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Block rotation by basement strike-slip faulting in the Sanchu graben, central Japan

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Abstract—In the Kanto Mountains, central Japan, Cretaceous fore-arc basin sediments are sandwiched by basement rocks in a narrow zone traditionally called the Sanchu graben. In the axial part of the graben they are divided into numerous blocks by a series of subparallel sinistral strike-slip oblique faults (block faults). These blocks have rotated clockwise together with block faults. Resulting clockwise deviation of strike of the strata from the general trend increases gradually from the margins toward the axial part of the graben, where it attains 30°. Block faults are traced in part of the graben where the strata show this clockwise deviation of strike.

The structural evidence and the high length/width ratio of the rotated domain suggest that a major dextral strike-slip fault lies beneath the Cretaceous cover of the axial part. The unconformable boundary between the Cretaceous cover and the underlying basement may have played the role of a detachment plane, and prevented the fault from extending into the cover. The rotation of the overlying Cretaceous system is thus a superficial manifestation of underlying dextral strike-slip faulting.

INTRODUCTION

IT IS well known that deformation is much more prevalent and variable in the continental crust than in the oceanic crust. Since the 1960s, an important style of continental deformation has been recognized in numerous regions: that is, rotation about vertical axes of a series of crustal blocks together with subparallel strike-slip faults separating them (Fig. 1). Most of this type of deformation tends to concentrate along ancient or contemporary plate boundaries such as boundary transform faults, subduction zones and collision zones (references are listed in the caption of Fig. 9).

The sense and amount of block rotation have been determined mainly from paleomagnetic data. However, in some cases, evidence comes from anomalous paleocurrent directions discordant to those in the juxtaposing areas (Karner & Dewey 1986) or geodetic data from triangulation surveys (Walcott 1984). The aerial extent of block rotation ranges from 0.12 km^2 (Woodcock 1987) to 1.2×10^6 km^2 (England & Molnar 1990); the mode of deformation of the crust is the same irrespective of a wide range of scale over at least an order of 10^7. Block rotation has also been known to produce a secondary nested fault system within the individual rotated blocks (Woodcock 1987, Kanaori *et al.* 1990a,b).

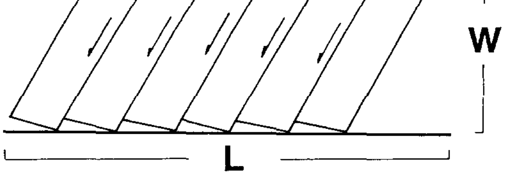

Fig. 1. Mode of deformation by block rotation. *L*—length parallel to the reference boundary of the deformed zone. *W*—width of the deformed zone.

This paper describes block rotational deformation in Cretaceous fore-arc sediments tectonically trapped between basement blocks. The mode of rotational deformation of the Cretaceous strata and the characteristics of strike-slip block faults responsible for block rotation are described. On the basis of the features of block faults and deformation style, a subsurface faulting model is proposed.

GEOLOGICAL SETTING

In the Kanto Mountains of central Japan, basement rocks of variable lithology form well defined belts with a WNW–ENE trend. From north to south, they are the Sanbagawa metamorphic complex, the Jurassic accretion complex of the Chichibu Terrane and the Cretaceous accretion complex of the Shimanto Terrane. Neritic Cretaceous strata occupy a narrow zone (2–4 km wide), called traditionally the Sanchu graben, along the axial part of the Chichibu Terrane with northern and southern margins bounded by longitudinal faults (Fig. 2b). At its eastern extremity, the Cretaceous system is unconformably overlain by Miocene sediments which are distributed discordantly to the above mentioned zonal arrangement of the pre-Cenozoic units.

The Cretaceous system consists of the Ishido, the Sebayashi and the Sanyama Formations in ascending order (Takei 1963) (Fig. 2c). The Ishido Formation, consisting of conglomerate and sandstone, represents the basal member of the Cretaceous system and is in fault contact with the basement Chichibu Complex on both sides of the graben. However, the original relationship between them is an unconformity (Takei 1963). The Sebayashi Formation, which conformably overlies the Ishido Formation, consists of well stratified sandy flysch. The Sanyama Formation disconformably overlies the

Sebayashi Formation and consists of basal conglomerate and muddy flysch. The Ishido, the Sebayashi and the Sanyama Formations are correlated to the Hauterivian to Barremian, Aptian to early Cenomanian and Cenomanian to Turonian, respectively, on fossil evidence (Takei 1963).

The Sanchu graben is tectonically subdivided into northern, middle and southern sub-belts by longitudinal faults. Of these, only the middle sub-belt contains all the formations, while the other sub-belts lack some parts of the succession mentioned above (Takei 1963). In the eastern part of the graben, the middle sub-belt occupies the largest area. The strata of the northern and the southern sub-belts are steeply inclined to the south and north, respectively, whereas those of the middle sub-belt are tightly folded to form a closed synclinorium. All the strata strike essentially parallel to the general trend of the graben except in the axial part of the middle sub-belt. The general deviation of the strike in this part is attributable to block rotation as will be discussed later.

The synclinorium is constituted of flexural-slip folds. Their axial traces are more or less parallel to the general trend of the graben, though the axes plunge at angles of 20–40° to the southeast near the eastern extremity (Saka & Koizumi 1977).

FAULTS IN THE CRETACEOUS SYSTEM

Six sets of faults are distinguished in the Cretaceous system (Table 1) based on inherent features such as orientation, shear sense and fracture zone width. How-

