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# PRELIMINARY REPORT ON STRUCTURES OF FOREFINGER POINT, ENDERBY LAND, EAST ANTARCTICA

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***Abstract:*** Granulite-facies metamorphic rocks of Forefinger Point, which lie on the Casey Bay coastline in Enderby Land, have been affected by three stages of folding, shear zone formation, and intrusion of pegmatite. The peak metamorphic structural evolution was characterized by the development of $F_n$ isoclinal to close buckling folds. This deformation was associated with the coexistence of orthopyroxene+sillimanite±quartz, and was followed by the formation of cordierite and symplectites of cordierite+sapphirine, orthopyroxene+cordierite+sapphirine in response to subsequent isothermal decompression. These symplectic intergrowths are generally unstrained except in some cordierite domains where cordierite exhibits a weak mineral lineation, implying that intense ductile deformation had ceased before the decompressional reactions: orthopyroxene+sillimanite+quartz=cordierite, orthopyroxene+sillimanite=cordierite+sapphirine, garnet+quartz=orthopyroxene+cordierite. Although the Forefinger Point granulites have undergone high strain deformation under peak metamorphic conditions, they experienced only low and local strain deformation after peak metamorphism. The post-peak-metamorphic structural evolution was characterized by the development of $F_{n+1}$ open to gentle buckling folds, narrow shear zones and emplacement of pegmatite.

## 1. Introduction

Forefinger Point (48°00′E, 67°30′S) is situated in the granulite-facies terrain (HARLEY *et al.*, 1990), which is located on the southern coastline of Casey Bay in Enderby Land (Fig. 1A) near the boundary between the Proterozoic Rayner Complex and the Archaean Napier Complex (SHERATON *et al.*, 1987). The Napier Complex is a very-high-temperature granulite terrain (ELLIS *et al.*, 1980; ELLIS, 1980; HARLEY, 1983, 1985a, 1987; SANDIFORD and POWELL, 1986) which is characterized by isobaric cooling at deep crustal depth from >900°C (HARLEY, 1983, 1985a; MOTOYOSHI and HENSEN, 1990). In contrast, the Rayner Complex is a lower-temperature granulite terrain which is characterized by substantial decompression (SHERATON *et al.*, 1980, 1987; ELLIS, 1983; BLACK *et al.*, 1987). HARLEY *et al.* (1990) have reported orthopyroxene+sillimanite assemblages from Forefinger Point, and estimated approximately 950°C at 1.0 GPa for regional granulite-

