Fault development around the Red Sea rift system : A finite element approach

Bull. Fac. Sci., Univ. Ryukyus, No.77 : 105 – 122 (2004)

Fault development around the Red Sea rift system: A finite element approach

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Abstract

Finite element method has been used in this study to know the fault development in the Red Sea rift system. Two models with fault zone and without fault zone are calculated to determine the effect of detachment fault on the distribution of deformation in the Red Sea area under plane strain condition with linear elastic rheology. Influence of layer properties on fault development are compared with two models. Three types of displacement boundary condition (extensional, spreading, and spreading with upward) are also used to examine results and to search the best fitted boundary conditions. Results of this study show that (1) detachment fault controls the normal fault system in the Red Sea area, (2) friction angle and cohesion are important parameters, and sensitive to fault development, (3) spreading and spreading with upward displacement boundary conditions show the reasonable results which support the active rifting hypothesis in the development of the Red Sea rift system.

1. Introduction

Continental rifting is one of the intraplate processes that takes place at the beginning of continental breakup. The Red Sea rift system is one of the world's largest active continental rift system. It comprises a variety of rifting stages, starting from initial faulting, advancing through several stages of continental rifting. The Red Sea rift system is therefore the best example for investigating the breaking of continent in different stages. The rifting of the Red Sea and associated system was initiated in the Oligocene, with thermally driven uplift and domal arching of the Arabian-African Shield. Two triple junctions characterize the Red Sea system, the Afar to the south and the Sinai to the north. As a result of rifting, the Arabian plate separated and moved NE to collide with the Eurasian plate.

In general, the formation of Gulf of Suez and the Gulf of Aqaba are considered to be the result of the divergence of lithospheric plates, where as the Gulf of Aqaba mainly

Received: January 6, 2004

result from strike-slip movements with few extensional components. The formation of Gulf of Aden has resulted from divergence of the Arabian African and Somalian continental plates. Structural analysis is the study of architecture of the earth and addresses the form, symmetry, geometry of the earth's crust, and focuses on the strength and mechanical properties of crustal materials, at present and at the time they were formed and deformed. For many problems in structural geology, it would be desirable to study the relationships between the present observed geometries of structures, their initial configuration and the stress distribution under which they developed.

The order in which tectonic events occur during continental rifting is a key to understand rift genesis whether "active rifting" or "passive rifting". The passive rifting hypothesis in which lithospheric stretching and fracture upset the pressure/temperature balance in the asthenosphere, resulting in partial melting and uplift. Passive mechanism for continental rifting generally relate the tensional failure of the lithosphere to preexisting tensional stresses. Crustal doming and volcanics are secondary processes (Turcotte and Emerman, 1983). The active rifting hypothesis whereby mantle convection is seen as responsible for doming and extensional fractures in the lithosphere. Active mechanism for rift formation associated the surface rifting due to mantle convection (Crough, 1983). Though some authors have proposed several models, still there is controversy about the active rifting and passive rifting of development history of the Red Sea rift system. Number of researchers (eg. Bohannon, 1986a; Bonatti and Seyler, 1987; Coleman and McGuire, 1988; Bohannon and Ettreim, 1991) mentioned that detachment fault occurred in the early stage of the Red Sea development, but the effect of detachment fault on the growth of normal fault system is still not well documented. From this point of view, to solve these problems, this study has been designed to achieve following objectives with respect to new approach "finite element method".

(1) To clarify the effect of detachment fault to the genesis of the normal fault system in the Red Sea area.

(2) To know the effect of layer properties and displacement boundary conditions on fault development.

(3) To know which boundary condition is best fit to the present situation of the Red Sea rift system.

2. Geologic and Tectonic Setting

The Red Sea rift system formed in the late Oligocene - early Miocene in response to the NE separation of Arabia away from Africa. The Red Sea rift system includes the Gulf of Suez Gulf of Aqaba in the north and the Gulf of Aden and East African rift system in the south (fig. 1.). This rift initiated in the late Oligocene-Miocene time and have fragmented the once continuous Afro-Arabian shield (Martinez and Cochran, 1988).

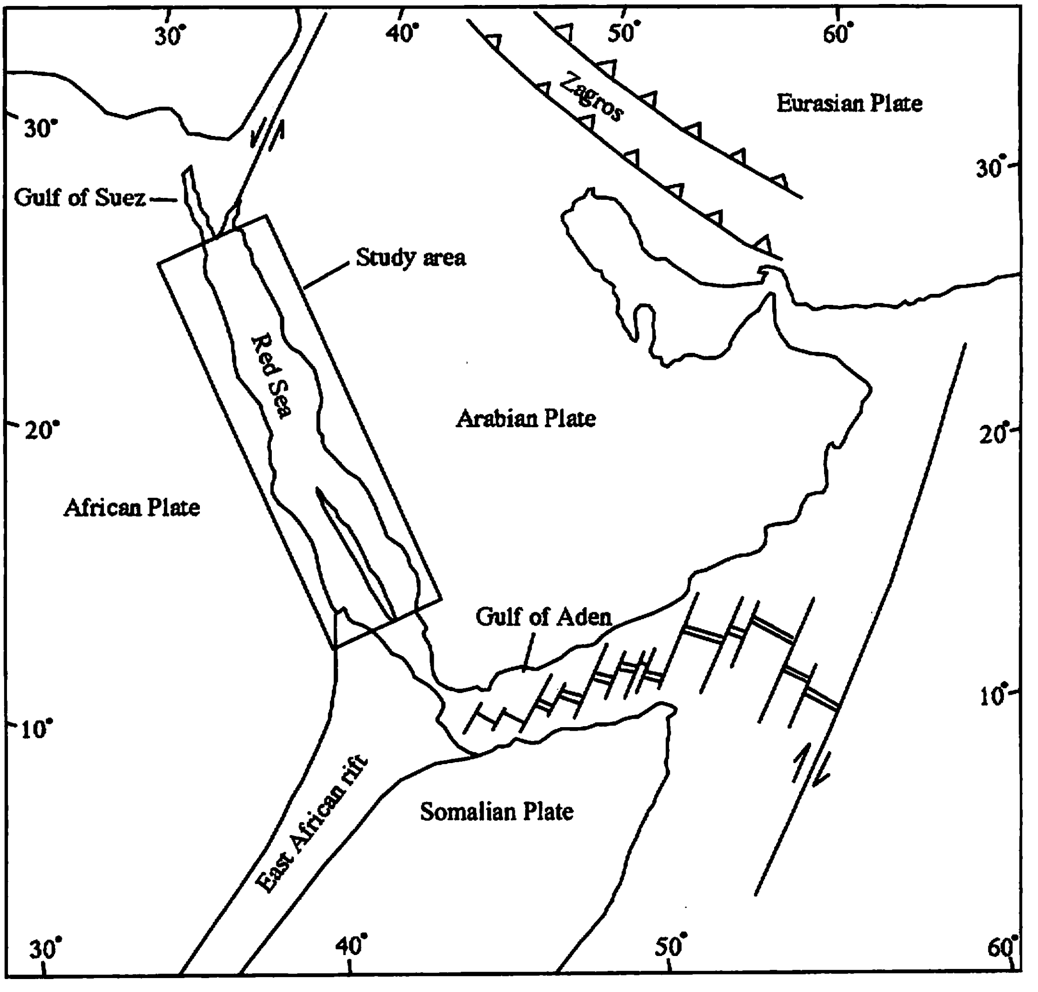

Fig. 1. Plate tectonic setting of the Red Sea area after Joffee and Gurfunkel (1987)

There is a general understanding of the plate motions involving the Neogene separation of Arabia from Africa. The northeastward movement of Arabia relative to Africa has created young oceanic basins of the Gulf of Aden and Red Sea. At the northern end of the Red Sea, the kinematics become more complex. Because here the Red Sea bifurcates into the Gulf of Suez rift and Gulf of Aqaba-Dead Sea transform zone.