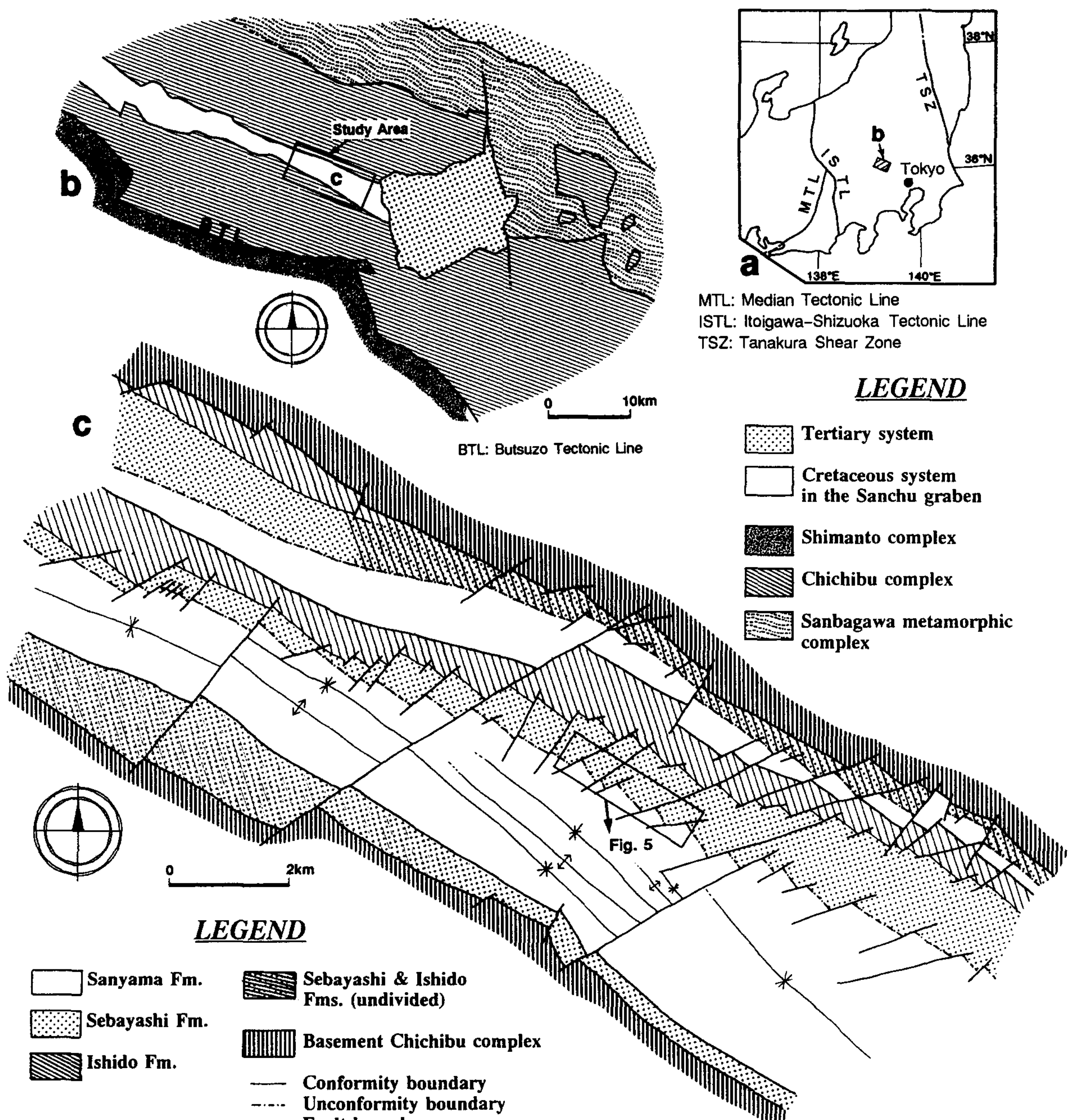

Fig. 2. Geological maps. (a) Location of the Kanto Mountains. (b) Geological sketch map of the study area. (c) Geological map of the study area in the Sanchu graben.

ever, there is a significant dispersion of orientation in each group. Thus, the designation of faults is approximate only. Fracture zones of these faults are associated only with cataclasite with or without fault gouge, indicating a shallow fault origin. The cataclasite and fault gouge are classified into foliated microbreccia and foliated fault gouge, respectively, as defined by McClay (1987). The shear sense of fracture zones can be determined from the asymmetric structures developed in them (Rutter *et al.* 1986, Chester & Logan 1987, Tanaka & Hara 1990). The general features of cataclasite zones developed along each set of the fault system are as follows.

Faults trending N60°W (a in Table 1) are longitudinal faults. Here, fault planes appear to have followed pre-existing discontinuities between the different lithologies, such as the unconformable boundary between the Cretaceous system and the basement as well as formation boundaries. Asymmetric structures such as *P* foliations and R_1 shears (Rutter *et al.* 1986) that are developed in cataclasite zones indicate normal sense of dip-slip along some faults and reverse-slip along others. This may imply that faults were activated in multiple stages. Group (b) (N80°W) and group (c) (N70°E) in Table 1 show a marked difference in that the former is widespread throughout the area, whereas the latter is dominant exclusively in the axial part of the middle sub-belt, even though both of them share the sense of the fault movement. Two sets of faults of group (e) in Table 1, less important in extent and displacement, form conjugate sets. Groups (e) and (f) were formed much later than the others because they also displace the Miocene sediments. Only the N70°E sinistral fault system (group c) is involved in block rotation about vertical axes as described below.

DEFORMATION INDICATIVE OF BLOCK ROTATION

Data for the Sanchu graben

Traces of the stratigraphic boundaries originally drawn on a 1/5000 map are shown in Fig. 3(a). The boundary between the Ishido and the Sebayashi Formations (4 in Fig. 3a) and that between the Sebayashi and the Sanyama Formations (5 in Fig. 3a) in the axial part of the graben show a marked left-stepping pattern identical to that given by Gamond (1987) (Fig 3b), with each stepped segment oriented diagonal to the general trend. The stepping is less prominent in the other boundaries outside the middle sub-belt. A marker bed of white tuff, 1 m in thickness, intercalated in the uppermost horizon of the Ishido Formation in the middle sub-belt (7 in Fig. 2) displays a similar left-stepping pattern on the map. Hence, the left-stepping of the formation boundaries is not attributed to the original arrangement of strata but to later deformation. The extent of this deformation is indicated by the orientation of strata throughout the graben; left-stepping of strata is expected where this deformation occurred. The orientation of strata of each formation measured at about 1500 locations (except in the southern sub-belt where exposures are hardly available) are plotted in equal-area projections (Fig. 4). Only the strata whose stratigraphical tops face south are used to eliminate the effect of the plunge of the fold axes. The strike of the strata in the axial part deviates clockwise by about 25° from the general trend of the Cretaceous system. Nevertheless, the map pattern of formations as a whole is roughly parallel to the general trend. It is also recognized that such a deviation of the strike decreases both northward and southward from the axial part of the graben (Fig. 4).

Competent strata consisting of massive sandstone and conglomerate occupy the axial part and both the northern and the southern marginal parts of the graben. The greatest deviation of strike occurs in competent strata in the axial part while no deviation is observed in those in the marginal parts. By contrast in the zones outside the axial part where the clockwise deviation of the strike decreases, strata are mainly of incompetent pelitic facies. Thus, the deformation, which is maintained by a clockwise deviation of the strike by about 25°, is concentrated in a narrow zone of the axial part of the graben.

Axial part of the graben

In order to obtain further information on the mode of deformation, a selected area of the axial part of the Cretaceous system has been mapped in detail (Fig. 5). Even more frequent left-stepping of the lithological boundaries has been found here. Furthermore, it has become clear that clockwise deviation of the strike of strata is highly consistent throughout the mapped area except in the northern margin (P) (Fig. 5).

