

Flower Structures and Strike-slip Deformation off Southwestern Taiwan

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ABSTRACT

Seismic data reveals the existence of flower structures offshore from southwestern Taiwan. Structures similar to transpressional flower structures occur off the coast from the cities of Tainan and Kaohsiung, whereas transtensional flower structures occur off the coast in Areas II&IV. The flower structures suggest that the structures in this area are influenced by strike-slip deformation. The trend of flower structures seems to conform to the orientation of secondary synthetic shears and antithetic X shears of the right-lateral strike-slip model. The mud diapirs in this study area were probably partly initiated by the en echelon folding during strike-slip deformation. That the transpressional flower structures develop in the orientation of secondary synthetic shears, while transtensional ones develop in antithetic X shear orientation, is possibly controlled by the mechanisms of convergence and divergence. The arrangements of the structures are also affected by pre-existing structures.

(Key words: Seismic, Flower structure, Strike-slip fault, Mud diapir, Southwestern Taiwan)

1. INTRODUCTION

The en echelon arrangement of mud diapirs offshore from southwestern Taiwan attracts the attention of these authors (Figure 1). It is believed that the en echelon pattern has some sort of relationship with the tectonic process. In general, tectonic features are most easily detected by analyzing seismic data. The seismic reflection profiles acquired by two cruises, designated number 320 and 329, aboard the *R/V Ocean Researcher I*, are analyzed. Flower structures and different kinds of strike-slip faults are discovered in this offshore area. The en echelon mud diapirs and the fault orientations can seemingly be interpreted through the strike-slip deformation model.

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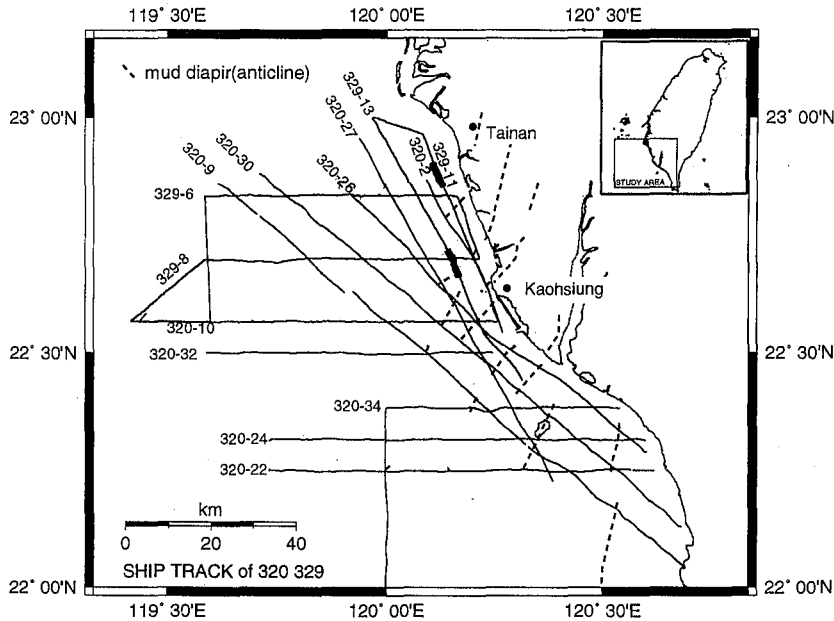


Fig. 1. The location of seismic sections and en echelon mud diapirs in the study area (trends of mud diapirs are modified from Chang, 1993).