The important geodynamic processes is the counterclockwise rotation of the Arabian plate relative to Africa, which led to the late Oligocene-Early Miocene opening of the northern Red Sea including its northern extension the Gulf of Suez.

According to Greiling *et al.* (1988), Red sea rifting led to isostatic readjustment and uplift of the bordering continental margins. The crystalline basement of the rifted area was consolidated in the pan-African Orogeny of latest Precambrian - early Cambrian age.

During most of the Phanerozoic times this region behaved as a stable platform and it was covered by an extensive veneer of sediments that accumulated in several periods of deposition which were separated by several stages of important differential uplifting and erosion. Pan-African rifting was accompanied by considerable uplifting and erosion of large areas. The crystalline basement in the Red Sea area is metamorphic and granitic rocks of pan-African age. The composition of volcanic rocks are dominantly basaltic. Numerous basaltic dikes was intruded the whole of the Red Sea and also the Gulf of Suez with parallel to the long axis of the rift during Pan-African phase of rifting.

Morphologically Red Sea consists of shallow continental shelves, a wide main trough and a narrow axial though. In the northern and central Red Sea the crust beneath the main trough consists of heterogenous mixure of gabbroic and doleritic intrusions, emplaced during the early phase of rifting in the late Oligocene and early Miocene (Bonatti and Seyler, 1987).

The structural pattern of the Red Sea rift is inherited from the basement tectonics. The pre-rift sedimentary cover includes Cretaceous and Eocene plateform deposits and the syn-rift sedimentary sequence comprises Oligocene to recent Pleistocene deposits. According to Cochran and Martinez (1988) Gulf of Suez rift appears to initially have been the northern extension of the Red Sea. The northern Red Sea is a continental rift. The development of present stage of Red Sea rift is dominated by two processes, first is the concentration of extensional deformation, which had been widely distributed across the rift, the second features is the segmentation of the rift. Bonatti (1985) interpreted that the northern Red Sea region as floored by thinned and stretched continental crust, associated with diffuse basaltic intrusions. The axial injection of oceanic crust and seafloor spreading have not yet started in the northern region of the Red Sea area. The crust beneath the main trough is continental crust and that was extended and modified by normal faulting and dike injection during late Oligocene to early Miocene phase of continental rifting.

Seafloor spreading has created the axial ridge-rift zone in the Gulf of Aden and the deep axial trough in the southern and central Red Sea (Girdler, 1991). Seafloor spreading along the Red Sea axial trough began at the beginning of the Pliocene and formed new oceanic crust (Cochran, 1983). The evolution of the Red Sea related to the Afar depression in Ethiopia, western Saudi Arabia and axial trough of the Red Sea. The spreading center has gradually extended itself to both the north and south, and active seafloor spreading documented in the southern Red Sea area. In the northern area appears to be presently changing from the diffuse extension to seafloor spreading in relation to plate separation. Thus the Gulf of Aden can be considered as a young ocean basin on continental margin. The Afar depression lies at the triple-point junction of the Arabian, Nubian and Somalian plates and its present condition is in the processes of breaking away of these three plates from one another.

3. Simulation

In this study, we have used two methods, (1) finite element method to simulate distribution of stress pattern and (2) Mohr-Coulomb criterion to identify failure elements on growth of fault.

(1) **Finite element method**: Finite element method is a numerical technique for solving problems which are described by partial differential equations or can be formulated as functional minimization. The powerful method of finite elements permits almost all problems of stress analysis and analysis of finite deformations of geological structures to be presented in a mathematical form. The finite element method is a general method of structural analysis in which a continuous structure is replaced by a finite number of elements interconnected at a finite number of nodal points. The method can be used to determine the displacements of the nodal points and the stresses within the elements. Forces acting at the nodal points of finite element system. The finite element method is the most important for numerical modeling in strucrural geology and tectonics.

(2) **Mohr-Coulomb criterion**: Nature of stress controls many processes in the earth crust including - fracturing, faulting, folding, landslides etc. Mohr-Coulomb criterion apply to predict which elements are more possible to fail on growth of fault.

3.1. Detachment fault model

We have proposed a detachment fault model of initial stage of Red Sea development (fig. 2). In detachment fault model a ductile shear zone was inserted between upper crust and lower crust, which expect to influence development of detachment fault caused by rising of asthenosphere. We have simulated this model to know how normal faults propagate above the detachment fault.

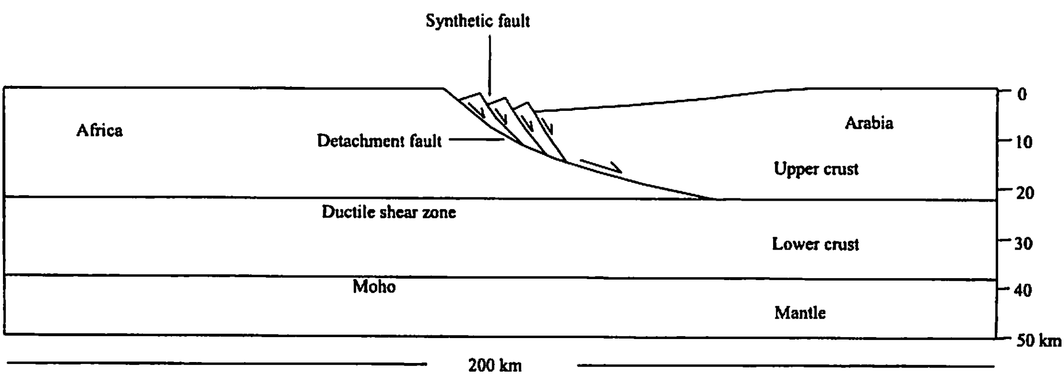

Fig. 2. A detachment fault model of initial stages of the Red Sea development

3.2. Layer properties

We have selected dominant rock type for each layer to get the homogenous stress field. The model without fault zone contains three layers; upper crust, lower crust, and mantle. The model with fault zone contains four layers; upper crust, lower crust, mantle, and fault zone. Layer properties are listed in Table-1 and presented by fig. 3.