A detailed map showing the left-stepping and clockwise deviation of the trend of lithological boundaries is

Table 1. Six systems of faults developed in the Sanchu graben, central Japan

Strike	Dip	Width of the cataclasite zone	Sense of the displacement
(a) N60°W±	Moderate to steep to SSW or NNE	~10–100 cm	Normal or reverse
(b) N80°W±	Vertical	~100–500 cm	Sinistral
(c) N70°E±	Vertical	100 cm ±	Sinistral
(d) N40°W±	Vertical	~100–200 cm	Dextral
(e) N–S	Vertical	~0–10 cm	Dextral
N50°E	Vertical	~0–10 cm	Sinistral
(f) N20°E±	Vertical	~10–30 cm	Dextral

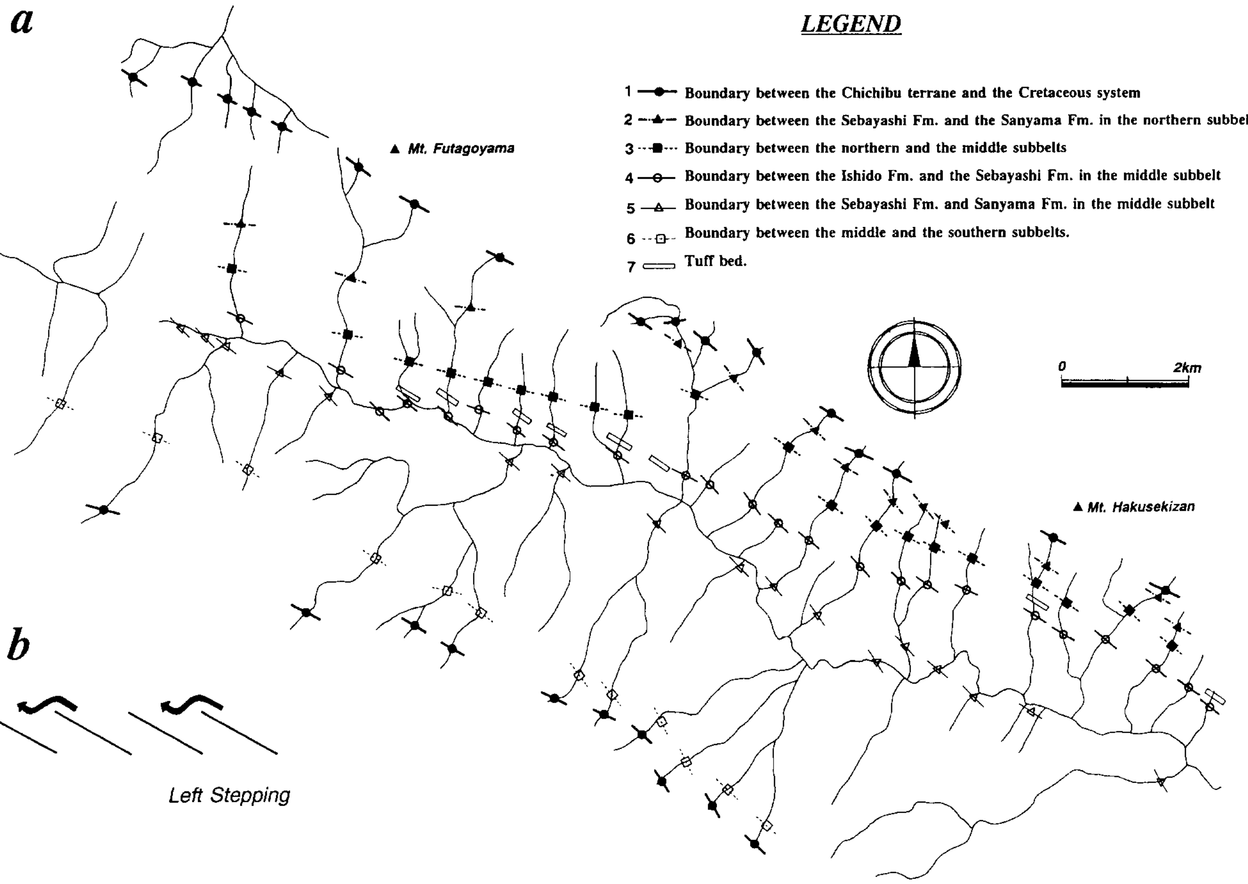

Fig. 3. (a) The orientation of the boundaries of various geological units. Dips of boundary surfaces are left out because they are essentially vertical. (b) Mode of left-stepping after Gamond (1987).

shown in Fig. 6. Faults (F_1–F_5 in Fig. 6), which strike N70°E to E–W and dip almost vertically, are arranged en échelon. These faults are associated with zones of foliated crushed rock ranging from 30 cm to 1 m in width (Fig. 7). In these fault zones, wall rocks are highly fractured by slip on the minor shear surfaces to form cataclasites in which the rock fragments range typically from 0.5 to 5 cm in diameter. As the slip on the minor shear surfaces is a principal mechanism of deformation on the mesoscopic scale, the shear directions can be determined by slickenlines. They lie essentially horizontal (Fig. 6). Foliations (P foliations) and shear bands (R_1 shear surfaces) are well developed in fracture zones (Fig. 7). The foliations are oriented clockwise by about 10–20° to the main fault surface (Y shear surface) and the shear bands are oriented in the anticlockwise sense (Fig. 6). Therefore, they constitute a composite planar fabric (Chester & Logan 1987) and indicate a sinistral shear sense, which is consistent with the offset of lithological boundaries on the map.

These facts suggest that N70°E-striking en échelon faults cause a series of left-lateral separations and clockwise deviation of the strike to strata occupying the axial part of the graben.

Table 2. (a) Equations for length of the fault after Ogata & Honsho (1981) and Freund (1970). (b) Equation for length of the block fault

(a) Equation	Parameters	Minimum(l) (m)	Maximum(l) (m)
(1) $\log l = 0.68 \pm 0.32 + 0.87 \log T$	$T = \sim 30\text{–}100$ cm	41	550
(2) $D = a \cdot l$, where $a = \sim 0.10\text{–}0.15$	$D = \sim 30\text{–}120$ m	330	1200

(b) Equation	Parameters	Minimum(l) (m)	Maximum(l) (m)
(3) $W = l \cdot \sin \alpha$	$W = \sim 500\text{–}700$ m. $\alpha = 40°$	780	1090

(1) Ogata & Honsho (1981): l, length of the fault (m); T, width of the shear zone (cm).
(2) Freund (1970): D, displacement (km); l, length of the fault (km).
(3) W, width of the zone of block rotation (see Fig. 1); l, length of the block fault; α, angle between the reference boundary L and the block fault.

