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published in

Tectonophysics
1994

DOI (link to publisher)

[10.1016/0040-1951\(94\)90263-1](https://doi.org/10.1016/0040-1951(94)90263-1)

document version

Publisher's PDF, also known as Version of record

[Link to publication in VU Research Portal](#)

citation for published version (APA)

Golke, M., Cloetingh, S. A. P. L., & Fuchs, K. (1994). Finite-element modelling of pull-apart basin formation. *Tectonophysics*, 240, 45-57. [https://doi.org/10.1016/0040-1951\(94\)90263-1](https://doi.org/10.1016/0040-1951(94)90263-1)

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Finite-element modelling of pull-apart basin formation

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Received 12 August 1993; revised version accepted 15 February 1994

Abstract

We present the results of a finite-element modelling study of pull-apart basin formation related to left-stepping left lateral strike-slip faults. The modelling quantifies the relationship between fault geometry (i.e., fault overlap and separation) and pull-apart basin formation. Two depocentres (subbasins) separated by a broad zone of relative uplift in between may develop if the strike-slip domain is characterized by fault underlap. For overlapping faults migration of the subbasins is predicted by the models. Deep subbasins in a large area of subsidence which spans the entire inner fault zone may form if fault overlap is about three times the fault separation.

The models suggest that a topographic asymmetry within the fault zone may arise due to a different displacement ratio of the strike-slip faults. The modelling results show that this asymmetry in topography becomes more pronounced towards the more active fault. Thus, basin deepening occurs progressively towards the fault characterized by the largest amount of lateral displacement. Moreover, the results indicate that the smaller the fault separation (less than basin length) the less pronounced the topographic asymmetry.

The models provide quantitative estimates for the effects of changes in elastic material properties, the magnitude of the compressive far-field stress and the coefficient of friction of the faults on the resulting topography.

Comparison of the modelling results with field observations from the Cerro Blanco–El Barranquete (CBB) subbasin located in the Internal Zone of the Betic Cordillera, southeastern Spain support an interpretation in which the interplay of major faults has formed the CBB subbasin.

1. Introduction

Pull-apart basins form as a result of crustal extension either in domains of overstepping divergent strike-slip faults or in a releasing fault overstep. In contrast, convergent strike-slip domains are characterized by small pressure ridges (Kingma, 1958) leading to topographic highs as a result of crustal shortening in a restraining over-

step (Crowell, 1974; Christie-Blick and Biddle, 1985; Woodcock and Fischer, 1986).

Pull-apart basins range in size from small sag ponds up to 200 km long and 80 km wide basins such as the Salton Trough in southern California (Rodgers, 1980). A common feature of these basins is their large sedimentary thickness (up to 10 km) due to the migration of the depocentre by means of syn-depositional strike-slip (Crowell, 1982a, b; Sylvester, 1988). The depocentre migrates in the direction opposite to that of strike-slip movement of the basin, forming a basin

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lengthening over time (Sylvester, 1988). In pull-apart basins the lateral heat loss through the margins of the basin is rapid and cannot be ignored (Pitman and Andrews, 1985). Thus thermal subsidence is likely to be more or less contemporaneous with stretching leading to very rapid subsidence (in the order of 0.5 cm/a) and initial sediment starvation (Pitman and Andrews, 1985; Cloetingh et al., 1992). Because of rapid syn-rift cooling, the thermal gradient remains remarkably stable throughout stretching and cooling. This, in turn, allows the syn-rift sediments to pass quickly through the field of isotherms. As a consequence, sediments deposited prior to and during the early stages of rifting are heated quickly and, therefore, are prone to be mature (Pitman and Andrews, 1985). Pull-apart basins can, therefore, represent prospective targets for geothermal and hydrocarbon exploration.