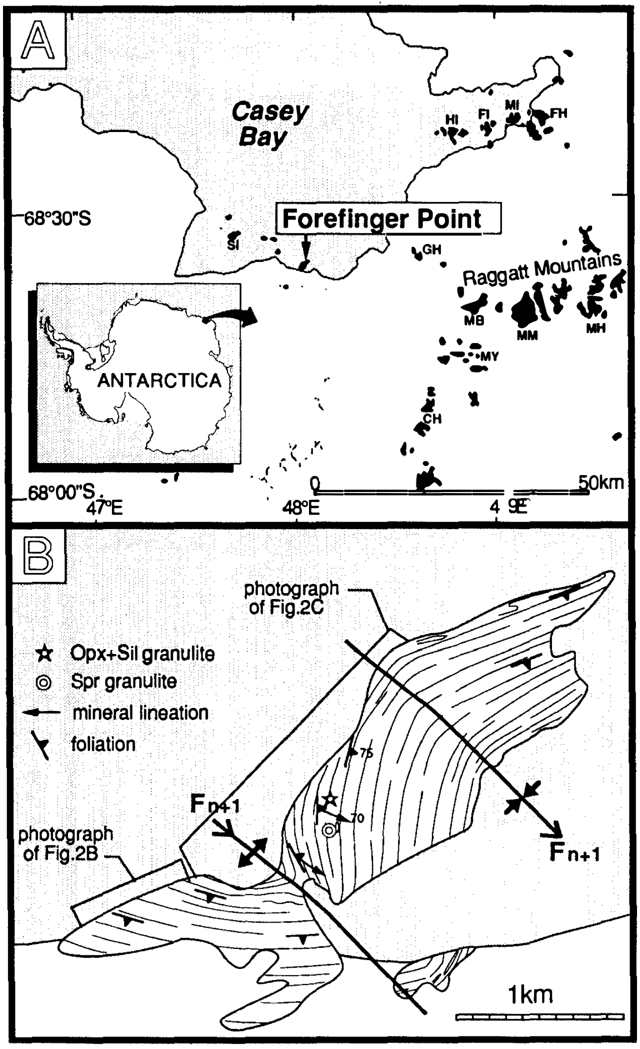

*Fig. 1.* *Location map and structural map of Forefinger Point. A : Location of Forefinger Point in Casey Bay, Enderby Land, East Antarctica. CH = Condon Hills. FH = Fyfe Hills. FI = Field Islands. GH = Geoffrey Hills. HI = Hydrographer Island. MB = Mount Bergin. MH = Mount Humble. MI = McIntyre Islands. MM = Mount Maslen. MY = Mount Yuzhnaya. SI = Shaw Island. B : Location of photographs and locality of Opx-Sil granulite and Spr granulite. Maps are modified after* Sheraton *et al. (1987) and* Harley *et al. (1990).*

facies metamorphism. These metamorphic conditions are higher than those reported from elsewhere in the Rayner Complex, leading Harley *et al.* (1990) to ascribe these high temperature assemblages to the Napier Complex.

The structural history of the Rayner Complex at the western part of Enderby Land has received relatively little attention except in the Molodezhnaya area (Grew, 1978), although that of the Rayner Complex in the eastern part of Enderby Land and Kemp Land has been studied by Clarke (1988) and White and Clarke (1993), who suggest evidence of strong reworking of Archaean crust during the Rayner structural episode. The detailed effect of the Rayner structural event on the Archaean Napier Complex is unclear but local ductile shearing related to retrograde post-Archaean metamorphism is identified in the Napier Complex by previous studies (BLACK *et al.*, 1983; SANDIFORD, 1985; SANDIFORD and WILSON, 1984; HARLEY, 1985b). Structural study of the western Rayner Complex, including Forefinger Point, will be important to further our understanding of the evolution of the metamorphic terranes in Enderby Land. Here we discuss the structural evolution of Forefinger Point region, focusing on the relation between deformation and reaction textures.

## 2. Lithologies and Textures

Forefinger Point is underlain by well-layered gneisses of various kinds of lithologies (Fig. 2). Lithologies are mainly classified into pyroxene gneiss, mafic grarulite (HARLEY *et al.*, 1990), Hbl-Bt pyroxenite (HARLEY *et al.*, 1990), Grt-Sil-Spl gneiss, Spr granulite and Opx-Sil granulites. Mineral abbreviations used in this paper are after KRETZ (1983).

Pyroxene gneiss: Opx, Bt, Pl, Kfs and Qtz are characteristic of pyroxene gneisses, defined as a felsic orthogneiss by HARLEY *et al.* (1990). It is the most dominant lithology throughout Forefinger Point. It generally contains elongated pyroxene grains (Fig. 3A), which are parallel to compositional bands composed of pyroxene-rich and feldspathic domains.

Grt-Sil-Spl gneiss: Medium-grained Grt-Sil-Spl gneiss crops out in the central part of Forefinger Point. Main constituents are Grt, Sil, Spl, Pl and Kfs. Grt-Sil-Spl domains and Pl-Kfs domains form well-layered compositional bands parallel to lithological boundaries. Sil and Grt grains show a strong mineral lineation parallel to compositional bands (Fig.

