TITLE:

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AUTHOR(S):

Koyama, Toshiyuki; Yamaji, Atsushi; Sato, Katsushi

CITATION:

Koyama, Toshiyuki ...[et al]. Bias correction for the orientation distribution of slump fold axes: Application to the Cretaceous Izumi basin. Computers & Geosciences 2012

ISSUE DATE:

2012-04

URL:

<http://hdl.handle.net/2433/156157>

RIGHT:

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Bias correction for the orientation distribution of slump fold axes: Application to the Cretaceous Izumi basin

Toshiyuki Koyama^a, Atsushi Yamaji^{a,*}, Katsushi Sato^a

^a*Division of Earth and Planetary Sciences, Graduate School of Science, Kyoto University,
Kyoto 606-8502, Japan*

Abstract

Linear structures perpendicular to an outcrop surface are easily discovered, but those parallel to the surface are not, giving rise to a biased orientation distribution of the structures. Here, we propose a bias correction method: Statistical inversion was conducted to unbiased the distribution of the axes of mesoscale slump folds in the Cretaceous Izumi Group, Japan using the orientation distribution of outcrop surfaces. The observed axes showed a cluster in the SE quadrant. Their unbiased distribution had a girdle pattern with a maximum concentration orientation in the same quadrant, but the unbiased one had a lower peak density than the observed one, and was more girdle-like than the observed one. The maximum concentration axis of the unbiased distribution was roughly perpendicular to the paleocurrents observed in the same area. Therefore, the popular view that the axes of slump folds are perpendicular to paleoslope applies to the folds in the area in a statistical sense. The hypothesis about the vergences of slump folds and paleoslope hold only about a half of the observed slump folds.

Keywords: selection bias, soft sediment deformation, statistical inversion, Bingham distribution

*Corresponding author. Tel.: +81 75 753 4266; fax: +81 75 753 4289.
Email address: yamaji@kueps.kyoto-u.ac.jp (Atsushi Yamaji)
Preprint submitted to Computers & Geosciences

June 3, 2012

9 1. Introduction

10 Observation of the orientation distribution of planar structures such as faults
11 and joints is known to be affected by selection bias (e.g., Terzaghi, 1965; Jing
12 and Stephansson, 2007). That is, if those structures have a preferred orientation,
13 their apparent number density along a scanline subparallel to this orientation is
14 smaller than the true density. Numerical techniques have been developed to infer
15 the unbiased orientation distribution for such cases (e.g., Mauldon et al., 2001;
16 Peacock et al., 2003; Barthélemy et al., 2009).

17 Likewise, the observed orientation distribution of linear structures such as the
18 axes of mesoscale slump folds is affected by selection bias. Here, mesoscale ones
19 refer to such folds that their attitudes are observed in an outcrop. For example,
20 folds with the axes perpendicular to an outcrop surface are easily discovered, but
21 those parallel to the surface are not (Fig. 1). We do not observe the true but biased
22 orientation distribution of such structures.

23 In this paper, we propose an inverse method to infer the unbiased distribu-
24 tion of the axes of slump folds. Such a technique is useful for basin analysis
25 and for the understanding of soft-sediment deformations, because slump folds are
26 often used to infer paleoslopes (e.g., Jones, 1939). The folds are thought to be
27 formed during a reduction in velocity of slump sheets (e.g., Strachan and Alsop,
28 2006; Alsop and Holdsworth, 2007; Alsop and Marco, 2011), and therefore, are
29 used to infer paleoslope directions. Folds are considered to dip upslope and to
30 strike approximately normal to the slopes (Jones, 1939; Tucker, 2003; Bridge and
31 Demicco, 2008). Hence, basin architecture has been inferred from their vergence
32 (e.g., Woodcock, 1976; Bradley and Hanson, 1998; Noda and Toshimitsu, 2009).
33 However, this popular view is known to have many exceptions (Hansen, 1971; La-

34 joie, 1972; Woodcock, 1979; Farrell, 1984; Strachan and Alsop, 2006; Debacker
35 et al., 2009; Alsop and Marco, 2012).

