Extensional deformation in the northern Ryukyu arc indicated by mesoscale fractures in the middle Miocene deposits of Tanegashima Island, Japan

Abstract

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The deformational structures (outcrop-scale normal faults and extensional joints) observed in the upper Osaki Formation of the middle Miocene (16-10 Ma) Kakinaga Group exposed on Tanegashima Island, northern Ryukyu arc, result from the superposition of two stages of extension: (1) a NE-SW (N 43° E on average) extension, well documented by fault-slip data from eight localities and by extensional joints or non-striated normal faults from eight localities; (2) a NW-SE (N 134° E on average) extension, inferred from fault-slip data at one locality and by joints or non-striated normal faults from five localities. These two orthogonal extensions probably correspond to a unique stress field with, in most localities, $\sigma_v = \sigma_1$ and permutating σ_2 and σ_3 axes. Like elsewhere in the Ryukyu arc (Miyako Island region), the permutation between the intermediate principal axis and the least principal axis can be accounted for by arc-parallel stretching in response to the increasing curvature of the oceanward-migrating arc.

The tensional stress field has been active since the time of deposition of the Osaki Formation (ca. 11-10 Ma). At present, it is expressed by NW-SE normal faulting (apparent N 55° E extension) of Quaternary coastal terraces.

Key words : Ryukyu arc, Tanegashima, Neogene, stress field, extension, normal fault.

Introduction

In an effort to reconstruct the tectonic stress history of southwest Japan during the Neogene, we have analysed the deformational structures recorded by Upper Miocene to Pliocene forearc deposits (Miyazaki and Uchiuigawa Groups; Tokushige and Fabbri, 1996), and by middle Miocene intrusive rocks (Osumi granodiorite; Fabbri et al., 1997). As a result, we showed that the mesoscale faults affecting the above-mentioned rocks pertain to intermediate-type to tensional-type stress fields: in both cases, the σ_3 axis is horizontal and trends NW-SE, the vertical stress being either σ_1 (tensional-type) or σ_2 (intermediate-type).

As a logical continuation of these investigations, we have examined the deformation recorded in middle Miocene strata of the Kakinaga Group exposed on Tanegashima, just south of Kyushu (Fig. 1). In 14 localities, striated normal fault planes and non-striated fault or joint planes, which are considered to

be extensional fractures (σ_3 perpendicular to the plane of fracture), identify two orthogonal directions of extension: NE-SW and NW-SE. These two extensions are interpreted as being the near-surface expression of a tensional stress field characterized by $\sigma_v = \sigma_1$ and by permutating σ_2 and σ_3 axes. This instability is discussed in the light of the arc-parallel stretching of the Ryukyu arc synchronous with the formation of the Okinawa Trough backarc basin.

Geological setting of the study area

Tanegashima Island lies about 140 km from the northern Ryukyu trench along which runs the Eurasia-Philippine Sea plate boundary (Fig. 1).

Stratigraphy and structure

The stratigraphy of the island is given on Fig. 2. The basement of the island, the Kumage Group, consists of Eocene to Oligocene strata belonging to the Paleogene sub-belt of the Shimanto zone (Hayasaka, 1988). Due to intense folding and faulting, the structure of the Kumage Group is very complex (Hayasaka,

Fig. 1. Geodynamical setting of Tanegashima Island with location of the study area (insert). PKR stands for Palau-Kyushu Ridge. The arrow near the plate boundary indicates the direction of relative displacement between the Philippine Sea plate and the Eurasia plate (based on Seno et al., 1993).

1988). Faulting is predominantly reverse and pre-dates the deposition of the 'post-tectonic' Kukinaga Group. It will not be examined here.

The Kumage Group is covered in the southeastern part of the island by the middle Miocene Kukinaga Group. This group is divided into three formations (Hayasaka, 1988). The lower Tashiro Formation consists predominantly of conglomerate with minor intercalations of sandstone, mudstone and rare coal beds. The intermediate Kawachi Formation consists mainly of mudstone with some sandstone and conglomerate layers, and minor lignite. It contains a shallow marine fauna. The upper Osaki Formation is composed of medium to coarse-grained sandstone with subordinate mudstone and conglomerate beds. Based on macrofossil and microfossil evidence, a 16 to 10 Ma minimum age for the Kukinaga Group has been proposed (Hatta, 1988; Kodama et al., 1991; Inoue, 1992; Kojima and Otsuka, 1995).