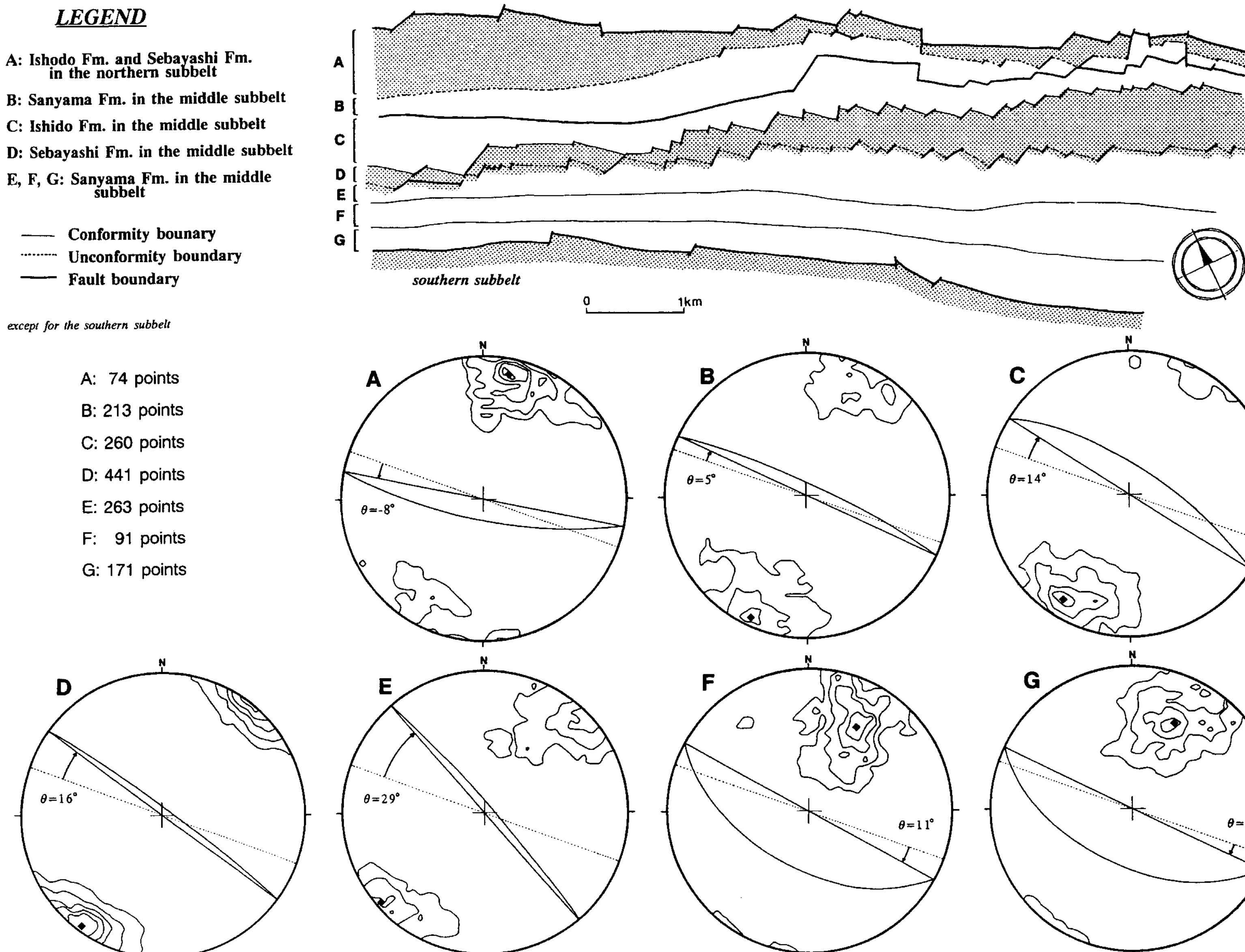

Fig. 4. (Above) Lithological units (A–G) in the graben. The Sanyama Formation in the middle sub-belt is tentatively subdivided into three sub-units (E, F and G). (Below) Orientation of the strata in each unit. Lower-hemisphere, equal-area projections. Contours: 2, 5, 8, 11 and 14%. Great circles show the mean orientation of the strata. Dotted lines in the projections indicate the general trend of the graben. θ—deviation of strike of strata from general trend (clockwise measurement).