The structural development of pull-apart basins related to en échelon strike-slip faults was first analyzed by Rodgers (1980), Segall and Pollard

(1980) and by Mann et al. (1983). The mathematical models of Rodgers (1980) and Segall and Pollard (1980) were based on infinitesimal strain theory, i.e., the displacement along the fault is small compared to the fault dimension. Rodgers (1980) assumed constant slip along the entire length of the fault. Segall and Pollard (1980) maximized the displacement near the middle of the fault segments and defined it to be zero at the end of the faults, constrained by geological observations (Deng et al., 1986). The models by Rodgers (1980) and Segall and Pollard (1980) provide clues to the displacement geometry of pull-apart basins, the orientation and kinds of faults which may be found in these basins, as well as the state of stress within and around those basins (Sylvester, 1988).

In the present paper we use the finite-element technique incorporating friction along the faults and displacements along these faults controlled by Byerlee's law (Byerlee, 1978). Offset along the strike slip faults occurs due to tectonic stresses

Fig. 1. 2D finite-element model employed in this study. A left-stepping left lateral strike-slip domain is modeled. The strike of the faults with respect to the orientation of the compressive far-field stress, the fault overlap, and separation are pre-defined. Also illustrated is the convention of fault overlap and separation (A). In (B) the finite-element grid is delineated. The horizontal dimensions of the model are 56 and 45 km, respectively. The lower boundary of the model is fixed with respect to displacements in y-direction, the left lower edge is constrained to have zero displacements in x-direction. A plane stress situation with an elastic plate thickness of 10 km is assumed.

applied at the model boundary. The purpose of our finite-element study is to analyze the patterns of pull-apart basin formation in a left-stepping left lateral strike-slip fault domain with respect to the fault overlap, the fault separation and displacement ratio of both faults. Furthermore, effects of variations of the friction coefficient, the elastic material properties (Poisson's ratio and Young's module), and the magnitude of the far-field stress are examined.

The modelling results are subsequently compared with field observations from the Cerro Blanco–El Barranquete subbasin (CBB subbasin) located in the Internal Zone of the Betic Cordillera, southeastern Spain.

2. The finite-element model

The finite-element model employed in this study is designed in order to simulate the formation of pull-apart basin with respect to the interaction of left-stepping left lateral strike-slip faults. To this aim, 2D ideally elastic finite-element models characterized by two strike-slip faults were utilized (Fig. 1). The finite-element models consist of 183 elements (i.e., 22 triangular, 16 fault and 145 quadrilateral elements) depicted in Fig. 1B. The ANSYS finite-element program is used (Kohnke, 1987; Mueller and Rehfeld, 1993). In the models the faults are pre-defined to strike at N45E in a compressional domain acting north-south. Also pre-defined is the fault overlap and separation (Fig. 1), since fault propagation, i.e., growth of the faults is not considered here. The displacement along the faults is constrained by a coefficient of friction assigned to the faults which, according to laboratory data is in the range of 0.3–0.6 (Ohnaka, 1975; Jaeger and Cook, 1971; Barton and Choubey, 1977). Sliding then occurs if the amount of stress tangential to the fault exceeds 0.3–0.6 of the normal stress (Byerlee, 1978).

Plane stress situation is considered. An elastic plate thickness of 10 km (effective elastic thickness, e.e.t.) is adopted based on previous modelling studies on the state of flexure of the Betic Cordilleras, southeastern Spain (Cloetingh et al., 1992; Van der Beek and Cloetingh, 1992). In

their studies they pointed out that the effective elastic thickness (e.e.t.) which corresponds to the lithospheric strength is about zero in the eastern part of the Betics, whereas the western part has maintained a limited strength with an e.e.t. of about 10 km. The strength of the lithosphere exerts control on the overall spatial dimension of pull-apart basins in the Internal Zone of the Betics. Approximately 20 km wide pull-aparts are found in the west in contrast with approximately 5 km wide pull-aparts in the east. In our model the calculated out of plane strain can be referred to relative changes in topography interpreted as uplift and subsidence. The horizontal dimensions of the finite-element model are 56 and 45 km (Fig. 1). The lower boundary of the model is fixed with respect to displacements in the y -direction, whereas the left lower edge is constrained to have zero displacements in the x -direction.

Values for the elastic material properties (for instance, Young's module and Poisson's ratio) are based on Byerlee (1978), Brace and Kohlstedt (1980), Carmichael (1983) and Bott and Kusznir (1984). The modelling parameters are listed in Table 1.

