Geology of the 1350m boring cores from the OYO CORPORATION TSUKUBA TECHNICAL RESEARCH AND DEVELOPMENT CENTER (5)
—— Segmentation and linkage of schistosity-parallel fault ——

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Abstract

Deformation microtextures around a schistosity-parallel microfault in biotite schist from 754.5m depth core of the 1350m boring drilled in the OYO CORPORATION TSUKUBA TECHNICAL RESEARCH AND DEVELOPMENT CENTER, Tsukuba, Japan, which shows a distinct planar schistosity of a single set defined by preferred shape and lattice orientation of biotite flakes, have been described and discussed in this paper. The biotite schist appears to have mainly been deformed during faulting by the formation of kink bands and folds of gentle form in biotite flakes, by sliding along grain boundaries of biotite, quartz and feldspar, accompanying decomposition of feldspar and crystallization of microflakes of white mica, but not by their brittle fracturing, showing that the faulting occurred probably under ductile strain condition.

As the fault plane runs through grain boundaries between biotite flakes and quartz (or feldspar), it commonly is irregular, and kink bands are commonly formed in its surrounding biotite flakes, while kink bands are scarcely recognized around the planar fault plane running through grain boundaries between biotite flakes and along (001) plane of biotite. The appearance of kink bands is clearly related to asperities along the fault plane.

The fault is a segmented fault trace consisting of fault segments and contractional offsets. Fault segmentation occurs where fault slips encounter quartz (or feldspar) grains as resistant block. The propagation of the fault tips is here deflected from the planes of the fault segments to a direction along grain boundaries of quartz (or feldspar) as obstacle, giving rise to linkage of adjacent fault segments at contractional offsets.

As read from orientation pattern of the kink bands, narrow domains just around the fault segments are shear zone, and the local state of stress within the domains and around asperities on the fault planes is characterized by the compressive stress trajectory oriented slightly oblique to the shear zone. The contractional offset is characterized by the strongest development of kink bands in biotite flakes and also by the strong compressive strain nearly parallel to the general trend of fault segments with shearing along the offset planes.

Keywords: kink band, linkage, segmentation, schistosity-parallel fault, strain

1. Introduction

Biotite schist of the Ryoke Belt, which has been collected from 754.5m depth core of the 1350m boring drilled in the OYO CORPORATION TSUKUBA TECHNICAL RESEARCH AND DEVELOPMENT CENTER (Fig. 1; Mimoto et al., 2000[1]), Tsukuba, Japan, shows a distinct planar schistosity of a single set defined by preferred shape and lattice orientation of biotite flakes and a schistosity-parallel microfault (Fig. 2). It consists mainly of biotite, quartz, plagioclase and K-feldspar, associating muscovite in quite minute amount.

Structural system of the schistosity-parallel microfault in the biotite schist is described in terms of fault segments and offsets (Fig. 2). The faulting examined in this paper appears to have occurred under ductile strain condition mainly by grain boundary slip for quartz and feldspar and by grain boundary slip and slip along and kinking of (001) plane for biotite flakes. Biotite flakes around the microfault show microtextures produced during the earlier stage of faulting, because of quite minute amount of displacement. The microtextures of biotite flakes are used in this paper to map local states of strain and stress around fault segments and offsets. The data obtained will be available to understand the origin of fault segmentation, stress orientation and deformation around fault segments and offsets, and coalescence (=linkage) of fault segments, which have recently been studied by many authors (e.g. Segall & Pollard, 1980[2]; Wesnowsky, 1988[3]; Martel et al., 1988[4]; Peacock & Sanderson, 1991[5]; Anders & Schlische, 1994[6]; Burgman & Pollard, 1994[7]; Burgman et al., 1994[8]; Cartwright et al., 1995[9]; Childs et al., 1995[10], 1996[11]; Dawers & Anders, 1995[12]; Huggins et al., 1995[13]; McGrath & Davison, 1995[14]; Ohlmacher & Aydin, 1997[15]; Vermilye & Scholz, 1999[16]).

2. Description of microtextures around microfault

2. 1 Rock structure

The specimen (boring core) examined in this paper is structurally characterized by a single set of schistosity, which is quite planar, and a single set of schistosity-parallel microcrack under naked eyes. Thin sections for the investigation of microtextures around the microcrack were produced normal to the microcrack and along three different directions. Fig. 2 is microphotographs for the microcrack observed on one of the thin sections, which clearly shows that the microcrack occurs along a microfault. Microtextures around the microfault are described and discussed in this paper.

It is clear from microphotographs of Fig. 2 that biotite flakes show preferred shape orientation forming a single set of schistosity. Their (001) planes are also preferably oriented parallel to the schistosity, as is obvious in Fig. 2, though their (001) fabric diagram is not shown in this paper. Quartz and feldspar are only weakly elongated and show only weakly preferred shape orientation along the schistosity (Fig. 2). The domain in which the microfault is found is rather mica-rich (Fig. 2).

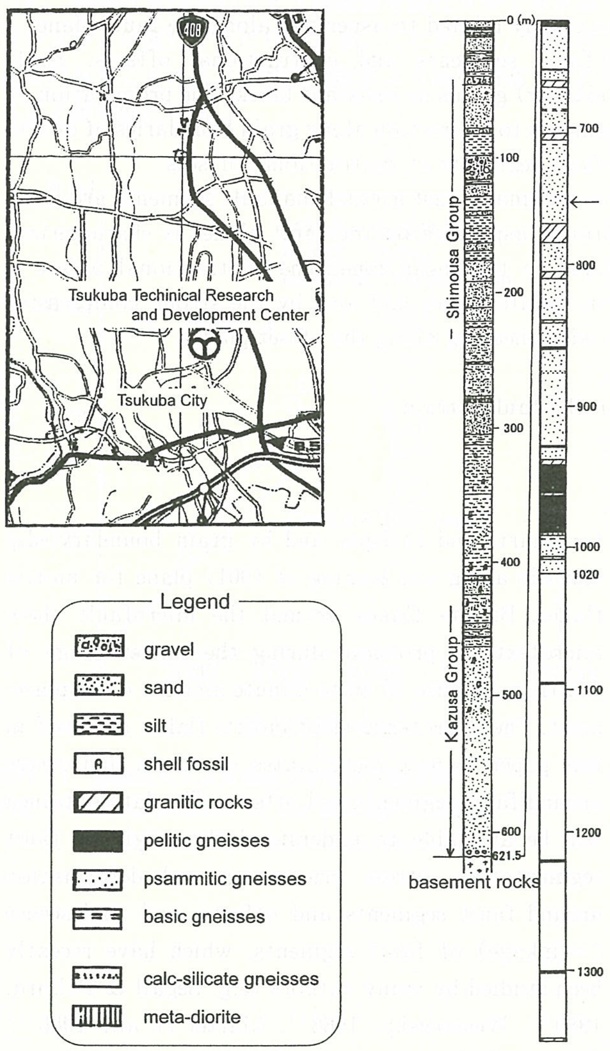

Fig. 1 Locality of the Tsukuba 1350m borehole and geological columnar section of the boring, showing the locality (arrow : G.L.-754.5m) of the specimen described in this paper.

2. 2 Microtextures around microfault

Figs. 2, 3, 4, 5 and 6 illustrate that the microfault contains offsets of the same sense, showing fault segmentation, but that fault traces at the junction between adjacent segments are continuous, showing curved shapes of fault plane, i.e. bend type offsets. Therefore, the microfault is described in term of a segmented fault trace, and the offsets should be referred to as either one of contractional bend and extensional bend, following Childs et al.'s (1996)[11] definition.

Kink bands are observed in biotite flakes but not in muscovite flakes of the biotite schist, although folds of gentle form are recognized in both flakes (Figs. 2, 3, 4, 5, 6, 8 and 9), but biotite flakes with kink bands and folds of gentle form are recognized only within a narrow domain restricted along the microfault, as shown in Figs. 2, 3a, 4a, 5a, 6a, 7, 8 and 9. Fig. 7d is a microphotograph for biotite flakes at the position of ca. 2 mm far from the microfault, not showing deformation structure such as kink band and fold.