2. THE EXISTENCE OF FLOWER STRUCTURE

After the seismic sections in this area are analyzed, some flower structures are discovered (Figures 2 and 3). The locations and orientations of these flower structures are shown in Figure 5. These flower structures (examples are shown in Figures 2 and 3) also exhibit several phenomena that are characteristic of the strike-slip fault proposed by Christie-Blick and Biddle (1985). They are (1) the principal displacement zone is sub-vertical at depth; (2) the upward diverging splay of faults; (3) the abrupt variations in seismic faces in a single stratigraphic unit across a fault; (4) the presence of both normal- and reverse-separation faults in a given seismic profile; (5) variable proportions of the same normal and reverse faults in different seismic profiles; (6) the magnitude and sense of separation of a given fault splay to vary from one horizon to another in a single profile; and (7) the tendency in successive seismic profiles for a given fault to dip alternately in one direction and then in the opposite direction, and to display variable separation (both magnitude and sense) for a single horizon.

These flower structures develop along both convergent strike-slip faults and along divergent faults. The ones along convergent faults imply much the same as the transpressional flower structures (Harland, 1971; Sylvester and Smith, 1976; Harding and Lowell, 1979; Harding *et al.*, 1983; Harding, 1985), whereas the ones along divergent faults imply the same as the transtensional flower structures (D'Onfro and Glagola, 1983; Harding, 1983; Harding *et al.*, 1985). Christie-Blick and Biddle (1985) have also pointed that the development of fault structural styles may also be influenced by the rotation of small blocks that can produce segments of divergence and convergence within a strike-slip fault regime.

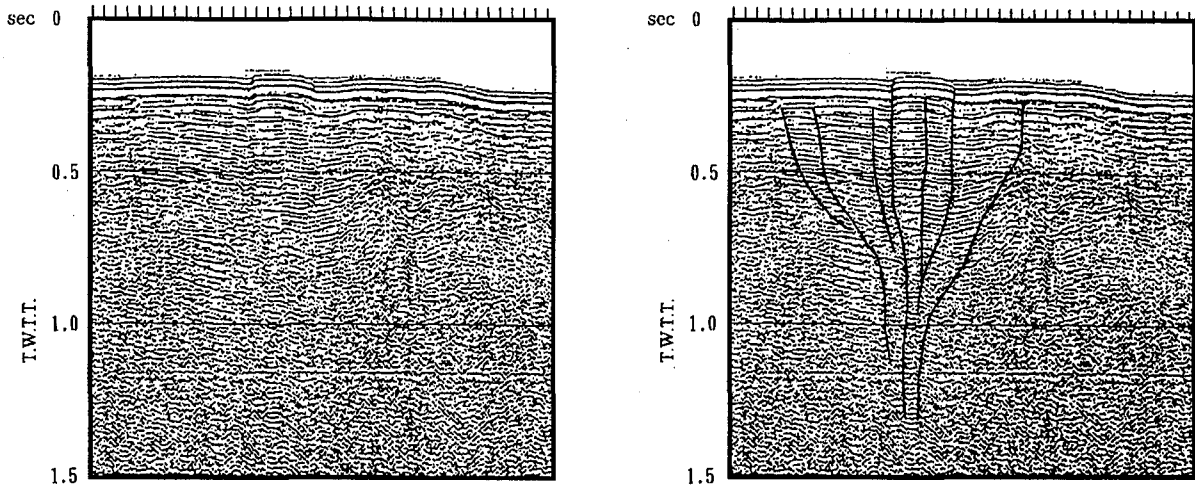


Fig. 2. Seismic section (left) and interpretation (right) of transtensional flower structure on seismic line MCS329-13. Location shown as heavy line in Fig. 1.