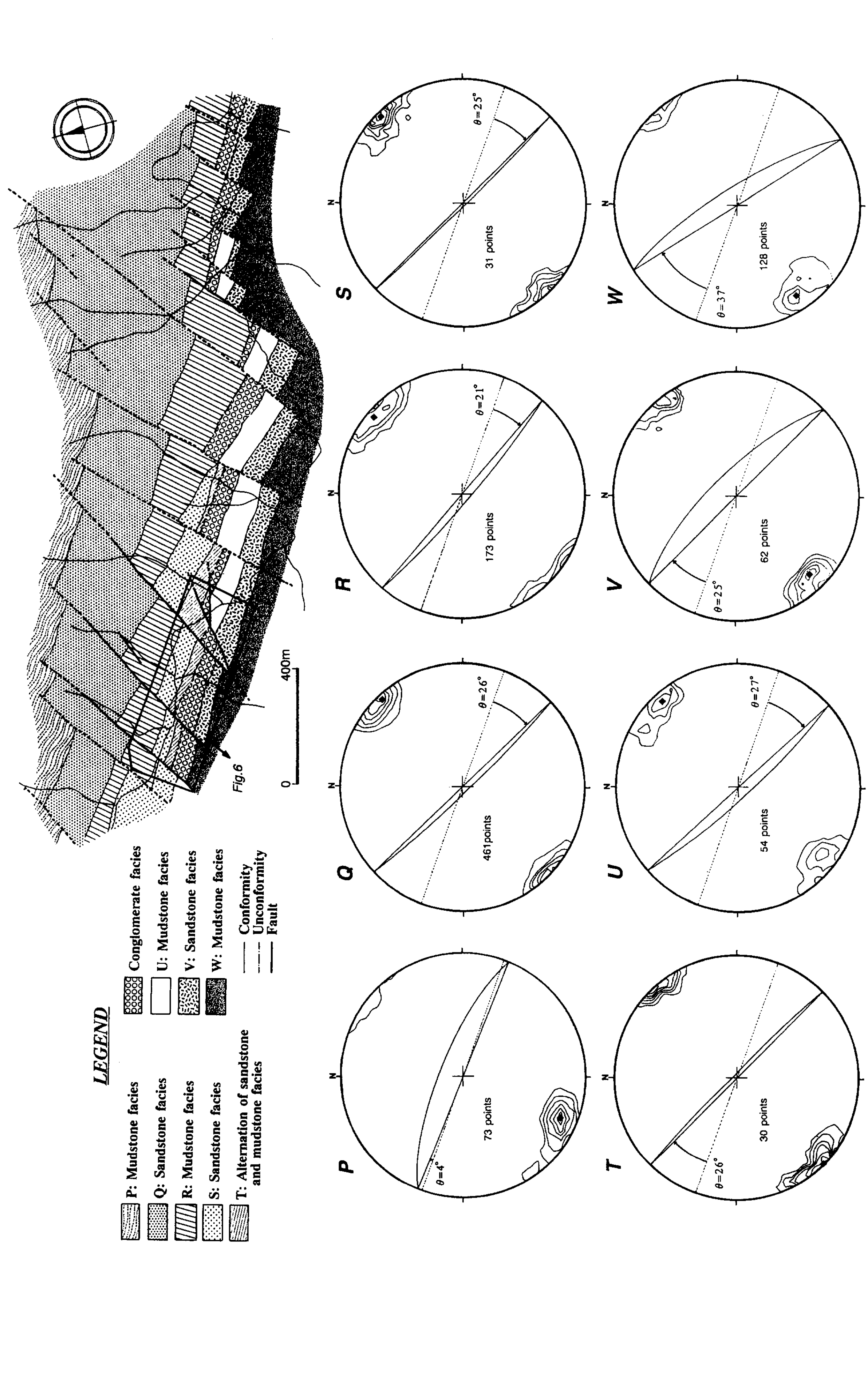

Fig. 5. Detailed geological map of the area marked in Fig. 2, with orientation of the strata in each lithological unit. See also caption of Fig. 4.

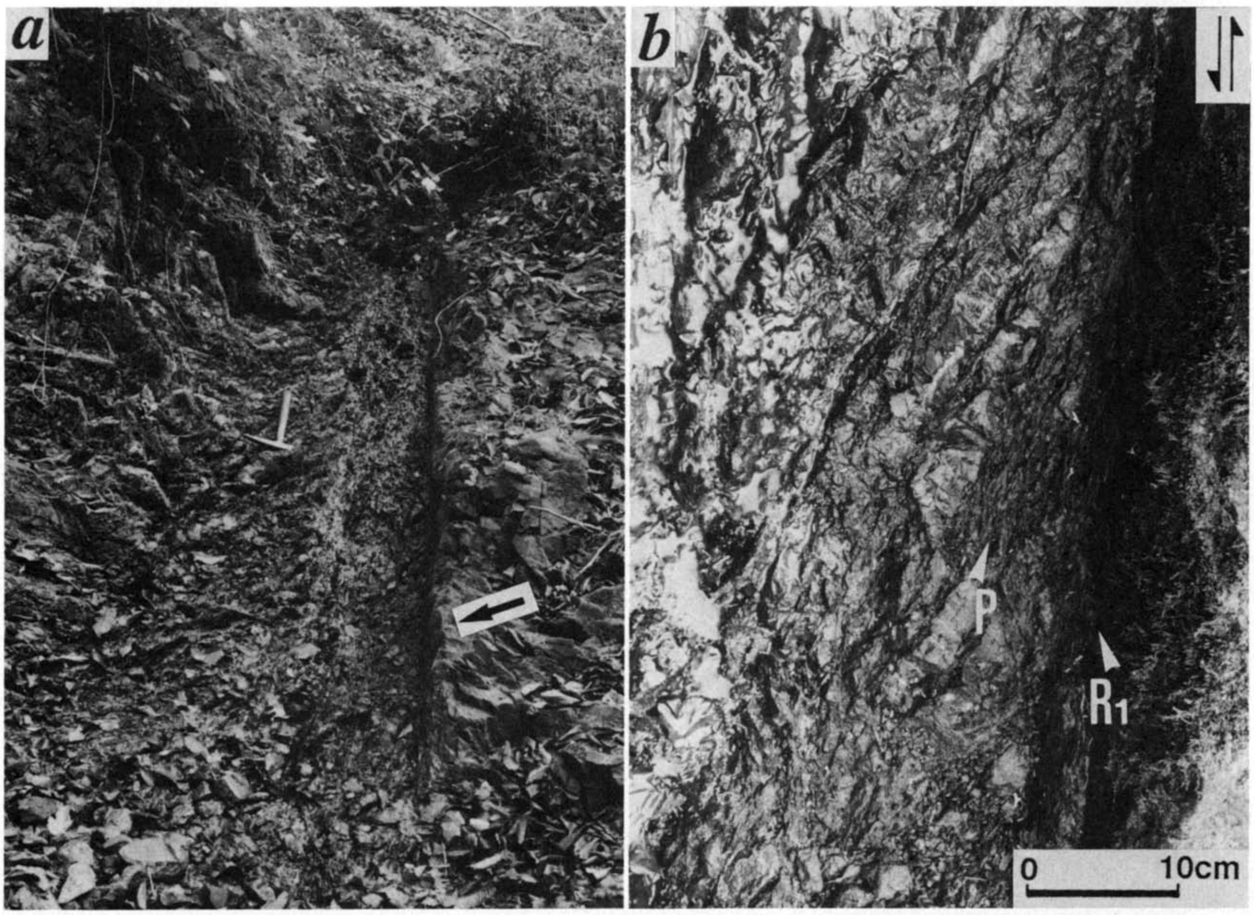

Fig. 7. An example of a block fault. (a) F_1 fault shown in Fig. 6. (b) Enlargement of the part shown by an arrow in (a), showing asymmetric fabrics developed in the cataclasite. The relation of R_1 shear planes to P foliation indicates left-lateral movement of the F_1 fault.

Distribution and length of en échelon faults

The en échelon faults apparently cause the clockwise deviation of the strike of the layering. If this is true, they should not extend much outside the axial part because left-stepping and clockwise deviation of the strike decrease there. This argument is tested by examining distribution and length of the faults.

The orientations of the faults developed in the graben, except the minor ones (e in Table 1), are shown in Fig. 8. The axial part is dominated by the N70°E en échelon fault system (Fig. 8a), whereas the whole area is affected by the N80°W fault system (Fig. 8b).

