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Diachronous development of master joints of different orientations in different lithological units within the same forearc-basin deposits, Kyushu, Japan

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Abstract

The geometrical and chronological characteristics of joints and subordinate fractures in the Miocene (12–6 Ma) Uchiumigawa Group, Kyushu, Japan, strongly depend on the host lithology. In massive sandstone units (11 stations), joints are normal to bedding and form two suborthogonal sets, a master joint set parallel to the bedding strike and a cross joint set perpendicular to the bedding strike. In interbedded sandstone–mudstone units (11 stations), joints are found only in sandstone layers and have the same characteristics as the joints in the thick sandstone units, except that the chronology is opposite: in nine stations, master joints are perpendicular to the bedding strike and cross joints are parallel to the bedding strike. The observed joint pattern is tentatively explained by a diachronous formation of master joints which appeared first in massive sandstone units and later in the interbedded units, as a result of the superposition in the study area of two different deformation episodes independently documented by regional fault-slip data. Transition between the two jointing events took place around 6 Ma. © 2001 Elsevier Science Ltd. All rights reserved.

1. Introduction

Orthogonal joint systems are common in sedimentary rocks, where they develop at high angles from the bedding surface (Hancock, 1985, and references hereafter). In some instances, joint architecture and abutting relationships between the two orthogonal systems indicate an unambiguous chronology of joint propagation, one set being younger than the other (Pollard and Aydin, 1988; Engelder and Gross, 1993; Gross, 1993). In some other cases, abutting relationships between individual joints preclude establishing a simple and definite chronology between the two sets (Hancock, 1985; Hancock et al., 1987; Dunne and North, 1990; Dunne and Hancock, 1994; Caputo, 1995). In such systems, sometimes referred to as 'grid-lock' systems, the impossibility of establishing a definite chronology can be explained by an interpretation where the two sets formed during the same overall time period, but alternated episodes of propagation. This possibility is demonstrated in the cases where fibrous joint-filling minerals allow the reconstitution of the joint opening history (Dunne and North, 1990). The alternating joint propagation has been attributed to (1) local elastic rebound (Stauffer and Gendzwill, 1987); (2) local or regional stress swaps (Dunne and North, 1990; Martel, 1994; Caputo, 1995); and (3) local stress release (Rives and Petit, 1990).

In this paper, we examine orthogonal joint sets where the relative age of the two sets depends on the host lithology. We propose to explain this specific pattern by taking into account the different mechanical properties of the strata and independent data that suggest the succession of two different regional stress fields in the vicinity of the study area.

2. Geological setting

2.1. Lithostratigraphy

The study area is located in the southeastern part of the island of Kyushu about 160 km from the boundary between the Eurasia and Philippine Sea plates (Fig. 1). Upper Miocene forearc deposits of the Uchiumigawa Group are exposed in beach sections along the Pacific coast (Fig. 2).

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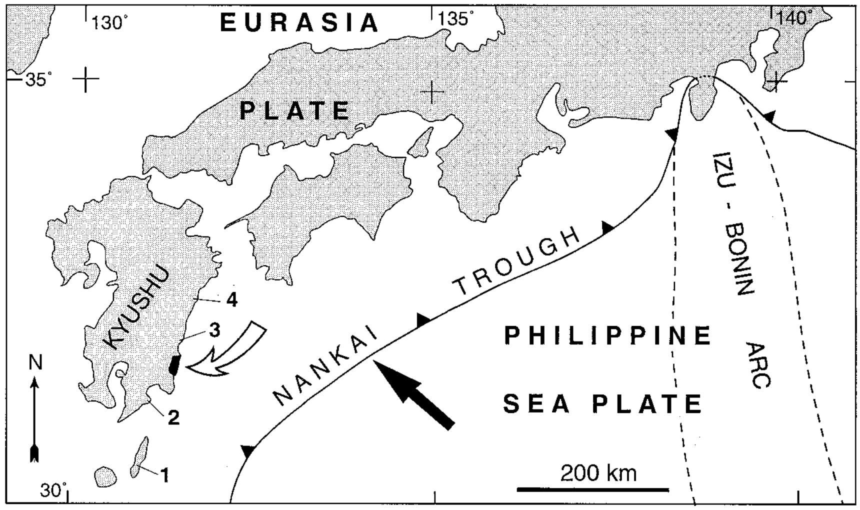

Fig. 1. Location of the study area (white arrow). Black arrow is the present-day relative direction of convergence between the Eurasia and Philippine Sea plates. Numbers indicate locations where fault-slip data allow paleostress reconstructions (see Section 4.3). 1: Tanegashima island; 2: Osumi area; 3: Miyazaki area; 4: Osuzuyama area.