36 To demonstrate our bias correction technique, we collected orientation data
37 from the axes of mesoscale slump folds in the Cretaceous Izumi basin, Japan. The
38 strata crop out along the Median Tectonic Line—the crustal-scale fault dividing
39 the high-T and high-P metamorphic belts along the SW Japan arc (Miyashiro,
40 1961). The basin formation is attributed to the wrench tectonics along the fault
41 (Ichikawa and Miyata, 1973) as a part of widespread wrench tectonics in Eastern
42 Asia in the Cretaceous (Ren et al., 2002) driven by the oblique subduction of the
43 Izanagi Plate (Taira et al., 1983; Maruyama et al., 1997). Miyata (1990) argue for
44 wrench tectonics based on the observed cluster of the fold axis orientations. Ac-
45 cordingly, the slump folds of the Izumi Group are important for the understanding
46 of the tectonic evolution of Japan and surrounding regions. The present technique
47 was applied to slump folds to test if the popular view that the vergence and ori-
48 entation of slump folds relates to paleoslope also holds true for structures in the
49 Izumi Basin.

50 **2. Method**

51 *2.1. Bias model*

52 To construct a bias correction technique we considered, first, the way the ori-
53 entation distribution was biased. The probability of the axis of a mesoscale fold to
54 be exposed at an outcrop is comparable to Buffon's needle problem (e.g., Aigner
55 and Ziegler, 2004, p. 135): What is the probability of a needle to lie across a line
56 on a plane if the needle has a random orientation? A needle parallel to the line
57 does not intersect the line, providing that the width of the needle is zero; whereas

the probability increases obviously with the angle made by the needle and the line.
A needle perpendicular to the line has the maximum probability.

Probability is always defined to have a value between 0 and 1. Comparing the
needle to an axis of mesoscale fold and the line to the surface of an outcrop (Fig.
2), it turns out that the probability of the axis to be exposed at the outcrop can be
written as

$$|\mathbf{a} \cdot \mathbf{n}| = \cos \varphi, \quad (1)$$

where $\mathbf{a}$ is the unit vector representing fold axis, $\mathbf{n}$ is the unit vector normal to the
outcrop surface and φ is the angle made by $\mathbf{a}$ and $\mathbf{n}$. This equation has a value
between 0 and 1. The lengths of the folds were assumed to be independent from
their orientations to regard Eq. (1) as the probability. In this work, we use this
equation to model the selection bias for the observation of the mesoscale folds.

2.2. Forward model

We conducted Monte Carlo simulation to show the effect of the bias as follows.
Slump folds were assumed to be embedded at various horizons of a sedimentary
package with a homoclinal structure for simplicity. It was further assumed that the
true orientation distribution of the fold axes had a clustered pattern with the central
line on the bedding or had a girdle pattern on the bedding. Our bias correction
aimed at inferring this pattern from the observed orientations of slump fold axes
and from those of outcrops.

Both the clustered and girdle patterns are parameterized by the Bingham statis-
tics (Love, 2007), the probability distribution of which has the maximum, inter-
mediate and minimum concentration axes that are perpendicular to each other
(Fig. 3). In addition, the distribution has the concentration parameters, κ_1 and κ_2

81 $(\kappa_1 \leq \kappa_2 \leq 0)$. The distribution has the probability density function,

$$F(\mathbf{x}) = \frac{1}{A} \exp [\mathbf{x}^\top \mathbf{Q}^\top \text{diag}(\kappa_1, \kappa_2, 0) \mathbf{Q} \mathbf{x}],$$

82 where $\mathbf{x}$ is the unit column vector representing an orientation, A is the normalizing
83 factor, $\mathbf{Q}$ is an orthogonal matrix representing the orientations of the axes. The
84 absolute value, $|1/\kappa_1|$, stands for the spread of fold axes from the maximum to
85 the minimum concentration axes, whereas $|1/\kappa_2|$ does from the maximum to the
86 intermediate concentration axes. A girdle pattern, elliptical and circular clusters
87 are represented by the parameters satisfying $\kappa_1 \ll \kappa_2 \approx 0$, $\kappa_1 \leq \kappa_2 \lesssim -10$ and
88 $\kappa_1 = \kappa_2 \lesssim -10$, respectively.

