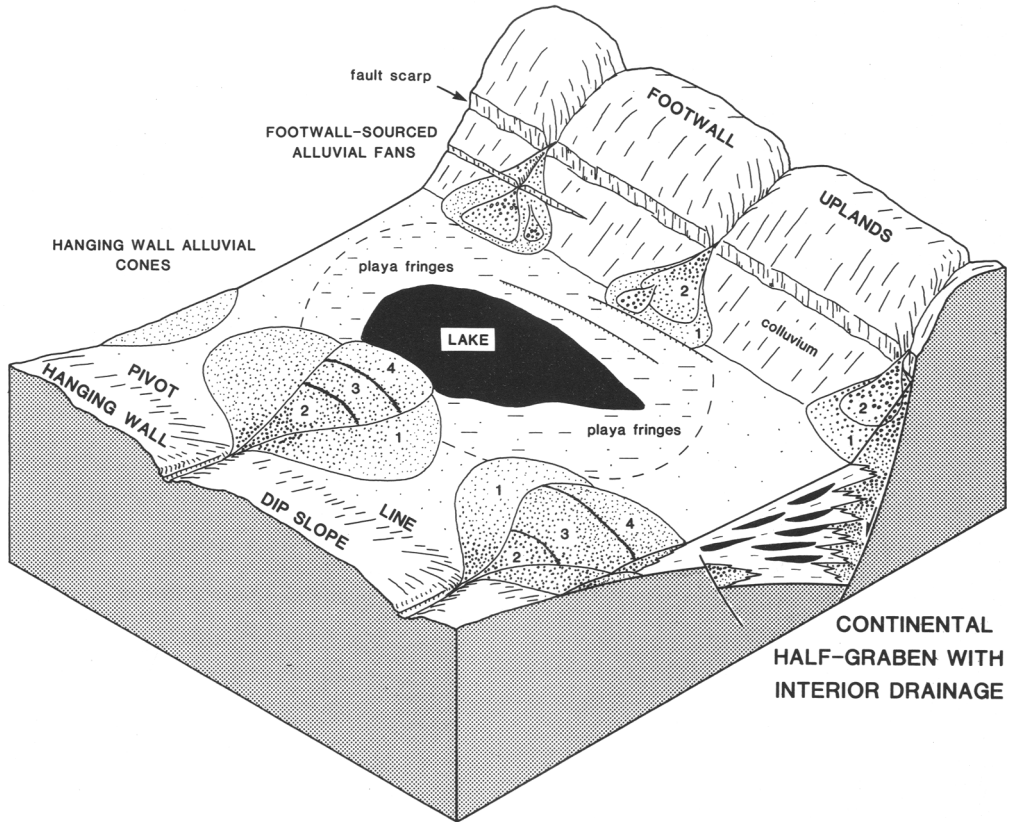


FIG. 3. Isometric diagram showing the main sedimentological features of facies model A: continental basin with interior drainage. Full discussion in text. Note: only the major basin-margin fault is shown; in natural examples the presence of antithetic, synthetic and transfer fault systems strongly modify certain depositional reactions to tilting. In addition, the sub-surface geometry is modified by differential compaction, thinning of the hanging wall associated with development of the roll-over and the presence of antithetic/synthetic fault systems within the sedimentary cover. 1, 2, 3 etc. indicate successive fan lobes.

generally predictable in terms of an extensional tilt-block model and may be amplified as follows.

Periods of fault motion cause the tectonic gradient and length of the footwall scarp to increase instantaneously. Hanging valleys are produced as fan-head channel incision occurs progressively. The gradient of the fan surface in the hanging wall is decreased though, so that renewed sedimentation leads to the construction of a new fan segment close to the fan apex. This is expected to prograde gradually over the old fan segment with time, causing a crude upward-coarsening cycle to develop in response to the progradation of the downslope-thinning clastic wedge. Fault motion will also cause instantaneous lake transgression over the distal portions of the footwall-sourced fans, causing them to shrink substantially in area. Should subsequent