Table 1. Layer properties

layer	rock species	poisson's ratio	density (kg/m³)	Young's modulus (GPa)	friction angle (degree)	cohesion (MPa)
upper-crust	sand stone, limestone	0.25	2700	30	30	10
lower-crust	granite, gneiss	0.25	2800	40	30	20
mantle	gabbro, peridotite	0.30	3100	60	40	30
fault zone		0.25	2700	1	20	10

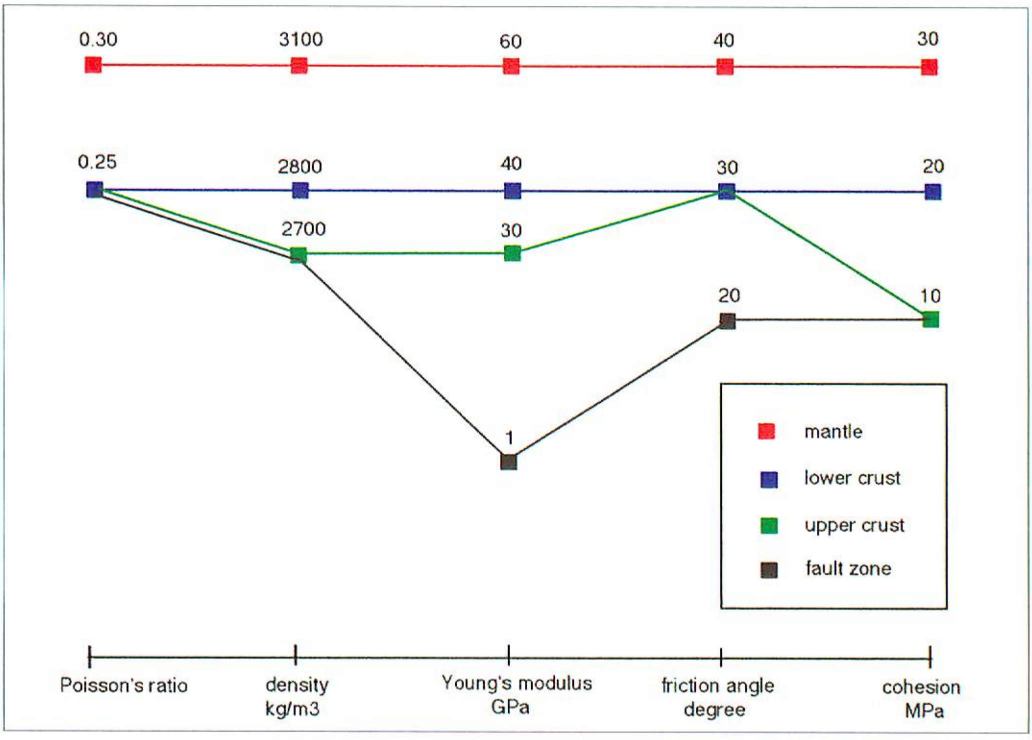

Fig. 3. Layer properties

3.3. Displacement boundary condition

In this study we have simulated two models with fault zone and without fault zone. In both models we imposed three types of displacement boundary condition (extensional, spreading, and spreading with upward). According to Labrecque and Zitellini (1985) spreading rate of Red Sea is 2 cm/year.

3.3.1.Extensional

This model contains 647 nodes and 1174 elements. For nodal points 647, 646, 645, 644, 643, 642, 641, 640, 639, 638, 637, 636, 635, 634 and 633 extensional displacement are imposed along horizontal direction. The upper surface of this model is free to move all direction. Nodal points 13, 12, 11, 10, 9, 8, 7, 6, 5, 4, 3, and 2 are free to move vertically but restricted to move horizontally. Nodal points 26, 27, 52, 53, 78, 79, 104, 105, 130, 131, 156, 157, 182, 183, 208, 209, 234, 235, 266, 267, 295, 296, 338, 339, 368, 369, 400, 401, 437, 438, 467, 468, 497, 498, 527, 528, 557, 558, 587, 588, 617 and 618 are free to move horizontally but restricted to move vertically and nodal point 1 is fixed in all direction (fig. 4. and fig. 5).

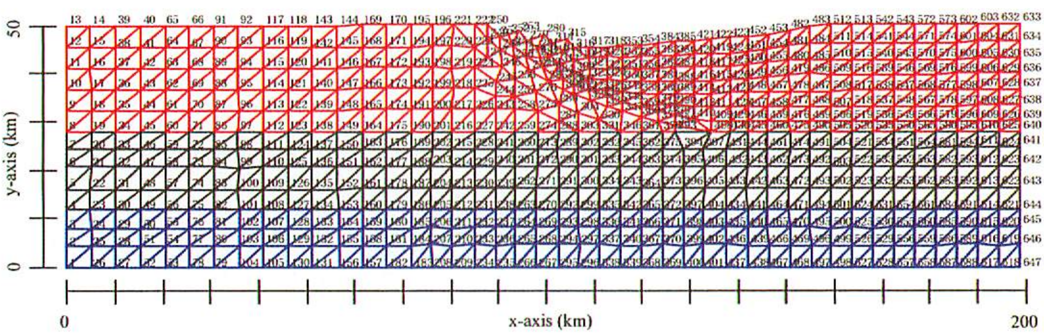

Fig. 4. Grid of model without fault zone

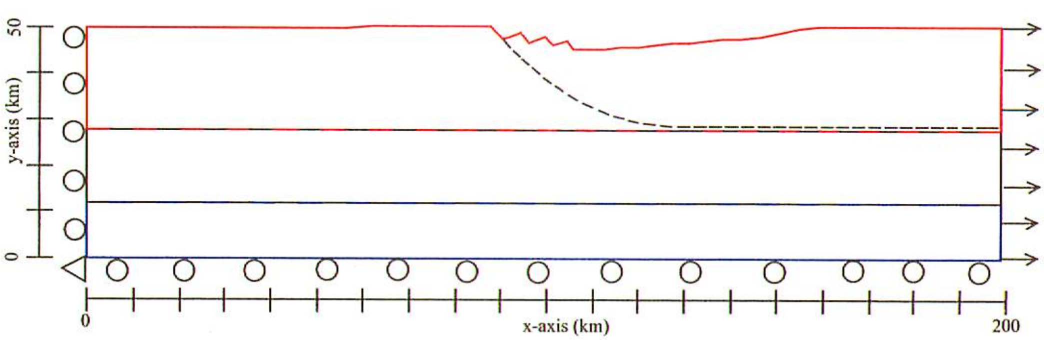

Fig. 5. Extensional displacement boundary condition

3.3.2. Spreading

For nodal points 26, 27, 52, 53, 78, 79, 104, 105, 130, 131, 156, 157, 182, 183, 208, 209, 234, 235, 266, 267, 296, 338, 339, 368, 369, 400, 401, 437, 438, 467, 468, 497, 498, 527, 528, 557, 558, 587, 588, 617 and 618 spreading displacement are imposed along horizontal direction. Nodal points 13, 12, 11, 10, 9, 8, 7, 6, 5, 4, 3, 2, 646, 645, 644, 643, 642, 641, 640, 639, 638, 637, 636, 635, 634 and 633 are free to move vertically but restricted to move horizontally. Upper surface is free in direction. Nodal points 1 is fixed in all direction and nodal point 295 is free to move horizontally but fixed in vertically (fig. 4. and fig. 6).