Therefore, the propagation of fault tips and fault growth, which are related to the formation of the microfault, are considered to have occurred through the formation of kink bands and folds of gentle form in biotite flakes. Quartz and feldspar around the microfault show quite locally only weakly wavy extinction, probably reflecting their intracrystalline plastic deformation during faulting (Figs. 4b, 5, 8 and 9), but feldspar shows rarely fracturing along cleavage (Fig. 6c). In order to understand local state of stress and deformation processes in the biotite schist during faulting, therefore, microtextures of biotite flakes around the microfault will be examined, clarifying mode of occurrence, orientation pattern and intensity variation of development of kink bands and folds of gentle form.

Microflakes of white mica are weakly crystallized only along fault planes of fault segments and offsets (Figs. 3, 4b, 5, 6, 8a and 9). They are considered to have been derived from decomposition of K-feldspar and plagioclase grains along the fault planes during faulting.

2. 2. 1 Detailed description of microtextures around fault segments

As is obvious in Figs. 2, 3, 4, 5, 6, 7 (a, b and c), 8 and 9, most part of fault planes of fault segments run through grain boundaries between biotite flakes, between biotite flakes and quartz (or feldspar) and between quartz and quartz (or feldspar). At the fault planes of fault segments which are placed along grain boundaries between biotite flakes and parallel to (001) planes of biotite, they are commonly rather planar, and kink bands and folds of gentle form are not or only weakly developed in their surrounding biotite flakes (Figs. 3a and 7 (a, b and c)). While, as they are not parallel to (001) planes of biotite, even though they are placed along grain boundaries between biotite flakes, kink bands and folds of gentle form are strongly developed in their surrounding biotite flakes (Figs. 4f, 5a, 8b, 8c and 9).

Where the central parts of fault segments run through grain boundaries between biotite flakes and quartz (or feldspar), they commonly show more or less curved irregular shapes, and both kink bands and folds of gentle form are uniformly observed in their surrounding biotite flakes (Figs. 4c, 6c, 8b and 9). It can be said that the formation of kink bands in biotite flakes is related to asperities along the fault planes.

Kink bands produced under coaxial strain condition are commonly developed in symmetric orientation of such conjugate sets that the sense of rotation of (001) plane of biotite flakes in the bands is reverse between the different sets (cf. Paterson & Weiss, 1966[17]; Price & Cosgrove, 1996[18]). Such the symmetric development of the conjugate kink bands is only rarely observed in the central parts of fault segments, as shown in Figs. 3b and 7c. The conjugate kink bands and folds of gentle form, whose axial surfaces are oriented at high angles to (001) planes of biotite flakes, are ascribed to compressive strain parallel and subparallel to the fault planes. As illustrated in Figs. 4c, 4f, 5a, 6c, 8b, 8c, 9b, 9c and 9d, however, kink bands in biotite flakes around the fault segments show a clear tendency to be developed in asymmetric fashion, being characterized by predominance of a single set, which shows parallel arrangement to each other and the same rotational sense of (001) planes of biotite flakes. The detailed observations further indicate that the angles between the trend of those kink bands and the fault plane frequently slightly but clearly decrease toward the latter plane, forming curved shapes (Figs. 4d, 4f, 5a and 8c). As elucidated by Dewy (1965)[19] and others, generally speaking, the predominance of kink bands of a single set, which show the same shear sense and parallel arrangement to each other, appears under non-coaxial strain condition. The sense of local shear along the predominant set is harmonic with that of the remote shear for the system concerned. From such the asymmetric development of kink bands as shown in Figs. 4c, 4d, 4f, 5a, 6c, 8b, 8c, 9b, 9c and 9d, therefore, it can be concluded that the biotite schist of narrow domains just around the fault segments was deformed as a right-lateral shear zone with the local compressive stress trajectory oriented only slightly oblique to their trend, giving rise to a microfault in its centers with the highest magnitude of strain, though stress and strain pictures are much more complicated just around sharp asperities.

The microfault is rarely associated with subordinate branching microfaults as, for example, shown in Fig. 9c. When they develop cutting across (001) planes of biotite flakes, they appear as kink bands and further as slip along the band boundaries. Their extension is also developed as slip along (001) planes of biotite and/or along grain boundaries of quartz (or feldspar). Such the subordinate microfaults may be referred to as thrust shear (P) (cf. Skempton, 1966[20]); Tchalenko, 1970[21]).

2. 2. 2 Detailed description of microtextures around offsets

As shown in Fig. 2, the fault segments are linked by bend type offsets, forming a segmented fault trace. The bend type offsets can be now referred to as contractional bends (cf. Childs et al., 1996[11]), judging from such the above-mentioned evidence that the deformation around the fault segments is as a whole explained in terms of compression subparallel to and right-lateral shear along the fault planes, as read from microphotographs of Figs. 4c, 4f, 5a, 6c, 8b, 8c, 9b, 9c and 9d.

The terminations of fault segments commonly appear, as the fault planes abut on quartz (or feldspar) grains, forming contractional bends. The offset separation is very small but clear between the adjacent fault segments, as shown in Figs. 2, 3a, 4a, 5a and 6.

At the contractional bend of the position A of Fig. 2a, the fault plane is continuous between the adjacent fault segments (Fig. 3a). Namely, the contractional bend is recognized as a single fault plane, which runs along the boundaries between biotite flakes and feldspar grain: at the one side of the fault plane occurs feldspar grain, though it is partly occupied by biotite flake, and at the other side occur biotite flakes (Fig. 3c). While, at the contractional bend of the position F of Fig. 2d, fault planes are developed branching along boundaries between quartz and quartz (or feldspar) grains and between biotite flakes and quartz (and feldspar) grains (Fig. 4).

Microflakes of white mica are newly crystallized along the fault planes of those contractional bends (Figs. 3c and 4b).

As is obvious in Figs. 3c and 4d, kink bands are considerably strongly developed in biotite flakes along the contractional bends. They show predominance of a single set, which is preferably oriented at high angles to the trend of the adjacent fault segments and at small angles to the fault planes of the contractional bends, and whose shear sense is harmonic with that of the remote state, showing that sense of shear along the contractional bends is harmonic with that of the remote state.

Fig. 3c also indicates that a thrust shear as subordinate microfault develops through biotite flakes, destroying orientation pattern of kink bands in and around the contractional bend. The development of such the kink bands and thrust shear indicates strong compressive strain at the contractional bend, which occurs in a direction parallel to the general trend of the adjacent fault segments.

The fault plane at the position E of Fig. 2c shows S shape. Its sharp refraction occurs where it encounters a K-feldspar (Fig. 6d). Namely, the tip of fault plane is absent from biotite flakes, like the case of the contractional bend of Figs. 3c and 4. The orientation pattern of kink bands in biotite flake of the position E is essentially the same as that of the contractional bend of Figs. 3c and 4d, showing strong compressive strain and right-lateral shear along the general trend of the microfault. It is clear that the position E is a contractional bend of the microfault, but, strictly speaking, it is not clear whether or not the position E is an offset as a junction of two fault segments.

The fault planes of Figs. 8b and 9 are gently curved. Their gentle refraction occurs along grain boundaries between biotite flakes and quartz (and K-feldspar). This type structure is also not referred to as bend type offset at a junction of two fault segments but as a curved fault segment. Many of kink bands at the position A in Fig. 9a, which biotite flake in the contractional bend of the position E of Fig. 2c, are oriented at high angles to the fault plane, and are referred to as chevron folds by Paterson & Weiss (1966)[17], which belong to the intersected conjugate kink bands produced under schistosity-parallel compressive strain of high magnitude. K-feldspar grain along this curved fault plane is also strongly decomposed into microflakes of white mica (Fig. 9a).

While the position C of Fig. 2b (= Fig. 5) is considered to be an offset, although the offset separation is very small. At the position C of Fig. 2b, namely, there is a linkage of fault segments, which is referred to as a contractional overlap following Childs et al.'s (1996)[11] definition: the straight extension of the fault segment along biotite-muscovite flakes E to A in the open crack side can be traced from the position F of Fig. 5a, through the position G of Fig. 5a (Fig. 5b), to the position H of Fig. 5b, and it is bifurcated near biotite A (Fig. 5a) to join with the fault segment running from the position K to the position L of Fig. 5a. The linkage of those two fault segments near biotite A looks like a contractional bend, even though its offset separation is very small. However, the straight extension of the fault segment running from the position K to the position L can be also traced closely to the grain boundary between biotite C and biotite D, showing that the linkage of fault segments occurs here as a contractional overlap. Kink bands in biotite flakes near the position H of Fig. 5b, which corresponds to the tip of the fault segments, are developed in the greatest intensity, showing fault-parallel compressive strain.