gradual fan progradation occur, these transgressive facies will be intercalated at the base of a tectonic fan cycle. Historic observations of lake-tilting, notable after the Hebgen Lake 'quake of 1959 (Myers & Hamilton 1964), show the occurrence of major seiches which may be expected to initiate erosive contacts and debris washover units over a much larger area than that covered by the permanent lake. The alluvial cones of the hanging wall dip slope react to tilting by incising their main fan-apex feeder channels close to the pivot line. The previous equilibrium-cone surface is tilted up by an amount determined by the magnitude of fault motion and a new active cone-lobe surface forms on a lower angle surface, often basinwards of the old cone lobe because of the steepening of the tilted dip-slope surface. Prominent breaks of slope occur at the

junction of old and new surfaces, the older surface becoming depositionally defunct and subject to pedogenesis (calcretization in the case of Death Valley). Basinwards, the cones will prograde over the latero-distal portions of older fan surfaces forming off-lap sequences of downslope-thickening and fining wedges (see Hooke 1972, fig. 3). Thin units of lacustrine facies will be incorporated in these successions as progradation occurs over the upslope abandoned portions of the old lake shoreline. Examples of such effects are known from the hanging wall cones of Hebgen Lake (Alexander & Leeder, in press).

It seems clear that fault-induced tilting causes a number of rapid facies changes to occur. It should be borne in mind, however, that fan, cone and lake shrinkage and growth cycles may also be caused by climatic fluctuations, as is frequently seen in the Pleistocene history of the western USA (Hawley *et al.* 1976) and elsewhere (Talbot & Williams 1979). These more gradual sorts of effects must be separated from the purely tectonic effects discussed above. This may only be possible in very well-exposed terrains where good stratigraphic dating is present.

The basin-centre facies in the present model are certainly the most variable since evaporitic deposits may form from playa lakes as well as the non-evaporitic deposits of more permanent, possibly stratified lakes. The primary control here is obviously climatic. A further possibility, where run-off is very low and where regional sand-laden winds blow across the basin, is that small desert ergs may develop, particularly in the axis of maximum subsidence. In such areas the decelerating winds drop portions of their bedload before they accelerate up the hanging wall dip slope or the footwall scarp. Other geometrical possibilities of minor erg formation clearly exist. The Great Sand Dunes of the San Luis basin, Colorado are proposed as an example of this kind of facies association.

Tectono-sedimentary facies model B—continental basin with axial through-drainage (Fig. 4)

Active examples of this style of basin are well developed in the Aegean region, e.g. the River Axios in the Vardar graben, River Speriohos in the Lamia graben, and the Great Meander River in one of the Anatolian grabens. Other examples are the lower Rhine graben (particularly the River Erft in the Erft graben), the Rio Grande rift of Colorado/New Mexico and the Madison River graben of Montana. Certain features are shared in common with model A, namely the

occurrence of footwall and hanging wall derived fans and cones respectively. Some basins have, in fact, evolved from interior to through-drainage during their extensional evolution, notably the Rio Grande composite linear graben system which now comprises the once isolated San Luis, Taos, Sante Fe/Espanola and Albuquerque sub-basins (Bachman & Mehnert 1978; Kelley 1977; Manley 1979).

The most fundamental characteristic of this kind of model concerns the reaction of the axial river to episodes of tectonic tilting which influence river migration. The effect to be described was briefly noted by Russell (1954, p. 370) in his Anatolian geomorphological study and independently explored by Bridge & Leeder (1979) in their simulation models of alluvial stratigraphy ('architecture'). The latter authors postulated that periodic abrupt channel movements (avulsions) would cause the 'low-seeking' channel to persistently reoccupy the axis of maximum subsidence in statistical preference to other areas of the half-graben. Thus, with time, a preferential stacking of alluvial sand-bodies would be observed in the axis of the sub-surface basin fill (see discussion in Alexander & Leeder, in press).

A number of other factors will influence this simple model.