Compared with the Kumage Group, the Kukinaga Group is much less deformed. It is affected by a general eastward or southeastward stratal tilting, most of which was completed before the formation of Quaternary coastal terraces that are themselves only

Epoch	Age(Ma)	Rock Unit
QUATERNARY	1.6	volcanic ash + alluvium Masuda Fm.
MIOCENE	5	KUKINAGA Gp.
	10	
	16	
OLIGOCENE	24	KUMAGE Gp.
	37	
	40	

Fig. 2. Stratigraphy of Tanegashima Island (compiled after Hayasaka (1988), Hatta (1988) and Kodama et al. (1991)). The wavy line indicates unconformities. Time scale after Kano et al. (1991).

weakly tilted (Nakata, 1968). The stratal dip is moderate (between 10 and 30°), but can locally exceed 45°. A few regional faults affecting the Kukinaga Group have been reported (Editorial Committee of the Geological Map of Kagoshima Prefecture, 1990). In the study area, the occurrence of shear zones up to 2m wide confirms the existence of important faults, but these have not been mapped during the course of this study.

The Kukinaga Group is in turn covered by the Pliocene Masuda Formation (3–2 Ma; Kano et al., 1991), and by Quaternary volcanic ash falls and coastal and alluvial deposits.

Quaternary crustal movements

a) Recent faulting

Four regional NW-trending faults displacing Quaternary terraces were mapped on the island (Nakata, 1968; Research Group for Active Faults in Japan, 1991). The offset of the terraces demonstrates a normal displacement. Faulting also induced a gentle tilting of a few degrees ($<5^\circ$) of the terraces. Three of the regional Quaternary faults are shown on Figs. 3 and 4. They delimit a median depression inside which the Kumage and Kukinaga Groups subsided and are almost entirely covered by Quaternary deposits.

b) Block rotations about vertical axes

Paleomagnetic investigations carried out by Kodama et al. (1991) on the Kukinaga Group have revealed a $33^\circ \pm 11^\circ$ westward deflection of the magnetic declination. The authors interpret this deflection as the result of a counterclockwise rotation of the whole Tanegashima-southeast Kyushu region since 2 Ma, following crustal stretching in the northern Okinawa Trough (Kodama et al., 1995). This rotation is thought to be still occurring at present.

Mesoscale fractures in the Kukinaga Group

Due to the quality of exposures, all our tectonic observations come from the upper part of the Kukinaga Group (Osaki Formation). Fractures in-

Fig. 3. Fault-slip data collected in the study area and attitudes of principal stress axes deduced from direct inversion method (Angelier, 1984). Geology is simplified after Editorial Committee of the Geological Map of Kagoshima Prefecture (1990). Active faults are after Research Group for Active Faults in Japan (1991). Fault-slip data are projected on lower-hemisphere, equal-area nets. N gives the number of slip vectors (striations) measured at each site and used for computation. Arrows inside the nets indicate the sense of slip. Lack of arrow head means that the sense of slip could not be determined and was inferred from nearby obtained senses. Complete head means that the sense of slip was determined with full confidence. Partly complete head means probable sense. The projection of the principal stress axes have the following symbols: five-branch star (σ_1), four-branch star (σ_2), three-branch star (σ_3). The black divergent arrows outside the nets indicate the directions of extension.

clude joints, along which there is no visible displacement, and faults, where some displacement can be detected.

Geometry and nature of the fractures

A total of 121 faults and 55 joints were measured along or near the southeastern coast of the island

Fig. 4. Fracture data (fault planes without slip direction indicators and joint planes) collected in the study area. The lack of sufficient slip vectors (at least 4) prevents a stress computation. N gives the number of fracture planes measured at each site. The white divergent arrows outside the nets indicate the inferred directions of extension.

(Figs. 3 and 4). Figure 5 shows a stereoplot of the poles to all measured fractures. There is no particular clustering of the strike angles. Regarding the dip angles, the lack or scarcity of poles in the central part of the diagrams indicate that dip angles are larger than 65° for all joints, and larger than 60° for 75% of the faults.

Two-thirds of the fault planes, 82 in number, show

one or two families of striations. These structures provide information about the direction of slip. The rakes of the striations are usually large: 81% fall between 70° and 90° . Faults in the Osaki Formation are predominantly of dip-slip type.