Microfossils indicate that the Uchiumigawa Group was deposited between 11–12 and 6 Ma (Suzuki, 1987; Kano et al., 1991; Nakamura et al., 1999). The Uchiumigawa Group, 3000–3500 m thick, represents a forearc-basin clastic sequence unconformably covering a Paleogene accretionary prism.

In the studied sections, strata belong to distal turbidites and consist of a repetition of two lithological units: (1) 10- to 15-m-thick, massive, homogeneous, medium-grained sandstone layers in the central and southern parts of the study area; and (2) thin-bedded interbedded units of fine-grained sandstones and mudstones, with 60–800 m unit thicknesses. In the thin-bedded units, the ratio of mudstone to sandstone is about 1:1, and sandstone and mudstone have the same range of bed thicknesses, from 10 to 80 cm. Thin section examination shows that, unlike the sandstones of the massive units, the sandstones from the thin-bedded units contain a small amount of clay.

2.2. Structure

The orientation of the bedding surface in the massive sandstone units cannot be measured because stratification markers are rare, but it can be estimated from the underlying or overlying interbedded units. The bedding strike progressively changes from 020° to 150° northward in the study area, and dips are gentle to moderate (Table 1; Fig. 2).

This progressive change can locally be disturbed by 060° to 110° striking faults (mean strike 080°), with trace lengths of a few kilometers and steep (>60°) northward or southward dips. Minor faults associated with kilometric faults have a normal slip sense, which suggests that the latter faults are normal faults.

3. Characteristics and chronology of joint sets

3.1. Joints in massive sandstone units

Two joint sets trend about 150° and 070°, i.e. parallel and perpendicular to the bedding strike, respectively (Table 1; Figs. 2a and 3a–d). The two sets enclose acute angles averaging 82°. The 150°-striking joints form the master joint set: (1) they have linear fracture traces with trace lengths of several meters; (2) they have spacings ranging from 0.5 to 1.5 m; (3) they never cross and rarely (less than 5% of the cases) abut against other joints; (4) they can sometimes be filled by granular calcite; and (5) they can display plumose structures in rare instances. Inferring bedding orientations from adjacent interbedded units, the 150°-trending joints are subnormal to bedding.

Conversely, the 070°-trending fractures have a cross joint morphology on bedding because most abut against 150°-trending joints with scattered strikes and irregular spacing (Pollard and Aydin, 1988; Engelder and Gross, 1993; Gross, 1993). Abutting relationships clearly show that the 070° set is younger than the 150° one. Across bedding, the 070°-trending fractures consist of a set of joints normal to bedding and of two distinct subsets showing a ‘conjugate’ geometry (Figs. 2a and 3c). The acute angle enclosed by the two subsets is between a few degrees and 60°, the average value being 20°, and the acute bisector is normal to bedding. The lack of abutting relationships suggests that the two subsets are coeval. No evidence for slip was found on the fractures. The ‘conjugate’ geometry, the low value of the acute angle, the apparently synchronous formation and the lack of slip evidence show that the ‘conjugate’ subsets are hybrid fractures in the sense of Hancock (1985) or Hancock et al. (1987).