Because the full length of faults cannot be traced due to poor outcrop conditions, the correlation between the length of a fault and the width of shear zones and that between the length of a fault and the amount of offset as proposed by Freund (1970) and Ogata & Honsho (1981) are applied (Table 2a). The width of shear zones ranges from 30 to 100 cm. The amount of offset is read from the geological map shown in Fig. 5. Although the calculated lengths of N70°E en échelon faults are variable (Table 2a), they are short enough to be confined to the axial part. They are also consistent with the length of faults as given by the characteristics of block rotation (Table 2b).

Here, we define these faults as block faults responsible for block rotation. The geological map (Fig. 2c) and the detailed map in Fig. 6 indicate that the interval of block faults is about 500 m or less.

DISCUSSION

Characteristics of the block rotation and origin of block faults

One characteristic of the block rotated zone in the graben is revealed by comparing its two-dimensional geometry with that of other block rotated zones in the world (Fig. 9). *L/W* is the ratio of the length parallel to the reference boundary of the deformed zone and that at right angles to it (Fig. 1). Except for the Sanchu graben, every *L/W* is less than 5, although respective deformed zones were formed by different mechanisms. The *L/W* for the Sanchu graben (e in Fig. 9) is much larger than that for any other area. The fact that the block rotation occurred about vertical axes in a very long and narrow deformation zone indicates that deformation in the Sanchu graben results from strike-slip faulting.

It seems unlikely that block faults are the reactivated pre-existing weak zones. Since block faults have been rotated clockwise by about 30° to trend N70°E, pre-existing weak zones before rotation would have been

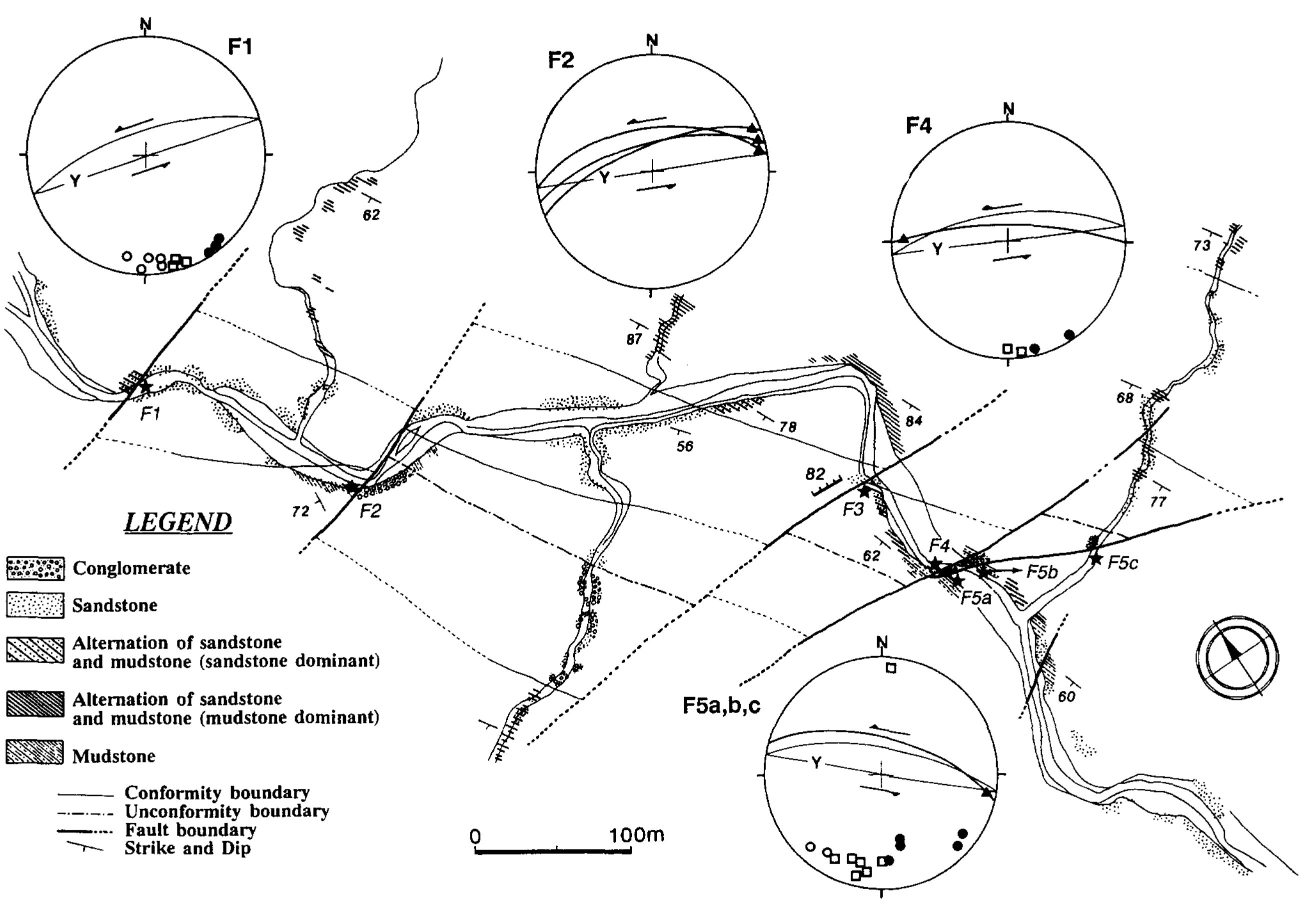

Fig. 6. Lithological map of the area marked in Fig. 5. Orientation of four faults (great circles marked 'Y' in F_1, F_2, F_4 and $F_{5a,b,c}$) and their asymmetric fabrics are plotted in lower-hemisphere, equal-area projections. Open circles: R_1 shear surface. Open quadrangles: Y shear surface. Solid circles: P foliation. Great circles with solid triangles: shear surfaces on which slickenlines are developed.

trending N40°E. However, no such set of faults is observed on both sides of the axial part where no rotation has occurred. This fact suggests that the block faults were generated at the same time as block rotation occurred.

Mechanism of the block rotational deformation

Two restrictions must be taken into account when we consider a mechanism of block rotation in the Sanchu graben. One is that deformation is related to strike-slip faulting and the other is that the block faults were generated at the same time as block rotation. We examine several alternative mechanisms including those proposed by Mackenzie & Jackson (1983, 1986) and Nelson & Jones (1987) to see if they apply to the Sanchu graben. Figure 10(a) shows the mode of deformation inferred for the Cretaceous system.

The first mechanism is that R_1 shears related to preceding sinistral shear along the boundary faults that have grown to block faults and have been rotated clockwise in the course of prolonged faulting (Fig. 10b). In such a case, large sinistral faults must bound the graben. Moreover, the strain trajectory should depict a Z shape because it should bend into parallelism with the sinistral faults. In the graben, there is little evidence for large and continuous sinistral faults parallel to the long axis of the graben. Moreover, strain trajectories which are normal to the strike of the strata do not bend into parallelism with the boundary even though they depict a Z shape. Thus, this mechanism can not explain the structural style of the Cretaceous system in the graben.