The sense of slip along fault planes in the Kakinaga Group can be established utilising either displaced markers, such as beds that were continuous before

Fig. 5. Attitude of mesoscale fractures in the Kukinaga Group (lower-hemisphere, equal-area projection). (a) poles to joint planes (55 points); (b) poles to fault planes (121 planes).

faulting (Fig. 6 a, c and g), or R-type antithetic secondary fractures (Petit, 1987), branching on the fault plane (Fig. 6 e) or drawing networks within shear zones (Fig. 6 b, c). In the case of fault planes bearing striations with large rakes ($>70^\circ$), the sense of slip is always normal. Oblique-slip faults ($20^\circ < \text{rake} < 70^\circ$; 16 planes) and strike-slip faults ($\text{rake} < 20^\circ$; 3 planes) show either dextral or sinistral senses. Whichever the sense, the dip-slip component of oblique-slip faults is always a normal one.

Tectonic joints in the Kukinaga Group can be regarded as extensional fractures formed perpendicular to the local least principal stress axis σ_3 (Hancock, 1985). This interpretation is based on the following observations: (1) the joints are commonly found in the vicinity of normal faults and, in this case, the two types of fractures are often parallel (e.g., sites TA 4, TA 6, TA 7, Fig. 4); (2) for a given site, joints preferentially form parallel rather than conjugate systems, this being an indicator of their extensional nature (Hancock, 1985).

Pre-lithification versus post-lithification displacements

It is notable of the faults in the Kukinaga Group that indicators of pre-lithification displacements are preserved in many places. These indicators are depicted on Fig. 6. The most frequent is the injection of conglomerate or coarse-grained sandstone along fault planes (Fig. 6 d). The injected pebbles are not fractured, and tend to align parallel to the fault plane. Injection takes place equally upwards or downwards, and also probably laterally. Another indicator is the absence of any intervening fault gouge or breccia along some fault planes (Fig. 6 c, e and f). Such faults have tightly closed lips and look like joints. Only the presence of a color change or displaced markers attests that shear and displacement actually occurred.

Post-lithification displacements are shown by: (1) fault breccia or gouge along the planes (Fig. 6 a, g); (2) sheared zones whose thickness can exceed one meter (Fig. 6 b); (3) well-developed striations on the slip planes.

Relative dating of tilting and faulting of strata

In the sites of fracture data acquisition, the dip angle of the bedding surfaces, when it is measurable, falls between 10° and 40° . Such dip angles are not negligible and have to be taken into account in tectonic interpretation. More precisely, if stratal tilting postdates faulting, this should be corrected in order to obtain less distorted stress axis orientations (Fig. 7 a). In the case of gentle to moderate (10 to 30°) dip angles, tilting correction did not reduce the complexity of the stress tensor. When correction is applied, the vertical axis, σ_1 or σ_2 in the present case, is shifted significantly away from the vertical. This is not satisfactory since, at the Earth's surface, one of the three principal axes is expected to be vertical. This suggests that stratal tilting was anterior or concurrent with normal faulting. At sites TA 9 and TA 10, a correction of the 40° dip angle creates the illusion of reverse faults and a compressive-type stress tensor (Fig. 7 b and 8). A compressive stress tensor is not compatible with field observations: no clear shortening structure could be found. We therefore conclude that most, if not all, of the tilting in the Osaki Formation occurred before or during the formation of the mesoscale normal faults.

Determination of the orientations of the principal stress axes

Method

In the localities where at least four fault-slip data (attitude of fault plane + attitude of striae + sense of slip) are known, it is possible to determine, with the help of computer software, the reduced stress tensor corresponding to the fault-slip data set (Angelier, 1984, 1990). The reduced stress tensor consists of the attitude (trend and plunge) of the three principal stress axes σ_1 , σ_2 , σ_3 and the value of the ratio $\Phi = (\sigma_2 - \sigma_3) / (\sigma_1 - \sigma_3)$. Table 1 gives the trends and plunges of the stress axes determined for each site, along with the

Fig. 6. Typical deformation structures associated with normal faults in the Kuki-naga Group. (a) Post-lithification normal faults showing conjugate geometry. (b) Post-lithification normal fault with a well-developed shear zone in roughly laminated sandstones. Note the antithetic fractures similar to R-type fractures within the shear zone. Electric pole is about 4 m high. (c) Pre-lithification normal fault with a 50 cm-thick shear zone (delimited by arrows) inside which a network of secondary fractures displays an analogy with an R-R' system (Petit, 1987). (d) Injection of conglomeratic material along a steeply dipping normal fault. In the present case, the injected pebbles most probably originate from the superior conglomeratic bed. (e) Conjugate network of normal faults in massive sandstone (large arrows). Note the R-type secondary fractures (small arrows) secant on the fault planes. (f) Horse-tail damping of a normal fault in laminated sandstone. (g) Normal faults affecting strongly tilted (about 40°) strata (hammer for scale).