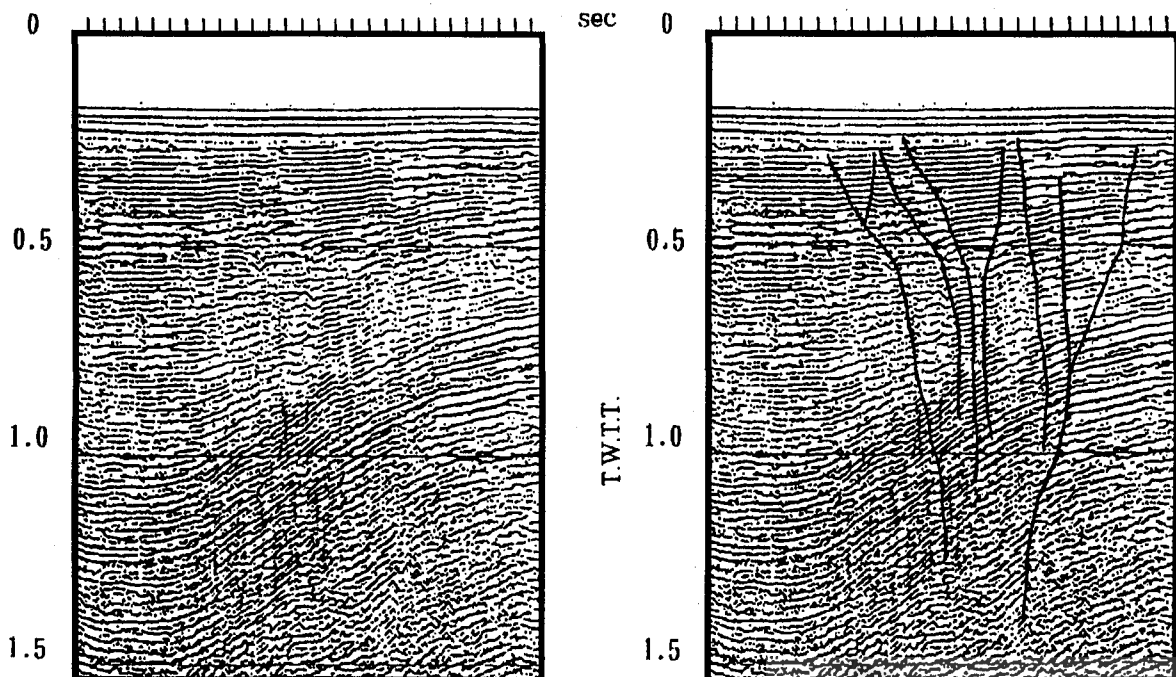


Fig. 3. Seismic section (left) and interpretation (right) of flower structures on seismic line MCS329-11 off the coast from Tainan. Location shown as heavy line in Fig. 1.

3. OTHER STRIKE-SLIP FAULTS

Generally, not only the flower structures exist in the shelf part of the studied area, but some structures in the continental slope area may also represent the existence of strike-slip faults. The apparent relative movement frequently found on seismic sections does not mean the actual relative movement (Davis, 1984). This is due to there being several factors which could result in such motion on the seismic section: the orientation of layering; the strike and dip of the fault plane; the slip on the fault; and the orientation of the seismic section in which any separation is viewed. The left-lateral strike-slip faulting of a tilted sequence of strata in this area have produced structural relationships that in a cross-sectional view are easily misinterpreted as simple reverse faulting. So, frequent occurrence of flower structures and strike-slip faults in this offshore area indicates that the sedimentary strata in many places in this area are deformed due to strike-slip faults.

Coincidentally, another earthquake strike-slip fault—the Hsinhua Fault (Chang *et al.*, 1947) is located onshore in an orientation extending from an offshore strike-slip fault zone where a flower structure trend developed. In addition to this, Biq (1990), Yang *et al.*, (1991) and Yang *et al.*, (1994) proposed that a large transtension zone does occur to the south of the Peikang High, which is close to the studied area. Also, owing to indentation tectonics, Lu (1994) suggested that the southern edge of the Peikang High is bounded by a strike-slip fault zone. All this evidence implies that strike-slip fault deformation should exist in the nearby onshore counterpart of the offshore area studied. The explanation as to why few strike-slip faults, such as the Hsinhua Fault, are discovered in this onshore counterpart is that the recognition of the strike-slip faults usually requires a high standard of outcrop or seismic data. Geomorphologically, some portions of this onshore counterpart are covered by mountains, and the other portions are coastal plain. The coastal plains have been developed into metropolitan areas and smaller cities, such as Kaohsiung and Tainan Cities. The elevation variance of the mountains, as well as the noise from the cities, causes the field seismic data to deteriorate badly. Nevertheless, the authors predict that more strike-slip faults will be recognized in this counterpart after much careful analysis. In fact, further such study is already in progress.