3. Modelling results

The modelling result of interest, i.e., strain in z -direction (out of plane strain) is converted into relative changes in topography by relating the out of plane strain to the model thickness.

Table 1
Listing of the modelling parameters

Input parameters	Symbol	Value
<i>Elastic material properties</i>		
Young's modulus	E	10–100 GPa
Poisson's ratio	ν	0.2–0.3
Coefficient of friction	μ	0.3–0.6
Magnitude of compressive far-field stress	σ	10–100 MPa
Fault overlap; fault separation ^a		

Rock parameters are taken from Jaeger and Cook (1971). The following parameters remain constant throughout the modelling: strike of the faults, elastic plate thickness of 10 km, and the model dimensions of 56 and 45 km, respectively.

^a From underlap to about 10 times the fault separation.

Fig. 2. Changes in topography of a strike-slip domain characterized by fault underlap. The results are shown for various profiles (A–D) which parallel the faults (see small inset). I and II indicate the area which is effected by the presence of fault B and A, respectively.

Fig. 3. Contour plot (map view) of changes in topography (in m) of a strike-slip domain characterized by fault underlap. Changes in topography associated with the formation of pull-apart basins are characterized by negative values, whereas relative uplift is characterized by positive values. The faults are indicated by the solid lines. Only the central part of the model is shown.

3.1. Effect of a change in fault overlap

The modelling result of a strike-slip domain characterized by fault underlap is shown in Fig. 2 for four profiles which parallel the faults, respectively. Profiles C and D are located within, profiles A and B outside the fault zone, respectively. As indicated by profile C a depocentre (location I) forms in the vicinity of the fault B tip. Offset, another less marked depocentre becomes apparent (location II). This depression is related to the presence of fault A. The same pattern in topography can be observed, as mirrored along profile D. Both main depocentres are separated by a broad zone of relative uplift. Outside the fault zone topographic highs (flanks) form in the vicinity of the fault ends, adjacent to the depocentres (profiles A and B). This modelling result is also shown in Fig. 3 for the central fault region.

The modelling results obtained for a strike-slip domain characterized by zero fault overlap show a similar arrangement of the depocentres and flanks (Fig. 4). As in the previous stage two depocentres (subbasins) form in the proximity of

the fault ends, still separated by a narrowed relative uplift, less developed than in the previous stage. The subbasins migrate in an opposite sense with respect to the displacement along the adjacent faults. The depth of the depocentres increases whereas the topographic highs juxtaposed to the depocentres outside the fault zone are less elevated than in the previous stage of fault underlap. This result probably can be explained in terms of fault interaction, i.e., constructive superposition of the effects of both faults within and outside the fault zone. Thus, for instance, the downwarping effect of fault B may extend beyond the area of fault A resulting in less uplift at the flanks. Within the fault zone the downwarping effects of both faults may interfere constructively enhancing subsidence.

If the strike-slip domain is characterized by fault overlap (in the order of three times the fault separation) a large area of subsidence which includes the inner fault zone becomes apparent. This subsided area is substructured in two local depocentres located in the vicinity of the fault ends. The maximum basin depth is increased,

Fig. 4. Contour plot (map view) of changes in topography (in m) of a strike-slip domain characterized by zero fault overlap. Figure convention as in Fig. 3.

whereas the elevation of the flanks is less with respect to the zero overlap situation. Again this basin configuration may be interpreted in terms of fault interaction.

As shown above, an increased fault overlap results in an enhanced subsidence and less elevated flanks. The results obtained indicate that the amount of subsidence and uplift are approximately in the same order, respectively (Figs. 3 and 4). However, this requires that the boundary conditions, e.g., magnitude of the far-field stress, remain constant.

3.2. Effect of a change in fault separation

The effects of a changing fault separation on pull-apart basin formation are delineated below. The fault separation is expressed in percent of the fault overlap. Three different fault geometries have been investigated, characterized by a 10, 20 and 30% fault separation.