Table 1. Trends and plunges of principal stress axes computed from fault-slip data.

			σ_1	σ_2	σ_3		
Site	N	bedding attitude	T (°)-P (°)	T (°)-P (°)	T (°)-P (°)	Φ	direction of extension
TA-1	7 (7)	non measured	154 - 23	297 - 62	57 - 15	0.681	057°E
TA-2	4 (8)	N164°E-26°E	122 - 73	273 - 15	5 - 8	0.056	005°E
TA-3	5 (6)	non measured	349 - 47	126 - 34	232 - 23	0.481	051°E
TA-5	4 (6)	N003°E-18°E	346 - 63	130 - 22	226 - 14	0.172	045°E
TA-9	17 (20)	N176°E-40°E	179 - 83	342 - 7	73 - 2	0.488	073°E
TA-10	8 (8)	N020°E-40°E	156 - 75	46 - 5	315 - 14	0.376	133°E
TA-12	14 (14)	N149°E-09°E	126 - 69	332 - 19	239 - 9	0.183	059°E
TA-13	14 (17)	N062°E-22°S	78 - 72	286 - 16	193 - 8	0.274	016°E
TA-14	4 (4)	non measured	106 - 77	319 - 12	228 - 8	0.192	047°E

N is the number of fault-slip data (striation and sense) used for computation at each site. The number between brackets is the number of all fault planes measured at each site.

T and P are the trends and plunges of the principal stress axes given in degrees.

Φ is the ratio $(\sigma_2 - \sigma_3)/(\sigma_1 - \sigma_3)$.

Fig. 7. Schematic illustration of two cases where faulting and tilting are clearly diachronous. (a) Tilting postdates faulting: cancelling the dip angle restores the original pre-tilting conjugate geometry. (b) Tilting predates faulting: cancelling the dip angle implies a loss of coherence in the fault geometry.

number of fault-slip data which were used for computation. The principal stress axes are projected on the nets of Fig. 3. Note that the orientations of the stress axes at sites TA 2, TA 5 and TA 14 are poorly defined, since they are computed with only four fault-slip data for each of them. Given the lack of indicators of slip directions, pre-lithification faults were not used for stress tensor computation.

Results

The validity of stress inversion methods strongly

depends on the homogeneity of the fault-slip data. If all faults were formed or activated during the same event, they can be explained by a unique stress tensor. Conversely, if a data set contains fault-slip data pertaining to two or more events, inversion will either be impossible or give erroneous results. The data retrieved at sites TA 1, TA 9, TA 10 and TA 14 are homogeneous (Fig. 3): for each of these four sites, the strikes of the fault planes are roughly parallel and the slip vectors (striations) are well clustered. Inversion provides two stress tensors: a tensional ($\sigma_v = \sigma_1$) to intermediate-type ($\sigma_v = \sigma_2$) tensor I characterized by a NE-SW σ_3 axis (sites TA 1, TA 9, TA 14), and a tensional tensor II characterized by a NW-SE σ_3 axis (site TA 10). The Φ values range from 0.192 to 0.688. Data from sites TA 2 and TA 3 probably correspond to two stress tensors: N-S to NW-SE faults may pertain to tensor I (NE-SW σ_3 axis) whereas the N 60°E to N 80°E faults may pertain to tensor II (NW-SE σ_3 axis). A low Φ value (0.056) at site TA 2 suggests that σ_2 and σ_3 have almost the same magnitudes. The direction of extension is thus poorly defined.

Data from sites 12 and 13 may also correspond to two stress tensors: most data seem to be relevant to tensor I. However, striations with trends falling between N 120°E and N 160°E suggest a NW-SE extension compatible with tensor II. Site TA 5 is more difficult to analyse, because of the paucity of data: a NW-SE extension can be expected from the geometry of faults, but stress inversion gives a NE-SW extension. Only additional data from this site could bring sufficient precision to define the orientations of the stress axes.

Fig. 8. Loss of coherence following a stratal tilting correction in the case where normal faulting affected already tilted strata. (a) Observed data (site TA 10). The projection of σ_1 is close to the vertical. The dashed great circle represents the projection of the bedding plane. (b) Cancelling the dip angle (40°) gives a shortening deformation (compressive stress tensor) which is not supported by any field data.