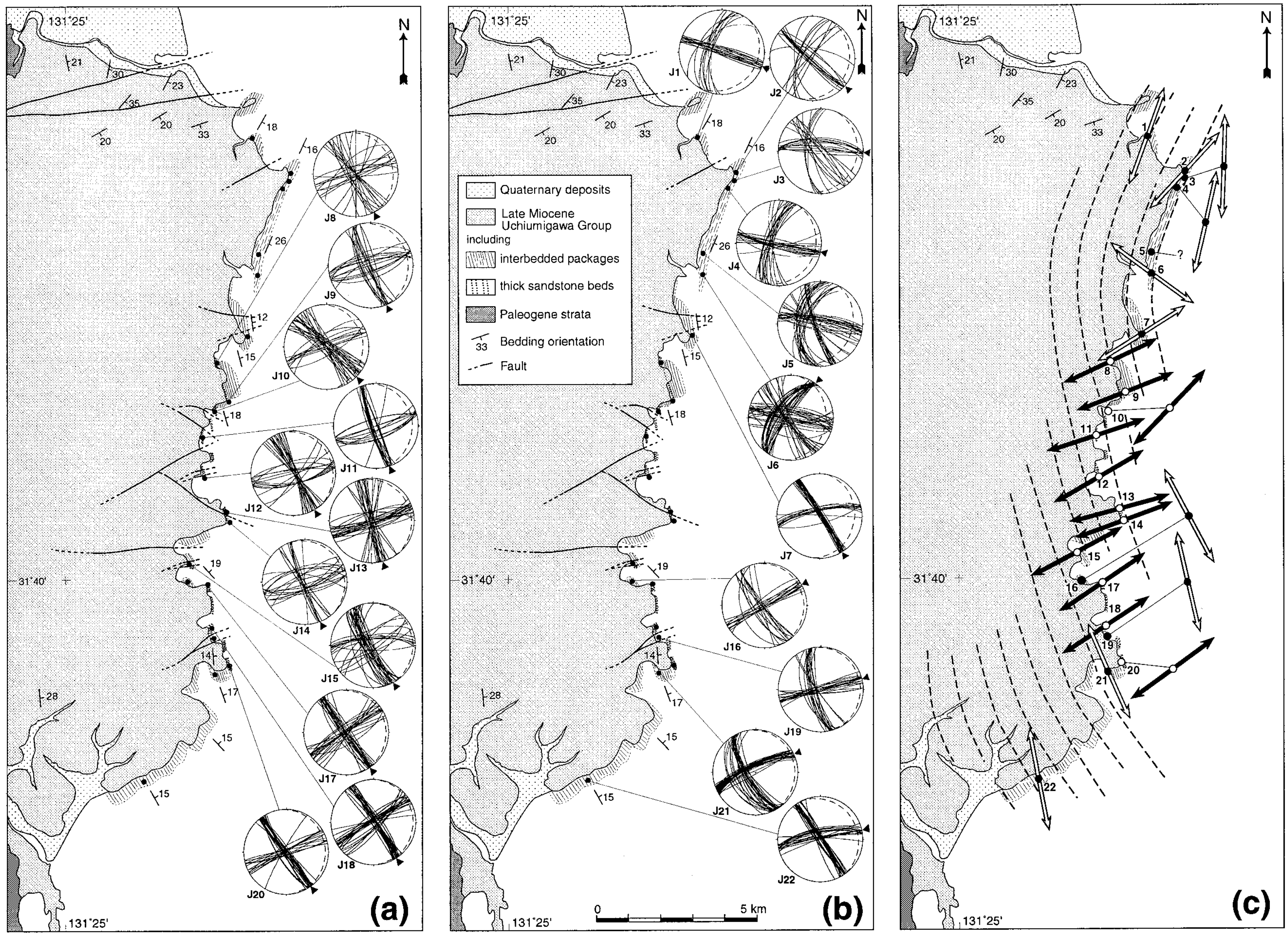

Fig. 2. (a) Orientation data for joints in massive sandstone units (lower hemisphere equal-area projections). Dashed traces are projections of inferred bedding. Black triangles indicate the older set in the sites where it can be determined. (b) Orientation data for joints in sandstone layers of the interbedded units (lower hemisphere equal-area projections). Dashed traces are projections of measured bedding. Black triangles indicate the older set in the sites where it can be determined. (c) Directions of extension (divergent arrows) deduced from master joint strikes. Black arrows for sites in massive sandstone units. White arrows for sites in interbedded units. Also shown is the trace of bedding.