1 The actual position of the axial river will be displaced from the axis of maximum subsidence by alluvial fans issuing from the footwall scarp slope. This is well seen in the Anatolian grabens (Russell 1954) and at the margins of the ancestral Rio Grande rift (Hawley *et al.* 1976, p. 250; Bachman & Mehnert 1978, p. 288) where the axial fluvial-channel facies are interdigitated with transverse piedmont facies.

2 Intrabasinal normal faulting may create mini-grabens within the main structure. Such features would tend to 'trap' the axial river and encourage the production of sharply defined fault-bounded sub-surface stacks of axial-channel sand or gravel units. A modern example is represented by the Velarde mini-graben in the Espanola portion of the Rio Grande rift (Reilinger *et al.* 1979, fig. 6; Manley 1979, fig. 2). Ancient examples occur in the axis of the Lower Carboniferous Northumberland graben, as discussed by Leeder (1986, in press).

3 Recent theoretical and field studies (Leeder & Alexander, in press) have shown that axial river channels also gradually respond to tectonic tilting by a process of preferential downslope cut-off and minor avulsion. This leads to the production of an abnormally wide channel belt sand-body, examples of which occur along the South Fork River in the Hebgen area of Montana

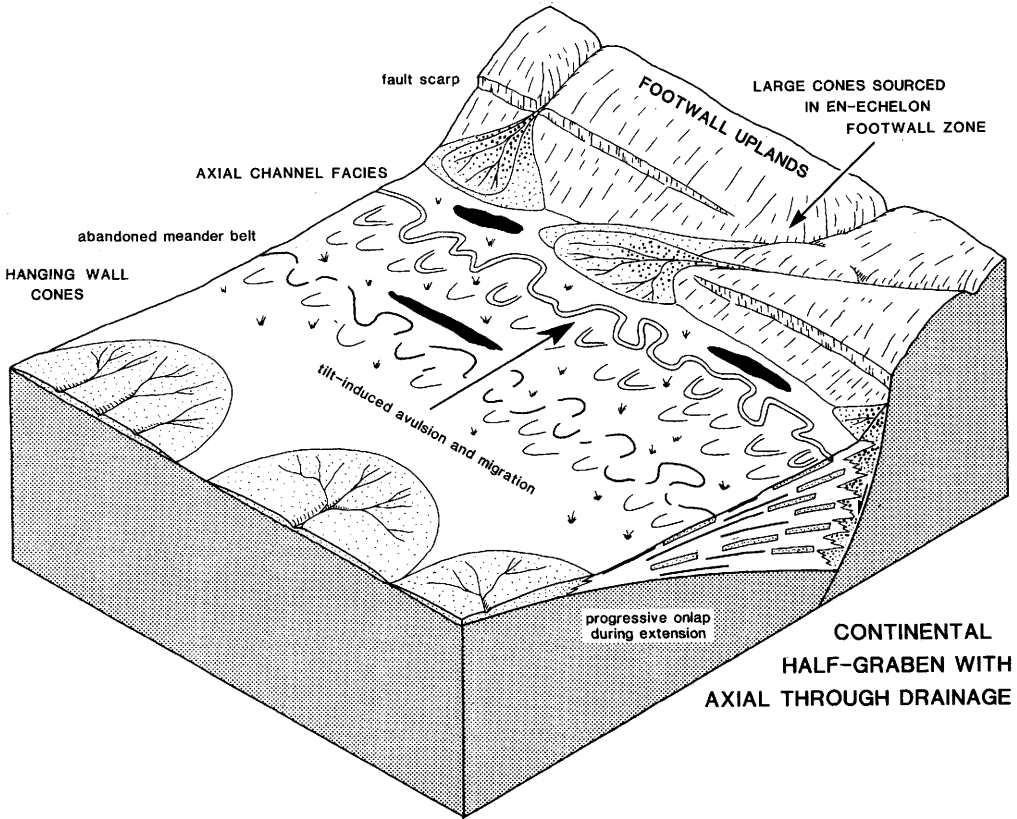


FIG. 4. Isometric diagram for facies model B: continental basin with axial through-drainage. Note the large alluvial fans sourced in the zone between two *en échelon* normal faults and preferential avulsion of the axial river channel(s) towards the faults. Full discussion in text.