4. RIGHT-LATERAL STRIKE-SLIP MODEL

The orientations of the above-mentioned structures found at the shelf portion in the studied offshore area can be interpreted as a right-lateral strike-slip fault system as shown in Figures 4 and 5, although the structural patterns at the continental slope have been obscured by canyons, mud volcanoes, and the highly irregular variance of the sea floor. Using clay, unconsolidated sand, or sheets of paraffin wax, this model can reproduce the frequently observed structures in strike-slip regimes (Lowell, 1972; Wilcox *et al.*, 1973; Courtillot *et al.*, 1974; Freund, 1974; Mandl *et al.*, 1977; Graham, 1978; Groshong and Rodgers, 1978; Rixon, 1978; Gamond, 1983; Odonne and Vialon, 1983; Harris and Cobbold, 1984), in the experimental deformation of homogeneous rock under confining pressure (Logan *et al.*, 1979; Barllett *et al.*, 1981), and in the deformation of alluvium during large earthquakes (Sharp, 1976, 1977; Philip and Megard, 1977). Seven sets of structures are commonly observed (Figure 4; Christie-Blick and Biddle, 1985): (1) en echelon folds; (2) synthetic strike-slip faults (R); (3) antithetic R' strike-

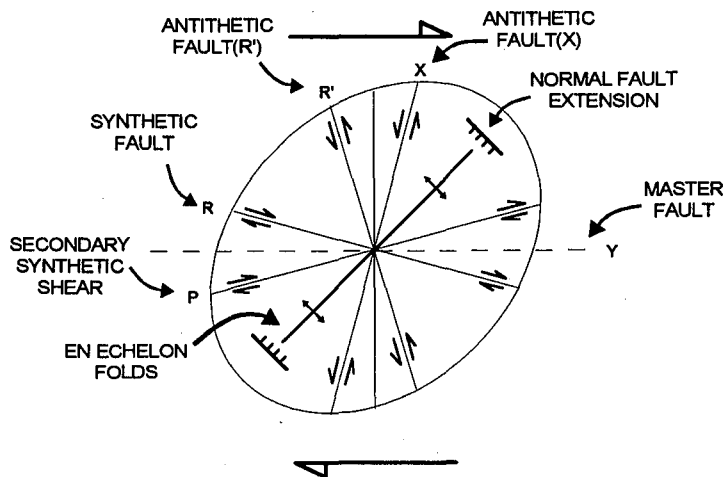


Fig. 4. Right-lateral strike-slip fault model, synthetic faults (R) and secondary synthetic faults (P) are right-handed, whereas antithetic R' and X faults are left-handed (modified from Wilcox et al., 1973).