Table 1
Orientation data of tectonic joint sets and bedding in the study area[a]

Locality number	Lithology	Bedding orientation	Number of measurements	Mean trend of older set	Mean trend of younger set	Acute angle between two sets (°)
J1	i	N40°E–18°E	24	N110°E	N20°E	90
J2	i	N24°E–16°E	20	N133°E	N30°E	77
J3	i	N24°E–16°E	27	N92°E	N150°E	58
J4	i	N24°E–16°E	39	N103°E	N20°E	83
J5	i	N25°E–26°E	61	?	?	?
J6	i	N10°E–17°E	72	N36°E	N102°E	66
J7	i	N170°E–20°E	38	N148°E	N78°E	70
J8	ss	N/A	27	N155°E	N70°E	85
J9	ss	N/A	28	N159°E	N73°E	86
J10	ss	N/A	37	N134°E	N71°E	63
J11	ss	N/A	31	N162°E	N72°E	90
J12	ss	N/A	35	N150°E	N80°E	70
J13	ss	N/A	47	N165°E?	N72°E?	87?
J14	ss	N/A	26	N160°E	N72°E	88
J15	ss	N/A	46	N152°E	N70°E	82
J16	i	N174°E–12°E	26	N62°E	N148°E	86
J17	ss	N/A	49	N146°E	N58°E	88
J18	ss	N/A	41	N147°E	N55°E	88
J19	i	N176°E–14°E	40	N77°E	N166°E	89
J20	ss	N/A	36	N144°E	N68°E	76
J21	i	N170°E–14°E	58	N66°E	N151°E	85
J22	i	N150°E–15°E	41	N79°E	N147°E	68
			Total: 849			mean: 80

[a] i, interbedded sandstone and mudstone units; ss, massive sandstone units; N/A: bedding measurements not available in massive sandstone units.

3.2. Joints in sandstones of interbedded units

Joints in the interbedded units are found almost exclusively in sandstone layers, where they are normal to bedding. Our data sets are composed only of joints from sandstone beds.

Nine stations out of 11 have two joint sets approximately parallel and perpendicular to the bedding direction, just like in the massive sandstone units (Table 1; Fig. 2b, all sites except J5 and J6). The mean acute angle shared by the two sets is 72°. With the exception of site J7, the set that is approximately perpendicular to the bedding direction has a master joint morphology (Figs. 2b and 3e, f, j, k). At site J7, the master joint geometry is shown by the set which is parallel to the bedding direction (Fig. 3i).

Two stations display more than two fracture sets. J5 contains three fracture sets of unknown relative age (Fig. 3g). J6 also has three fracture sets, but the set which is parallel to the bedding direction has a master joint geometry and is older than the two others (Fig. 3h).

3.3. Summary

The general picture of the fracture systems in the study area shows that the strikes of the near orthogonal joint sets follow the regional variations of the bedding direction (Fig. 2c). This geometry indicates that jointing was achieved before or during bending and tilting of the strata.

The fracture geometry with respect to bedding in the interbedded units is the opposite of that in the massive sandstone units. The master joints in the sandstone layers of the interbedded units are normal to the bedding strike direction, which is perpendicular to the master joints in the massive sandstone units. This key observation must be accounted for in any scenario of joint formation in the Uchiumigawa Group.

4. Discussion of a multistage jointing scenario

A scenario of jointing can be proposed based on: (1) assumptions about the evolution of the mechanical behavior of the strata with increasing extension; and (2) independent fault-slip data which indicate the succession between 16 and 2 Ma of two stress fields in the forearc region of southwest Japan. This scenario takes into account only the stations where the observed joint architecture fits the general pattern; the three stations J5, J6 and J7 are excluded from the discussion.

4.1. Diachronous propagation of the master joints

Synchronous nucleation and propagation of the master joints striking 150° in the massive sandstone units and 070° in the interbedded units would require σ_3 to be oriented, at the same time and throughout the whole study area, about 060° in the massive units and 160° in the interbedded units. This large difference between the two stress