(Myers & Hamilton 1964; Leeder & Alexander, in press) and along the Mississippi River in the New Madrid uplift area (Russ 1982; Alexander & Leeder, in press). Very large-scale examples of such behaviour were originally postulated by Mike (1975) in his analysis of channel migration over the Carpathian molasse plain.

4 It is also a possibility that instantaneous, low-seeking avulsion could occur as a direct result of a tilting movement.

A corollary of the tendency for channels to seek out the axis of subsidence by the various means outlined above is that fine-grained out-of-channel flood sediments should be deposited progressively more infrequently as the hanging wall dip slope is ascended. This is because, like the axial-channel system, surface floodwaters will always tend to follow the main basin gradient. In a suitable climatic regime, especially humid tropical, and in areas away from hanging

wall cones, this process will cause the formation of a broad belt of hanging wall dip-slope swamplands which will gradually lead to the occurrence of sub-surface peat layers and hence, ultimately, to the formation of coals which will tend to thicken into the basin axis. Minor intrabasinal faulting may cause abrupt thickness changes of the peats. Examples of these sorts of consequences of our model are illustrated by Teichmuller & Teichmuller (1968, figs 5 & 8) and by Brunacker & Boenigk (1983, fig. 5) from the lower Rhine graben. As the hanging wall is further ascended it may be expected that the lowered water table should encourage the swamplands to peter out and let oxygenated soil horizons develop in their place as the pivot line of the tilted surface is approached. In a more arid climatic regime, the above facies mosaic would be replaced by calcrete-type soil-profile development away from the loci of active hang-

ing wall dip-slope cones. Examples are seen in the Rio Grande rift (Llano de Albuquerque—Bachman & Mehnert 1978, p. 288).

Tectono-sedimentary facies model C—coastal marine gulf basin (Fig. 5)

Active examples of these basins occur at many localities around the margins of the Aegean e.g. the Gulf of Corinth, the Thermaic Gulf, and the Gulf of Euboea. As shown in Fig. 5, the gulf is often actively being infilled by axial drainage systems. Transverse fans and cones are characteristically present in all examples. The gulf morphology is a direct result of half-graben morphology, with the major bounding normal faults determining the position and characteristic cliffed morphology of the linear footwall shoreline. Ancient analogues are discussed by Surlyk & Clemmensen (1983).

Basins with axial drainage will closely follow certain behavioural tendencies proposed for the

previous alluvial model. Thus the terminal deltaic lobes to the drainage system will migrate or avulse preferentially towards the axis of maximum tectonic subsidence, thereby leading to the preferential stacking of delta lobes in the sub-surface (Leeder & Strudwick 1986) and a tendency for maximum back-swamp peat development to occur some way up the hanging wall slope. Important additional features will result from instantaneous marine transgression over the delta lobe, and adjacent shorelines following motion along the normal fault. In general, the effects of such transgressions will lessen in importance up the hanging wall slope. In the footwall and on the footwall scarp slope, emergence will occur, as elegantly demonstrated from geomorphological features in the Corinth Gulf by Jackson *et al.* (1982b) after the 1981 earthquakes. The extent of instantaneous transgressions over the low-gradient axial gulf coastal plain may be very large indeed e.g. a 3 m fault throw in an axial coastal plain of gradient 1:500 would flood a maximum of 1.5 km inland.