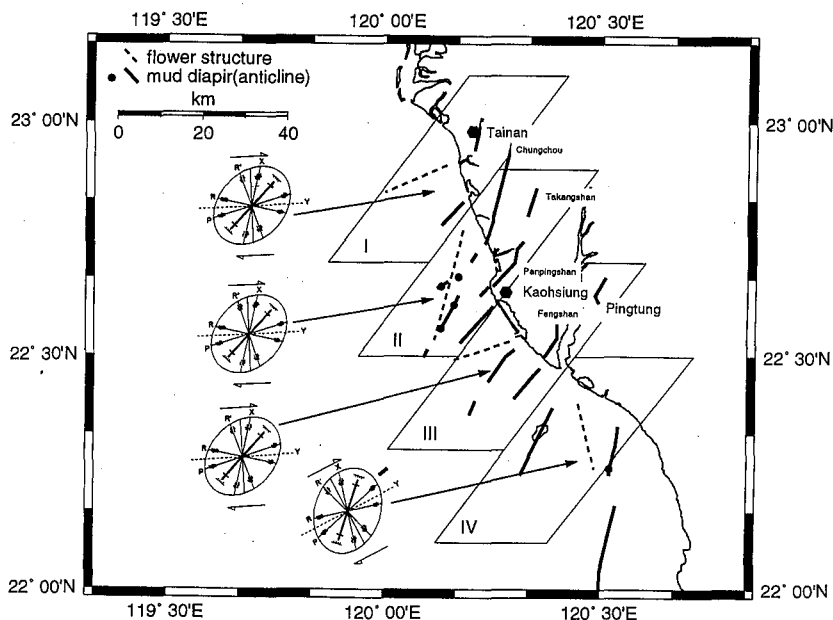
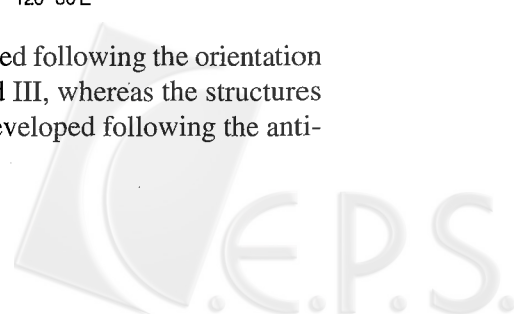


Fig. 5. The transpressional flower structures developed following the orientation of secondary synthetic shears in Areas I and III, whereas the structures similar to transtensional flower structures developed following the antithetic X shears in Areas II and IV.



slip faults; (4) antithetic X strike-slip faults, which are described by Bartlett *et al.* (1981) as having the same sense of offset with R'; (5) secondary synthetic faults (P); (6) normal faults resulting from extension; and (7) faults parallel to the principal displacement zone (Y). Figure 4 indicates the approximate orientation of the folds and associated faults in simple conditions. For the illustrated right-lateral system, synthetic faults (R) and secondary synthetic faults are right-handed (Wilcox *et al.*, 1973; Biddle and Christie-Blick, 1985), whereas antithetic R' and X faults are left-handed. As discussed below, however, the real geological situation tends to be more complicated, and the observed arrangements do not have to coincide with those predicted by models or experiments (Christie-Blick and Biddle, 1985). This is due to the rocks being heterogeneous, the structures developing sequentially rather than instantaneously, and pre-existing structures tending to be rotated during protracted deformation.

On closer investigation of the flower structures and mud diapirs, followed by comparison with the strike-slip fault model, it seems that the trends of mud diapirs and the faults in flower structures can indeed be interpreted by this model. The en echelon mud diapirs can probably be related to the en echelon folds in the model (Figure 4). The trend of similar transpressional flower structures off Tainan (Area I) is oriented approximately N75°E-S75°W (Figure 5). If the orientation of the mud diapirs off Tainan is to fit the orientation of the en echelon folds of the strike-slip fault model, then the trend of the strike-slip faults of these transpressional flower structures seems to conform to the secondary synthetic faults in this model. Coincidentally, the trend of the strike-slip faults off Tainan is similar to that of the strike-slip Hsinhua Fault caused by earthquake. Therefore, it is suggested that the Hsinhua Fault has some sort of relationship with the origin of the strike-slip faults. Further study into this kind of relationship is being done. Besides Area I (the area off Tainan City), the transpressional flower structures were also discovered in Area III (the area off Kaohsiung City). Similarly, if the orientation of the mud diapirs in Area III is fitted to the en echelon folds of the strike-slip model, the trend of the strike-slip faults of the transpressional flower structures seems to conform to secondary synthetic faults (Figures 4 and 5). In contrast, the transtensional flower structures occur in Areas II&IV (Figure 5). It's interesting that, after fitting the orientations of the mud diapirs to the en echelon folds of this model, the trends of the strike-slip fault of the transtensional flower structures in Areas II&IV tend to occur in the direction of the antithetic X faults of this strike-slip model (Figures 4 and 5). The phenomenon that the secondary synthetic faults noticeably develop along with the transpressional flower structures, and that the antithetic faults develop with the transtensional structures, is probably due to the mechanisms of divergence and convergence during strike-slip.