The modelling results for a 30% fault separation show two relatively large and elongated sub-basins apparently separated by a zone of relative

uplift which strikes at a low angle oblique to the faults. Both sub-basins are located within an elongated depression which includes the area between both fault ends. As pointed out above, such a basin configuration can be explained in terms of fault interaction. Probably due to both the fault separation and the large lateral offset of the fault tips from each other, the fault interaction is small adjacent to the bulge.

The effects of fault interaction become also evident in the strike-slip model characterized by a 20% fault separation. This fault geometry results in the formation of an elongated depocentre within the fault zone. The flanks are less uplifted than for a 30% separation. The depocentre comprises the area determined by the fault geometry, i.e., overlap and separation. Within this depocentre an additional subbasin has formed, located half way between the fault ends.

In a strike-slip area characterized by a 10% fault separation, i.e., small separation and large amount of overlap an elongated basin forms (Fig. 5). For this fault geometry the maximum basin depth is predicted. Both the increased subsidence

Fig. 5. Contour plot (map view) of the relative changes in topography (in m). The fault separation was modeled to be 10% of the fault overlap. Figure convention as in Fig. 3.

Fig. 6. Effect of increasing the Poisson's ratio on basin formation. The overall basin shape remains constant whereas the basin deepens.

and the absence of uplifted flanks point to an interaction of both faults.

However, a fault separation of 10% of the fault overlap represents a rather unrealistic situation as a worldwide compilation of the dimensions of 62 active pull-apart basins indicates a

ratio of basin length to width of approximately 3 (Aydin and Nur, 1982). This observation also suggests that pull-apart basins form in a relatively rapid changing tectonic environment. Rather often pull-apart basins become inverted structures after a short time span of a few million years (Aydin and Nur, 1982).

The changes in topography of the fault zone due to a change in fault separation seem not to be that unique as observed for changes in overlap. However, as indicated by the modelling results, the smaller the fault separation, the deeper the subbasins and the less elevated are the adjacent flanks.

3.3. Effect of a change of material properties

In order to quantify the relative importance of rock parameters, the magnitude of the far-field stress and a different coefficient of friction on the faults on pull-apart basin formation, we consider a strike-slip zone characterized by zero fault overlap.

The modelling results suggest that a higher Poisson ratio increases the depth of the evolving depocentre, whereas the overall basin geometry remains constant (Fig. 6). Similar effects are pre-

Fig. 7. Changes in topography of a strike-slip domain characterized by an unsteady fault activity. The location of profiles A–E is shown in the small inset. Fault A is modeled to be more active in terms of lateral displacements than fault B.

dicted for an increased magnitude of the compressive far-field stress, and for a reduction in Young's module and coefficient of friction of the faults. The modelling results show that basin geometry is not very sensitive to the elastic material properties, the coefficient of friction and the magnitude of the far-field stress. These parameters seem primarily to influence the relative magnitude of topography changes.

3.4. Effect of a displacement ratio of the strike-slip faults

In the following we investigate the effect of a possible displacement ratio of both strike-slip faults on pull-apart basin formation. A displacement ratio of the associated faults may stand out of an unsteady activity of the faults. The terminology (more active fault) used here refers to the fault characterized by the largest amount of displacement.

In the finite-element model, fault A (Fig. 1) was considered to be more active with respect to fault B. The modelling results shown for various

profiles (A–E) (see inset in Fig. 7) indicate that the evolving pull-apart basin deepens towards the more active fault (profiles B–D) resulting in an asymmetry in topography both within and outside the fault zone. Maximum topographic elevation is predicted outside the fault zone (profile E) adjacent to the end of the more active fault. In contrast the relative changes in topography associated with the less active fault are rather small (profiles A and B). The modelling results show that this asymmetry in topography becomes less pronounced if the fault separation is small, i.e., fault separation is less than basin length.