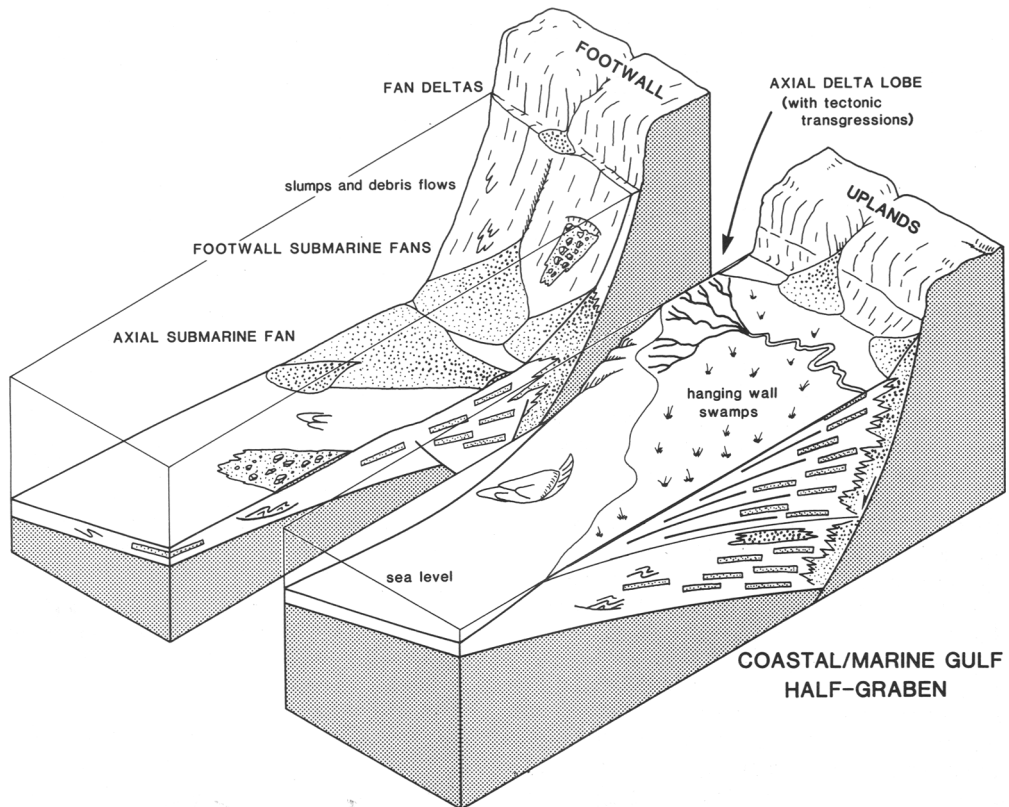


FIG. 5. Isometric diagram showing sedimentological characteristics of facies model C: coastal/marine gulf basin. Location of axial submarine fan, controlled by intrabasin synthetic and antithetic faults, is shown schematically. Full discussion in text.

Renewed clastic progradation after the period of fault motion would then give rise to a very distinctive abrupt transgressive and gradual regressive-facies sequence.

The hanging wall cones and footwall fans sourced in the exposed gulf-perimeter uplands will both show dynamic interactions with the marine-gulf coastal facies after periods of fault-induced subsidence. Footwall-sourced alluvial fans will be subject to the instantaneous effects of marine transgression across their distal aprons. Our observations in the Gulf of Corinth where the fans are largely inactive, being late-Wurmian features, reveal that fan aprons are often cliffed and are subject to marine erosion at present. Eventually, more active fans will prograde once more over such marine transgressive surfaces. Particularly distinctive facies occur in arid climates, where fan aprons may contain sabkha evaporites. Wave-modified shorelines and near-shore carbonate build-ups should provide characteristic markers of fault-generated transgression followed by renewed progradation. Examples of such fans are commonplace around the periphery of the Red Sea and in the Gulf of Eilat (Sellwood & Netherwood 1984).

The footwall alluvial fans may border particularly steep offshore slopes leading into the marine-gulf proper. Such fan systems define the fan-delta complexes of some authors (e.g. Westcott & Etheridge 1982) and these may source important submarine-fan complexes issuing from channels cut into the submarine margins of the faulted gulf margin. Examples were inferred from the Mesozoic tilt blocks of E Greenland by Surlyk (1977, 1978) and are also known in the North Sea (Stowe *et al.* 1982). On the gulf basin floor these transverse fan complexes may interact with axial fans sourced from the axial delta front. These environments are particularly susceptible to earthquake-induced liquefaction and provide a potent and active source for slumps, debris flows and turbidity currents issuing on to the gulf floor via major submarine fans (e.g. the Gulf of Corinth, Perissoratis *et al.* 1984). A major control of fan-lobe location by submarine topography is to be expected since each of these above-mentioned re-sedimentation processes is controlled by the gravity slope. Major episodes of tilting, and internal sub-basins formed by intragraben faults will closely control sand and gravel deposition. Subtle topographic effects on the faulted basin floor will thus cause important lateral changes in turbidite thickness and 'proximity'. Examples are revealed in Sparker surveys across the Gulf of Corinth by Brooks & Ferentinos (1984) and stacked offset fan lobes are seen in seismic

reflection charts across Californian borderland fans (Graham & Bachman 1983).