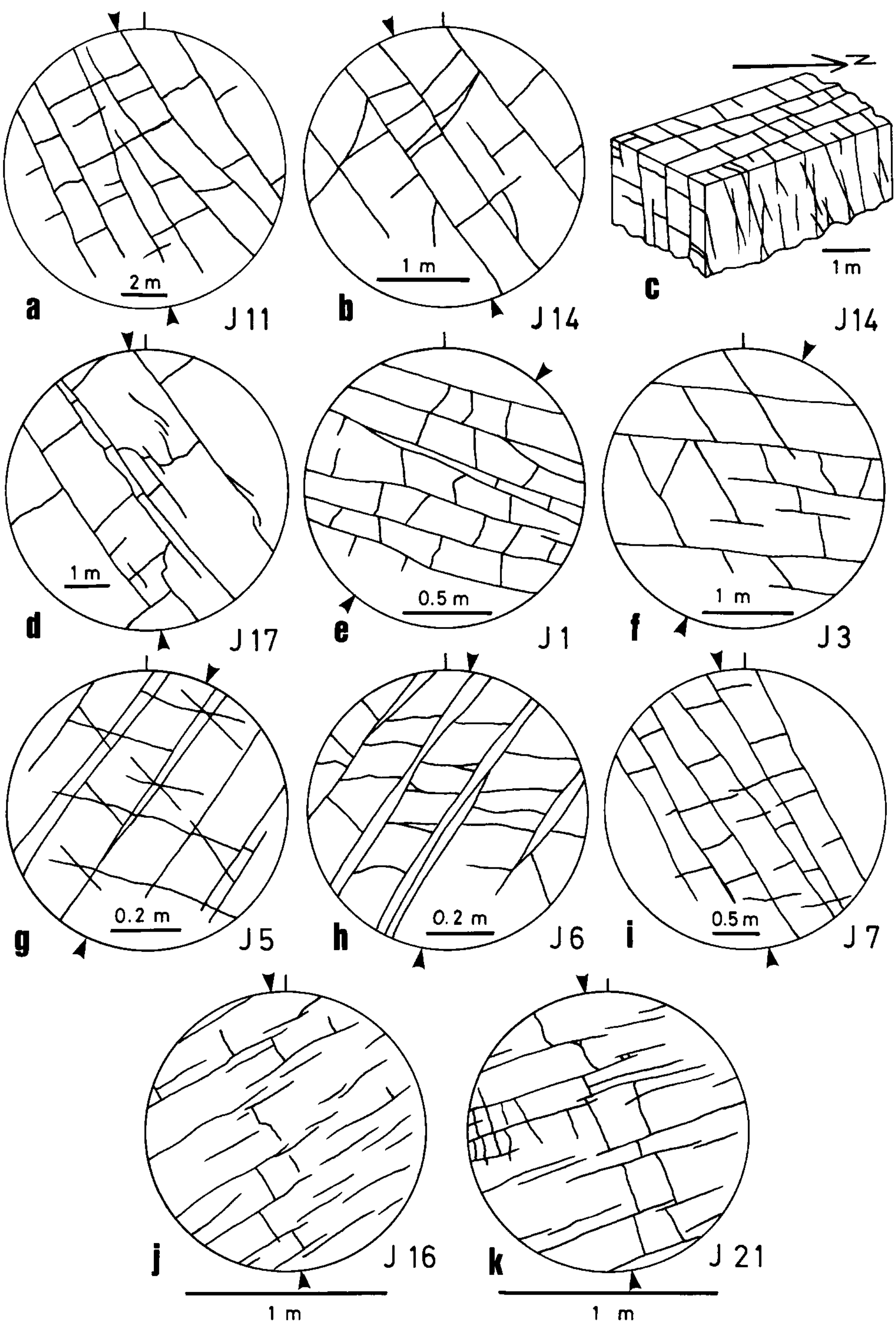

Fig. 3. Joint patterns as traces on bedding in massive sandstone units (a–d) and in sandstone layers of interbedded units (e–k). North is at the top of the circular sketches and black arrows indicate the inferred (a–c) or measured (e–k) strike of the bedding surface.

orientations is not possible without a significant mechanical decoupling between the two units. Such a decoupling is not supported by any evidence of layer-parallel slip at the unit interfaces. This lack of evidence for decoupling implies that the formation of the master joints is diachronous. A consequence of this interpretation is that the formation of master joints in the Uchiumigawa Group cannot be explained by local stress swaps, since these are considered to take place at the same time and under the same remote stress field (Caputo, 1995).