89 We assumed that the maximum concentration axis lay on the bedding. It does
90 not mean that fold hinges lay on the bedding. Instead, the hinges were assumed to
91 be generally oblique to the bedding, and the spread of their orientations across the
92 bedding is denoted by $|1/\kappa_1|$. The symbol, ψ , denotes the rake of the maximum
93 concentration axis on the bedding (Fig. 4). The same symbol refers to the trend of
94 the axis for horizontal bedding. In either case, ψ has a value between 0° and 180° .
95 We dealt with slump folds in a homoclinal structure, but bedding attitudes had a
96 variation to some extent. Variation of the angles made by the axes and the bedding
97 is assumed, here, for dealing not only with the variation of the axes themselves
98 but also that of the bedding attitudes in a largely homoclinal structure.

99 Observed orientation distribution of fold axes depends not only on the true
100 distribution of the axes themselves but on the orientations of outcrop surfaces
101 (Eq. 1). Fig. 5 shows the forward modeling of the bias using artificial data: the
102 Bingham distribution with the parameters, $\kappa_1 = -10$ and $\kappa_2 = -1$, was assumed
103 to be the true distribution (Fig. 5a). Horizontal bedding was assumed. Therefore,
104 the trend of the maximum concentration axis is denoted by ψ . The stereogram in

Fig. 5b shows the poles to uniformly oriented 200 outcrop surfaces, whereas that in Fig. 5c shows the poles to N-S trending 200 cliffs where folds were assumed to be observed. Each of the poles is represented by the vector $\mathbf{n}$ in Eq. (1).

The observed orientation distributions for the cases of uniform and clustered orientations of outcrops were synthesized as follows. First, the unit vector, $\mathbf{a}$, representing a fold axis was generated thousands of times to make the Bingham distribution with $\kappa_1 = -10$ and $\kappa_2 = -1$ (Fig. 5a). Second, each of the times a uniform random number, p , between 0 and 1 was generated; and at the same time a vector $\mathbf{n}$ were randomly chosen from Fig. 5b or 5c. Third, the axis denoted by $\mathbf{a}$ was accepted if the vectors satisfy

$$\mathbf{a} \cdot \mathbf{n} > p. \quad (2)$$

Each of Figs. 5d and 5e shows the results with 10,000 accepted axes for the cases of Figs. 5b and 5c, respectively. The observed distribution resembles the true one if outcrops have random orientations (Fig. 5d). However, the peak density of the observed one is smaller than the true one, because fold axes subparallel to outcrop surfaces have non-zero probability to be observed. On the other hand, when the poles to outcrop surfaces were clustered, the synthesized orientation distribution of observed axes had a cluster similar to that of the outcrop poles (Fig. 5e), which was significantly different from the ‘true’ distribution.

2.3. Bias correction

Observed orientation distribution was unbiased by statistical inversion to determine the parameters, κ_1 , κ_2 and ψ . Given the values of those parameters, the probability to discover a fold axis parallel to the unit vector $\mathbf{a}$ was calculated

127 through the procedure described in §2.2 (Fig. 5). Let $P(\mathbf{a} | \kappa_1, \kappa_2, \psi)$ be this prob-
128 ability. If $\mathbf{a}$ is regarded as a free variable, $P(\mathbf{a} | \kappa_1, \kappa_2, \psi)$ denotes the apparent or
129 biased orientation distribution. Then, the similarity between the observed distri-
130 bution and $P(\mathbf{a} | \kappa_1, \kappa_2, \psi)$ can be evaluated by the logarithmic likelihood function
131 (e.g., van den Bos, 2007),

$$\mathcal{L}(\kappa_1, \kappa_2, \psi) = \sum_{i=1}^N \log P(\mathbf{a}^i | \kappa_1, \kappa_2, \psi),$$