Microphotograph (Fig. 6a) of the position B of Fig. 2b shows two steps of the fault plane. The fault step in the upper part of the figure is essentially the same as the contractional bend of Fig. 3 (Fig. 6b). While that in the lower part appears to be a contractional overlap for two fault segments a long plagioclase grain boundaries: the one is running from the position A to the position B, and the other from the position C to the position D. The former is connected by a cleavage crack with the latter. Microflakes of white mica are found along those fault segments and cleavage clack (Fig. 6c).

3. Discussion

The above-described microfault is a segmented fault trace produced along the schistosity of biotite schist, which consists of fault segments linked by contractional bends and rarely contractional overlap. On the basis of the data obtained, scenarios for fault segmentation and linkage of fault segments and local states of strain and stress around fault segments and contractional offsets would be to some extent examined.

The microfault as a segmented fault trace is developed within a narrow domain parallel to the schistosity of the biotite schist, which is rather biotite-rich as a weakness zone. The fault planes of individual fault segments run along the grain boundaries between biotite flakes and between those and quartz (or feldspar), and the terminations of fault segments occur where the fault planes abut on quartz (or feldspar). Like the case of large-scale fault investigated by Vermilye & Scholz (1999)[16], thus, the fault segmentation is considered to occur where the fault slip encounters quartz (or feldspar) grains as resistant block, even though they show contractional overlap (Figs. 5 and 6c).

Fault traces at the junction between adjacent segments are continuous, refracting along surfaces of quartz (or feldspar) grains. As the propagation of their tips encounters quartz (or feldspar) grains as obstacle, they are considered to be deflected from the planes of the fault segments to the obstacle surfaces. At the contractional bends where biotite flakes do not present along the obstacle, the propagation of fault tips occurs branching along some grain boundaries (or cleavage crack) between quartz and quartz (or feldspar) (Fig. 5).

As the fault planes of the central parts of fault segments run through grain boundaries between biotite flakes and along (001) planes of biotite, they commonly are rather planar, and deformation fabrics such as kink bands are scarcely produced in their surrounding biotite flakes. Judging from orientation pattern of such the kink bands, however, the local state of stress around the planar grain boundaries along which the faulting occurs is characterized by the compressive stress trajectory oriented nearly parallel to the fault planes. As they run through grain boundaries between biotite flakes and quartz (or feldspar) and they are not parallel to (001) planes of biotite, even though they run through grain boundaries between biotite flakes, however, they commonly are irregular, and kink bands are commonly produced only in their surrounding biotite flakes, showing that their development of kink band is restricted within a narrow zone along the microfault. The propagation of fault slip along the irregular grain boundaries as asperities is thus considered to be responsible for the formation of kink bands. As read from orientation pattern of such the kink bands, roughly speaking, the local state of stress around the irregular grain boundaries along which faulting occurs is also characterized by the compressive stress trajectory oriented slightly oblique to the fault planes.

Such the stress pattern just around the fault planes is approximately compared to theoretical stress pattern given by Segall & Pollard (1980)[2] and Ohlmacher & Aydin (1997)[5]. However, the modes of occurrence of kink bands and folds of gentle form, as shown in Figs. 8 and 9, appear to be related to much more complicated stress patterns around sharp asperities.

The kink bands in biotite flakes along the fault planes of the contractional bends, which are developed in the greatest intensity and in predominance of a single set harmonic with shear sense of the remote state, indicate that the linkage of the fault segments occurs accompanying strong compressive strain nearly parallel to the general trend of fault planes. Such the deformation style (biotite B in Fig. 4a; Fig. 4d) is different from that of biotite flakes (biotite C in Fig. 4a; Fig. 4e) just behind quartz (or feldspar) grains along the fault planes of the contractional bends, which develop in conjugate sets, owing to abrupt decrease of non-coaxiality of strain.

The segmented fault trace can now be assumed to be a microfault system localized from an elastic proto-shear zone with narrow width along the schistosity plane, following Childs et al. (1996)[11].

Judging from the above-described microtextures around the microfault, the biotite schist appears to have mainly been deformed in ductile fashion during faulting, which is characterized by the formation of kink bands and folds of gentle form in biotite flakes, slip along (001) plane of biotite, formation of wavy extinction (= intracrystalline plastic deformation) in quartz and feldspar, and sliding along grain boundaries of those constituent minerals accompanying decomposition of feldspar grains and crystallization of microflakes of white mica. Brittle fracturing did not play any important role in deformation mechanism of the constituent minerals during faulting. The formation of kink bands in biotite flakes is rarely associated with slip along their band boundaries as subordinate mechanism.

Fig. 5a illustrate deformation types of biotite and muscovite flakes near the segment boundary: biotite A, muscovite B, biotite C, biotite D and biotite E are orderly oriented along the fault plane as observed from the fault tip toward the central part of fault segment. The (001) plane of biotite A and that of muscovite B are parallel to the fault plane, that of biotite C is subnormal to it and subparallel to the slip direction on it, and that of biotite D is subparallel to it. Biotite E is a composite grain consisting of biotite (E) and muscovite (E). Kink bands are strongly developed in biotite A and biotite D, while they are not in muscovite B and biotite C. Biotite E is characterized by the development of folds of gentle form. Muscovite is generally more resistant to deformation than biotite (cf. Passchier & Trouw, 1996[22]). The (001) plane of biotite C is oriented nearly parallel to the XZ plane in the shear zone around the microfault, while that for biotite A, biotite D and biotite E is oriented nearly parallel to the YZ plane. Namely, biotite C is more unfavorably oriented for the formation of kink bands and folding than biotite A, biotite D and biotite E (cf. Grujic & Mancktelow, 1995[23]). In muscovite flakes around the microfault are recognized folds of gentle form but not kink bands. That biotite E shows only folds of gentle form, unlike the case of its adjacent biotite D, is inferred to be because it is a composite grain containing muscovite (E). Such the difference in deformation type between biotite and muscovite is an available information about physical condition under which the schistosity-parallel faulting occurred in the biotite schist.