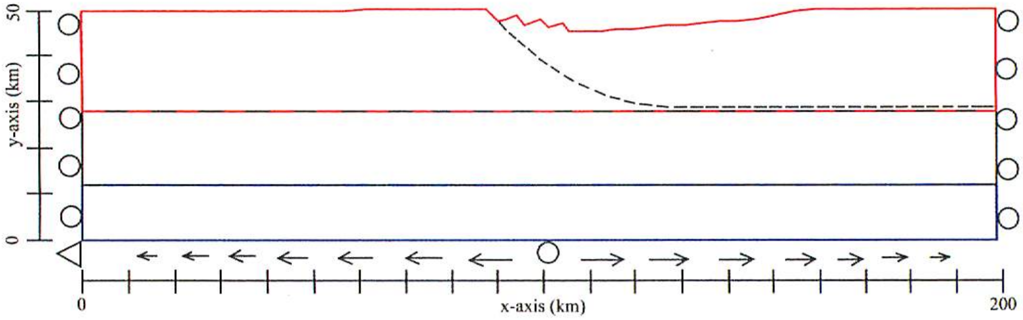

Fig. 6. Spreading displacement boundary condition

3.3.3. Spreading with upward

For nodal points 26, 27, 52, 53, 78, 79, 104, 105, 130, 131, 156, 157, 182, 183, 208, 209, 234, 235, 266, 267, 296, 338, 339, 368, 369, 400, 401, 437, 438, 467, 468, 497, 498, 527, 528, 557, 558, 587, 588, 617 and 618 spreading displacement are imposed and for nodal points 156, 157, 182, 183, 208, 209, 234, 235, 266, 267, 295, 296, 338, 339, 368, 369, 400, 401, 437, 438 and 467 upward displacement are imposed. Nodal points 13, 12, 11, 10, 9, 8, 7, 6, 5, 4, 3, 2, 646, 645, 644, 643, 642, 641, 640, 639, 638, 637, 636, 635, 634 and 633 are free to move vertically but restricted to move horizontally. Upper surface is free to move all direction. Nodal point 1 is fixed (fig. 4. and fig. 7).

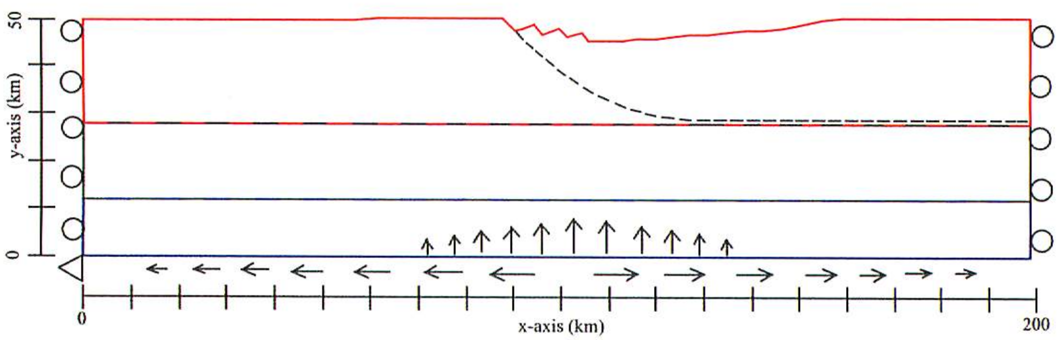

Fig. 7. Spreading plus upward displacement boundary condition

4. Results

Results of model without fault zone and model with fault zone are given bellow.

4.1. Results of the model without fault zone (fig. 8 - fig. 13)

Very few elements are failed in the upper crust under the extensional displacement 0 meter, but in case of extensional displacement 100 meter most of the elements are failed in the upper and lower crust. Under spreading displacement 0 meter, and 20 meter few elements are failed in the upper crust. In case of spreading displacement 0 meter with upward displacement 0 meter few elements are failed in the upper crust. Under spreading displacement 20 meter with upward displacement 10 meter few elements are failed in the upper crust. Increasing friction angle and cohesion decrease failured area and increasing Young's modulus increase failured area in all case of displacement boundary condition (extensional, spreading, and spreading with upward).

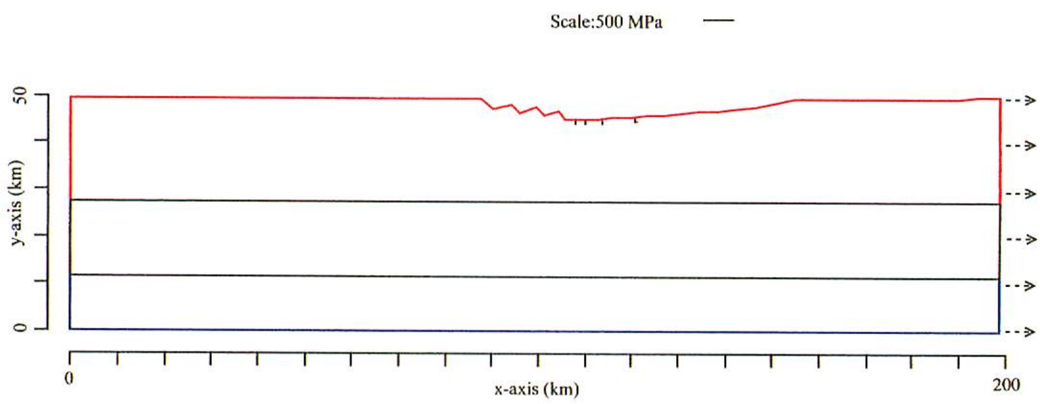

Fig. 8. Stress of failured element under extensional displacement 0 meter, without fault zone

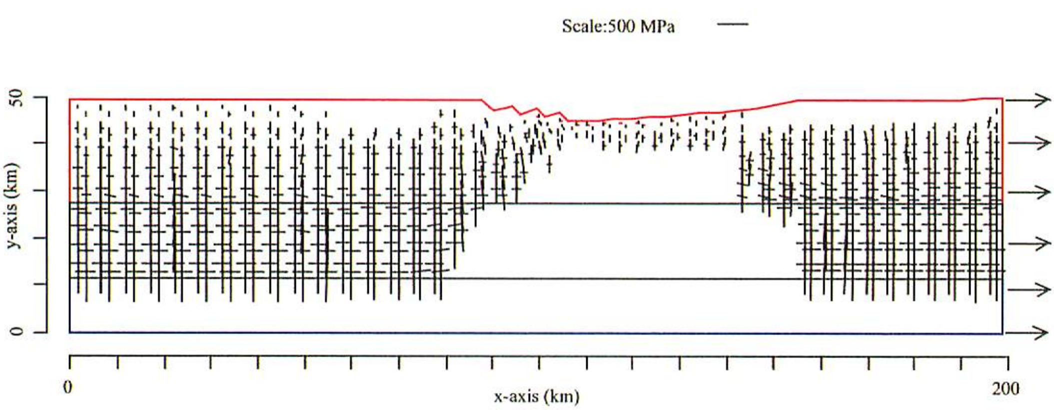

Fig. 9. Stress of failured element under extensional displacement 100 meter, without fault zone