4.2. Tentative chronology of master joint propagation

The synchronous propagation of master joints in the two

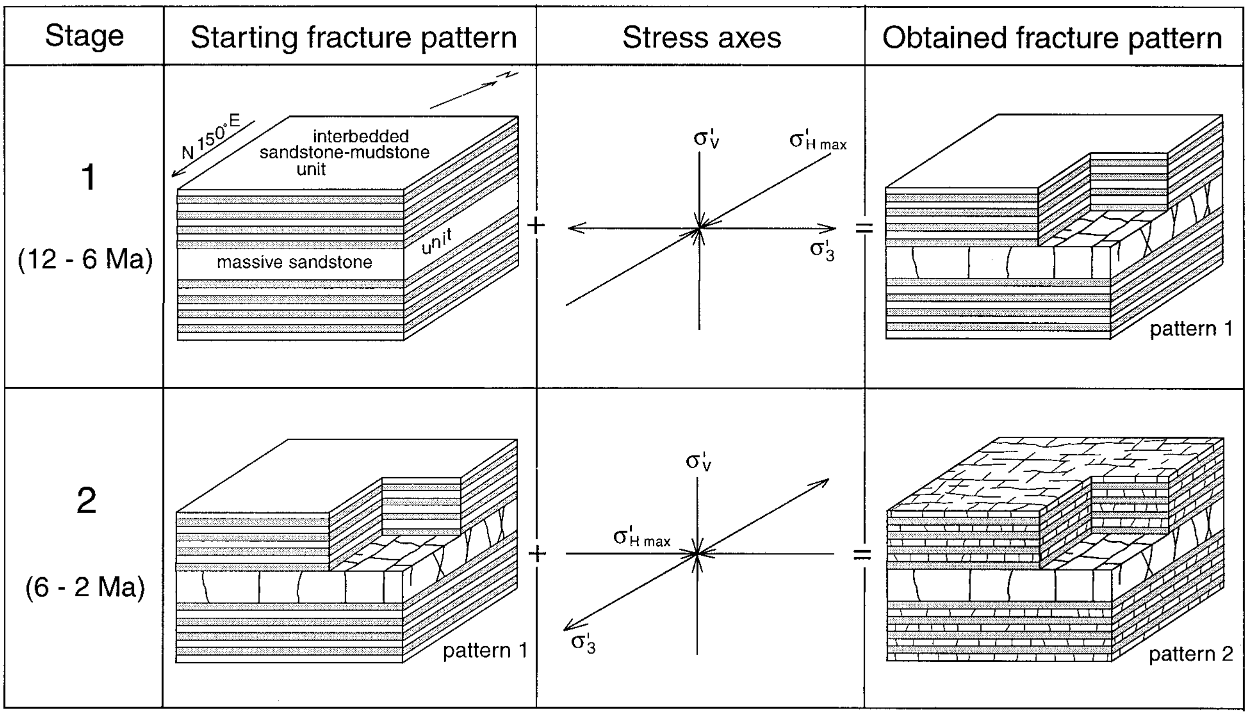

Fig. 4. Scenario for jointing in the study area, based on the superposition of two diachronous regional stress fields. σ'_V is the vertical effective stress and σ'_{Hmax} is the horizontal greatest effective stress.

lithological units being ruled out, the next question is: did the master joints first appear in the massive sandstone units or in the thin-bedded units? We did not measure any elasticity moduli, but we can safely suppose that the clay-free sandstones of the massive units have higher Young's moduli than the clay-bearing sandstones of the interbedded units. Most published values of Young's moduli for sandstones are between 40 and 60 GPa, while those for siltstones and shales are between 15 and 30 GPa (Jaeger, 1969; Carmichael, 1982). This difference suggests a decrease of the value of Young's modulus of a sandstone with increasing clay content. More precisely, Polo-Chiapolini (1974) documented a drop in the values of Young's moduli from 25–40 to 15–25 GPa between clay-free quartzitic sandstones and sandstones containing about 20% clay in volume.

During burial in the forearc tectonic setting, the sedimentary pile should undergo a layer-parallel stretching and a layer-perpendicular shortening. Since Hooke's law states that, for a given value of strain, stress will be higher in the bed with the higher Young's modulus (Gross et al., 1995), the massive clay-free sandstones would fail for smaller magnitudes of layer-parallel extension than the interbedded units. Consequently, master joints could form in the massive sandstones while not forming in the sandstones of the interbedded units. Failure in the interbedded units would occur at a later stage of deformation.