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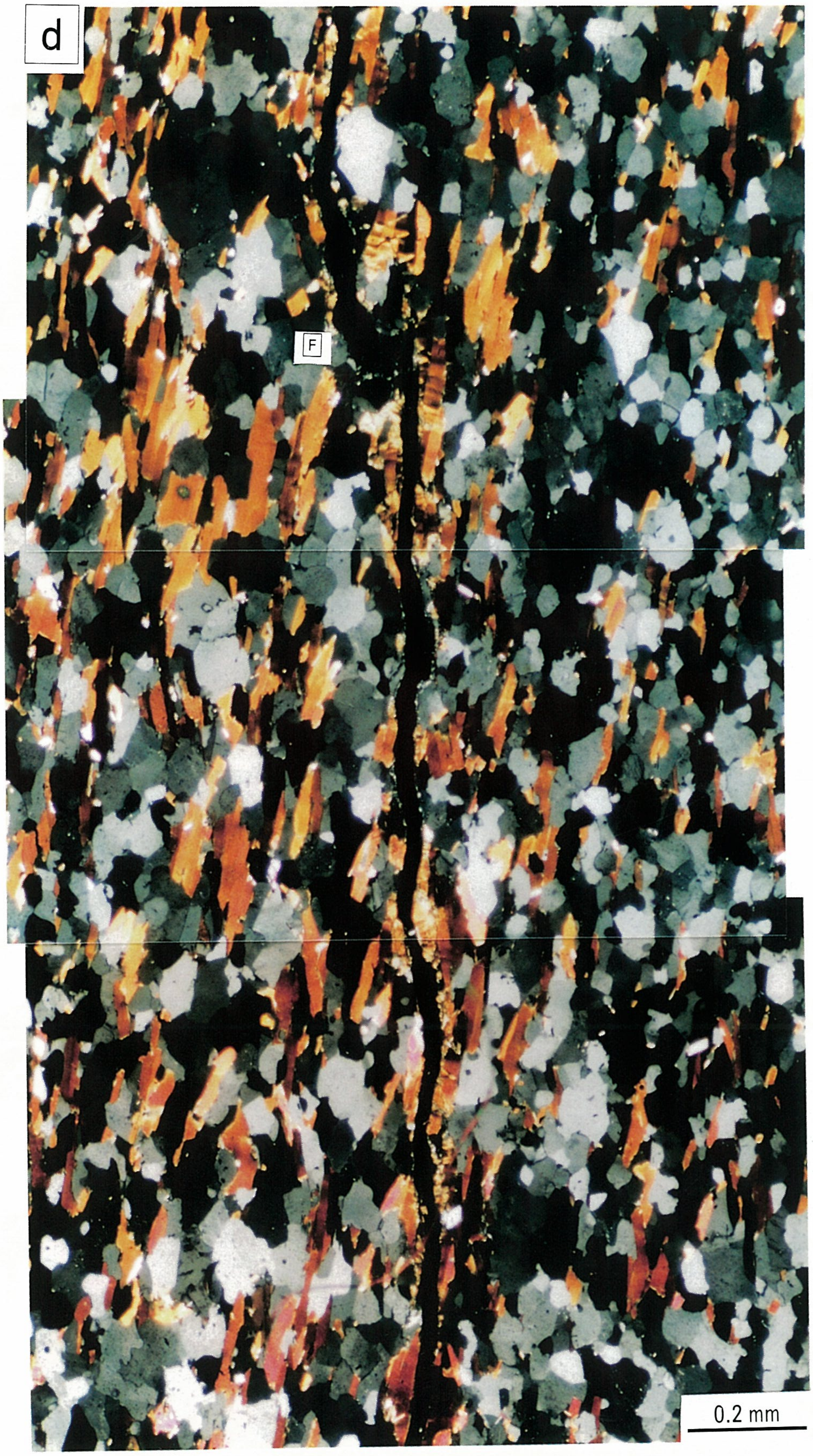
Fig. 2 (*continued*)



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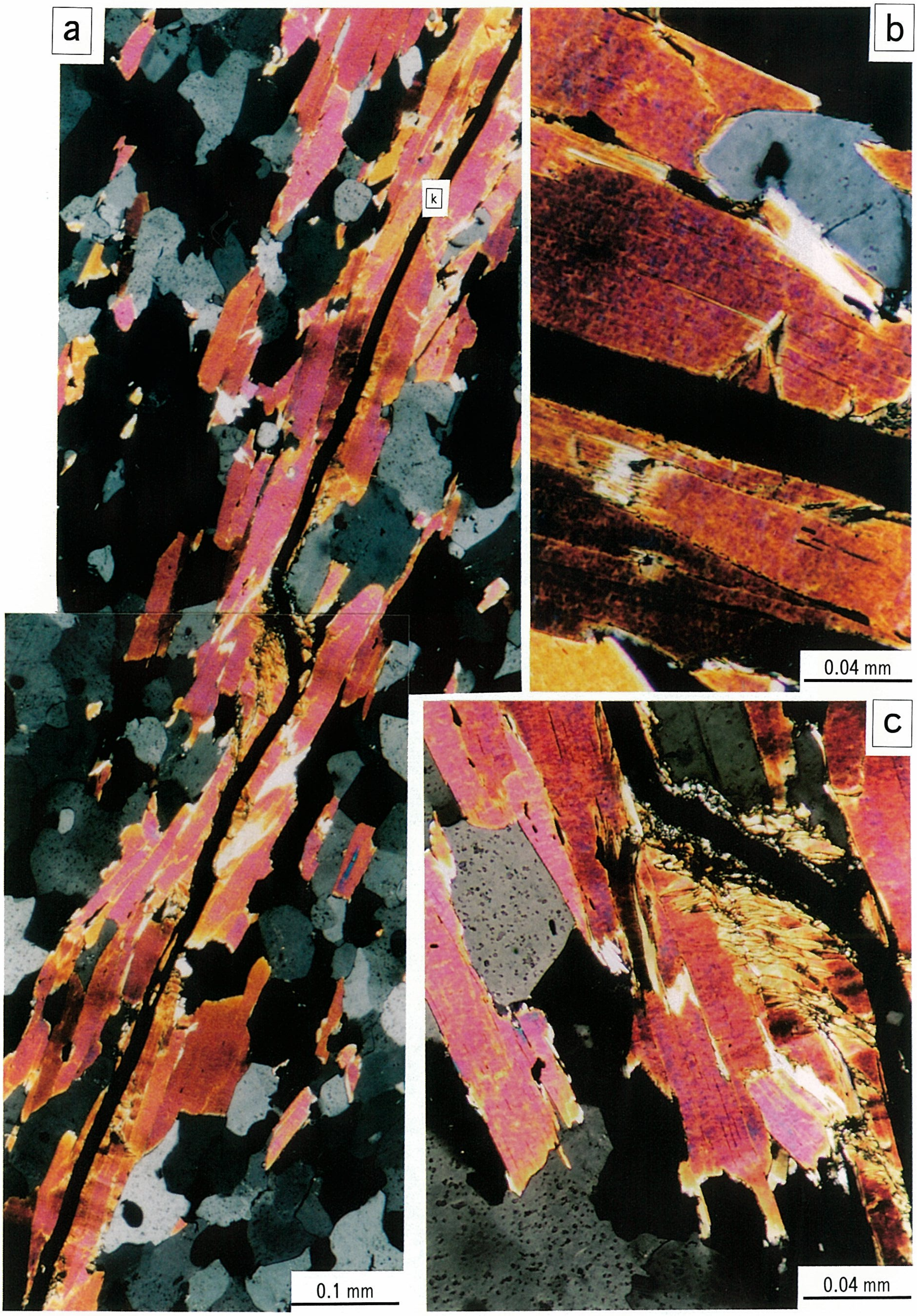


Fig. 3 (a) Enlarged microphotograph of the microfault around the position A of Fig. 2. (b) Enlarged microphotograph of the position k in Fig. 3a, showing conjugate kink bands in biotite flake. (c) Enlarged microphotograph of the contractional bend of Fig. 3a.