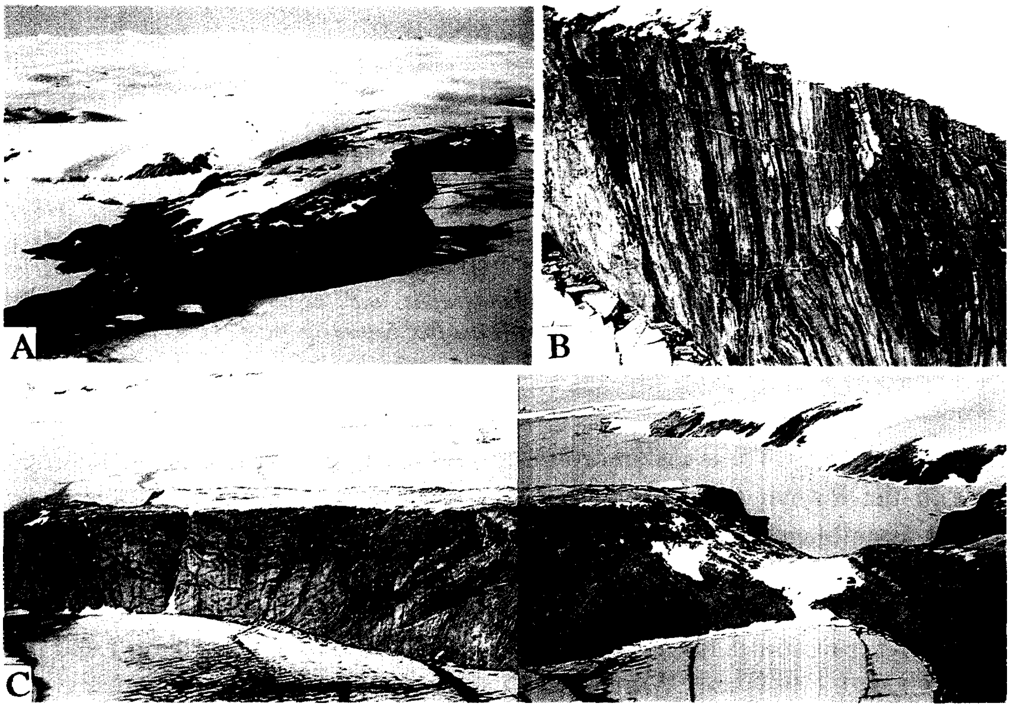

*Fig. 2. Aerial photograph of Forefinger Point. A : Aerial view of Forefinger Point. B : Shear zone and pegmatite. C : Fold structures.*

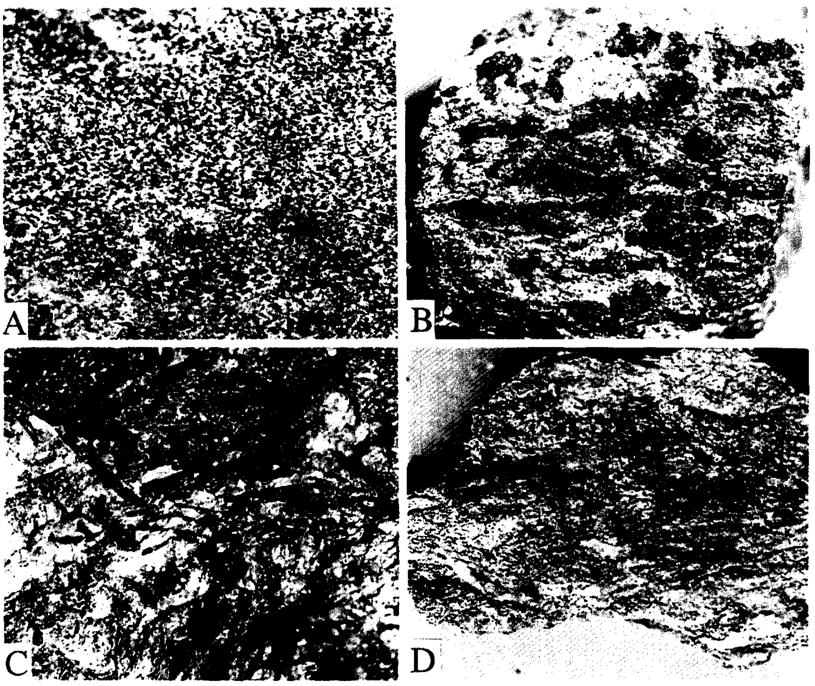

Fig. 3. Photographs of the metamorphic rocks described in this paper. A : Mineral lineation of Opx in pyroxene gneiss. B : Mineral lineation of Sil and Grt in Grt-Sil-Spl gneiss. C : Preferred orientation of Spr in Spr granulite. D : Compositional bands in Opx-Sil granulite. Width of photographs : (A) 10 cm, (B) 10 cm, (C) 13 cm, (D) 8 cm.