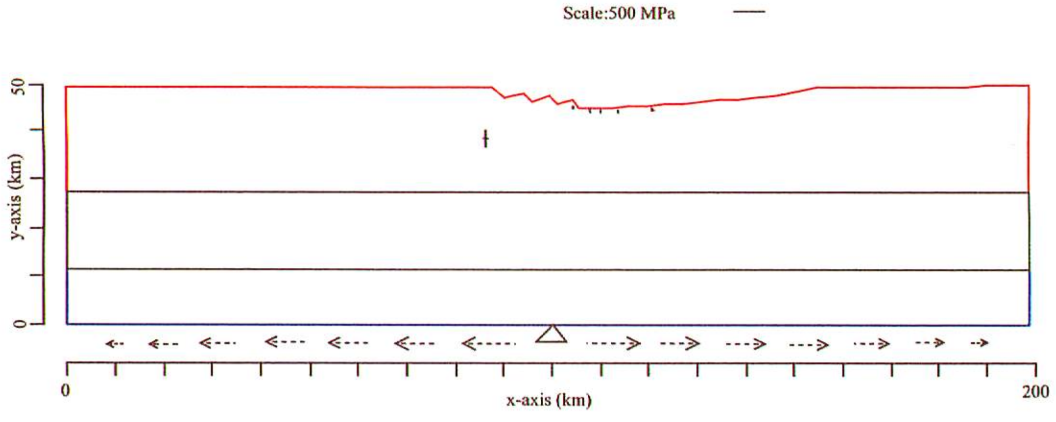

Fig. 10. Stress of failured element under spreading displacement 0 meter, without fault zone

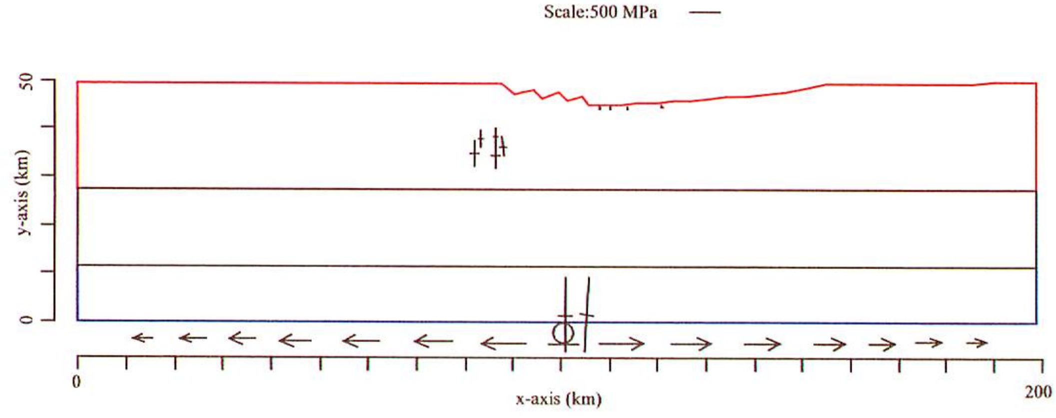

Fig. 11. Stress of failured element under spreading displacement 20 meter, without fault zone

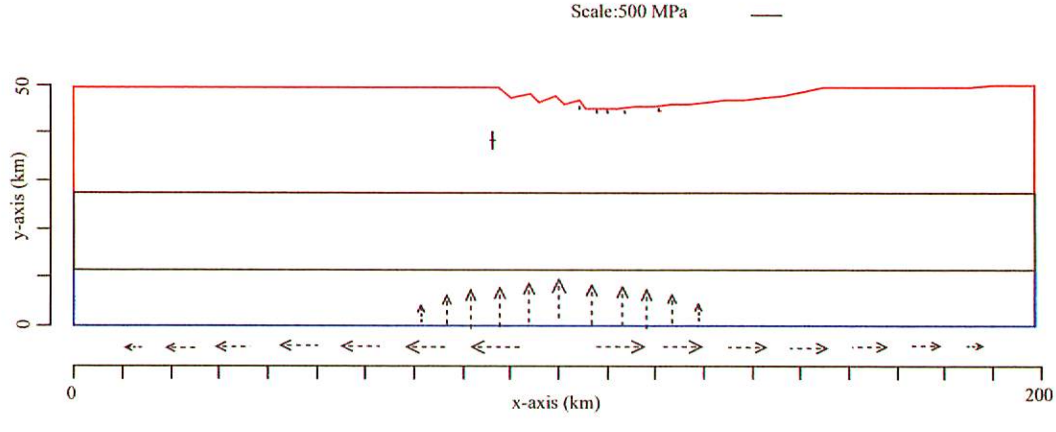

Fig. 12. Stress of failured element under spreading displacement 0 meter and upward displacement 0 meter, without fault zone

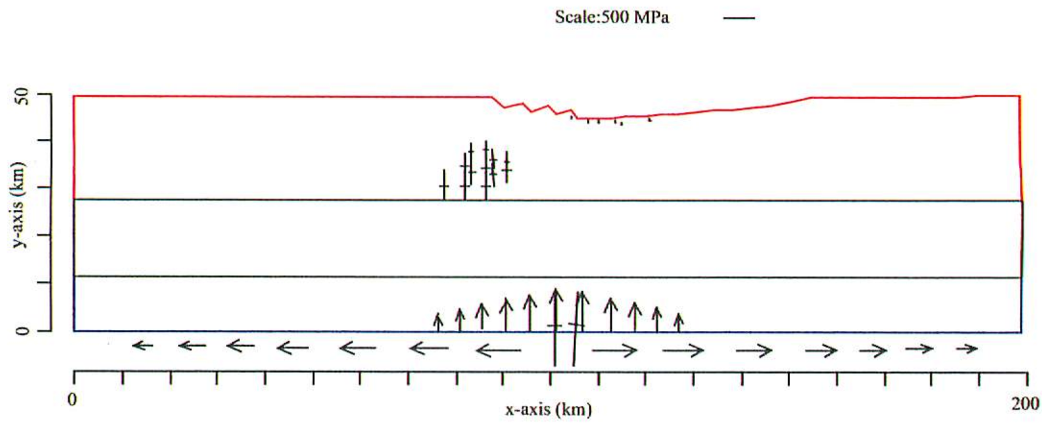

Fig. 13. Stress of failured element under spreading displacement 20 meter and upward displacement 10 meter, without fault zone

4.2. Results of the model with fault zone (fig. 14 - fig. 19)

Under extensional displacement 0 meter elements are failed in the upper crust above the detachment fault, but in case of extensional displacement 100 meter most of the elements are failed in the upper and lower crust. Under spreading displacement 0 meter and 20 meter elements are failed in the upper crust above the detachment fault. In case of spreading displacement 0 meter with upward displacement 0 meter, and spreading displacement 20 meter with upward displacement 10 meter elements are failed in the upper crust above the detachment fault. Increasing friction angle and cohesion decrease failured area and increasing Young's modulus slightly decrease failured area in all case of displacement boundary conditions (extensional, spreading, and spreading with upward).