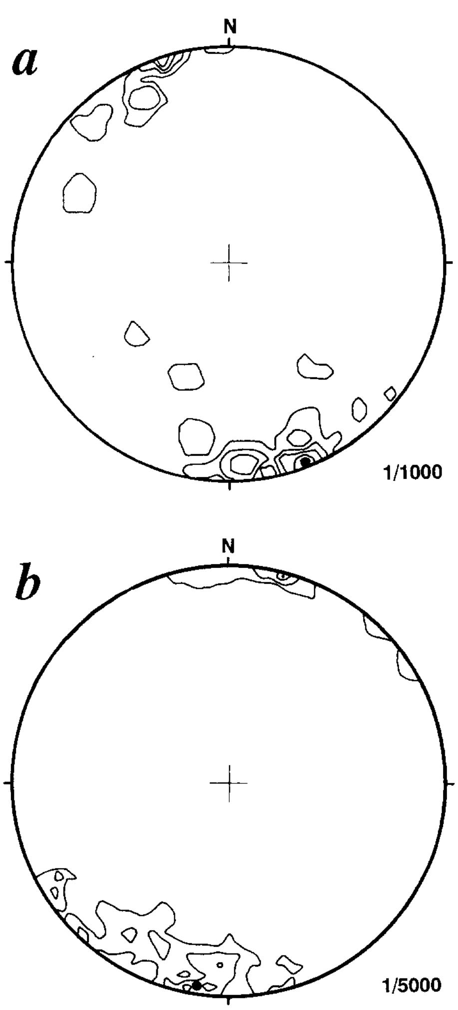

Fig. 8. (a) The orientations of 45 faults in the area shown in Fig. 5, and (b) those of 99 faults in the whole area shown in Fig. 2(c). Lower-hemisphere, equal-area projection. Contours: 3, 5, 7, 9 and 11%.

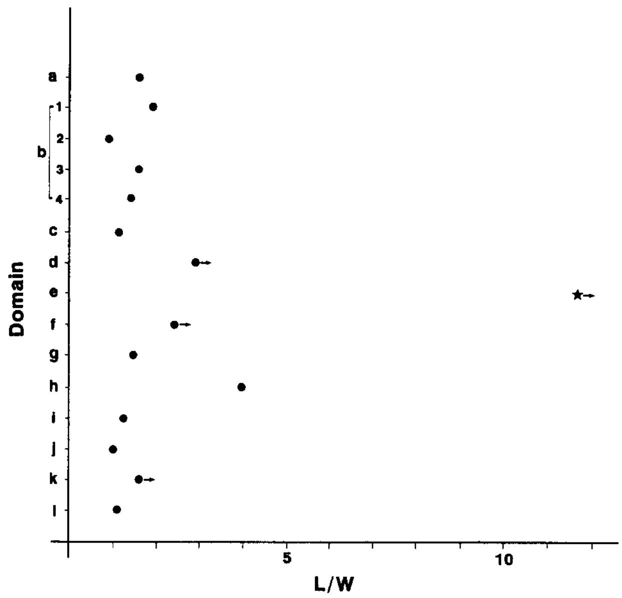

Fig. 9. *L/W* ratios of block rotational domains of the world. (a) Central Greece (Mackenzie & Jackson 1983, 1986). (b) 1–4, four domains near the Dead Sea Transform (Garfunkel & Ron 1985). (c) Eastern Tibet (England & Molnar 1990). (d) Inner belt of southwest Japan (Kanaori 1990). (e) The Sanchu graben (this study). (f) Region between the Hope fault and the Alpine fault (Freund 1971). (g) Southern California (Garfunkel 1974). (h) Lake Mead Fault system, southern Nevada (Ron *et al.* 1986). (i) Las Vegas Valley shear zone, southern Nevada (Nelson & Jones 1987). (j) Eastern Idaho (Crone & Machette 1984). (k) High Boundary fault, U.K. (Garfunkel & Ron 1985). (l) Builth Inlier, U.K. (Woodcock 1987).

Another possible mechanism is similar to the first one but differs in that the shear sense of the master longitudinal faults is dextral (Fig. 10c). Mackenzie & Jackson (1983, 1986) denoted this mechanism as the floating block model. They documented that the resulting blocks are small compared with the interval of the boundary faults and are floating between them. This mechanism is also invoked by Nelson & Jones (1987) to explain discordant paleomagnetic declinations in the Las Vegas shear zone, southern Nevada. However, this mechanism cannot explain the mode of deformation in the graben in two aspects. First, the strain trajectory in the Cretaceous system does not coincide with that of this model. Second, large dextral faults trending parallel to the graben do not exist.

A third possible mechanism is major sinistral faulting beneath the axial part of the Cretaceous cover, which failed to reach the surface and did not extend upward beyond the base of the cover (Fig. 10d). In such a mechanism, the unconformity plane between the Cretaceous cover and the underlying basement may have played a role as a detachment surface. Although the fault formed in the basement could not grow upward beyond the detachment, it may be of sufficient importance to bring about deformation in the cover. This mechanism may explain the extremely long and narrow geometry of the deformed zone and lack of important superficial strike-slip faults. However, the strain trajectory expected by this mechanism does not appear in the graben. Furthermore, in this case, the block faults are regarded as Riedel shears formed by sinistral faulting beneath the cover. It is, however, difficult to regard them as Riedel shears for the following reason. The strike of the main shear zone inferred to exist beneath the Cretaceous cover should be parallel to the extension direction of block rotated zone, that is about N70°W, but the mean strike of block faults is N70°E. Since block faults were rotated clockwise by about 30°, they would have had a trend of 70° to the main shear zone when block rotation was initiated. This is inconsistent with the fact that, in most cases, the angle between the main shear zone and Riedel shears is less than 30°.

Our interpretation is that major dextral faulting has taken place beneath the axial part of the Cretaceous cover but failed to reach the surface (Figs. 10e and 11). This mechanism is similar to the third one except for shear sense of the underlying fault. It is in good agreement with all the structural data such as the strain trajectory, an exceptionally high *L*/*W* ratio of the deformed zone and lack of important superficial strike-slip faults. In this case, the block faults were generated as large-scale fracture cleavage planes associated with strike slip faulting beneath the cover. This type of deformation is commonly observed on a mesoscopic scale associated with folding (Wilson 1982) and faulting (Terres & Sylvester 1981). On the microscopic scale, such deformation is well described from fault rocks. The mineral grains which are deformed in such a manner are called "displaced broken grains" (Simpson & Schmid 1983).