3B).

Spr granulite : Unusual lithology, which is characterized by Spr, Opx, Crd, Bt and Kfs, occurs as boudinaged lenses within pyroxene gneiss in the central part of Forefinger Point (Fig. 1B). Coarse-grained, euhedral Spr (up to 2 cm), which includes Spl and Crn, exhibits a strong mineral lineation parallel to lithological boundaries (Fig. 3C).

Opx-Sil granulite : The important lithology, including very-high-temperature and Crd-bearing mineral assemblages (HARLEY *et al.*, 1990 ; MOTOYOSHI *et al.*, 1994), forms boudinaged layers or lenses within pyroxene gneiss in the central part of Forefinger Point (Fig. 1B). The initial mineral associations observed in the granulites is Opx+Sil±Grt±Qtz. The granulite exhibits compositional bands due to the alternation of Opx-Sil-rich and Opx-Kfs-rich domains (Fig. 3D), which are parallel to lithological boundaries. In the Sil-absent Opx-Kfs-rich domains, perthitic Kfs grains were strained (HARLEY *et al.*, 1990). Sil and porphyroblastic Opx show a strong mineral lineation (Fig. 4A) parallel to compositional bands, implying intense ductile deformation. However, Opx and Sil, never direct contact, are separated by Crd±Spr (Figs. 4A, B), suggesting the reactions (HARLEY *et al.*, 1990 ; MOTOYOSHI *et al.*, 1994) :

$$\mathrm{Opx} + \mathrm{Sil} = \mathrm{Spr} + \mathrm{Crd},$$
$$\mathrm{Opx} + \mathrm{Sil} + \mathrm{Qtz} = \mathrm{Crd}.$$

The Crd exhibits a mineral lineation in places, subparallel to lineation of Sil and Opx (Fig. 5). However the intergrowth of Crd+Spr was not strained. In addition, Grt-bearing