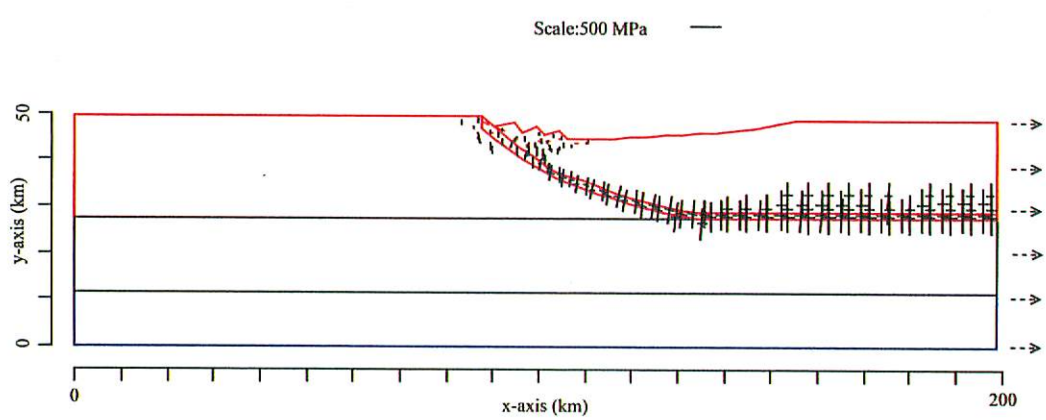

Fig. 14. Stress of failured element under extensional displacement 0 meter, with fault zone

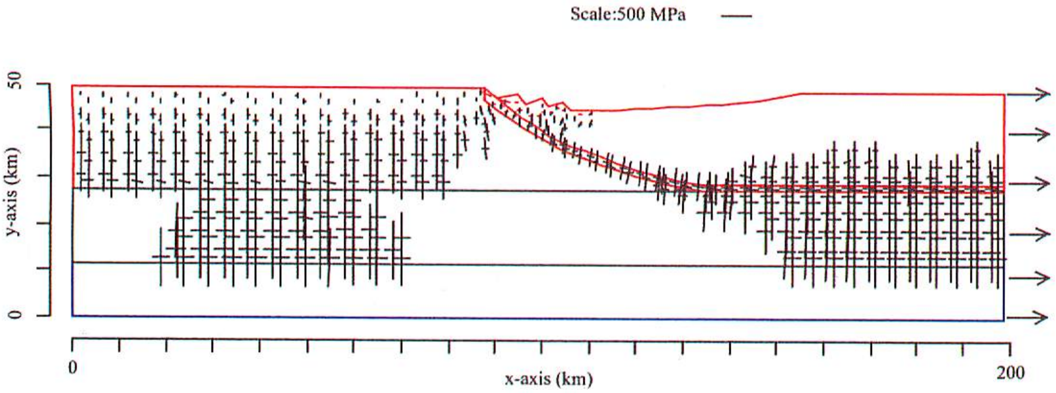

Fig. 15. Stress of failured element under extensional displacement 100 meter, with fault zone

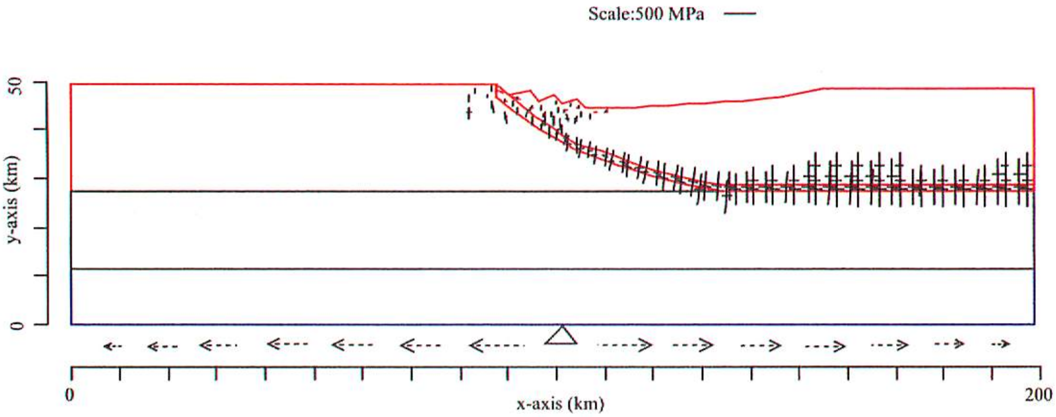

Fig. 16. Stress of failured element under spreading displacement 0 meter, with fault zone

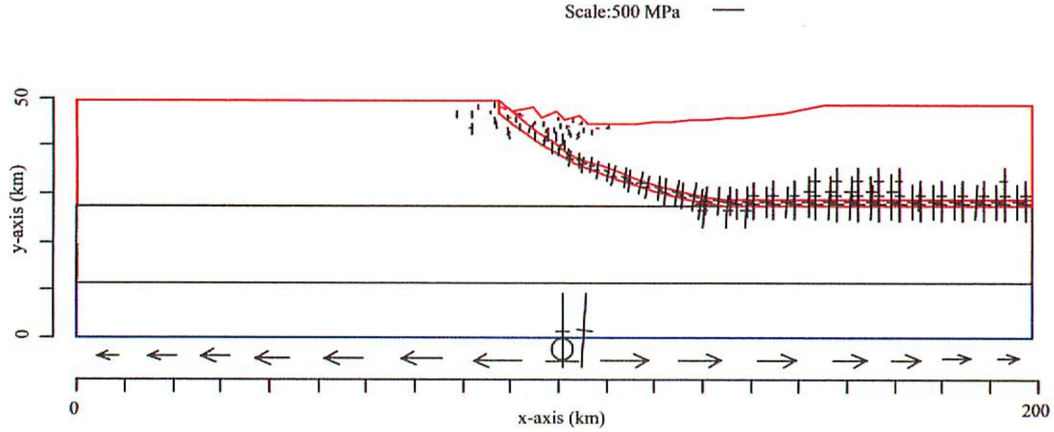

Fig. 17. Stress of failured element under spreading displacement 20 meter, with fault zone