4. Application of the model to the Cerro Blanco–El Barranquete (CBB) subbasin

The Pliocene sedimentation in the CBB subbasin (Fig. 8) that forms part of the larger Almería–Níjar Carboneras Basin (ANC Basin) is controlled by a releasing bend and a restraining zone in the NE-trending Serrata strike-slip fault zone (Boorsma, 1992). Since the Early Miocene,

Fig. 8. General sketch map of the location of the Serrata fault zone and the Cerro Blanco–El Barranquete (CBB) subbasin. The position of the CBB subbasin is indicated by the box in the centre of the map.

the structural development of these basins took place in a tectonic regime controlled by the converging African and Iberian plates (Montenat et al., 1987). The main principal axis of the stress tensor has an approximately horizontal N–S orientation, measured in Pliocene sediments in the Serrata fault zone (Biermann, 1994). The main and most penetrative fault trend is oriented N40°E (Fig. 8). Two major faults in this orientation, the northwestern Serrata Boundary fault (NWSB fault) and the southeastern Serrata Boundary fault (SESB fault), are present in the CBB subbasin (Boorsma, 1992).

A four-stage interpretative model for the non-palinspastic reconstruction of palaeogeography of the Cerro Blanco–El Barranquete (CBB) subbasin, related to the framework of major faults, is described by Boorsma (1992). In our finite-ele-

ment study we will refer to two of these stages, i.e., stages A and B as shown in Figs. 9 and 11.

4.1. Evolution stage A of the CBB subbasin

Evolution stage A of the CBB subbasin is characterized by two depocentres separated by a zone of relative uplift as indicated by the thickness distribution of Middle Pliocene–Pleistocene subswash deposits (Fig. 9). Boorsma (1992) interpreted the evolutionary stage A to be controlled by an increasing fault overlap in relation to fault separation between the NWSB fault and the B fault (Fig. 9) whereas the CB fault continued to act as a restraining uplift zone. According to his interpretation the SESB fault and the A fault have been inactive during this stage.

Fig. 9. Stage A of the four stage interpretative model for the non-palinspastic reconstruction of palaeogeography, as related to the framework of major faults. Thickness distribution of shallow-water (sub-swash) deposits is indicated by isopach contours (in m) based on 52 data points. Depocentres are indicated by the hatched area. Dashed line represents an interpreted possible fault B propagation (modified after Boorsma, 1992).

As shown in Figs. 2 and 3, fault underlap results in the formation of depocentres in the proximity of the fault ends, respectively. Thus, the formation of the depocentres characterized by a maximum sedimentary thickness of 16 and 18 m (Fig. 9) may be associated with fault underlap of the B fault with respect to the NWSB fault. As indicated by profile D (Fig. 2) an additional but less subsided depocentre (I) forms apparently due to the presence of the fault B end. This effect may also have caused the formation of the less marked depocentre characterized by a maximum sedimentary thickness of about 12 m, next to the A fault (Fig. 9).

Presumably, due to B fault propagation (dashed line in Fig. 9) resulting in a zero to fault overlap situation the depocentre characterized by a maximum sedimentary thickness of 20 m may have formed. The latter is quantitatively illustrated in Fig. 10. Since fault propagation can not be considered in the finite-element model, evolution stage A (Fig. 9) can be fairly well reproduced by models characterized by fault underlap to overlap.

However, it should be noted that the sedimentation of the shallow-marine sediments may have been not only controlled by tectonic processes as modeled, i.e., slip along the faults.

4.2. Evolution stage B of the CBB subbasin

During the stage B of the evolution of the CBB subbasin, the activity of the land segment of the B fault continues (Fig. 11; Boorsma, 1992). The NWSB fault propagated through to the offshore A fault (Fig. 9) and acted as a hinge fault, with uplift of the southeastern fault block (Serrata mountains) at its northeastern section, and subsidence of the southeastern fault block (Morales depression) at its southwestern section (Baena et al., 1977; Boorsma, 1992). In addition to differences in topography along the strike of fault A, a topographic asymmetry between the A fault and the B fault exists as indicated by the present-day topography of the Serrata fault zone (Fig. 11).

This asymmetry across the fault zone may have several implications. For example, Baena et al.

Fig. 10. Contour plot (map view) of the relative changes in topography (in m) of a strike-slip domain characterized by fault overlap (fault overlap is about three times the fault separation). Figure convention as in Fig. 3.