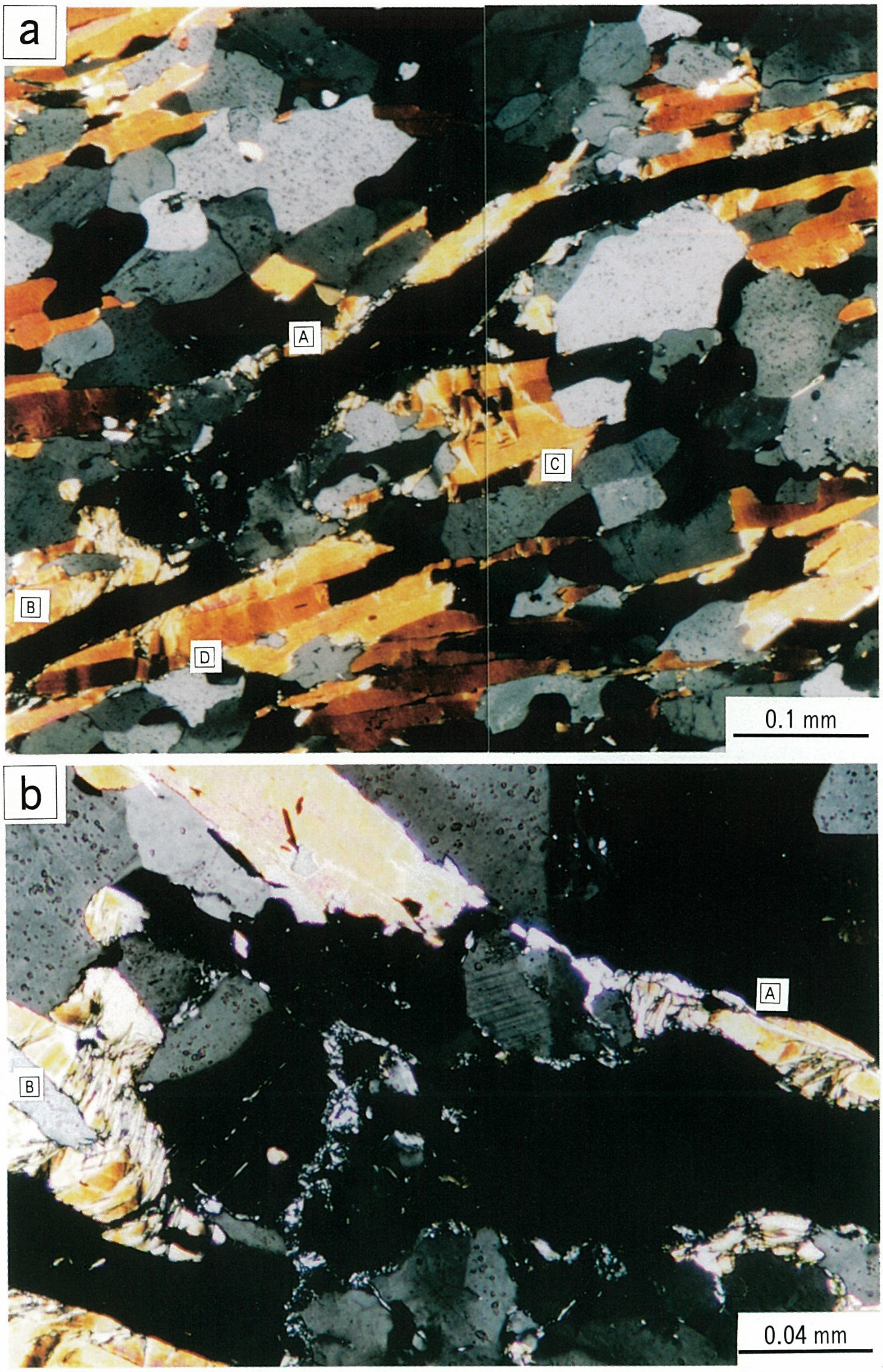
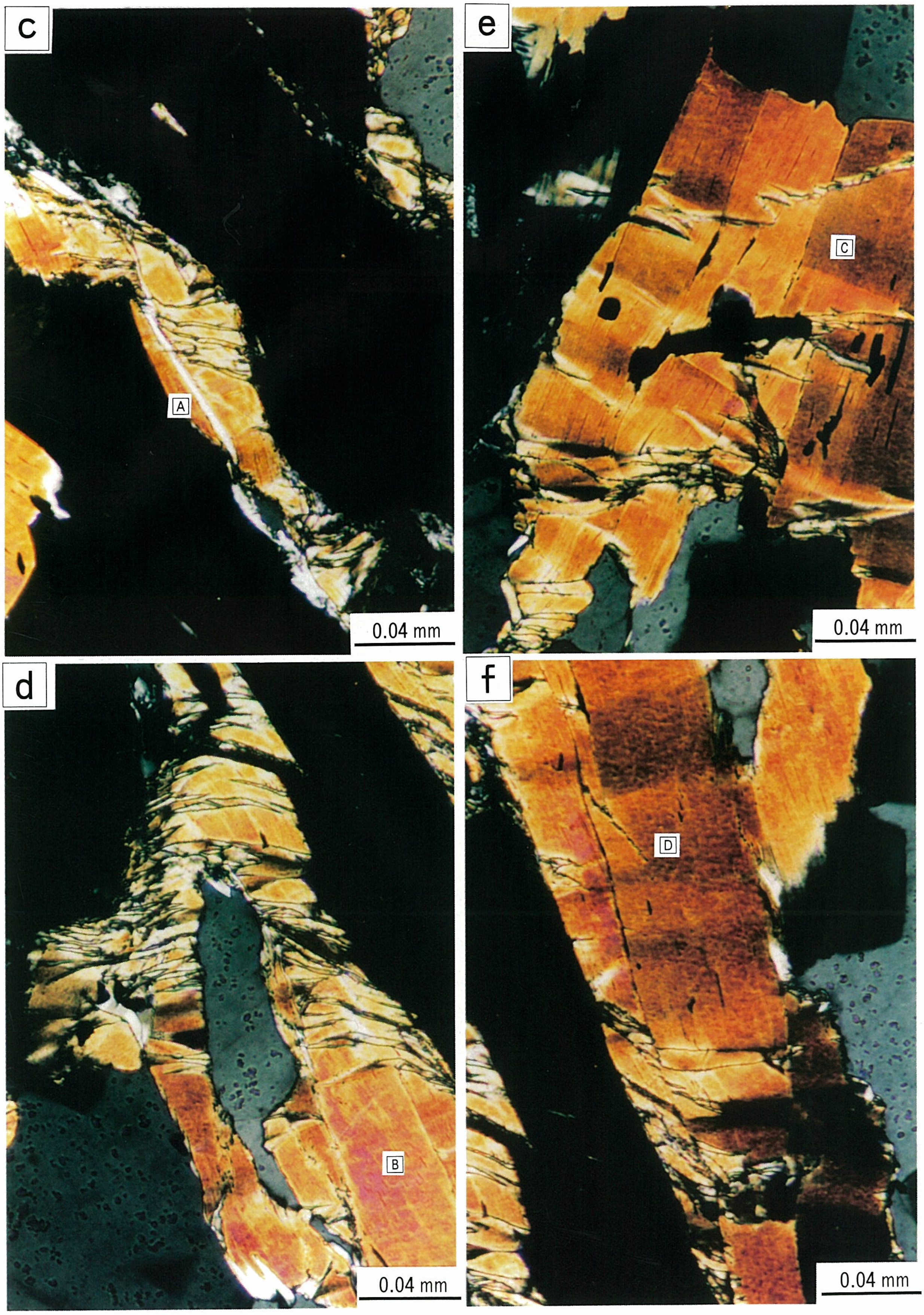


Fig. 4 (a) Enlarged microphotograph for the fault segments with the contractional bend of the position F in Fig. 2. (b) Enlarged microphotograph for feldspar and quartz of the contractional bend of Fig. 4a. (c) Enlarged microphotograph for biotite flakes of the position A in Fig. 4a. (d) Enlarged microphotograph for biotite flakes of the position B in Fig. 4a. (e) Enlarged microphotograph for biotite flakes of the position C in Fig. 4a. (f) Enlarged microphotograph for biotite flakes of the position D in Fig. 4a.