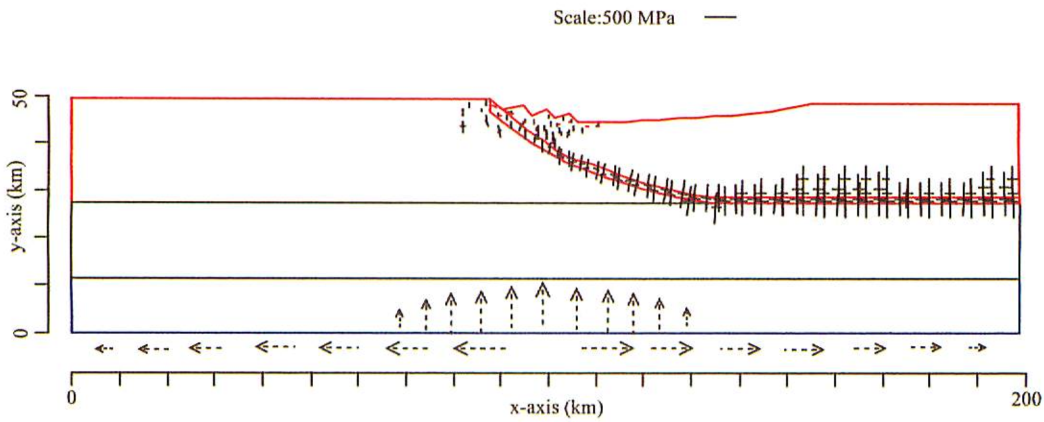

Fig. 18. Stress of failured element under spreading displacement 0 meter and upward displacement 0 meter, with fault zone

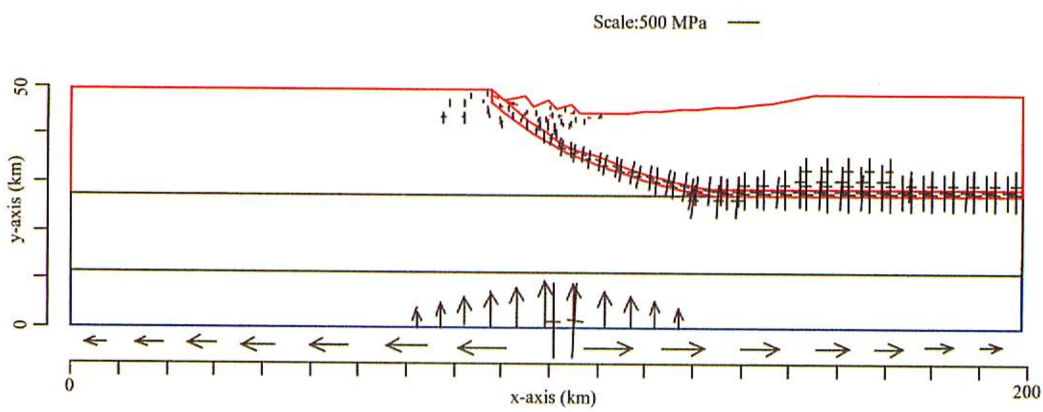

Fig. 19. Stress of failured element under spreading displacement 20 meter and upward displacement 10 meter, with fault zone

On the basis of overall results, the effect of layer properties shown in Table-2 and Table-3, and presented by fig. 20. The effect of displacement boundary condition on growth of faults shown in Table-4.

Table 2. Effect of layer properties on growth of faults (model without fault zone)

displacement boundary condition	layer properties	effect
extensional,	increasing friction angle	decrease failured area
spreading,	increasing cohesion	decrease failured area
spreading, + upward	increasing Young's modulus	increase failured area

Table 3. Effect of layer properties on growth of faults (model with fault zone)

displacement boundary condition	layer properties	effect
extensional,	increasing friction angle	decrease failured area
spreading,	increasing cohesion	decrease failured area
spreading, + upward	increasing Young's modulus	slightly decrease failured area

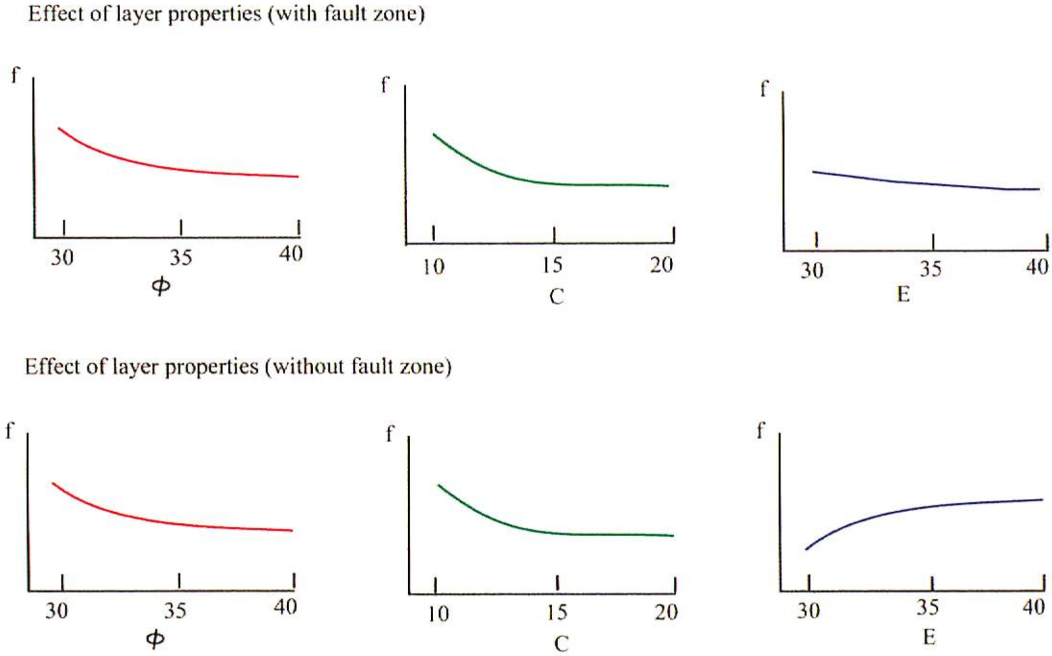

Fig. 20. Effect of layer properties

5. Geological Interpretation

The Red Sea is a young ocean basin formed by divergence of the African and Arabian continental plate, which began to spread in the Oligocene time. Red Sea is underlain by extended continental crust and seafloor spreading being limited to beneath the axial trough. The African and Arabian plates are moving a part and creating oceanic crust in the southern Red Sea area. The presently active Red Sea, Gulf of Aden, Afar and main Ethiopian rift system assembles at the Afar triple junction.

According to Bohannon (1986a), Bonatti and Seyler (1987), Coleman and McGuire (1988) and Bohannon and Ettreim (1991), detachment fault developed in the early stage of the Red Sea rifting, but they did not describe clearly the effect of detachment fault on the growth of normal fault system and how normal faults are propagated. We have

Table 4. Effect of displacement boundary conditions on growth of faults

	displacement boundary condition	displacement (meter)	tendency of failure
with fault zone	extensional	0 meter	elements are failed above the detachment fault
		100 meter	most of the elements are failed in the upper and lower crust
	spreading	0 meter	elements are failed above the detachment fault
		20 meter	
	spreading + upward	0+0 meter	
		20+10 meter	
without fault zone	extensional	0 meter	very few elements are failed in the upper crust
		100 meter	most of the elements are failed in the upper and lower crust
	spreading	0 meter	very few elements are failed in the upper crust
		20 meter	
	spreading + upward	0+0 meter	
		20+10 meter	

proposed a detachment fault model for initial stage of the Red Sea rift system.