(1977) postulated an apparent normal vertical displacement along the A fault with the upthrown block to the north. However, normal faulting can not be considered in the 2D finite-element model.

We suggest that a possible and additional mechanism which may have favoured this asymmetry can be found in an unsteady activity of the faults, i.e., fault A was partly more active in terms of lateral displacements than fault B. As shown in Fig. 12 (and Fig. 7) this model assumption results in a progressive deepening of the fault zone towards fault A and may partly account for the field observations.

5. Conclusions

An elastic finite-element model has been used in this study to simulate pull-apart basin formation related to left-stepping left lateral strike-slip

faults. The modelling results quantify the relationship between fault geometry (fault overlap and separation) and pull-apart basin formation.

Two depocentres separated by a broad zone of relative uplift may form if the strike-slip zone is characterized by fault underlap. Outside the fault zone, topographic highs form, restricted to the vicinity of the fault ends.

A similar arrangement of the depocentres and flanks is predicted by a model involving a strike-slip domain characterized by zero fault overlap. The depocentres are almost approaching each other being still separated by a narrowed and less uplifted zone in between. The depth of the depocentres increases whereas the topographic highs outside the fault zone are less elevated. The relative changes in topography, in and outside the fault zone with respect to the topography obtained for fault underlap are approximately in the same order.

Fig. 11. Stage B of the four-stage interpretative model for the non-palinspastic reconstruction of palaeogeography, as related to the framework of major faults. Present-day topography is indicated in metres above sea level. Major faults are reflected in the topography. The southeastern fault block of the A fault is down thrown giving rise to the Morales depression (hatched area). The southeastern block of the NWSB fault is uplifted as indicated by the Serrata mountains. Note the relative difference in topography of the southeastern block of the A fault and the northwestern block of the B fault (modified after Boorsma, 1992).

If the fault zone is characterized by fault overlap (in the order of three times the fault separation) deep subbasins form in the proximity of the fault ends. The subbasins are separated by an intervening zone of relative uplift which strikes oblique to the faults. Maximum basin depth is increased whereas the flank uplift is less than in the previous stage of zero fault overlap.

In a strike-slip area characterized by a fault separation of 10% of the amount of overlap, an elongated basin forms. For this fault geometry a maximum basin depth is predicted.

The modelling results suggest that an increase in Poisson's ratio increases the depth of the evolving depocentre, whereas the overall basin geometry remains constant. Similar effects have been observed for an increased magnitude of the compressive far-field stress, a reduced Young's module, and a reduced coefficient of friction of the faults. Thus, these parameters seem primarily to influence the relative magnitude of topography changes.

The modelling results also indicate that if one fault behaves more active in terms of lateral

displacements the evolving pull-apart basin deepens towards the more active fault resulting in an asymmetry in topography in and outside the fault zone. Maximum topographic elevation is reached outside the fault zone adjacent to the end of the more active fault. The modelling results show that this asymmetry in topography becomes less pronounced if the fault separation is small, i.e., fault separation is less than basin length.

A comparison of the modelling results with field observations (Boorsma, 1992) from the Cerro Blanco–El Barranquete strike-slip subbasin (CBB) in the Internal Zone of the Betic Cordillera (southeastern Spain) confirms that the CBB subbasin developed by the interaction of major strike-slip faults.

Acknowledgements

L. Boorsma and F. Beekman are thanked for discussions and suggestions on pull-apart tectonics and finite-element techniques, respectively. A. Krammer is thanked for his kind help preparing

Fig. 12. Contour plot (map view) of the relative changes in topography (in m) of a strike-slip domain characterized by unsteady activity of the faults. Fault A is modeled to be more active in terms of lateral displacements. Figure convention as in Fig. 3.

the figures. The paper also benefited from constructive reviews by G. Tibor, M. Grasso and C.D. Reuther.

This work was supported by the IBS (Integrated Basin Studies) project, part of the JOULE II research program funded by the Commission of European Communities (contract No. JOU2-CT 92-0110). IBS contribution No. 5.

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