4.3. Inferences from regional fault-slip data

Joints clearly indicate a finite layer-parallel extension along two subperpendicular directions (Fig. 2c). This strain pattern can be explained by a succession of two different diachronous regional stress fields, following a general scenario already proposed by Engelder and Geiser (1980), Bergerat et al. (1992), or Engelder and Gross (1993).

Independent fault-slip data from 16- to 6-Ma-old sedimentary and igneous rocks (Fig. 1, localities 1–3) indicate two extensions, a 045–060° extension and a 135–150° extension (Fabbri and Tokushige, 1996; Fabbri et al., 1997; Fabbri, 2000), whereas fault-slip data from the 6- to 2-Ma-old Miyazaki Group sedimentary strata, exposed immediately to the north of the study area (Fig. 1, locality 4), document only the 135–150° extension (Tokushige and Fabbri, 1996). These data show that the age of the 045–060° extension is bracketed between 16 and 6 Ma, and the 135–150° extension is younger than 6 Ma. This later extension is also older than 2 Ma, since no appropriately oriented fractures recorded it in Quaternary strata (Tokushige and Fabbri, 1996). These regional extensions match the two extensions documented in the Uchiumigawa Group.

4.4. Jointing scenario

In the first stage (Fig. 4), the Uchiumigawa sedimentary pile is stretched in the 060–070° direction because of an effective tensile σ'_3 regional stress trending about 060°. The different lithological components do not show the same response to this stress. While the interbedded units can accommodate stretching without failure, the massive sandstone units fail and joints propagate in a 150° direction.

In the same units, 070° cross joints may possibly start to propagate by local stress release (Rives and Petit, 1990) or stress swaps (Martel, 1994; Caputo, 1995).

During the second stage (Fig. 4), master joints in the sandstone layers of the interbedded units form along a 070° direction because of an effective tensile σ'_3 regional stress trending about 160°. At the same time, in the massive sandstone units, 070° cross joints may form, in addition to the joints with similar orientation already formed by stress release or stress swaps during stage 1, if any. Again, stress release or stress swaps may be responsible for propagation of 150° cross joints in the interbedded units.

Regional fault-slip data and age of deformed or non-deformed rocks suggest that the change in regional stress directions took place around 6 Ma.

5. Conclusion

Fractures affecting the massive sandstone units and the interbedded thin-bedded sandstone–mudstone units of the Uchiumigawa Group consist mostly of extensional joints and have the following characteristics:

- In most localities, the joints form two suborthogonal sets, a master joint set and a cross joint set. The master joints in one type of lithological unit strike perpendicularly to the master joints in the other type of lithological unit.
- Joints did not propagate simultaneously in the two lithological units, but first appeared in the least deformable massive sandstone units and then in the interbedded units.
- Formation of the master joints is the result of two regional stress fields, an older one dating between 12 and 6 Ma, and a younger one dating between 6 and 2 Ma.
- A part if not the totality of the cross joints may have propagated because of local stress swaps or stress releases following the formation of master joints within each unit.

The scenario proposed for the Uchiumigawa Group suggests that lithological units with different mechanical characteristics may not record the same fracturing episodes, at least as far as jointing is concerned. This lithological filtering effect should be examined further by means of rock mechanics investigations.

Acknowledgements

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References

Bergerat, F., Bouroz-Weil, C., Angelier, J., 1992. Palaeostresses inferred from macrofractures, Colorado Plateau, western USA. Tectonophysics 206, 219–243.

Caputo, R., 1995. Evolution of orthogonal sets of coeval extension joints. Terra Nova 7, 479–490.

Carmichael, R.S., 1982. Handbook of Physical Properties of Rocks, vol. 2. CRC Press, Boca Raton, FL.

Dunne, W.M., Hancock, P.L., 1994. Palaeostress analysis of small-scale brittle fractures. In: Hancock, P.L. (Ed.), Continental Tectonics, Pergamon Press, Oxford, pp. 101–120.

Dunne, W.M., North, C.P., 1990. Orthogonal fracture systems at the limits of thrusting: an example from southwestern Wales. Journal of Structural Geology 12, 207–215.