We imposed three types of displacement boundary condition on the basis of consideration of divergence of African and Arabian plate (extensional) and upwelling of asthenosphere beneath the Red Sea (spreading, and spreading with upward). Linear elastic rheology with plane strain condition is considered in this study. In addition we have simulated two models without fault zone and with fault zone to clarify the effect of detachment fault on growth of normal fault system in the early stages of Red Sea development. According to results without fault zone case only a few elements are failured and form faults in the upper part of the upper crust. In contrast, in the presence of fault zone new faults are initiated and grow continuously, resulting in a relatively homogenous fault pattern. Thus this style of deformation produced large amount of extension between Arabia and African plate.

Generally fault development depends on layer properties of rocks. Changing of layer properties allow to study how the model accommodates the extension. The distribution of the deformation show reverse effect for changing of Young's modulus in the model without fault zone and model with fault zone. The effect of changing of friction angle and cohesion for experiments with fault zone is systematically higher than in experiments without fault zone. Thus friction angle and cohesion are most important parameters, which control the distribution of deformation in the upper crust. Fault networks in the model with fault zone are composed of faults with statistically larger displacement than in the model without fault zone. This observation highlights that the deformation is more localized in the model with fault zone.

So far we have demonstrated that the presence of fault zone strongly influence the distribution of deformation as a whole and effect of detachment fault is significant. Detachment fault developed caused by influence of ductile shear zone and rising of asthenosphere. Extensional displacement boundary condition in the model without fault zone show that very few elements are failured but increasing displacement boundary condition most of the elements are failured in the upper and lower crust. The model with fault zone show that some elements are failured in the upper crust above the detachment fault but with increasing displacement boundary condition most of the elements are failured in the upper and lower crust which is not suitable for natural case. Spreading and spreading with upward displacement boundary condition in the model without fault zone show very few elements are failured in the upper crust and in the model with fault zone show elements are failured above the detachment fault, which is fit to the natural case and supports active rifting hypothesis.

6. Conclusions

1. The distribution of deformation in the model with fault zone is larger than that of in the model without fault zone; fault zone has a strong influence on the growth of normal faults. Therefore the detachment fault play a significant role in controlling the distribution of deformation in the Red Sea rift system.
2. Causes of rising of asthenosphere firstly developed detachment fault, ductile shear zone between upper crust and lower crust influenced to developed detachment fault. Continuing rising of asthenosphere and the effect of detachment fault normal faults are propagated above the detachment fault in the upper crust.
3. Increasing friction angle and cohesion influence on growth of faults and in case of increasing Young's modulus show reverse effect on growth of faults in the model without fault zone and model with fault zone. Therefore friction angle and cohesion are important parameters and sensitive to fault development.
4. Results of extensional boundary condition is not suitable for expected results. The results of spreading, and spreading plus upward displacement boundary condition show naturally best fitted which favors active rifting hypothesis rather than passive rifting hypothesis of progressive stages of continental rifting in the Red Sea rift system.

Acknowledgement

M. S. H. would like to express gratitude to Monbukagakusho (Japanese Ministry of Education, Culture, Sports, Science and Technology) for financial support to pursue study under the special graduate program of the Graduate School of Engineering and Science, University of the Ryukyus, Japan.

References

Bohannon, R.G., 1986a. Tectonic configuration of the western Arabian continental margin, southern Red Sea. Tectonics, 5(4): 477-499.

Bohannon, R.G., 1986b. How much divergence has occurred between Africa and Arabia as a result of the opening of the Red Sea? Geology 14: 510-513.

Bohannon, R.G. and Eittreim, S.L., 1991. Tectonic development of passive continental margins of the southern and central Red Sea with a comparisn to walkers land, Antarctica. Tectonophysics, 198: 129-154.

Bonatti, E., 1985. Punctiform initiation of seafloor spreading in the Red Sea during transition from a continental to an oceanic rift. Nature, 316: 33-37.

Bonatti, E. and Seyler, M., 1987. Crustal underplating and evolution in the Red Sea rift: uplifted gabbro/gneiss crustal complexes on Zabargad and Brothers Islands. J. Geophys. Res., 92: 12803-12821.

Bosworth, W., Strecker, M.R., 1997. Stress field changes in the Afro-Arabian rift system during the Miocene to Recent period. Tectonophysics, 278: 47-62.

Cochran, J.R., 1983. A model for development of Red Sea. Am. Assoc. Pet. Geol. Bull., 67(1): 41-69.

Cochran, J.R. and Martinez, F., 1988. Evidence from the northern Red Sea on the transition from continental to oceanic rifting. Tectonophysics, 153: 25-53.

Coleman, R.G. and McGuire, A.V., 1988. Magma systems related to the Red Sea opening. Tectonophysics, 150: 77-100.

Crough, S.T., 1983. Rifts and swells: Geophysical constraints on causality. Tectonophysics, 94, 23-38.

Garfunkel, Z., 1988. Relation between continental rifting and uplifting: evidence from the Suez rift and northern Red Sea. Tectonophysics, 150:33-49.

Gettings, M.E., Blank, H.R.J., Mooney, W.D. and Healey, J.H., 1986. Crustal structure of southwestern Saudi Arabia. J. Geophys. Res., 91: 6491-6512.

Girdler, R.W., 1991. The Afro-Arabian rift system - an overview. Tectonophysics, 197: 139-153.

Girdler, R.W. and Underwood, M., 1985. The evolution of early oceanic lithosphere in the southern Red Sea. In: G.F. Sharman and J. Francheteau (eds.), Oceanic Lithosphere.

Tectonophysics, 116: 95-108.

Greiling, R.O., El Ramly, M.F., El Akhal, H. and Stern, R.J., 1988. Tectonic evolution of the northwestern Red Sea margin as related to basement structure. Tectonophysics, 153: 179-191.

Joffe, S. and Garfunkel, Z., 1987. Plate kinematics of the circum Red Sea-a re-evaluation. Tectonophysics, 141: 5-22.

Labrecque, J.L. and Zitellini, N., 1985. Continuous sea-floor spreading in Red Sea: An alternative interpretation of magnetic anomaly pattern. Am. Assoc. Pet. Geol. Bull., 69 (4): 513-524.

Le Pichon, X. and Gaulier, J.M., 1988. The rotation of Arabia and levant fault system. Tectonophysics,153: 271-294.

Lybaris, N., 1988. Tectonic evolution of the Gulf of Suez and Gulf of Aqaba. Tectonophysics, 153: 209-220.

Martinez, F. and Cochran, J.R., 1988. Structure and tectonics of the northern Red Sea: catching a continental margin between rifting and drifting. Tectonophysics, 150: 1-32.

Turcotte, D. L. and S. H. Emerman, S. H., 1983. Mechanisms of active and passive rifting. Tectonophysisc, 94: 39-50.