132 where $\mathbf{a}^i$ is the unit vector parallel to the i th of N observed fold axes. Given
133 the values of the triplet, ψ , κ_1 and κ_2 , the left-hand side of this equation can be
134 calculated from the observed directions, $\mathbf{a}^1, \mathbf{a}^2, \dots, \mathbf{a}^N$. If $P(\mathbf{a} | \kappa_1, \kappa_2, \psi)$ had large
135 values for those directions, the simulated distribution through the sampling bias
136 was similar to the observed distribution. Therefore, the Bingham distribution with
137 the triplet of parameter values that maximize $\mathcal{L}(\kappa_1, \kappa_2, \psi)$ was regarded as the most
138 probable unbiased distribution of fold axes. The optimization of the parameters,
139 κ_1 , κ_2 and ψ , was conducted by the exhaustive search technique (e.g., Zabinsky,
140 2003).

141 The above method is tested with the artificial data in Fig. 5e. That is, a hundred
142 orientations drawn from the distribution in the figure were assumed as the axes of
143 observed folds, and we tested the method if it resulted in an unbiased distribution
144 similar to the ‘true’ one in Fig. 5a. Fig. 6a shows the 100 orientations that were
145 assumed to be observed axes of folds. Their maximum concentration axis had a
146 NNW-SSE trend. They were unbiased using the orientations of outcrops in Fig.
147 5c. The grid search with the intervals of 0.5 for the concentration parameters and
148 15° for the trend of the axis resulted in the optimal values, $\hat{\kappa}_1 = -11.0$ and $\hat{\kappa}_2 =$
149 -1.5 , and the trend of 165° (Fig. 6c). The E-W trending maximum concentration

axis in Fig. 6a was clearly shown to be an artifact. The unbiased distribution (Fig. 6c) was similar to the 'true' one (Fig. 5a), which had the values, $\kappa_1 = -11$, $\kappa_2 = -1$ and $\psi = 0^\circ$. The low κ_2 value indicated that girdle patterns were favorable for the data. Therefore, unlike a dense and small cluster it was difficult to determine precisely the trend of the maximum concentration axis on the girdle.

3. Application to natural data

The bias correction technique was applied to mesoscale slump folds in the Cretaceous Izumi basin, SW Japan, to infer their true orientation distribution. We collected the orientation data along coasts to the south of Osaka, Japan (Fig. 7). Turbidites with a SE-dipping homoclinal structure cropped out along sea cliffs and on wave-cut platforms (Figs. 8, 9a).

Slump sheets and debris flow deposits were often intercalated in the turbidites (Tanaka, 1965). Groove and flute casts at the bases of turbidite beds evidence coherent west- to southwestward-directed paleocurrents (Fig. 7) (Miyata et al., 1987). South by southwestward paleocurrents were found in our study area (Fig. 9a)—southerly deflected from the west by southwestward regional average. Since the paleocurrent directions were determined from such sole marks that were observed excavated bedding planes, the orientation distribution of paleocurrents was free from the sampling bias that affected that of fold axes.

The succession shown in Fig. 9a was ~ 750 m in thickness—an apparent thickness because of the presence of outcrop-scale duplexes embedded in the succession. The slump folds that we measured the orientations of fold axes were not involved in the duplexes.

173 3.1. *Observed slump folds*

174 Slump sheets in the study area had thicknesses ranging from 0.3 to 2 m with
175 the dominant thickness of ~1 m. Sandstone layers in the sheets were typically
176 0.1 m in thickness with the maximum of 0.8 m, but were thickened or thinned or
177 sometimes rifted during slumping. Slump sheets are thought to evolve into debris
178 flows and eventually into turbidity currents (Strachan, 2008). We paid attention
179 to such slump folds that sandstone beds in the folds were not disaggregated. The
180 beds made asymmetric, tight–isoclinal folds: Isoclinal ones were usually recum-
181 bent (Fig. 10).