As mentioned above, the initial relationship between the basement and the cover is an unconformity which can play the role of a detachment plane (Fig. 11). It seems clear that rotated blocks must be detached by a shallow, more or less horizontal shear surface at their base (Sylvester 1988). The presence of horizontal zones of mechanical detachment is reported from *P*-residual studies in southern California (Hardley & Kanamori 1977, Yeats 1981), where large-scale block rotation has been observed. Small-scale detachment associated with block rotation was also found in association with the 1979 Imperial earthquake (Terres & Sylvester 1981). Blocks of soil separated by sinistral slip faults were reported to have rotated clockwise by 20–40° on a detachment 15 cm below the surface: the dry soil–wet soil interface.

The mechanism of our model is in some aspects similar to the floating block model proposed by Mackenzie & Jackson (1983, 1986) and Nelson & Jones (1987). However, we stress the concept of a shallow detachment plane and strike-slip faulting beneath it that cause block rotational deformation. Other examples of block rotation apparently unrelated to the superficially important strike-slip faults may be explained by our subsurface-seated fault model.

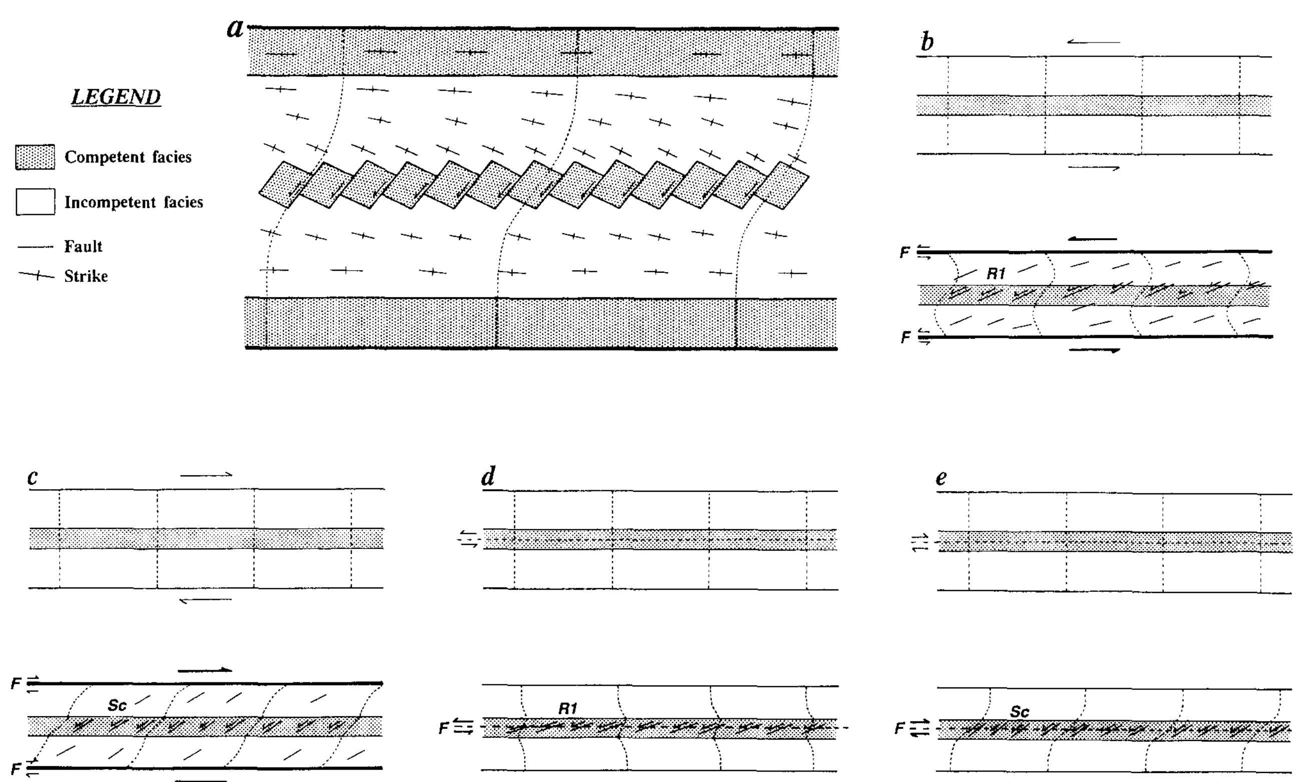

Fig. 10. Idealized style of block rotation in the Sanchu graben (a) and possible mechanisms to explain it (b–e), (b) by large and continuous sinistral strike-slip faults, (c) by large and continuous dextral strike-slip faults, (d) by a shallow interrupted sinistral fault and (e) by a shallow interrupted dextral fault. R1: R_1 shears, Sc: large-scale shear cleavages.

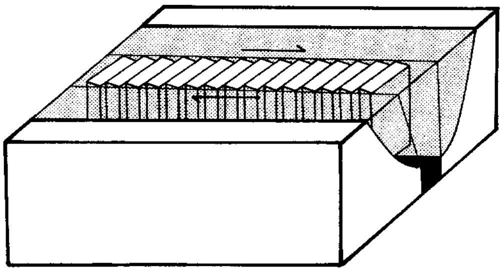

Fig. 11. Schematic diagram of block rotation in the Sanchu graben. Bottom of the concave-down surface (unconformity plane) plays a role as a detachment surface. Shear zone (dextral) beneath the cover is indicated in black.

CONCLUSIONS

The Cretaceous fore-arc sediments are tectonically trapped in a WNW–ESE-trending zone, the Sanchu graben, between the basement rocks in the Kanto Mountains, central Japan. The essentially vertical strata and lithological boundaries show a left-stepping pattern on the map especially in the axial part of the graben. Competent strata distributed in the axial part of the graben are rotated clockwise by 30° and the rotation angle gradually decreases from the axial part towards both the northern and southern margins of the graben. This deformation is attributed to an en échelon arranged sinistral fault system of N70°E trend, so short as to be confined in the axial part. All lines of evidence indicate that the mode of deformation is block rotation about vertical axes. The N70°E sinistral faults responsible for block rotation are referred to as the block faults. The *L*/*W* ratio of the Sanchu graben area is much larger than those of the other areas characterized by block rotational structures. This suggests that block rotation in the graben is related to strike slip faulting below the surface. After examination of several models, we propose a subsurface-seated fault model in which a major dextral fault occurred beneath the axial part of the Cretaceous cover and controlled its deformation. The unconformity plane between the Cretaceous cover and the basement may have played a role of detachment beyond which the fault could not grow upwards.

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