Engelder, T., Geiser, P., 1980. On the use of regional joint sets as trajectories of paleostress fields during the development of the Appalachian plateau, New York. Journal of Geophysical Research 85, 6319–6341.

Engelder, T., Gross, M.R., 1993. Curving cross joints and the lithospheric stress field in eastern North America. Geology 21, 817–820.

Fabbri, O., 2000. Arc-parallel extensional deformation in the northern Ryukyu arc indicated by mesoscale fractures in the middle Miocene deposits of Tanegashima Island, Japan. Journal of the Geological Society of Japan 106, 234–243.

Fabbri, O., Tokushige, H., 1996. Evolution of the tectonic stress field along the southwest Japan forearc domain during the Neogene. 103rd Meeting of the Geological Society of Japan, Sendai, Abstract Volume, p. 192.

Fabbri, O., Tokushige, H., Hayamizu, M., 1997. Normal faulting in the Middle Miocene Osumi granodioritic pluton, southern Kyushu, Japan, and its significance. Journal of the Geological Society of Japan 103, 141–151.

Gross, M.R., 1993. The origin and spacing of cross joints: examples from the Monterey Formation, Santa Barbara Coastline, California. Journal of Structural Geology 15, 737–751.

Gross, M.R., Fischer, M.P., Engelder, T., Greenfield, R.J., 1995. Factors controlling joint spacing in interbedded sedimentary rocks: integrating numerical models with field observations from the Monterey Formation, U.S.A.. In: Ameen, M.S. (Ed.), Fractography: Fracture Topography as a Tool in Fracture Mechanics and Stress Analysis. Geological Society Special Publication 92, Geological Society, pp. 215–233.

Hancock, P.L., 1985. Brittle microtectonics: principles and practice. Journal of Structural Geology 7, 437–457.

Hancock, P.L., Al-Kahdi, A., Barka, A.A., Bevan, T.G., 1987. Aspects of analysing brittle structures. Annales Tectonicae 1, 5–19.

Jaeger, J.C., 1969. Elasticity, Fracture and Flow. Methuen, London.

Kano, K., Kato, H., Yanagisawa, Y., Yoshida, F., 1991. Stratigraphy and geologic history of the Cenozoic of Japan. Report of the Geological Survey of Japan 274, 114 p.

Martel, S.J., 1994. On the paradox of systematic, contemporaneous, orthogonal opening-mode fractures. In: Nelson, P.P., Laubach, S.E. (Eds.), Proceedings of the 1st North American Rock Mechanics Symposium (Austin, Texas), pp. 801–808.

Nakamura, Y., Ozawa, T., Nobuhara, T., 1999. Stratigraphy and molluscan fauna of the upper Miocene to lower Pliocene Miyazaki Group in the Aoshima area, Miyazaki Prefecture, southwest Japan. Journal of the Geological Society of Japan 105, 45–60.

Pollard, D.D., Aydin, A., 1988. Progress in understanding jointing over the past century. Geological Society of America Bulletin 100, 1181–1204.

Polo-Chiapolini, C., 1974. Caractéristiques géomécaniques des roches du bassin houiller de Liège. Mémoires du Centre d'Etudes, de Recherches et d'Essais Scientifiques du Génie Civil University of Liège 47, pp. 1–50.

Rives, T., Petit, J.P., 1990. Experimental study of jointing during cylindrical and non-cylindrical folding. In: Rossmanith, H.P. (Ed.), Mechanics of Jointed and Faulted Rocks, pp. 205–211.

Stauffer, M.R., Gendzwill, D.J., 1987. Fractures in the northern plains, stream patterns, and mid-continent stress field. Canadian Journal of Earth Science 24, 1086–1097.

Suzuki, H., 1987. Stratigraphy of the Miyazaki Group in the southeastern part of Miyazaki Prefecture, Kyushu, Japan. Contributions from the Institute of Geology and Paleontology, Tohoku University 90, 1–24.

Tokushige, H., Fabbri, O., 1996. Mesofaults and associated stress field in the Late Miocene to Pliocene forearc deposits of the Miyazaki district, southeast Kyushu Japan. Journal of the Geological Society of Japan 102, 622–634.