182 We observed slump fold axes along the coast (Fig. 9b). The axes made a
183 cluster in the SE quadrant (Fig. 9c), roughly perpendicular to the southwestward
184 paleocurrents (Fig. 9a). Therefore, the axes seem consistent with the classical
185 view by Jones (1939). However, the vergences of the folds were bimodal with
186 peaks in NE and SW quadrants (Fig. 9b), the former of which is inconsistent
187 with the view. Fig. 9d is the histogram of the vergences, indicating the bimodal
188 distribution. Miyata (1990) attributed the folding with northwestward vergences
189 to pre-lithification gravity sliding by eastward tectonic tilting while the strata were
190 soft.

191 However, we found that slump folds even in a slump sheet had various axial
192 orientations (Fig. 11). The thicknesses of the sheet and the turbidite sandstone
193 beneath it were measured along a coast, the location of which is shown in Fig. 7,
194 for testing the correlation between the local undulations of the basin floor and the
195 slump directions. The thickness of the sandstone had variations with an ampli-
196 tude and wavelength of 10–20 cm and 20 m, respectively, suggesting a relatively
197 smooth basin floor at the time of the slumping. In addition, the variations had no

198 systematic correlation with the slip directions.

199 Therefore, the applicability of the classical criteria to the slump folds to infer
200 paleoslopes seems problematic. Since the dominant orientation of the fold axes
201 were roughly perpendicular to the coast line (Fig. 9b), we suspected that the
202 cluster of fold axes in the SE quadrant (Fig. 9c) was an artifact coming from
203 sampling bias.

204 3.2. *Inversion*

205 The attitudes of outcrop surfaces were measured at 61 locations with the inter-
206 vals of 70 m along the coast irrespective of the presence or absence of slump folds
207 (Fig. 8). The poles to the outcrop surfaces had a cluster in the SE quadrant (Fig.
208 9e). The clustered orientations of the outcrops give rise to the apparent orienta-
209 tion distribution of the fold axes in favor of having a cluster in the same quadrant.
210 On the other hand, the strata cropping out along the coast showed a homoclinal
211 structure with the mean dip direction and dip was $154^\circ/33^\circ$. We used this bedding
212 attitude for the inversion.

213 The orientation distribution of the fold axes in Fig. 9c was unbiased with
214 the orientations of outcrops in Fig. 9e. The exhaustive search with the intervals
215 $\Delta\kappa_1 = \Delta\kappa_2 = 0.25$ and $\Delta\psi = 10^\circ$ resulted in the optimal values, $\hat{\kappa}_1 = -5.75$,
216 $\hat{\kappa}_2 = -0.5$ and $\hat{\psi} = 50^\circ$. That is, the absolute value of $\hat{\kappa}_1$ was greater than that of
217 $\hat{\kappa}_2$ by an order of magnitude. The corresponding Bingham distribution is shown
218 in Fig. 9g, and the simulated distribution for the synthesized distribution of fold
219 axes is shown in Fig. 9h.

220 The optimal values satisfy the condition, $\kappa_1 \ll \kappa_2 \approx 0$, indicating a girdle
221 pattern of the unbiased distribution of fold axes. The minimum, intermediate and
222 maximum concentration orientations of the unbiased orientation distribution had

223 the ratio of densities about 1:6:10. That is, our slump folds had largely random
224 orientations on bedding planes with tendency to be clustered in the SW quadrant.
225 The apparent orientation distribution had a cluster roughly in the same orientation,
226 but the unbiased one had a lower peak density on the girdle compared to the
227 apparent one (Fig. 9). The unbiased distribution was shown to have such a cluster,
228 though the unbiased one was more girdle-like than the observed one.

229 The maximum concentration axis of the unbiased orientation was more or
230 less perpendicular to the southwestward paleocurrents (Fig. 9), though the nearly
231 girdle pattern of the unbiased distribution gave rise to a limited precision of the
232 axis. Therefore, the popular view that the axes of slump folds are perpendicular
233 to paleoslope applies to the folds in our study area in a statistical sense, but not
234 necessarily to each of the folds. In addition, the hypothesis about the vergences of
235 slump folds and paleoslope hold only about a half of the observed slump folds.