Tectono-sedimentary facies model D—coastal/shelf basins with carbonate facies (Fig. 6)

Once the hinterlands around a half-graben system become more-or-less submerged and the basin becomes part of an actively extending shelf (e.g. modern Aegean Sea) the rate of clastic input may become substantially reduced. Should the graben be located in low-latitude areas of high organic productivity then a purely carbonate facies mosaic will be superimposed upon the structural topographic template discussed previously. Since carbonate production and facies distributions are strongly depth and slope dependent we expect to see marked contrasts in depositional style across a half-graben system. The degree of facies contrast will depend critically upon the relative rates of subsidence versus carbonate production rates. In the following discussion we assume that an adequate differential exists to maintain water depths.

We postulate that the footwall scarp slope will ensure that the footwall-to-hanging wall margin develops into a bypass margin (McIlreath & James 1978) with the scarp fringed by periplatform talus and the upper slope cut by gullies feeding debris flows and density currents on to the basin floor as allodapic carbonates. More extensive debris-flow units may also form from slumps of the talus fringe, particularly when directly activated by fault motion.

The footwall will be dominated by relatively shallow-water facies such as build-ups and carbonate sand shoals, the exact facies type being dependent upon scarp-slope orientation relative to prevailing winds, and upon the magnitude of the local tidal-current vectors. One important feature that will develop is minor cyclicity related to shallowing during periodic footwall uplift, with the possibility of periodic emergence giving rise to karstic surfaces and calcrete development. The minor cycles themselves should be markedly asymmetrical, with rapid upward shallowing followed by a more gradual deepening trend as subsidence due to thermal decay occurs. The hanging wall dip slope should initially develop into a ramp-type margin (Ahr 1973) deepening (sloping) towards the footwall scarp as a result of the induced tectonic tilt. This will gradually evolve into an up-dip shelf with a rimmed margin, following the evolutionary trend outlined by Read (1982, 1984), and pass down-slope into basinal facies. The rimmed shelf margin may include reef build-ups and sand shoals and may eventually develop into a bypass