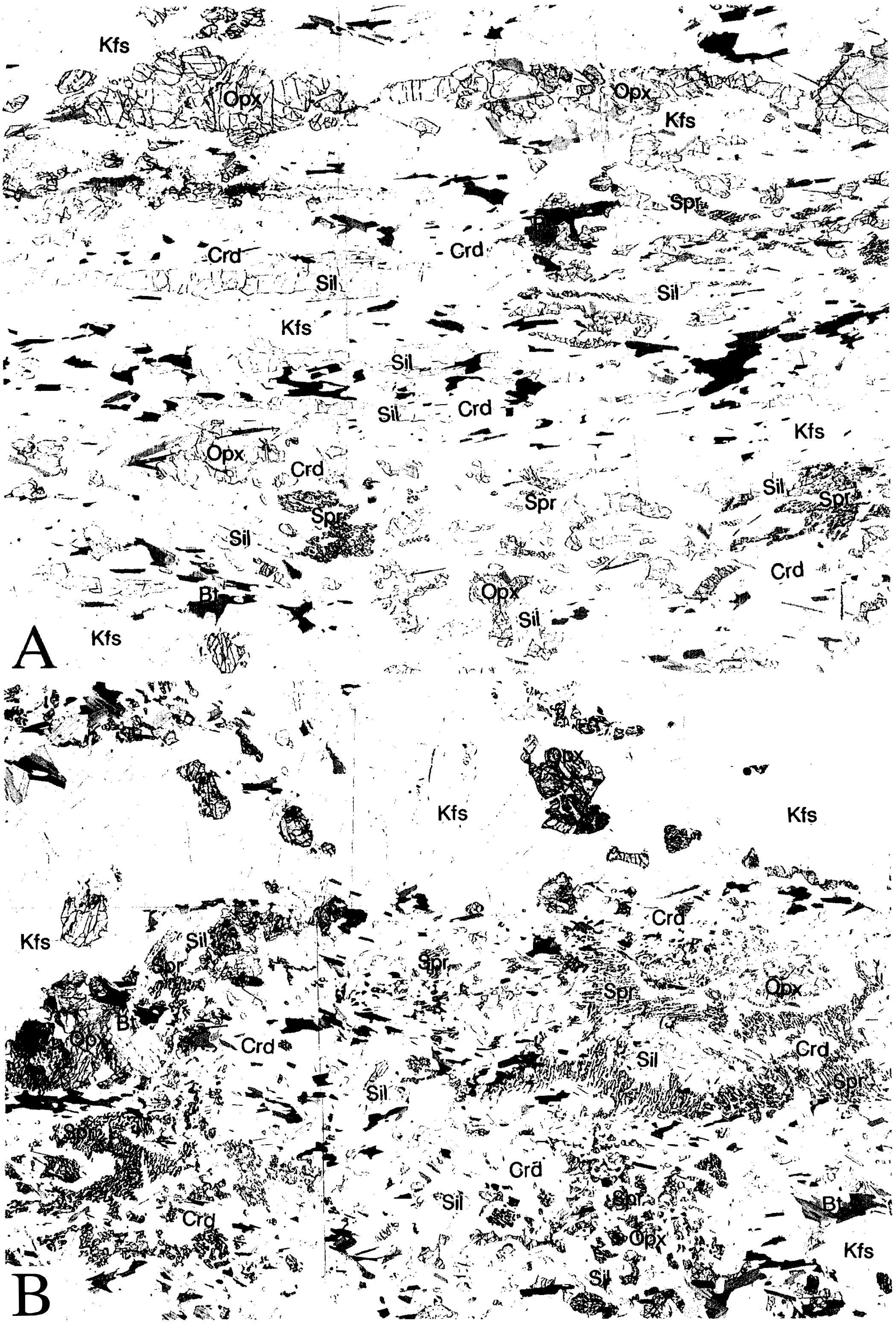

*Fig. 4. Photomicrographs of Opx-Sil granulite. Plane polarized light. Preferred orientation of Sil and Opx and symplectic textures of Spr + Crd around Opx and Sil in Opx-Sil granulite. A : This view is parallel to mineral lineation of Sil and perpendicular to compositional banding. B : This view is perpendicular to mineral lineation of Sil. Width of photographs : (A) 10 mm, (B) 10 mm.*

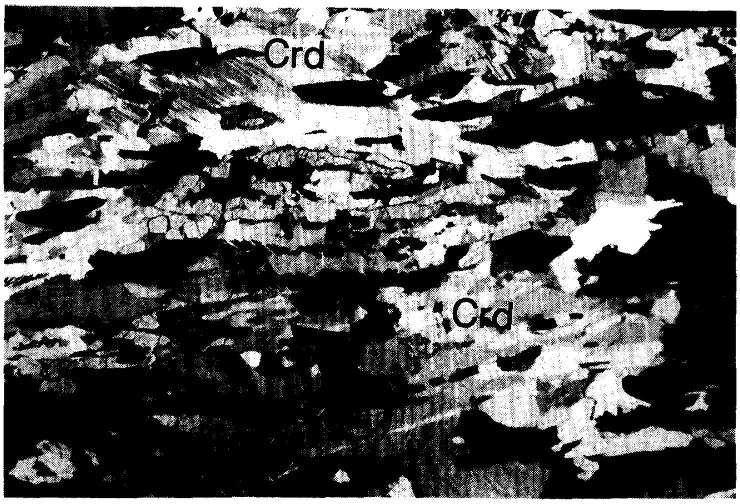

*Fig. 5. Photomicrographs of the preferred orientation of Crd in Opx-Sil granulite. Cross polarized light. Width of photograph = 2 mm.*