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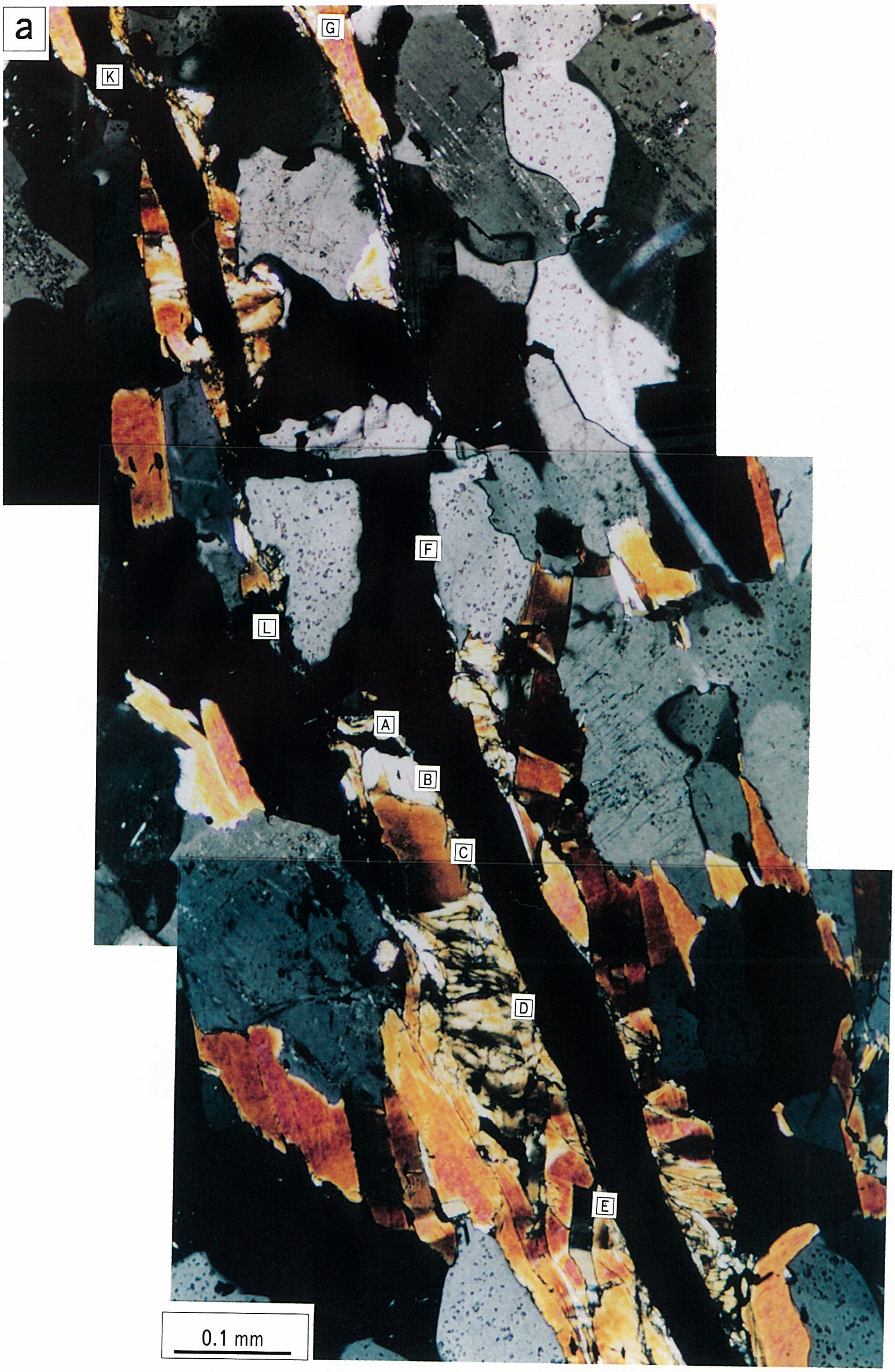

Fig. 5 Microphotographs for the fault segments with the contractional overlap of the position C in Fig. 2b. The position G in Fig. 5a coincides with the position G in Fig. 5b.
A: biotite flake with kink bands, B: muscovite flake, C: biotite flake, D: biotite flake with kink bands, E: composite grain consisting of biotite and muscovite, which shows folds of gentle form. For further explanation see the text.

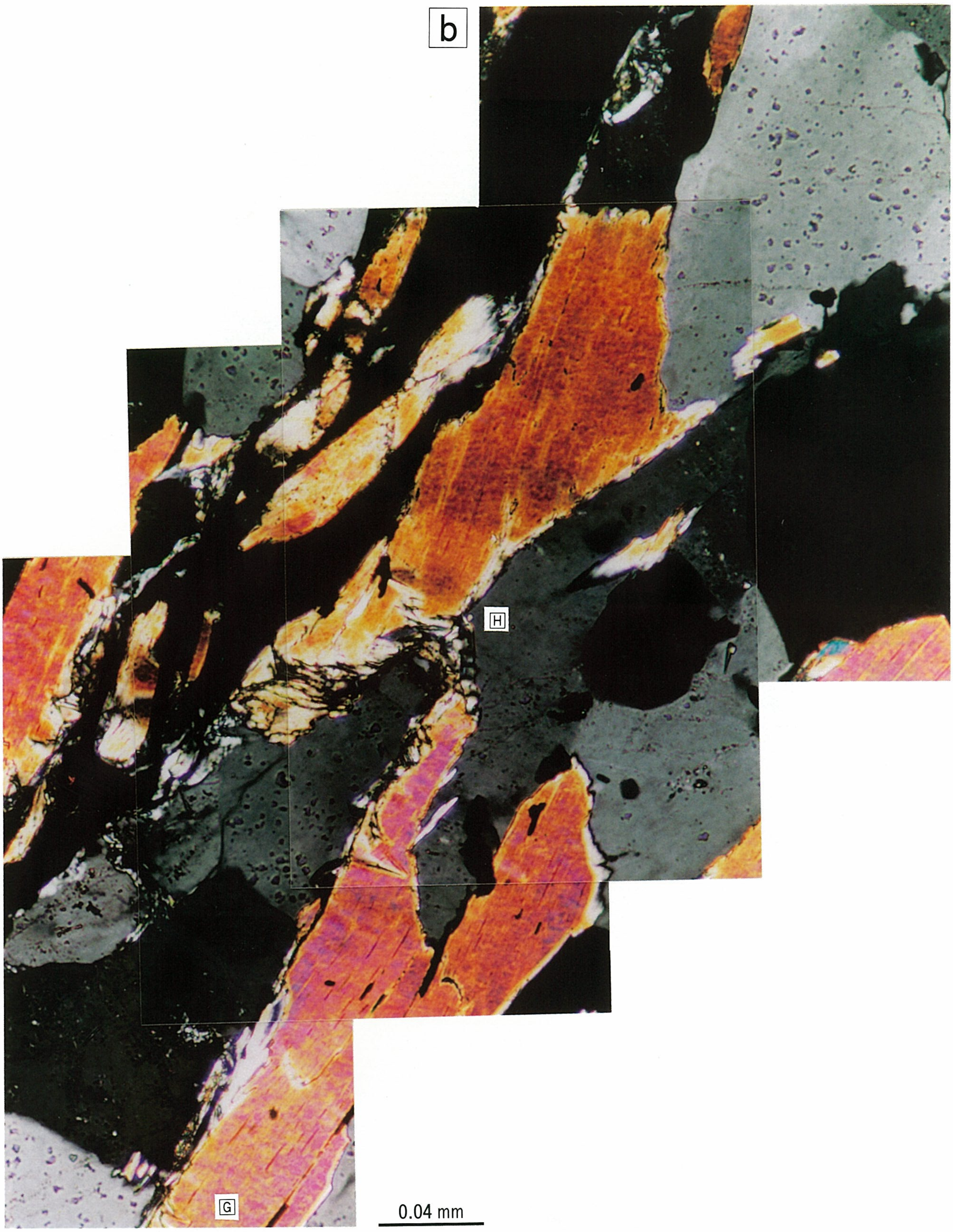

Fig. 5 (*continued*)