236 Strachan and Alsop (2006) noticed the relationship among fold axis, interlimb
237 angle and paleoslope. That is, gentle and open folds had a tendency to have hinge
238 lines perpendicular to paleoslope, and that tighter folds had random orientations
239 because of the progressive rotations during folding. The slump folds in our study
240 area showed this tendency: The hinges of gentle and open folds were perpendicu-
241 lar to the paleoslope that was indicated by paleocurrents (Fig. 12). In contrast, the
242 folds with the angles smaller than $\sim 80^\circ$ had random orientations. However, this
243 tendency may have been resulted also from the selection bias, because folds with
244 large interlimb angles are discovered in an outcrop perpendicular to their hinge
245 lines more easily than those in outcrops subparallel to the lines. Tight and isocli-
246 nal folds are readily recognized in outcrops, provided that their hinge zones are
247 sectioned at the outcrops.

248 Miyata (1990) attributed the northeastward vergences of slump folds in the
249 same area to post-burial and pre-lithification tectonic tilting resulting from the
250 wrench tectonics along the Median Tectonic Line. The results of our study indi-
251 cate that the slump folds do not evidence the tectonics. Alsop and Marco (in press)
252 provide possible cause for the down-slope vergence of slump folds including the
253 oscillatory currents induced by Tsunami. The sedimentological implications of
254 the diverging vergences of slump folds is a matter of further studies in the Izumi
255 basin.

256 4. Summary

257 Observation of the orientation distribution of mesoscale linear structures are
258 affected by sampling bias, which comes from the angle made by the structures and
259 an outcrop surface.

260 A numerical method to unbiased the observed distribution using not only the
261 observed one but also the orientations of outcrops.

262 The method was applied to the axes of mesoscale slump folds embedded in
263 turbidites in the Cretaceous Izumi Group, SW Japan. Their apparent orientation
264 distribution had a cluster in the SE quadrant. Their unbiased distribution had
265 a girdle pattern with a maximum concentration axis in the same quadrant. The
266 unbiased one had a lower peak density than the observed one.

267 The maximum concentration axis of the unbiased one was roughly perpendic-
268 ular to the paleocurrents observed in the same area. Therefore, the popular view
269 that the axes of slump folds are perpendicular to paleoslope applies to the folds in
270 our study area in a statistical sense, but does not to each of the folds. In addition,
271 the hypothesis about the vergences of slump folds and paleoslope hold only about

272 a half of the observed slump folds.

273 **Acknowledgments**

274 We thank Ian Alsop and an anonymous reviewer for helpful comments to im-
275 prove the manuscript. Discussions with Hajime Naruse was fruitful. The stereonet
276 software, Stereo32, written by Klaus Röllner and Claudia Trepmann was used to
277 draw some of the figures. This work was partly supported by the grant 21740364
278 from JSPS.

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371 **Fig. 1.** The popular view about the shape of a slump fold and paleoslope: The
372 latter is thought to be perpendicular to the fold axis and parallel to the vergence of
373 the fold (e.g., Jones, 1939). Folds with the hinge lines perpendicular to an outcrop
374 surface are discovered much more easily than those parallel to the surface.

375
376 **Fig. 2.** The hinge lines of slump folds (bold lines) in a rock body. The probability
377 for a fold to be exposed depends on the angle, φ , made by the fold axis and the
378 surface of an outcrop (dashed line).

379
380 **Fig. 3.** Equal-area projections showing the probability densities of Bingham dis-
381 tributions with different κ_1 and κ_2 values. Triangle, diamond and star depict the
382 maximum, intermediate and minimum concentration axes of the distributions, re-
383 spectively.

384
385 **Fig. 4.** Lower-hemisphere, equal-area projection showing an example of Bingham
386 distribution to approximate the unbiased distribution of fold axes. The maximum,
387 intermediate and minimum concentration orientations are indicated by triangle,
388 diamond and star, respectively. The last one is perpendicular to bedding plane.
389 The rake of the maximum concentration axis is denoted by ψ .