Comparison with non-striated faults or joints

Figure 4 shows fracture data which do not permit computation of reduced stress tensors, either because the measurements are taken from joints (sites with suffix JT), or because insufficient striations can be observed and measured. However, some information can be drawn from these data, especially with joint sets, assuming that they are extensional fractures. If so, the σ_3 axis can be approximated as perpendicular to the joint planes. This assumption allows us to propose two directions of extension for joints from sites TA 5 (JT), TA 6 (JT) and TA 7 (JT): NE-SW and NW-SE. At site TA 4 (JT), the joint strikes are scattered. By taking a mean N 126° E strike, an average NE-SW direction of extension can be proposed. Poorly or non-striated faults which, in all cases, show a normal component of displacement, can be treated in the same way as extensional joints. If so, one or two directions of extension, similar to those inferred from the joints, can be deduced from sites TA 4, TA 6, TA 7, TA 8 and TA 11.

As a whole, two directions of extension can account for the formation of poorly or non-striated normal faults and extensional joints in the study area. These two directions are the same as obtained from the fault-slip data, thus justifying the various interpretations suggested (σ_3 axis perpendicular to joint plane or to non-striated normal fault plane). Logically, the NE-SW and NW-SE extensions correspond to the stress tensors I and II, respectively.

Conclusion

Two directions of extension corresponding to two stress tensors can account for the deformational structures observable in the Osaki Formation of the Kukinaga Group. The first direction, NE-SW, is suggested by 8 fault-slip data sets (average direction of extension: N 44° E) and 8 non-striated fracture sets

(average direction of extension: N 42° E). The second direction, NW-SE, is suggested by one fault-slip data set (site TA 10, N 133° E extension), by a few fault-slip data sporadically present in other fault-slip data sets, and by 5 sets of non-striated faults or extensional joints (average direction of extension: N 134° E).

Discussion

One or two stress fields?

Two orthogonal directions of extension are apparently recorded in the Osaki Formation. These two directions can result from either two distinct stress fields active during two different periods, or from a unique stress field with permutating σ_2 and σ_3 axes. The generally low Φ values (8 out of 9 Φ values are < 0.5) obtained from inversion of fault-slip data suggest that the magnitudes of σ_2 and σ_3 are close and, therefore, can easily permute (the extreme case $\Phi = 0$ means that σ_2 and σ_3 have the same magnitudes). Permutations between two of the three principal stresses were described from several extended regions (Angelier and Bergerat, 1983; Charvet et al., 1992; Fabbri et al., 1996). A local example is provided by the tensional stress field having been active for the Late Neogene and Quaternary in the central and southern Ryukyu arc (Fabbri and Fournier, 1999; Fournier et al., 2000). Most onland fracture data and focal mechanisms of shallow (focal depths < 50 km) earthquakes in the Okinawa Trough indicate a NW-SE to N-S, that is arc-perpendicular, extension. The relevant stress field is characterized by $\sigma_1 = \sigma_2$ and by σ_3 trending N 135° E to N 180° E. This general scheme however suffers from exceptions in the two islands of Miyako and Okinawa. Active fault scarps on Miyako island (Research Group for Active Faults of Japan, 1991) testify to a NE-SW extension. This is further corroborated by the focal mechanisms of two earth-

quakes whose epicentres were located close to Miyako and whose T-axes trended NE-SW. At Okinawa, mesoscale fracture data commonly indicate two orthogonal directions of extension, one roughly perpendicular to the local trend of the arc, the other roughly parallel (Fournier et al., 2000). These discrepancies can be explained by local permutations between σ_2 and σ_3 , and most probably reflect an arc-parallel stretching following an increase of curvature of the Ryukyu arc. There is no need to propose two distinct stress fields. In a similar way, normal faulting of the Osaki Formation can be accounted for by a single stress tensor undergoing permutations of the two horizontal principal axes.

Age of faulting

The age of deformation in sedimentary strata is usually bracketed between a lower limit given by the age of the sediment itself and an upper limit provided by an undeformed covering layer or intruding rock. In the case of normal faulting of the Osaki Formation, the lower limit is 12–10 Ma, the approximate time of deposition of the strata. The Osaki Formation is unconformably covered by the Pliocene Masuda Formation and Quaternary terraces. The Masuda Formation was not examined during this study and no information concerning its possible deformation has so far been published. However, the Quaternary terraces are weakly tilted and locally faulted with normal displacement (Nakata, 1968 ; Research Group for Active Faults of Japan, 1991). The apparent direction of extension, taken as perpendicular to the fault strikes, is about N55°E, which is close to the N44°E direction obtained in the Osaki Formation. This apparent concordance suggests that the NE-SW extension is still underway at present. It may signify that normal faulting has been active continuously for the past 10 millions years.