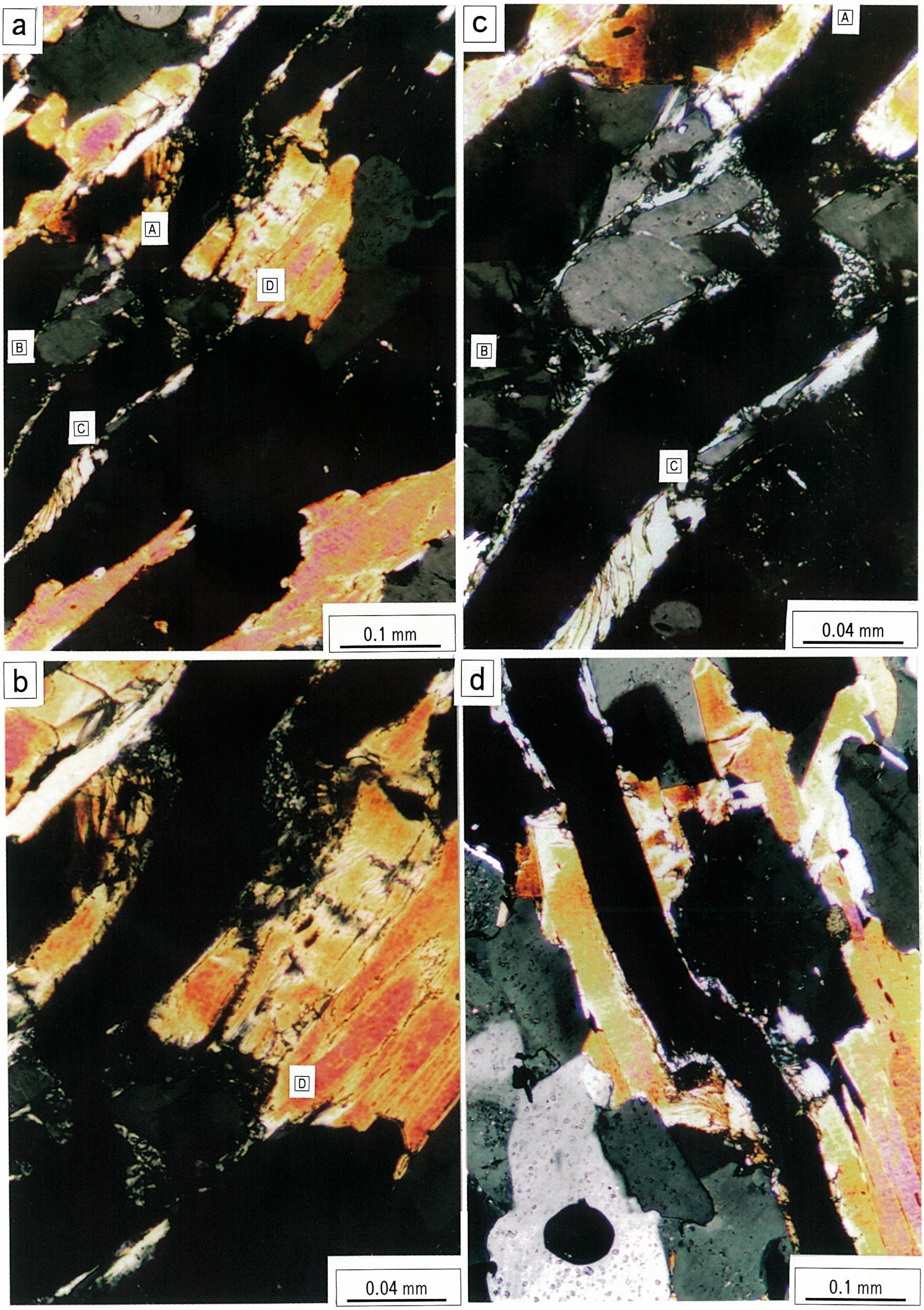

Fig. 6 (a), (b) and (c) Microphotographs for the fault segments with the contractional offsets of the position B in Fig. 2b. (d) Microphotograph for the fault segments with the contractional bend of the position E in Fig. 2c. For further explanation see the text.

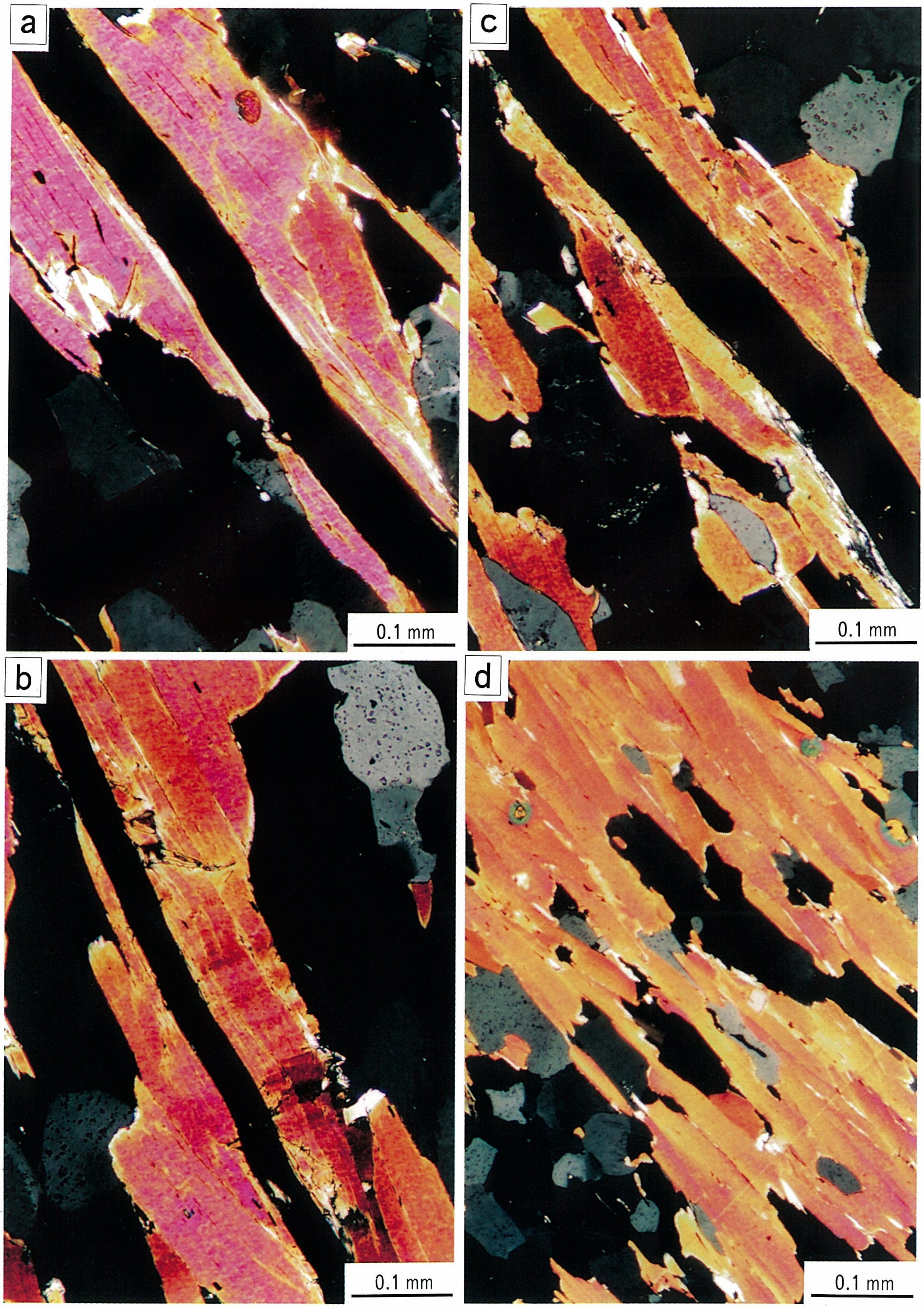

Fig. 7 (a), (b) and (c) Microphotographs for the central part of the fault segments, which run along (001) planes of biotite flakes. (d) Microphotograph for biotite flakes at the position of ca. 2 mm far from the fault plane.