5. DISCUSSION

Development of the structural patterns in the study area seems to be controlled by three factors, which derive from the above-mentioned strike-slip fault model. These factors are: (1) the mechanisms of flower structure; (2) the sequence of formation; and (3) the pre-existing structures. Each of these factors tends to vary along any given fault and, except for the latter, they change with time (Reading, 1980; Aydin and Nur, 1982; Mann *et al.*, 1983).

Mechanisms of flower structures – The fact that secondary synthetic faults develop in Areas I and III (with structures similar to transpressional flower structures) in the study area

while antithetic faults develop in Areas II&IV (with transtensional flower structures), is probably related to the mechanisms of either convergence or divergence present in flower structures. The coexistence of convergent and divergent strike-slip deformations in a specific area commonly occur in the world (Terres and Sylvester, 1981; Dibblee, 1977).

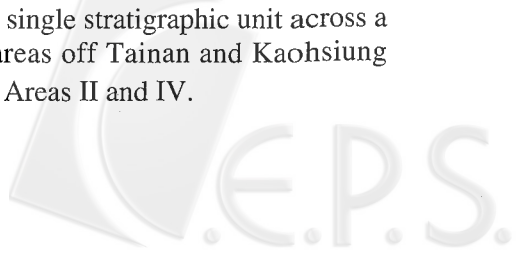
The convergent strike-slip faults that produce transpressional flower structures lead to the development not only of en echelon folds, but also of many reverse faults (Lowell, 1972; Wilcox *et al.*, 1973; Sylvester and Smith, 1976; Lewis, 1980; Mann *et al.*, 1986; Steel *et al.*, 1985). It's not surprising that the en echelon folding resulting from basement-involved strike-slip faults can initiate the raise of the en echelon mud diapirs. In cases of pronounced convergence, as in the western Transverse and Coast Ranges of California, the structural style becomes similar to that of the thrust and fold belts (Nardin and Henyey, 1978; Suppe, 1978; Yeats, 1981, 1983; Crouch *et al.*, 1984; Davis and Lague, 1984; Wentworth *et al.*, 1984; Namson *et al.*, 1985). The folds and faults located in the onshore counterpart of the study area may involve pronounced convergence with strike-slip deformation as in the western Transverse and Coast Ranges.

Sequence of formation – It was noted that some sort of rotation occurs in the trends of the mud diapirs near the coastal area (Figure 5). This same rotation also happens in the trends of the Barnpinsarn and Sousarn mud diapirs, probably because early-formed structures tend to rotate during later progressive deformation (Tchalenko, 1970; Wilcox *et al.*, 1973; Rixon, 1978; Odonne and Vialon, 1983). Therefore, the final orientations of folds and faults depend upon the time at which these structures formed during the deformation history. Individual faults are frequently the elements of broader regions of deformation, and different faults may be active episodically at different times as a result of block rotation or the reorganization of the block boundaries. Given a long geological timescale and the fact that rocks and sediments are heterogeneous even before deformation, it is easily understood that the orientation and geometry of observed structures in the strike-slip regime depart significantly from those predicted by the above-mentioned model (Christie-Blick and Biddle, 1985).

Pre-existing Structures – In addition to the rotation of mud diapirs (folds) mentioned above, some normal faults were reactivated as strike-slip faults in this area. Thus, the arrangements of the strike-slip faults in this area are probably influenced by the pre-existing normal faults. This kind of process can also be observed in other parts of the world. The pre-existing normal faults parallel to the Upper Rhine graben were reactivated to become strike-slip faults during the uplift of the Alps in the Pliocene to Holocene period (Illies, 1975; Illies and Greiner, 1978; Ahorner, 1975). The location of some major transform faults in the Atlantic equatorial mega-shear zone has been controlled by the weakness within the continents since a time prior to continental separation (Bonatti and Crane, 1984; Zalan *et al.*, 1985).