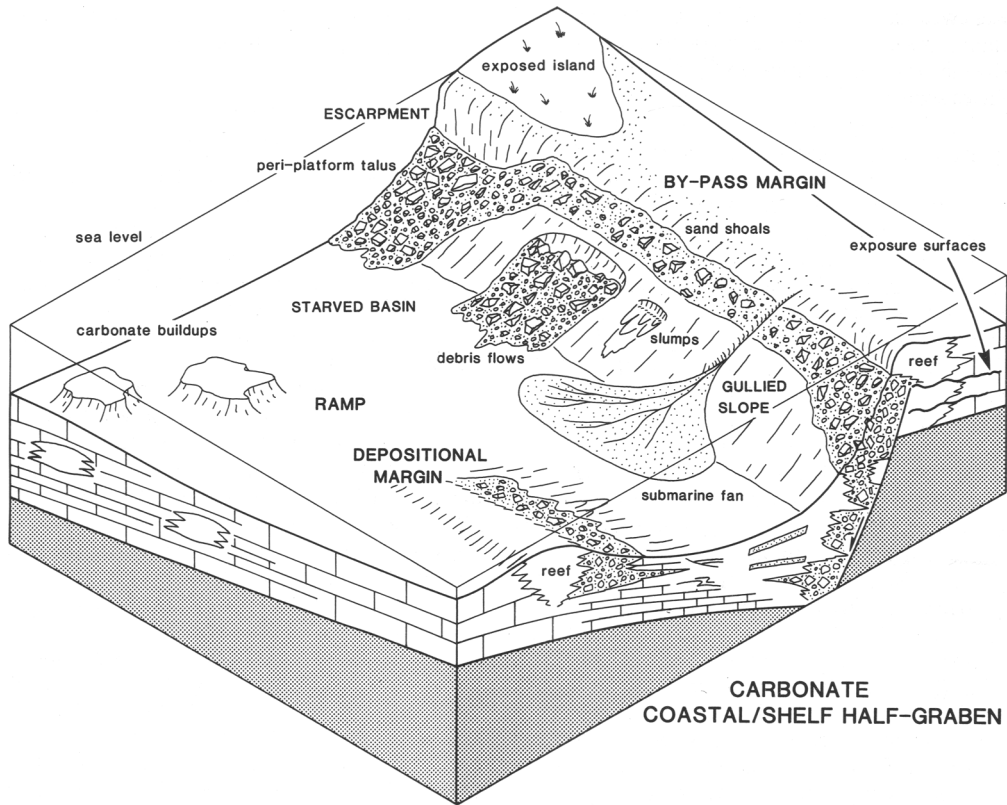


FIG. 6. Isometric diagram showing characteristic sedimentary features of facies model D: coastal/shelf basin with carbonate facies. The variety of carbonate margins associated with tilt block/half-grabens is shown; footwall scarp characterized by a bypass margin of gullied slope or escarpment type while the hanging wall may develop from a carbonate ramp into a rimmed shelf associated with a depositional slope. Full discussion in text.

margin, bordered downslope by talus fans, by now closely resembling the bypass margin on the opposite side of the basin. Thus at an advanced evolutionary stage the carbonate-shelf basin may show a symmetrical geometry, irrespective of the underlying basin geometry. The two margins have markedly different modes of origin, however; the footwall-to-hanging wall margin being predominantly controlled by tectonism and the hanging wall dip-slope margin largely the result of sedimentary processes.

The axial basin floor will in general be starved of sediment and of condensed aspect unless a distant source is available and axial transport of this sediment is possible. Clastic mud plumes may be important in such environments leading to thick mud-dominant sequences in the axial zone of carbonate-shelf basins.

Ancient examples of this type of tilt block/half-graben are present in the Lower Car-

boniferous (Dinantian) of central/northern England, in particular the Bowland basin and Derbyshire dome (Gawthorpe 1986, in press; Miller & Grayson 1982; Smith *et al.* in press) provide good examples.

Basin evolution and abandonment

During the development of an extensional basin it is clear that an evolutionary sequence of basin fills may develop, starting with continental-interior facies and ending up with shelf/coastal facies. Thus the various characteristic basin-fills noted above may succeed each other stratigraphically. It is becoming increasingly clear, however, following the work of Jackson *et al.* (1982a, b) and Jackson & McKenzie (1983), that entire tilt-block/half-graben systems may become inactive at any stage of their evolution

due to a change in position of the major bounding crustal-scale normal-fault system. Should the new fault system propagate on the hanging wall side of the former active basin, then footwall uplift associated with the new fault may cause gradual uplift of the whole basin-fill. Such a process should lead to the occurrence of upward-shallowing trends in the highest sequences of the abandoned basin, followed by continental facies and finally by marked erosional dissection as uplift proceeds above the depositional base-line. Examples of such sequences have been observed by the authors in the footwall-uplifted basin of Alipohori in the Gulf of Corinth and in the Mygdonia area east of Thessaloniki.

Conclusions

We have tried to show how the characteristic kinematic features of extensional half-graben/tilt-block systems give rise to predictable surface effects due to the primary control on depo-

sitional processes exerted by imposed tectonic slopes. Such surface depositional controls thus exert a major influence upon resulting facies distributions in the sub-surface. We expect the general models presented above to have applicability in geologically ancient basins, but it is stressed, finally, that basin analysis must involve the tectonic analysis of fault trends and their relation to a mapped lithofacies pattern. Only an integrative study of this kind can truly reconstruct the once-active extensional basin system.

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