Comparison with adjacent areas and tentative interpretation

North of Tanegashima, in the Osumi peninsula, Fabbri et al. (1997) reported normal faults from the Uchinoura district in the eastern part of the middle Miocene Osumi granodiorite pluton. Though no computer-aided determination of the reduced stress tensor was performed, the stress field is clearly of tensional type and the direction of extension runs approximately NW-SE. Further north, in the upper Miocene to Pliocene deposits of the Miyazaki district, southeastern Kyushu, Tokushige and Fabbri (1996) reconstructed a tensional stress field with a general extension axis running NW-SE, just as in the Uchinoura district. This NW-SE extensional deformation can be traced southwards to Tanegashima, but its effects there seem to be less pronounced than those of the NE-SW extension. The NW-SE extension recorded in Mio-Pliocene rocks probably constitutes the near-surface expression of the generalized crustal stretch-

ing that affects the Eurasia plate margin in the Okinawa Trough region between Taiwan and Kyushu (Aiba and Sekiya, 1979 ; Letouzey and Kimura, 1986 ; Sibuet et al., 1987). The NE-SW extension may be a consequence of an arc-parallel stretching affecting the Ryukyu arc in several places, such as Miyako Island (Fabbri and Fournier, 1999) or Okinawa (Fournier et al., 1999). As the Ryukyu arc migrates oceanwards, its initial length increases and arc-parallel stretching follows in response to this increase. It is not surprising that, at Tanegashima, the NE-SW extension is more expressed than that running NW-SE. Indeed, most of the NW-SE extension is probably accommodated in the (northern) Okinawa Trough where the crust is thinner and already largely faulted. The arc itself will mainly suffer from lateral stretching, hence a more visible NE-SW extensional deformation.

Conclusion

Normal faulting in the Osaki Formation of the Kukinaga Group started before complete lithification of the strata and to some extent may still be underway at present. Two directions of extension can be reconstructed from the analysis of post-lithification fractures in the Osaki Formation : a predominant NE-SW extension and a less common orthogonal NW-SE extension. The two extensions probably correspond to a unique stress tensor with permutating σ_2 and σ_3 axes. The NW-SE extension already recognized in Kyushu (Osumi and Miyazaki) is interpreted as the near-surface expression of crustal stretching affecting the Eurasia plate margin in the Okinawa Trough region. The NE-SW component of extension may be related to the stretching of the Ryukyu arc in response to the opening of the Okinawa Trough and accompanying oceanward migration of the arc. A good way to check the viability of this interpretation would be to examine the focal mechanisms of earthquakes nucleated within the arc crust of the Tanegashima region.

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*: in French with English abstract

**: in Japanese with English abstract

(要 旨)

Fabbri, O., 2000, Extensional deformation in the northern Ryukyu arc indicated by mesoscale fractures in the middle Miocene deposits of Tanegashima Island, Japan. *Jour. Geol. Soc. Japan*, 106, 234-243. (ファブリ, O., 2000, 種子島における中部中新統のメソスケール・フラクチャーによって示された北部琉球弧の島弧平行型伸張変形. 地質雑, **106**, 234-243.)

北部琉球弧にある種子島の中部中新統茎永層群(16-10 Ma)の上部で見られる変形構造(メソスケールの正断層と引張節理)には北東-南西方向の伸張を示すものが卓越している。8地点における断層のずれから復元した応力テンソルでは、 $\sigma_v = \sigma_1$ (7地点) または σ_2 (1地点) であり、 σ_3 軸は N5°E から N73°E (島弧に平行した伸張) であった。この北東-南東方向の伸張変形は東部九州や南部九州とは異なり、種子島に限定されたものである。島弧直交型の伸張の欠如は中間主応力軸 σ_2 と最小主応力軸 σ_3 が入れ替わったことによるであろう。琉球弧の他地域(宮古島)と同様に、応力配置のこの入れ替わりは海洋側に張り出した島弧の曲率増加に対応して局所的な島弧平行型ストレッチングが起こるとすれば容易に説明できる。