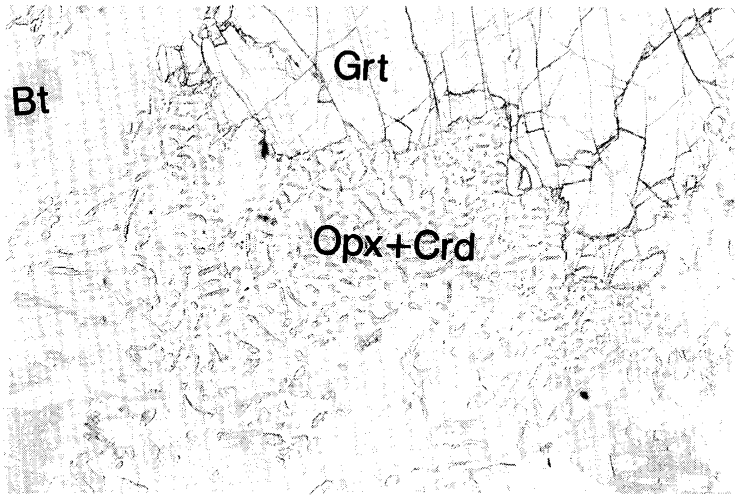

*Fig. 6. Photomicrographs of symplectites of Opx + Crd around Grt in Opx-Sil-Grt granulite. Plane polarized light. Width of photograph = 2 mm.*

assemblage is observed to be partially broken down to symplectite of Opx+Crd (Fig. 6), which are explained by the following reaction (HARLEY *et al.*, 1990; MOTOYOSHI *et al.*, 1994);

$$\mathrm{Grt+Qtz=Opx+Crd}.$$

This Crd is also locally strained, but the symplectic Opx is generally unstrained (Fig. 6).

## 3. Geologic Structures

The metamorphic rocks commonly exhibit compositional bands which are generally parallel to lithological boundaries. The strikes of these foliations are disturbed by large-scale earliest $F_{n-1}$ isoclinal folds, $F_n$ isoclinal to close folds, and late $F_{n+1}$ open to gentle folds, and they are generally NS to EW with moderate to steep dip in Forefinger Point (Fig. 7). Most metamorphic rocks show mineral lineations described above. The strong lineations of minerals, except for Crd, in pyroxene gneiss, Grt-Sil-Spl gneiss, Spr granulite and Opx-Sil granulite are parallel to each other, suggesting that they formed contemporaneously during a ductile deformation. Therefore we define the strong mineral lineation as

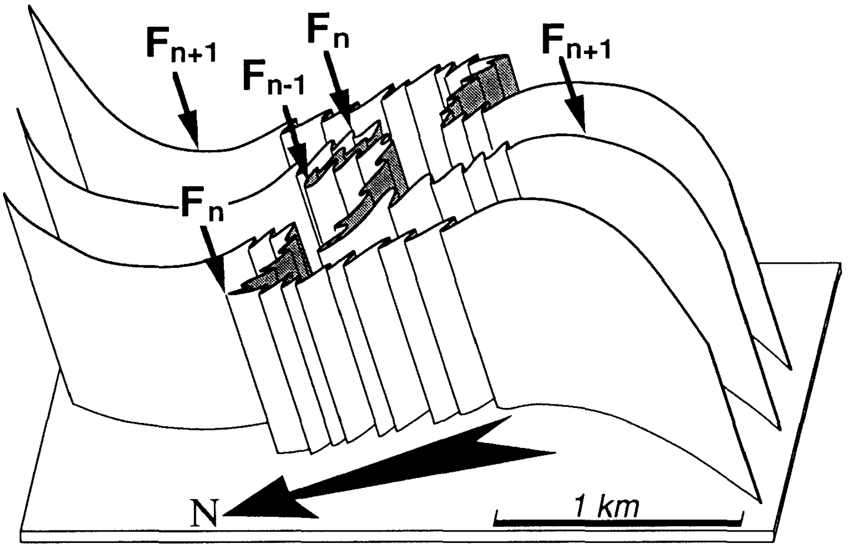

*Fig. 7. Schematic illustration of regional fold structure of Forefinger Point.*

$L_n$ lineation. The dominant trends of mineral lineations ($L_n$) are ESE at moderate to steep angles (Fig. 1B).