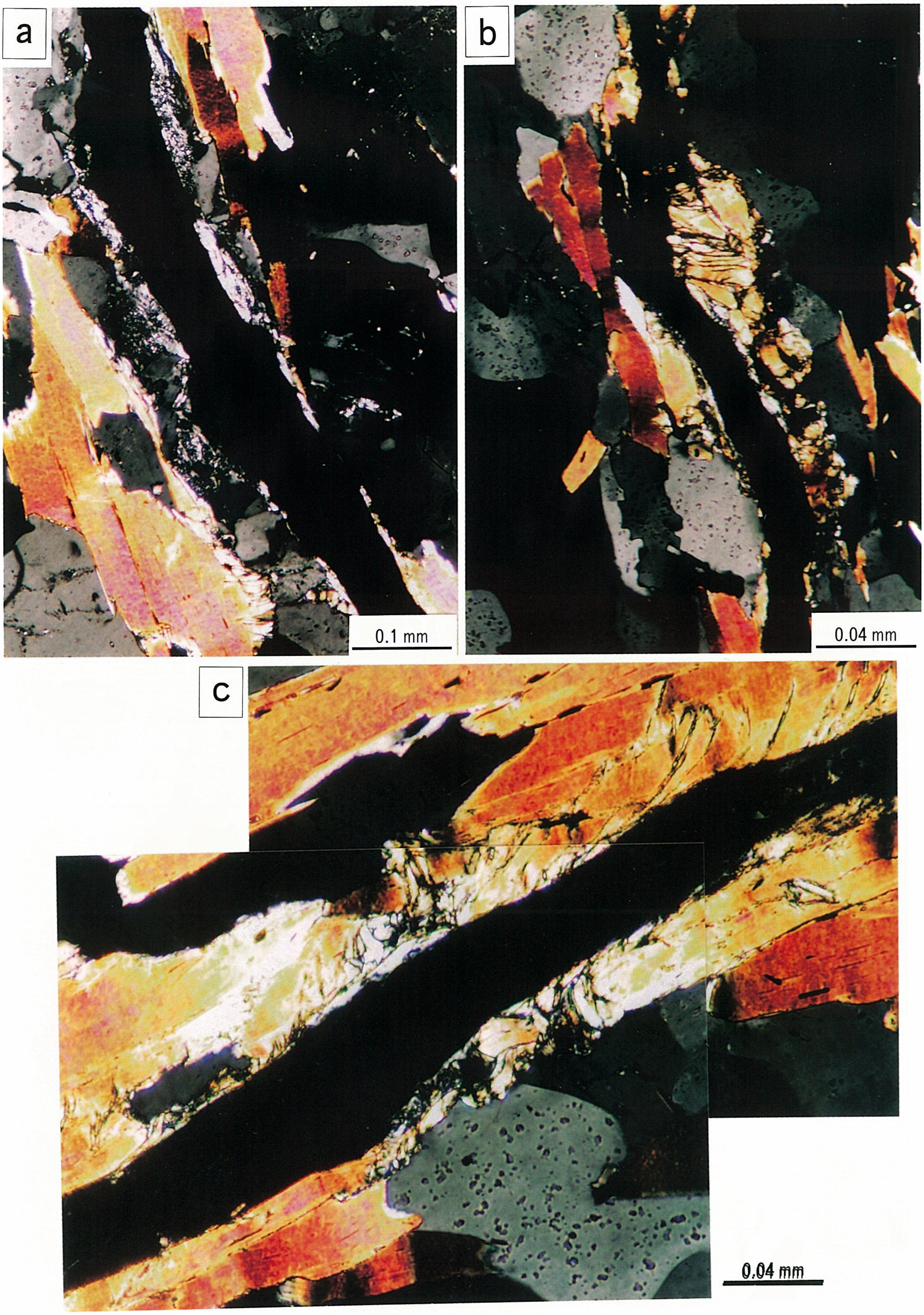

Fig. 8 Microphotographs for curved fault segments. For further explanation see the text.

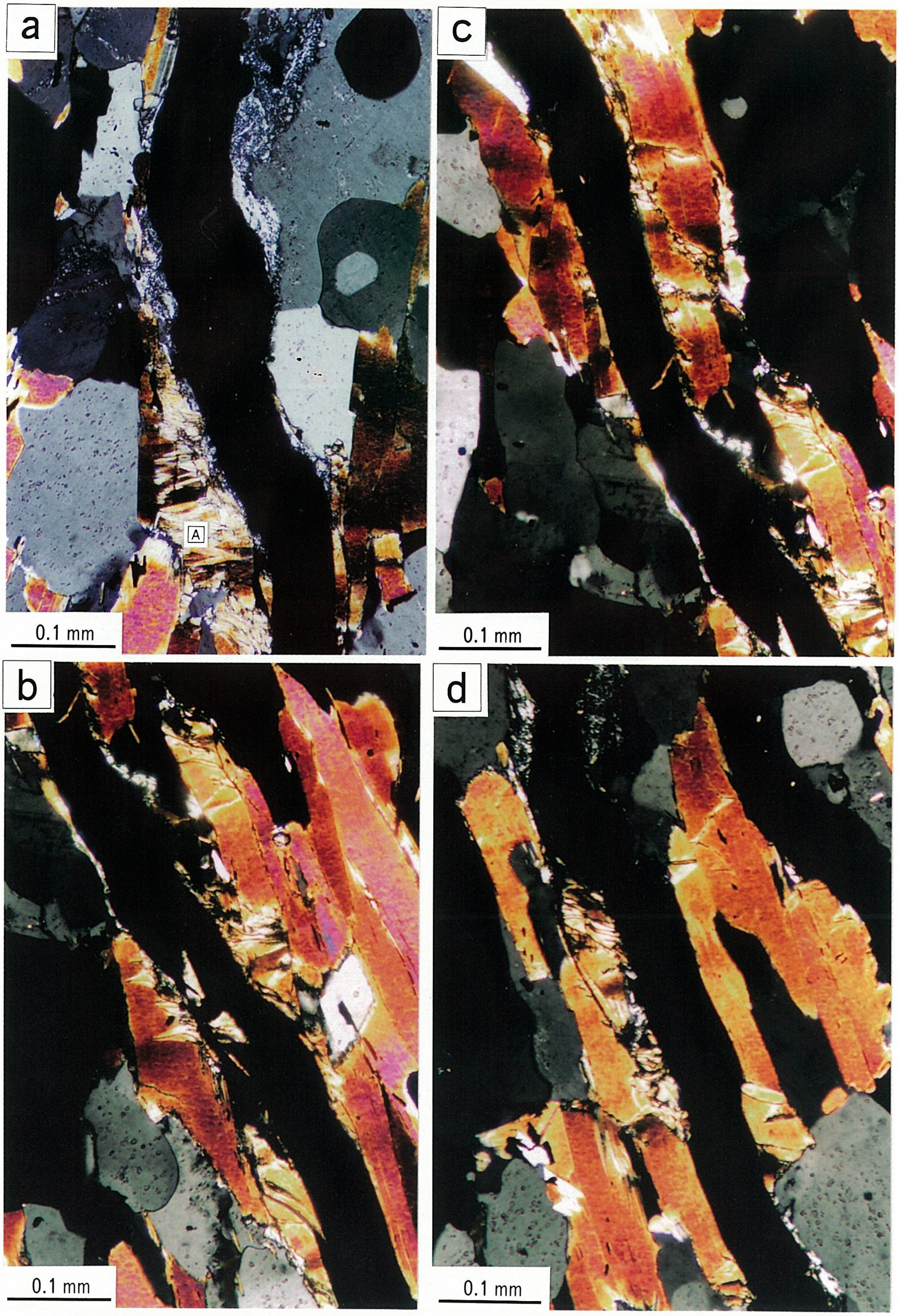

Fig. 9 Microphotographs for curved fault segments. For further explanation see the text.

つくば技術開発センター1350mボーリングコアの地質学（5）
―― 片状構造平行断層のセグメント化と連結 ――

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（要　旨）

応用地質株式会社つくば技術開発センター（茨城県つくば市）において掘削された1350mボーリングの深度754.5mから採取された黒雲母片岩には，黒雲母片の形態・格子定向配列によって規定されるひとつの平滑な片理が顕著に発達する。この片理に沿ってひとつの微小断層が発達する。本論文では，この片理平行微小断層に沿って発達する微細組織を記載し考察した。微小断層は，構成鉱物の脆性的破断によるのではなく，黒雲母片の（001）面に沿うすべり，キンキングと緩やかな褶曲の形成，黒雲母・石英・長石粒界すべり，断層面に沿った長石の粒界変質と白色雲母微小片の結晶作用によって起こっているようである。断層形成はおそらく塑性変形条件下で起こったものと考えられる。
断層面が黒雲母片と石英（あるいは長石）の粒境界を通過するところでは，断層面は不規則で，周囲の黒雲母片にキンク帯が形成されるのが一般的である。一方，黒雲母片の間を通過する，あるいは黒雲母の（001）面に沿った平滑な断層面では，キンク帯の形成はまれである。キンク帯形成の有無が断層面に沿ったアスペリティ（asperities）と相関を持つことは明白である。

断層は，圧縮オフセット（contractional offsets）と断層セグメント（fault segments）からなるひとつのsegmented fault traceである。断層のセグメント形成は，断層すべりが石英（または長石）粒子にさえぎられたところで起こっている。ここで，断層の先端の伝播方向は，断層セグメントの行方をさえぎる石英（または長石）の粒界に沿う向きへと屈折し，隣接する断層セグメントと圧縮オフセットを介して連結している。

キンク帯の配列パターンから，断層セグメントのまわりの狭い領域は剪断帯であり，この領域と断層面上のアスペリティに沿った局所応力状態は，剪断帯に低角で斜交する方向の圧縮応力分布で特徴付けられるものであることが読み取れる。圧縮オフセットにおいては，黒雲母片にキンク帯が最大強度をもって発達し，断層セグメントの一般的トレンドにほぼ平行に強い圧縮応力が働いたものと考えられる。

キーワード：キンク帯，セグメント化，歪み，片理平行断層，連結