6. CONCLUSIONS

Transtensional structures and structures similar to transpressional flower structures are discovered in this area. The flower structures have seven of the same characteristics as strike-slip faults, such as the abrupt variation in seismic facies in a single stratigraphic unit across a fault. The transpressional flower structures occur in the areas off Tainan and Kaohsiung Cities, whereas the transtensional flower structures occur in Areas II and IV.



In this offshore area there exist not only the flower structures, but also other structures that represent segments of strike-slip faults. Another onshore earthquake strike-slip fault is located in the same orientation as an offshore strike-slip fault zone in a transpressional flower structure zone. All these data suggest that the strike-slip fault does indeed influence the structural patterns in this study area.

The orientation of the structures of the shelf portion in the studied area can be interpreted in the right-lateral strike-slip fault system model. If the trends of the mud diapirs are fit to the en-echelon folds of the strike-slip system model, the orientation of the strike-slip faults of the transpressional flower structures off Tainan and Kaohsiung Cities (Areas I and III) seem to conform to the secondary synthetic strike-slip faults of this model, whereas the orientation of the strike-slip faults of the transtensional flower structures in Areas II&IV seem to conform to the antithetic X strike-slip faults of this model.

The real geological situation tends to be more complicated than the strike-slip model in the experimental deformation of homogeneous materials. Therefore, although this model can explain most of the arrangement of the structures in the study area, there are three other control factors derived from this model which influence the development of the structural pattern in this area.

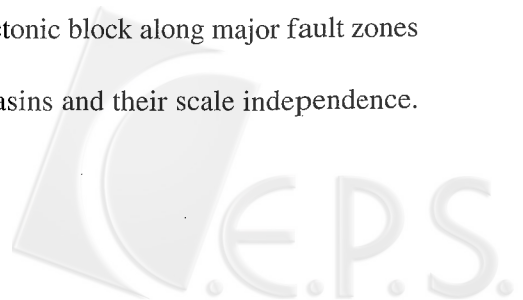
The strike-slip fault-induced en echelon folds possibly play a role in the initiation in the raising of the mud diapirs. The transpressional flower structures develop in the orientation of the secondary synthetic shears of the strike-slip faults model, whereas the transtensional flower structures develop in the orientation of the antithetic X shears. The occurrence of either secondary synthetic shears or antithetic X shears is probably a result of mechanisms being either convergent or divergent.

A sort of rotation is present in the trends of the mud diapirs near the coastal area. Such rotation possibly took place with the early-formed mud diapir trends during later deformation. Some normal faults were reactivated as strike-slip faults in this area, which means that the arrangement of the strike-slip faults in this area is likely to be influenced by pre-existing normal faults.

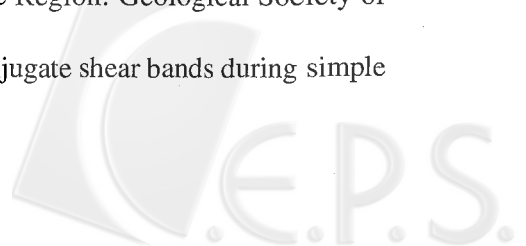
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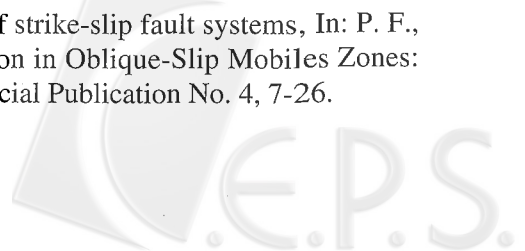
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