390
391 **Fig. 5.** Lower-hemisphere, equal-area projections showing the Monte Carlo sim-
392 ulation of the effect of the bias denoted by Eq. (1). (a) The contours of a Bingham
393 distribution with the parameters, $\kappa_1 = -10$ and $\kappa_2 = -1$, with the N-S trending
394 maximum concentration axis, for denoting the axes of mesoscale slump folds. (b,
395 c) Poles to assumed 200 outcrop surfaces. (d, e) The contours of $P(\mathbf{a} | \kappa_1, \kappa_2, \psi)$.

396 That is, the orientation distributions of fold axes whose orientation data are ex-
397 pected to be collected from the outcrops. The distributions were synthesized from
398 the true distribution (a) and the outcrop orientations (b, c). Triangle and star indi-
399 cate the maximum and minimum concentration orientations, respectively.

400

401 **Fig. 6.** Lower-hemisphere, equal-area projections showing the bias correction ap-
402 plied to the artificial data in Fig. 5e. (a) A hundred orientations drawn from the
403 data for representing observed fold axes. Triangle and star indicate the maximum
404 and minimum concentration axes, respectively, determined through the orienta-
405 tion matrix of the data (Fisher et al., 1993). (b) Orientations representing the
406 poles to the outcrop surfaces—the same data with Fig. 5c. (c) The Bingham dis-
407 tribution representing the orientation distribution of fold axes unbiased from (a).
408 The distribution has the optimal values, $\hat{\kappa}_1 = -11.0$ and $\hat{\kappa}_2 = -1.5$, and the trend
409 of the maximum concentration axis (triangle) at 165° . Star indicates the minimum
410 concentration axis.

411

412 **Fig. 7.** Geologic map around the study area (Kurimoto et al., 1998) and paleocur-
413 rent directions of the Izumi Group (Miyata et al., 1987). The Median Tectonic
414 Line is a crustal scale fault along the SW Japan arc.

415

416 **Fig. 8.** Outcrops in the study area, where the planar turbidite beds of the Creta-
417 ceous Izumi Group are exposed. The orientations of outcrops were measured at
418 locations with intervals of 70 m along the coast.

419

Fig. 9. (a) Paleocurrents inferred from groove and flute casts. (b) Vergences of slump folds, the axes of which are perpendicular to the vergences. The lengths of arrows indicate the plunge angles. Tilt-corrections were not applied. (c–g) Lower-hemisphere, equal-area projections. Dotted lines depict the mean attitude of bedding. (c) Axes of mesoscale slump folds observed along the coast. Density contours were drawn by the software, Stereo32, using the cosine sum method with the cosine exponent at 20. (d) Histogram of the vergences, to which tilt-corrections were made. (e) Outcrop surfaces measured at locations with 70 m intervals along the coast. (f) Bedding planes observed on the coast. Cross denotes the mean. (g) Unbiased orientation distribution of fold axes determined from the data in (c) and (e). (h) Simulated orientation distribution of fold axes that are expected to be observed along the coast, i.e., the contours of $P(\mathbf{a} | \hat{\kappa}_1, \hat{\kappa}_2, \hat{\psi})$, where the parameters with accent marks denote the optimal values determined by the inversion. This distribution was synthesized from the data in (e) and the unbiased distribution in (g).

Fig. 10. A slump sheet in the study area. The lateral variations of the thicknesses of the sheet and underlying sandstone are shown in Fig. 11.

Fig. 11. Arrows indicate the vergences of folds in a slump sheet, and the lateral variations of the thicknesses of the sheet and its substratum (turbidite sandstone). A fold in the sheet with unclear vergence is depicted by a thin solid line perpendicular to the fold axis. The beds were exposed for a length of > 200 m along their strike. The location of this cliff is shown in Fig. 7.

445 **Fig. 12.** Polar plot showing the trends and interlimb angles of slump folds in the
446 study area. Most of folds with the angles greater than $\sim 80^\circ$ (highlighted by gray
447 lines) had hinges perpendicular to the general trend of paleocurrents (Fig. 9a).
448 Tilt correction was not applied to the trends.

Figure 1:

Figure 2:

Figure 3:

Figure 4:

Figure 5:

Figure 6:

Figure 7:

Figure 8:

Figure 9:

Figure 10:

Figure 11:

Figure 12: