Journal of Structural Geology, Vol. 11, No. 5, pp. 509 to 522, 1989
Printed in Great Britain

0191-8141/89 $03.00 + 0.00

Crustal-scale strike-slip deformation in Hokkaido, northern Japan

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(*Received* 1 *July* 1988; *accepted in revised form* 3 *January* 1989)

Abstract—Field surveys in Hokkaido reveal that the entire tectonic belt in northern Japan was a right-lateral shear zone from Eocene to Middle Miocene time. This zone of deformation can be followed northwards in Sakhalin for more than 2000 km, and formed at the same time as the opening of the Japan Sea. A thrusting component during the strike-slip deformation and later deformation stages led to the uplift of the deep parts of the shear zone, exposing a complete section through the upper crust. The stress field inferred from the analysis of fault sets is consistent with the non-coaxial deformation observed in the deeper ductile parts of the shear zone.

There is a transition from west to east across the width of the belt (100 km) from en échelon folds, thrusts and nappes at upper structural levels, through the brittle–ductile transition with an incipient vertical schistosity, into ductile deformation with a vertical foliation and metamorphic recrystallization in the amphibolite facies. Deep parts of the crust (granulites) were uplifted and retrogressed during the strike-slip movement. Fault-set analysis together with data concerning the direction and sense of nappe emplacement imply that thrusting, west of the ductile deformation zone, occurred during the strike-slip deformation. Minor flat-lying structures coexist with vertical pure strike-slip structures. This study and previous ones reveal a crustal-scale half-flower structure with superficial thrusting associated with a deep narrow ductile zone, with a high gradient of deformation and temperature.

INTRODUCTION

THE Hokkaido Central Belt (Figs. 1–3) is located along a major right-lateral strike-slip fault that was active during the opening of the Japan Sea from Cenozoic until the end of Middle Miocene time (Kimura & Tamaki 1986, Lallemand & Jolivet 1986). The strike-slip deformation can be followed for more than 2000 km from south to north across Sakhalin and Hokkaido (Kimura *et al.* 1983). Lallemand & Jolivet (1986) proposed that the Japan Sea opened as a right-lateral pull-apart basin during Miocene time between two major fault zones, one along the eastern coast of Korea and one along the Hokkaido Central Belt and Tartary Strait. The understanding of the timing of motion and stress field related to this deformation is thus very important. The deformed zone is up to 100 km wide. Thrusting during the strike-slip movement and post-Middle Miocene thrusting events led to the uplift of the deep parts of the crust (Komatsu *et al.* 1983). A complete cross-section of a strike-slip fault zone from upper structural levels to deep ductile deformation in the amphibolite facies can thus be observed. The aim of this paper is to describe and synthetize structural data acquired during field surveys through the entire belt in Hokkaido.

There has been a controversy whether Cenozoic deformation in the Hokkaido Central Belt is related to intracontinental strike-slip deformation (Jolivet 1986, 1988) or to oblique collision (Kimura *et al.* 1983). The strike-slip component of the movement is important in both cases. We do not intend to debate this controversy in this paper; instead we describe at different scales a structure which implies an important component of right-lateral strike-slip, and we reconstruct the behaviour of the crust during the deformation.

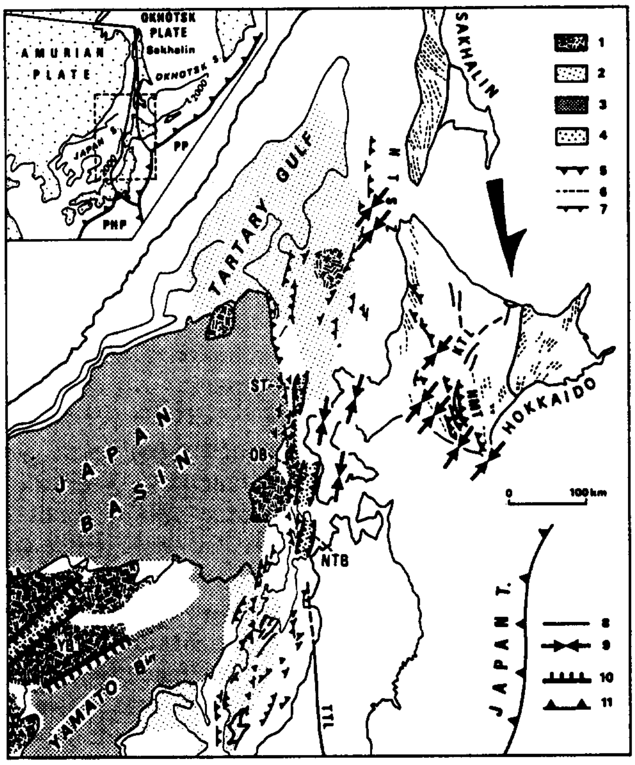

Fig. 1. Geodynamic context of the studied area and structural map of the northern Japan Sea area. 1: continental crust in the Japan Sea, 2: stretched continental crust, 3: oceanic crust, 4: recent sedimentary infill of en échelon depressions along the eastern margin of the Japan Sea, 5: Oligo-Miocene thrusts, 6: Oligo-Miocene fold axes, 7: active thrusts in the Japan Sea, 8: Oligo-Miocene strike-slip faults, 9: maximum horizontal compression for the Oligo-Miocene stage, 10: normal faults in the Japan Sea, 11: trace of subduction zone. P.P.: Pacific plate, PHP: Philippine plate, KTL: Kamishiyubetsu Tectonic Line, HMT: Hidaka main thrust, HTSZ: Hidaka Tartary shear zone, ST: Shiribeshi trough, OB: Okushiri basin, NTB: Nishi Tsugaru basin, YB: Yamato bank, TTL: Tanakura Tectonic Line.

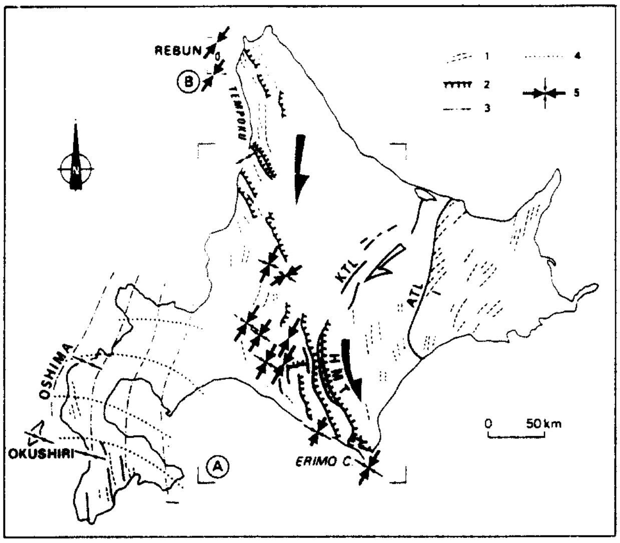

Fig. 2. Synthetic tectonic map of the Cenozoic deformations. 1: fold axes, 2: thrusts, 3: early compression directions (Oligocene to Middle Miocene) in the Oshima Peninsula after Yamagishi & Watanabe (1986), 4: late compression directions (Late Miocene to Recent), 5: compression directions deduced from this work (thick arrows: early stage, thin arrows: recent stage).

Kimura *et al.* (1983) first emphasized this strike-slip movement, describing the en échelon pattern of folds and thrusts in the western part of the belt (Figs. 2 and 3). Jolivet & Miyashita (1985) described the ductile deformation within the metamorphic parts and showed that it corresponds to a zone of right-lateral strike-slip deformation of Oligo-Miocene age, called the Hidaka shear zone. Watanabe (1988) described similar features in the northern Hidaka Belt. Jolivet & Cadet (1984) described the Iwani nappe in the Kamuikotan zone, which was emplaced towards the south during the early Tertiary. They proposed that the nappe was emplaced during the strike-slip movement, based on the direction and sense of emplacement. This contemporaneity was disputed, however, because it implies that a nappe was emplaced in a strike-slip zone, which may not be very usual. Our recent survey included analysis of fault sets in the folded Paleogene and Neogene sedimentary rocks west of the ductile zone. It shows that a stress field compatible with both the nappe emplacement and the strike-slip movement along the Hidaka shear zone was still active after the thrusting of the Iwanai nappe until Middle Miocene. It is therefore not necessary to postulate the existence of two different deformation stages, but rather a single progressive event that led to the formation of the pure strike-slip structures in the deeper parts of the crust and flat thrusts in shallower levels. We propose in this paper that the entire Hokkaido Central Belt formed a flower structure at a crustal scale during the strike-slip movement.

GEOLOGICAL SUMMARY

The Hokkaido Central Belt, which trends N–S, is located immediately to the north of the Kuril trench—Japan trench junction, and to the east of the Okhotsk plate–Amurian plate boundary (Fig. 1) (Eurasia–North America for Chapman & Solomon 1976, Okhotsk-Amurian for Savostin *et al.* 1983), which is now expressed as a compressive deformation zone along the eastern margin of the Japan Sea. There the oceanic lithosphere of the Japan Sea underthrusts the northern Japan arc (Fig. 1) (Fukao & Furumoto 1975). The deformation zone is wide, and the normal and strike-slip faults contemporaneous with the opening of the Japan sea have been reactivated as thrusts verging either west or east (Nakamura 1983, Tamaki & Honza 1984, Lallemand *et al.* 1985, Okada *et al.* 1985). The Central Belt is a Mesozoic suture later reworked by Cenozoic deformation and mostly by the Oligo-Miocene right-lateral strike-slip shear.

Various models have been proposed concerning the Mesozoic collision. The discrepancies between the models concern the age of the collision, which could be latest Jurassic, Middle or late Cretaceous, or even Cenozoic (Kimura *et al.* 1983, Kiminami *et al.* 1985, Jolivet 1986, Kimura 1986). We do not enter into this debate in this paper as we have only examined the structures formed during the Oligo-Miocene strike-slip deformation. Whether it is an intracontinental strike-slip fault or an oblique collision zone is another discussion we have addressed elsewhere (Jolivet *et al.* 1988).

The Cenozoic deformation can be divided in two main stages: a recent (post-Middle Miocene) E–W compression and an early (Eocene? to Middle Miocene) right-lateral strike-slip with a component of thrusting. Only the early deformation is in the scope of this paper. During the recent stage, which encompasses mainly the southern part of the belt, W-verging thrusts were formed (Mitani 1978, Kimura 1986). It was probably an early expression of the present day compression along the Japan sea eastern margin. By contrast the strike-slip stage encompasses the entire belt from north to south.

TECTONIC ZONING OF THE HOKKAIDO CENTRAL BELT

From west to east the following tectonic zones can be distinguished: the Rebun-Ishikari zone, the Cretaceous syncline, the Hidaka zone and the east Hidaka zone (Figs. 3 and 4).

The *Rebun-Ishikari* zone is constituted by Cretaceous turbidites (5000 m) called the Yezo Group (Matsumoto 1942, Okamura 1977, Kito *et al.* 1986), syntectonic Paleogene coal-bearing sandstones and Miocene molasse with Middle Miocene thick conglomerates and late Miocene and Pliocene tuffs and volcanics. The molasse was deposited in narrow N–S-trending basins with detrital supply coming from either east or west (Hoyanagi *et al.* 1986). Paleogene sandstones record rapid subsidence (Aihara 1978). This detrital sequence rests unconformably upon the oceanic material (ophiolite and blueschists of the 'Kamuikotan zone') emplaced as thrust sheets (Ishizuka *et al.* 1983) during the

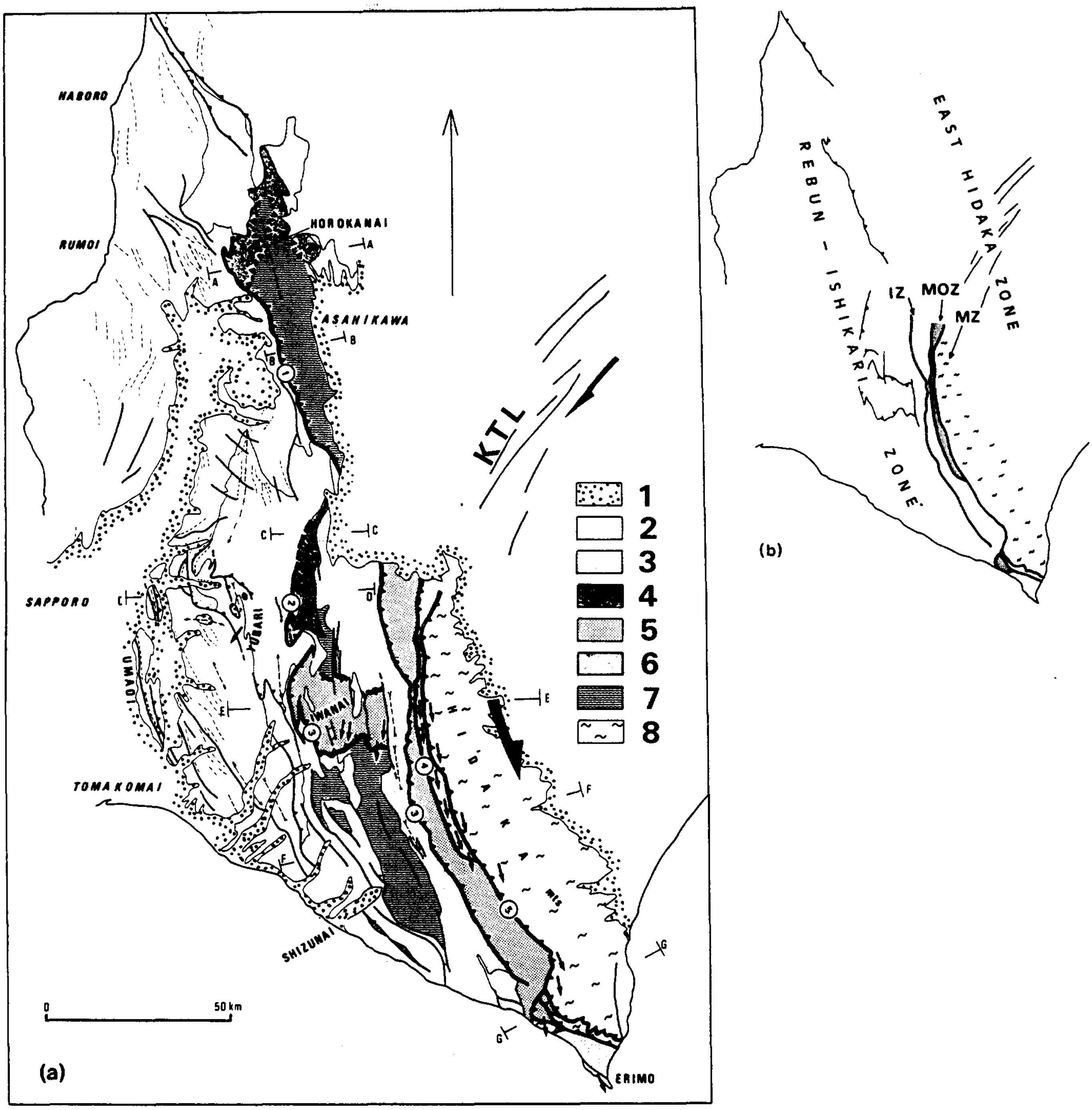

Fig. 3. (a) Structural map of the central part of the Hokkaido Central Belt. 1: Quaternary, 2: Tertiary, 3: Cretaceous, 4: Horokanai ophiolite unit, 5: Iwanai nappe unit and Idonnappu zone, 6: Meta-ophiolite zone, 7: Kamuikotan schists, 8: Main zone. Small arrows represent the direction and sense of shear. Circled numbers refer to the main thrust fault described in the text. AA, BB, . . ., GG refer to the cross-sections of Fig. 4. (b) Tectonic zoning. IZ: Idonnappu zone, MOZ: Meta-ophiolite zone, MZ: Main zone.

Mesozoic collision. The whole sequence from the blueschists to the detrital sequence was deformed during the strike-slip faulting and the later westward thrusting event. En échelon folds and nappes are the main expressions of the strike-slip deformation in this zone.

The *Cretaceous syncline* is a narrow belt of late Cretaceous turbidites similar to that of the Rebun-Ishikari zone, which suffered a pervasive deformation leading to refolded folds with N–S-trending axes.

The *Hidaka zone* corresponds to the ductile deformation zone formed during the strike-slip deformation. It reworks the original tectonic contact between the ophiolite and a continental granulitic basement. From west to east one can distinguish the Idonnappu zone (IZ), the Meta-ophiolite zone (MOZ) and the Main zone (MZ). The IZ contains the upper part of the ophiolite (pillow lavas and radiolarites, bearing late Jurassic to early Cretaceous radiolarians, Jolivet 1986) and the late Cretaceous detrital cover (lateral equivalent of the Yezo group). The Meta-ophiolite zone contains the main part of the ophiolite body (tectonites to dyke complex, Miyashita 1979, 1983). The Main zone is composed of a complex metamorphic sequence that starts with granulites retrogressed in the amphibolite facies

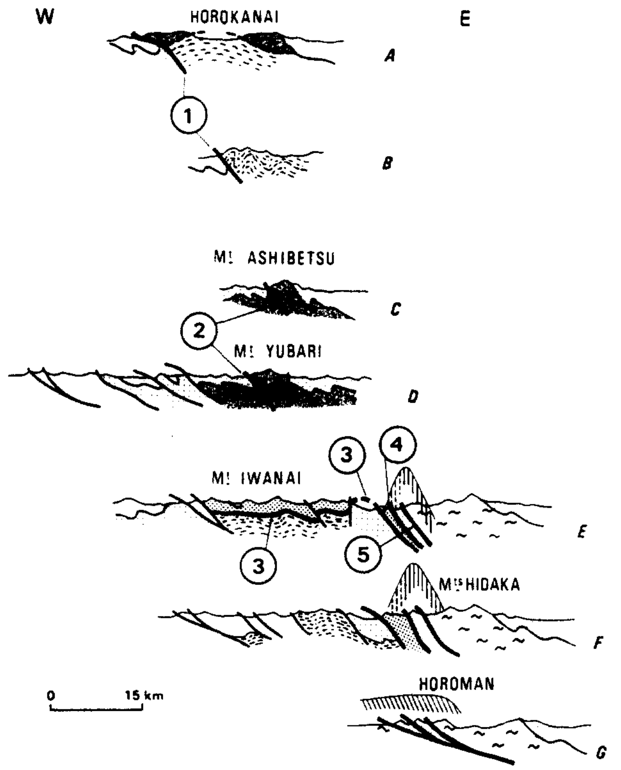

Fig. 4. Cross-sections in the Hokkaido Central Belt (see Fig. 3 for location and legend). In sections E, F and G the cleavage front is shown.

near the contact with the Meta-ophiolite zone, and goes up to non-metamorphic sandstone and conglomerate with rare late Cretaceous (Campanian) radiolarians (Komatsu *et al.* 1983, Osanai 1985, Osanai *et al.* 1986b, Arita *et al.* 1978, 1986, Kimura in preparation). Oligo-Miocene granodiorite and gabbro intrude the middle and upper part of the sequence (Shibata 1968, Hashimoto 1975, Hashimoto *et al.* 1975, Miyashita & Maeda 1978, Shibata & Ishihara 1979, Shibata *et al.* 1984). It is not clear whether the granulites represent an old basement unconformably covered with late Cretaceous sediments or if they are the metamorphosed deep part of the late Cretaceous sequence.

A vertical foliation progressively appears from west to east, the first appearance being in the Idonnappu zone (Jolivet & Miyashita 1985). A strong gradient of deformation and metamorphism is then observed through the eastern part of the Idonnappu zone, through the Meta-ophiolite zone until the western part of the Main zone (Grapes *et al.* 1977, Miyashita 1979, Miyashita *et al.* 1980, Ishizuka 1981).

The *east Hidaka zone* is essentially made of late Cretaceous black shale and sandstone (Kontani 1978, 1980) which yield Campanian radiolarians (Kimura in preparation). Pillow lavas with abyssal tholeiite composition (Miyashita & Katsushima 1986) were erupted when the sediments were not yet consolidated during the sedimentation. The detrital sequence was deposited during the Campanian in a narrow basin with an oceanic crust, or at least a strongly stretched continental crust, with a very efficient sediment supply. The structure of this zone is not yet clearly understood, field work being in progress. However Kimura (in preparation) describes thrust sheets emplaced towards the east during the Cenozoic, and Watanabe & Iwata (1985) described the deposition of Middle Miocene sediments in small pull-apart basins along N–S-trending strike-slip faults.

RECENT DEFORMATION (POST-MIDDLE MIOCENE)

The N–S trend of tectonic zones is perturbed at the latitude of Ashibetsu by a slight dextral virgation (Fig. 3). Fold axes are bent from a 160° regional trend to a local trend of 010°. This virgation is located exactly at the western end of the Kamishiyubetsu Tectonic Line (KTL) (Fig. 1) described by Kimura *et al.* (1982). The KTL is a right-lateral strike-slip fault which was active from late Miocene to Recent time. Shallow earthquakes attest to its present activity. This fault offsets the Hidaka granites and crosscuts the N–S-trending faults of the east Hidaka zone. The virgation shows an offset by about 20 km westwards south of the Kamishiyubetsu Tectonic Line. A part of the uplift of the metamorphic zones must be related to this recent event (Kimura *et al.* 1986). Kimura (1986) interprets the KTL as a transcurrent fault at the rear of the slightly oblique Kuril subduction and suggested a comparison with the Sumatra fault to the rear of the Sumatra trench (Huchon & Le Pichon 1984).

During this westward movement the Hokkaido Central Belt south of the KTL was reworked by W-verging thrust faults. Figures 5 and 6 show field examples of compressive structures formed during this recent stage, which affects all strata including Pliocene. The most interesting structures related to this recent stage are observed in the Paleogene and Cretaceous sandstones. The analysis of fault sets reveals that this deformation is indeed compatible with the recent stage and not with the early stage which is overprinted. Figure 5 (upper) is an outcrop observed along the Sorachi river, where Paleogene sandstones are folded and thrusted toward the west. Fault-set and striation analysis on this outcrop reveal two successives stages: the oldest gives a horizontal 050° compression and the youngest a 130° compression which is compatible with the folds and thrusts observed as the major structures. Figure 6 is a succession of outcrops in the Cretaceous syncline: late Cretaceous sandstone and shale are deformed by W-verging overturned folds. Disharmonic folding characterizes the thinner alternations of sandstone and shale, and décollement of reverse limbs and thrusts onto the subsequent normal limbs are common. Fold axes are curved. It is not clear whether the curvature of fold axes is due to progressive shearing during the second stage folding or to a superimposition of two folding events: a first one related to the strike-slip deformation and a second one related to the westward thrusting. The occurrence of vertical fold axes in the late Cretaceous sandstone near the ductile deformation zone strengthens the second interpretation. In any case the most obvious

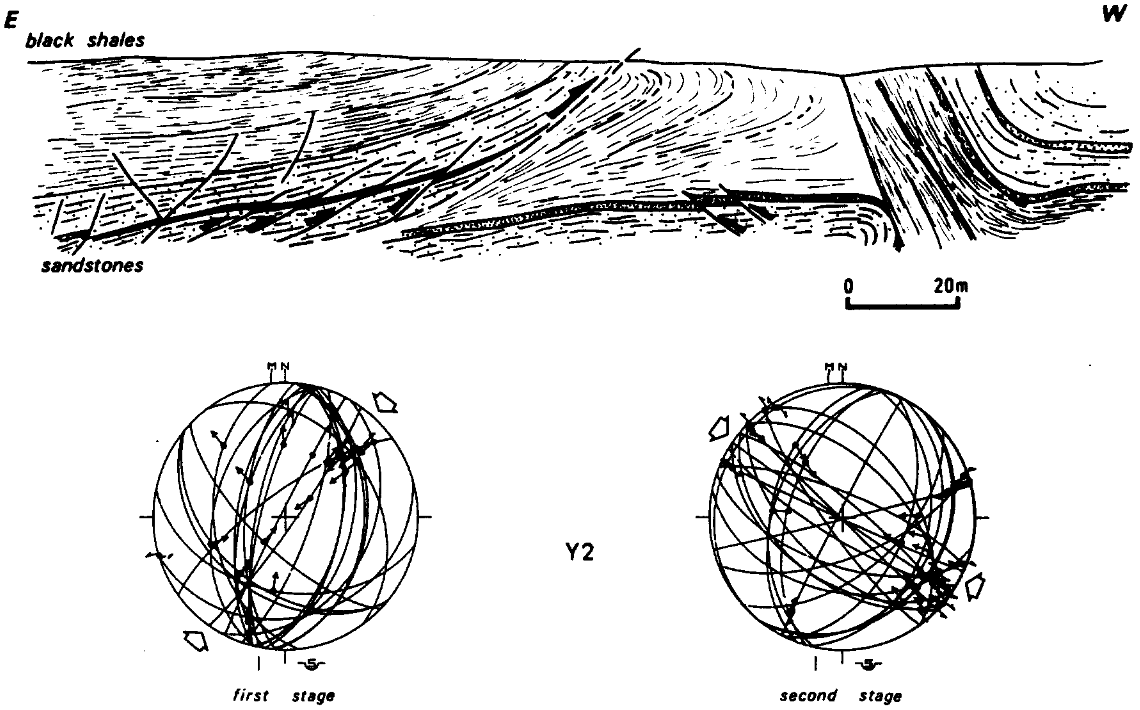

Fig. 5. Outcrop of alternating Paleogene sandstone and shale along the Sorachi River and the corresponding fault-set data (locality Y2 on Fig. 8).

deformation in the Cretaceous syncline was formed during the recent westward thrusting.

RIGHT-LATERAL STRIKE-SLIP DEFORMATION

En échelon thrusts, folds and reverse faults are observed from north to south. Two thrust faults trending 150° reaching the Japan Sea coast in the Haboro area are typical (Figs. 2 and 3). In the Yubari area, the geological maps established in the coal field show flat thrust sheets of Cretaceous sandstone resting on the coal-bearing Paleogene sandstone (Geological Survey of Japan 1954). Those thrusts are connected to the south with vertical faults. More important thrusts bring the pre-Cretaceous metamorphic and ophiolitic basement onto the Cenozoic deposits (Figs. 3 and 4).

Thrust 1 crosscuts the Mesozoic contact of the ophiolite nappe on the blueschists. These two Mesozoic tectonic units are transported over the Middle Miocene deposits. The contact itself is a steeply E-dipping thrust except in the north where the contact between the peridotites and the Miocene is flat. Thrust 2 is the exaggeration of the overturned anticline of Mt Ashibetsu. The upper part of the ophiolite sequence crops out in the core of the anticline. Early Cretaceous tuffites and the late Cretaceous Yezo Group crop out on both flanks. To the south, foliated serpentinite including tectonic blocks of the underlying blueschists have been thrust upon the Yezo Group and older deposits on the west flank at Mr Yubari (Nakagawa & Toda 1987). Thrust 3 is the basal contact of the Iwanai nappe which has its root in the thrust zone that bounds the Cretaceous syncline to the east. The thrust is flat below the nappe

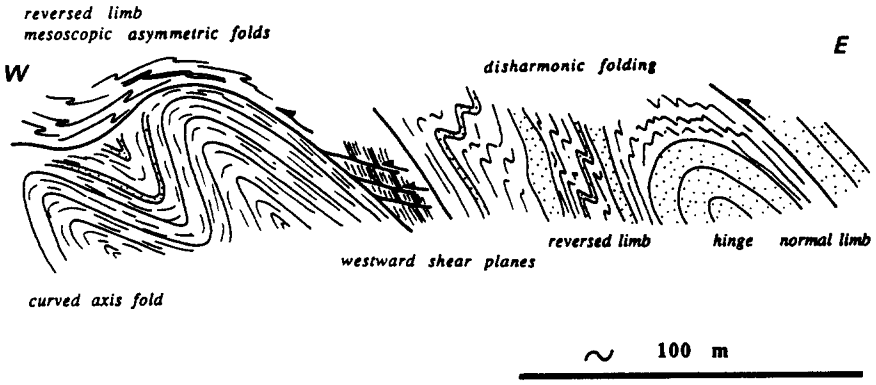

Fig. 6. Cross-section in the late Cretaceous sandstone of the Cretaceous syncline showing the effects of the recent thrusting event.

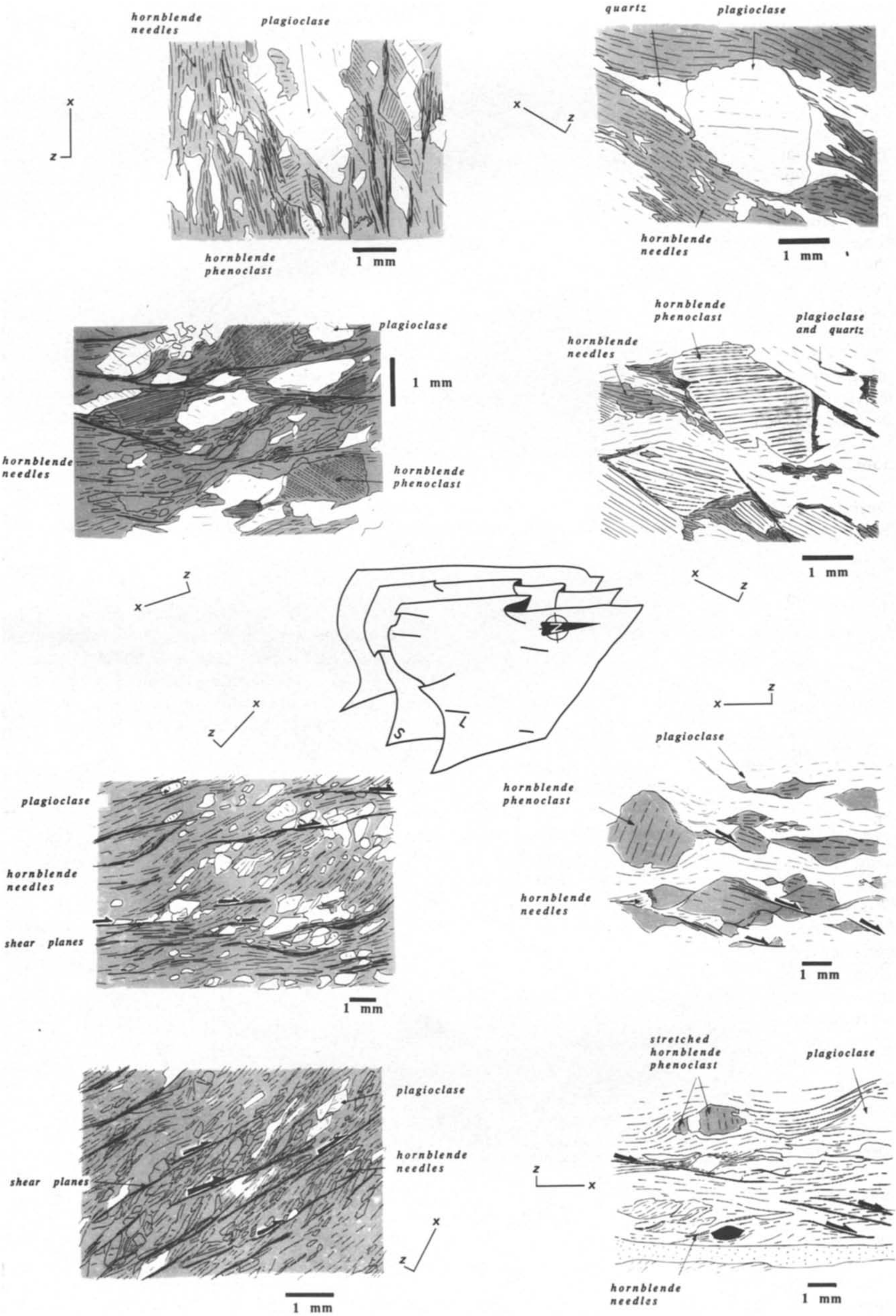

Fig. 7. Meta-ophiolite zone metagabbro and amphibolite showing evidence of right-lateral non-coaxial deformation. Drawings from thin sections parallel to the *XZ* plane. General pattern of the foliation in the Meta-ophiolite zone (centre).

and steep or even vertical in the root zone (Jolivet & Cadet 1984). Thrust 4 is the front of the Meta-ophiolite zone, which dips steeply east. Thrust 5 is the contact between the Meta-ophiolite and Main zones, which is also steeply E-dipping in the north, but changes to several horizontal thrusts in the Cape Erimo area (Horoman nappes, Arita *et al.* 1986). There the gneiss rests with horizontal contacts on the Meta-ophiolite zone peridotite.

The gross structure is thus characterized by overturned folds, thrusts and flat-lying nappes to the west, which are rooted to the east in a narrow zone where all the structures are vertical. To relate the thrusts with the recent stage and the vertical shear zone to the early strike-slip is a tempting idea; but first, the Iwanai nappe is cut by later vertical N–S faults, which are probably linked with the strike-slip deformation; and second, the analysis of small-scale structures shows (see below) that the nappe and the strike-slip shear zone were formed during the same deformation (except for the examples of more recent deformation we have described above).

The deformation in the Hidaka zone (Jolivet & Miyashita 1985)

The western thrust of the Idonnappu zone is marked by a thick zone (about 100 m) of schist and cataclasite. Eastwards the deformation is restricted to narrow zones of cataclasite along vertical faults or thrusts. In more competent material such as dolerite vertical faults with horizontal striation are common. Further east a N–S-trending vertical pressure-solution cleavage appears and becomes penetrative eastward with an increase in deformation. Basic rocks metamorphosed in the greenschist facies appear in the east of the zone (Ishizuka 1981, Nakano 1981). The transition into the Meta-ophiolite zone is gradual with a rapid increase of metamorphic grade and appearance of a synmetamorphic vertical foliation which bears a horizontal lineation. In narrow en échelon zones the foliation in the Meta-ophiolite zone is flat though the lineation remains N–S (Fig. 7). The deformation is heterogenous at all scales and preserves lenses of weakly strained rocks. Dolerite and gabbro of the ophiolite sequence were recrystallized during the deformation into amphibolites. All the intrusive contacts (dolerite dykes in gabbro for instance) have been transposed into the foliation.

To the north the contact between the Meta-ophiolite and Main zones is usually marked by several hundred metres of mylonite that has retrogressed the granulites. The vertical foliation and the horizontal lineation are the most obvious structures. In the Horoman nappe (Erimo area on Fig. 3) a N–S lineation is found in both peridotite and gneiss (Niida 1974, 1984, Arita *et al.* 1986).

The stretching lineation

The position of the finite deformation ellipsoid is consistent throughout the schistose part of the Idonnappu zone, the entire Meta-ophiolite zone and the western part of Main zone (Fig. 8). Although we cannot quantify it precisely we can qualitatively say that the ellipsoid is a prolate one with a horizontal X-axis trending N–S (Jolivet & Miyashita 1985). It is characterized in the Idonnappu zone by stretched pebbles and E–W vertical tension cracks. In the Meta-ophiolite zone and Main zone pretectonic and syntectonic minerals are stretched horizontally with clear pressure shadows in XZ sections (Fig. 7). YZ sections show neither stretching nor mineral elongation.

Non-coaxiality

In the three zones XZ sections show a consistent asymmetry (Fig. 7). Pressure shadows are systematically asymmetric indicating a right-lateral shear sense (Choukroune 1971, Malavieille *et al.* 1982). Less deformed or undeformed rock-lenses have right-lateral sigmoidal shape and their bounding shear zones display a sigmoidal pattern of foliation consistent with a right-lateral shear sense (Ramsay & Allison 1979, Ramsay 1980). Discrete shear zones within the weakly strained lenses right-laterally offset magmatic features such as compositional banding (Fig. 9). In thin section oblique shear planes offset the foliation in a right-lateral sense (Fig. 7).

Conclusion

A metamorphic gradient is demonstrated from west to east, from weakly metamorphosed rocks in the Idonnappu zone to high-temperature amphibolites near the Meta-ophiolite zone–Main zone contact. In the Meta-ophiolite zone this metamorphism is contemporaneous with the deformation (Jolivet & Miyashita 1985). Along shear zones the recrystallization of gabbro into amphibolite is complete, whereas inside the less deformed lenses magmatic parageneses are preserved as relics. Late fractures trend parallel to the foliation with indication of right-lateral sense. These fractures are filled with LT–LP metamorphic minerals such as prehnite showing that this deformation is colder. In the Main zone granulite parageneses are retrogressed to the amphibolite facies (Osanai *et al.* 1986a,b), and we showed previously that the deformation is contemporaneous with a decrease of temperature (Jolivet & Miyashita 1985). In the eastern part of the Main zone amphibolites pass to migmatites. The more basic parts are stretched giving N–S-trending boudins some of which are asymmetric in the right-lateral sense.

The Hidaka shear zone shows a rapid and gradual transition from deep ductile to more superficial deformation within a strike-slip shear zone. The deformation is associated with vertical and horizontal zones of foliation with a gradual transition between them. The shear direction, indicated by the lineation, is always N–S. The problem then is the mechanism which allowed the deep parts of the shear zone to be uplifted. The late thrusts are probably partly responsible for the uplift but they cannot explain the gradual transition from shallow to deep

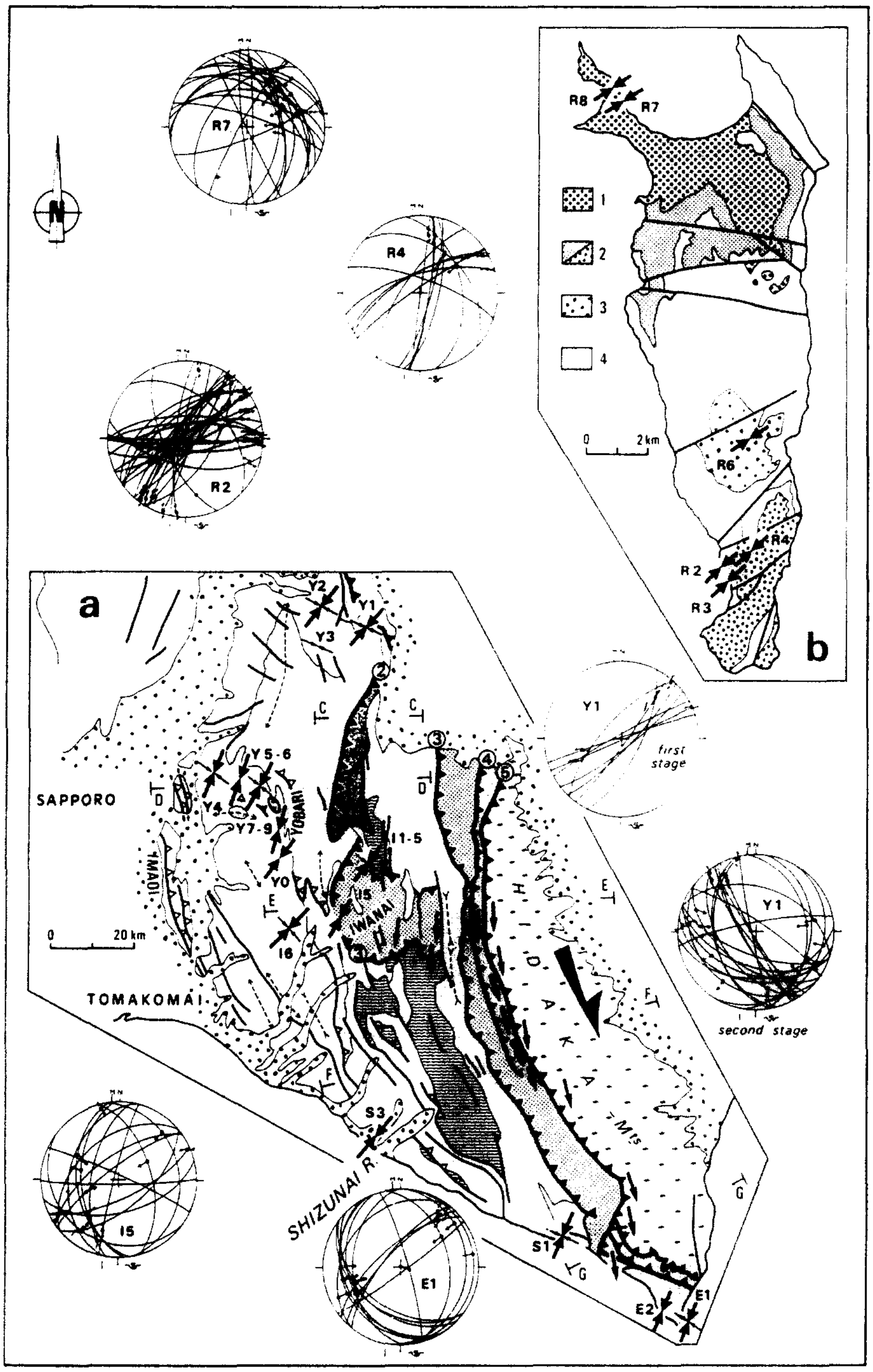

Fig. 8. Plot of the direction of compression deduced from analysis of fault sets on the structural map of Fig. 3(a) and the data obtained on Rebun island (b), north of the Hokkaido Central Belt (geology after Nagao *et al.* 1963). 1: Hamanaka Formation (11.5–10 Ma), 2: Meshikuni and Kabuka Formations (13.5–12.5 Ma), 3: Motochi Formation (16–14.5 Ma), 4: Cretaceous volcanics.

facies through the zone. We shall come back later to a discussion of this problem.

The deformation in the Rebun-Ishikari zone

Numerous observations of fault sets (Angelier 1984) in the Rebun-Ishikari zone allow a reconstruction of the stress field. In almost all measurement sites two stages were observed, crosscutting relations between faults and superimposed striations attesting to an older stage with a horizontal 050° compression, followed by a younger compression 100–140°. These directions are plotted on Figs. 2 and 8. The recent compression is compatible with the recent westward thrusting event and is recorded in all the formations including late Miocene and Pliocene deposits. The older one is compatible with the en échelon folds and thrusts and the strike-slip deformation observed in the ductile zone. It is observed in all formations until the Middle Miocene but not in more recent terrains.

Although the deformation is essentially brittle in the Rebun-Ishikari zone some particular levels display local

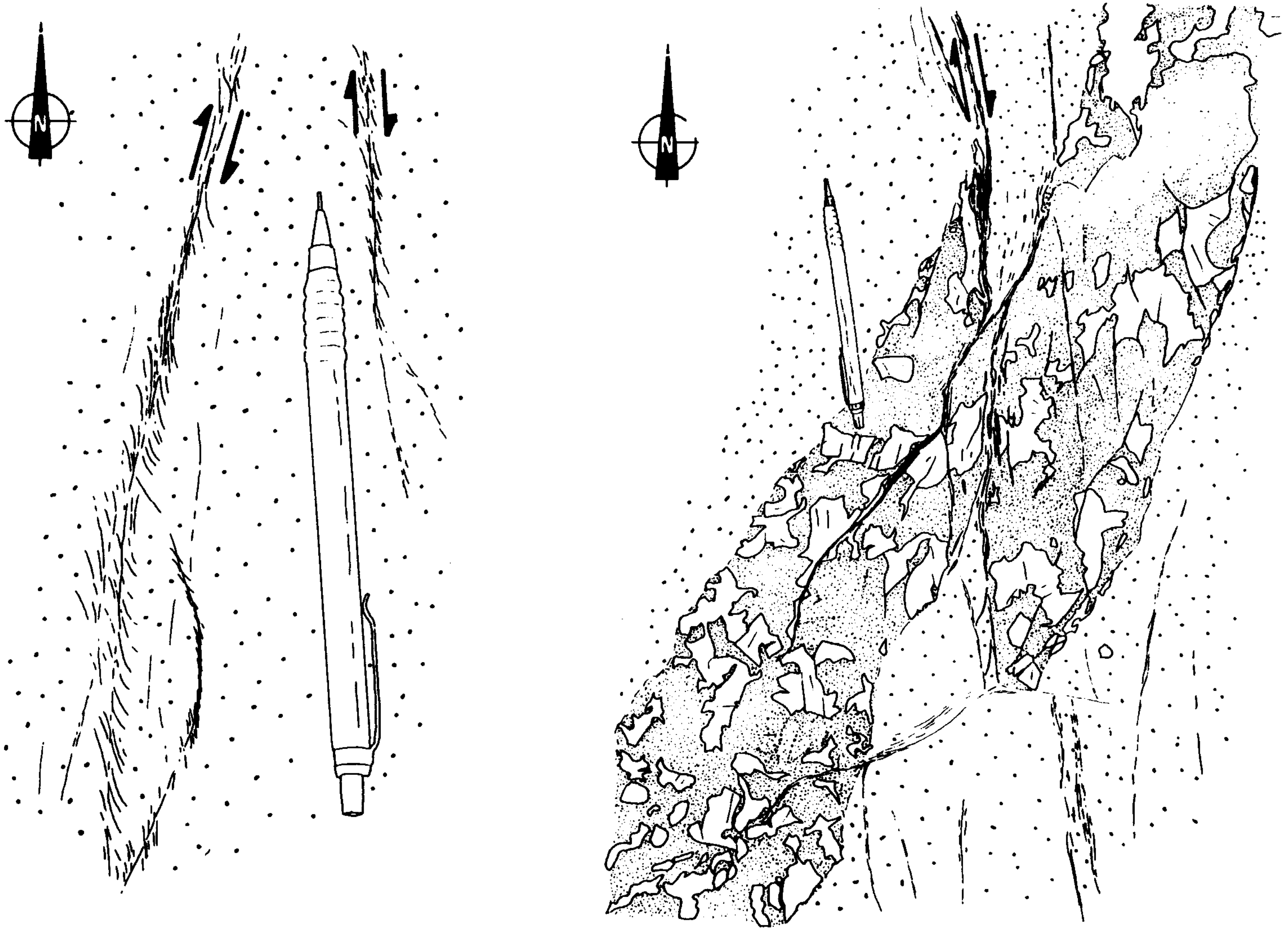

Fig. 9. Plane view of discrete vertical shear zone with sigmoidal foliation in otherwise poorly deformed gabbro (left) and right-lateral offset of a pegmatoid gabbro vein (right).

ductile deformation which gives the shear sense. Paleogene shales include stretched and flattened limestone nodules which give a southward shear along flat lying shear zones. Uda (1973, 1976) describes in the south of the zone the deformed Utaro conglomerate. A coarse conglomerate of Middle Miocene age displays a N–S-trending vertical foliation in the shaly matrix, pebbles being stretched horizontally and showing clear evidence of right-lateral shear. Our own observations confirm this interpretation (localities E1 and E2, Fig. 9a).

Figure 2 synthesizes our data and those of Yamagishi & Watanabe (1986) obtained from strikes of dykes. They are consistent both in direction and timing.

Strike-slip deformation and thrusts: the Iwanai nappe as a case example

A precise mapping of the Mt Iwanai area (Fig. 3) reveals the existence of a major thrust, along which the Iwanai nappe has been thrust upon the late Cretaceous deposits and the underlying Kamuikotan schist (Jolivet & Cadet 1984). The nappe is made of a sole of serpentinized or fresh peridotite (Katoh 1978) with overlying pillow basalts and an unconformable cover of black shales including scarce olistoliths of limestone, followed by sandstone on top attributed to the early Cretaceous. Similarity with the rocks outcropping in the Idonnappu zone suggests that the nappe roots east of the Cretaceous syncline. We describe in the following a typical cross-section through the basal contact (Fig. 10).

The N–S cross-section begins in schistose sandstone, microconglomerate and shale belonging to the Kamuikotan schist. The foliation is vertical and trends E–W. The schist is cut into several units by gently N-dipping thrust faults. Limestone blocks are dragged along these faults. Observations of the sequence in less deformed areas show that they are olistoliths. Up section (closer to the basal contact of the nappe) satellites of these major thrusts cut the vertical foliation and are more and more common upwards. There is a clear southward offset on these thrust planes, which show slickensides with NNE–SSW striations. The contact with the serpentinite is not clearly visible, but mapping shows that it is flat. There are two flat-lying slices of sandstone within the serpentinite. The cover of schistose black shale lies above a horizontal contact. Given the attitudes of the contact and of the bedding in the shale, a décollement is probable between the serpentinite and the sedimentary cover.

All the observed cross-sections show the same succession with additional observations such as flat-lying shear zones within the serpentinite. Stretched nodules or small olistoliths in the sedimentary cover are common, trending N–S with indication of southward movement. The upper part of the allochtonous body, the sandstone, displays shear zones parallel to the roughly horizontal bedding; the movement along these shear zones is clearly towards the south. Though the cross-section of Fig. 11 is E–W and the arrows represent only the E–W component of movement along shear planes, the main component is N–S and is plotted on the structural map of Fig. 3.

Middle Miocene molasse unconformably overlies the basal contact of the Iwanai nappe (Fig. 3) in the northern part of its outcrop area, and is overthrust by the front of the nappe to the west. Fault data show that until the end of Middle Miocene the stress field was compatible with the strike-slip movement. The stress field with the main compressive horizontal component toward 050° is present below and above the nappe. The nappe emplacement occurred before the Middle Miocene towards the south, which is also compatible with the same stress field. Consequently the nappe emplacement and its remobilization during the Middle Miocene belong to the same continuum of deformation with a compression toward 050°.

DISCUSSION

The strike-slip deformation in the ductile zone is contemporaneous with the emplacement of granodioritic plutons which yield K–Ar ages ranging from 40 to 17 Ma (Shibata *et al.* 1984), and with the deformation in the Rebun-Ishikari zone and the emplacement of the

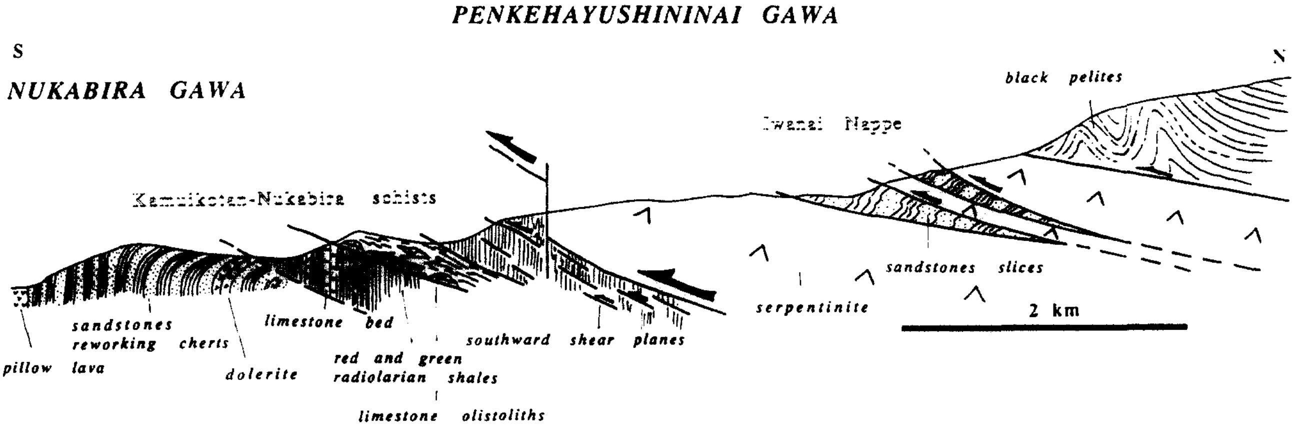

Fig. 10. Section across the basal contact of the Iwanai nappe.

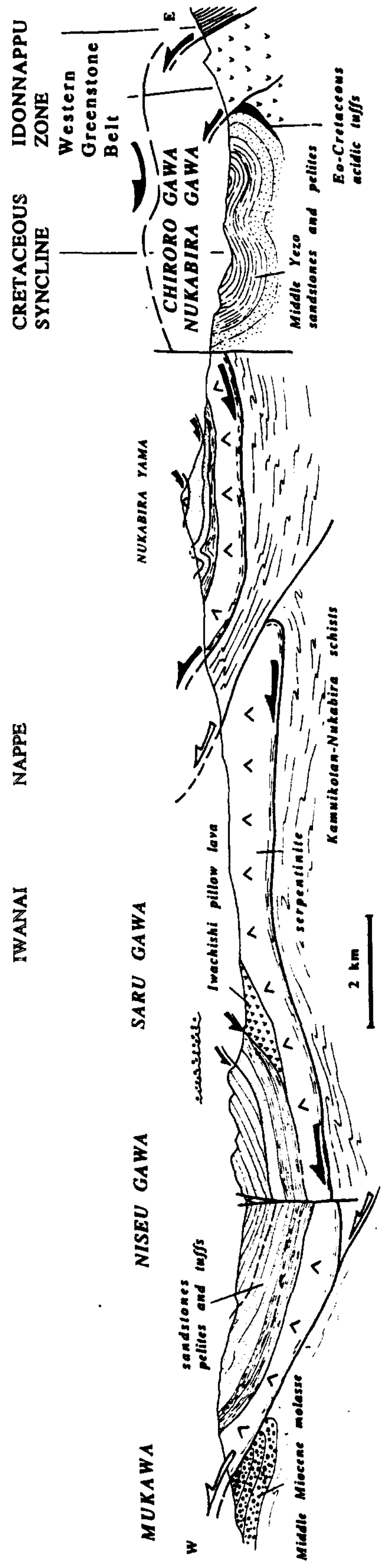

Fig. 11. Generalized cross-section of the Iwanai nappe.

Iwanai nappe. All these deformations occurred in the same stress field which continued until the end of Middle Miocene, and was then replaced by a more E–W compression which induced the formation of W-directed thrust faults.

During the strike-slip deformation, thrusts were formed both in the ductile and in the brittle zones. Two questions summarize the problem.

(1) The ductile zone is narrow and the movement occurred mainly along vertical planes, horizontal planes being minor. The brittle deformation zone is wider and the movements within it occurred mainly along flat-lying shear planes. The whole deformed zone is wide and pure strike-slip structures coexist with thrust structures. Can a single mechanism explain both these features?

(2) A metamorphic gradient is well established from west to east, and the deformation is contemporaneous with this metamorphism in the Meta-ophiolite zone and with retrogressive metamorphism in the Main zone. The deformation thus affects a thick part of the crust, at least 20 km. How were these deep terrains uplifted during the deformation?

Figures 12 and 13 describe a tentative model to answer these two questions. The model is described with E–W cross-sections and thus does not show the strike-slip component of the deformation but only the thrusting one. The first cross-section of Fig. 13 represents the initial state at the very end of the Cretaceous. The sedimentary basin of the late Cretaceous Yezo group rests upon the earlier structures. An alternative solution takes into account the late Cretaceous crustal stretching and even the occurrence of oceanic crust in the east Hidaka zone. The third cross-section represents the strike-slip stage. The movement was along curved surfaces, vertical planes in the deeper parts passing westward and upward to flat-lying movement planes such as the basal contact of the Iwanai nappe. Flat-lying foliation zones in the Meta-ophiolite zone provide other examples of curved movement planes within the ductile deformation zone. The deeper parts were mainly characterized by vertical movement planes. The deformation zone is less wide in the deeper parts of the crust than in the shallower levels. In the deep parts of the shear zones, flat-lying foliation zones such as those described in the Meta-ophiolite zone or that of the Horoman nappe complex were used as ramps for the uplift of deep material during the strike-slip deformation. All the deformation features that are consistent with the stress field and the timing of the strike-slip deformation belong to a single progressive deformation stage in the sense of Brun & Choukroune (1981).

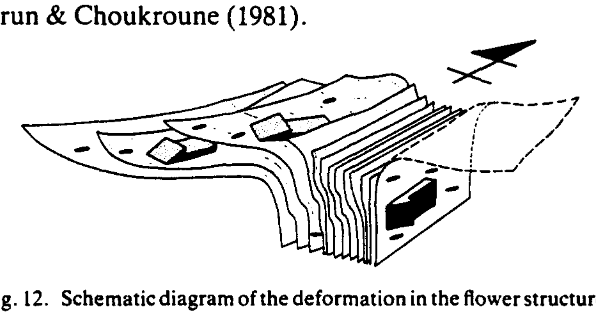

Fig. 12. Schematic diagram of the deformation in the flower structure.

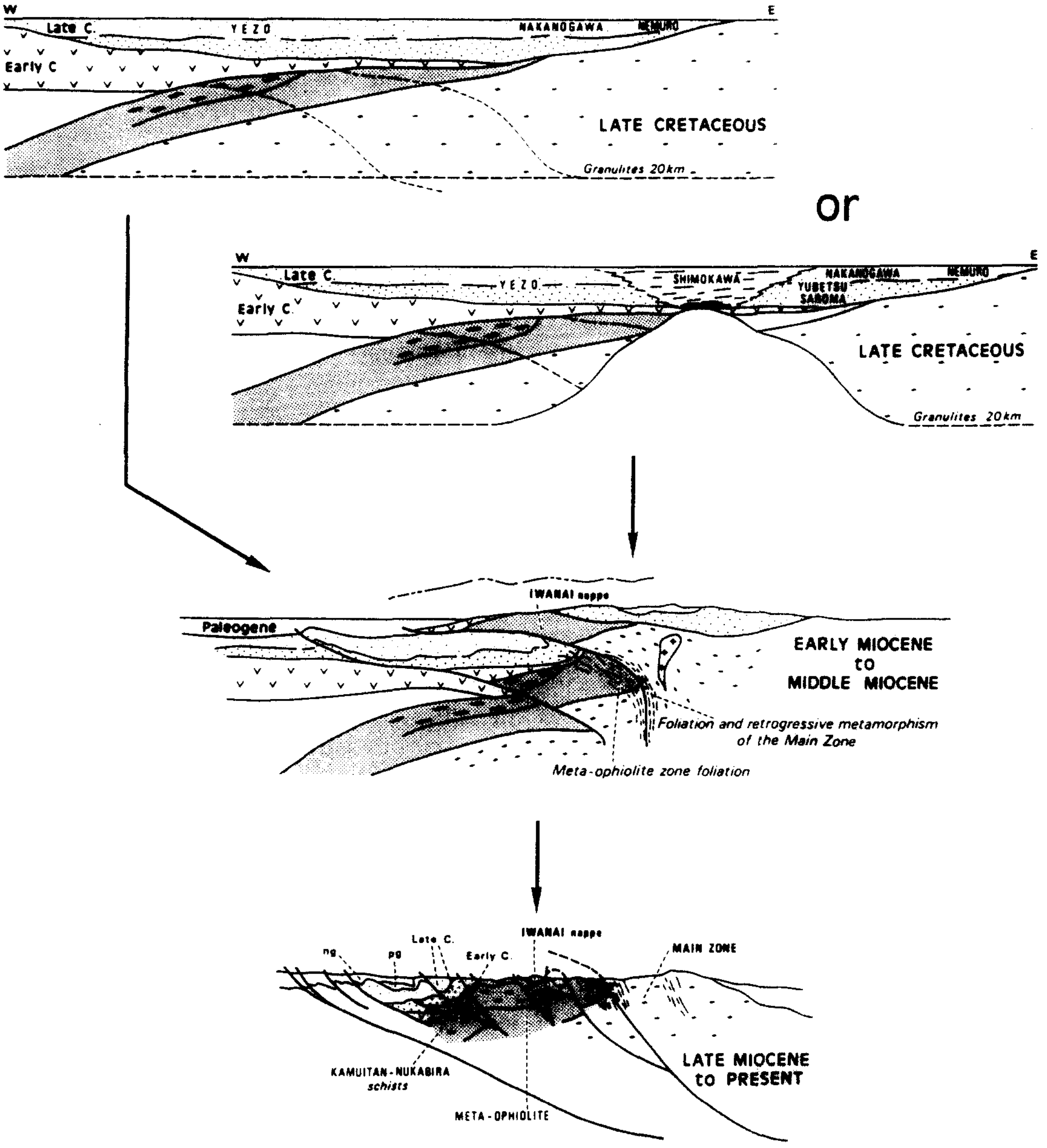

Fig. 13. Cross-sections showing the tectonic evolution of the strike-slip shear zone. See text for explanation.

If we add in the west the E-verging thrusts, the cross-section at this stage is typical of a positive flower structure on a crustal-scale (Wilcox *et al.* 1973, Harding 1985, Vigneresse 1987).

The last cross-section represents the recent thrusting stage.

Acknowledgements—This work was funded by the Centre National de la Recherche Scientifique and the French Ministry of Foreign Affairs. The authors are greatly indebted to Professors J. P. Cadet and P. Choukroune for fruitful discussions in the field.

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