### *3.1. Early intense ductile deformation*

The dominant deformation produced intense folding ($F_n$) and associated ductile boudinage, suggesting rocks of Forefinger Point behaved as ductile crust during peak metamorphism.

#### 3.1.1. $F_n$ folding

Figures 2C and 8 demonstrate the development of isoclinal to close folds, which are termed $F_n$ folds. Fold axes plunge nearly ESE to SE at 50°-70° (Fig. 1B). The trends of fold axes are parallel to those of mineral lineations ($L_n$) described above, suggesting $F_n$ folding and formation of the $L_n$ mineral lineation were nearly coeval. Axial surfaces of the folds dip to the east in the northern and central area, and nearly south in the southern area due to later open folding. The wavelength of the folds, which ranges up to hundreds of meters, depends on layer thickness, suggesting that $F_n$ folds are buckled-folds. The $F_n$

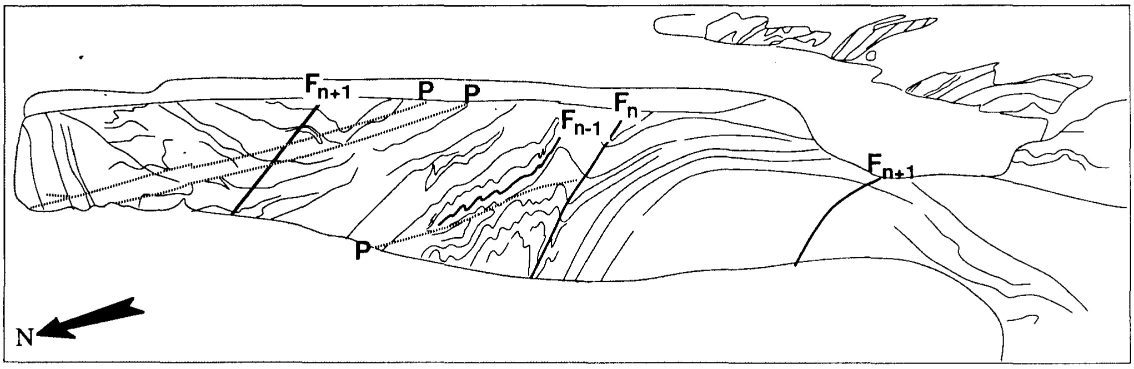

*Fig. 8. Illustration of Fig. 2C. Three stages of folding ($F_{n-1}$, $F_n$, and $F_{n+1}$). Pegmatites (P) cut fold structures.*

folds locally folded earlier isoclinal folds termed $F_{n-1}$ (Fig. 8).

3.1.2. Ductile boudinage

Spr granulite and Opx-Sil granulite generally occur as symmetrically boudinaged lenses. Generally, orientation of boudin necks indicate that there has been WNW-ESE stretching parallelly to $L_n$ fabrics. The strong preferred orientation of Spr is better-developed in the marginal parts of the boudins than in the central parts, indicating that formation of the $L_n$ mineral lineation and boudinage were coeval.

### *3.2. Late weak and local deformation*

Subsequent to the strong deformation, gentle folding took place. After the gentle folding, narrow shear zone was formed. The latest structural event was the emplacement of pegmatites.

3.2.1 $F_{n+1}$ folding

The lithological foliation of the gneisses strikes generally NE-SW, locally N-S to EW, and dips approximately 50°-70°E. The regional strikes of Forefinger Point metamorphic rocks are slightly re-oriented by a $F_{n+1}$ antiform and synform (Figs. 1B, 2C, and 8). The $F_{n+1}$ folds, which postdate the $F_n$ folding, are gentle to open folds with subvertical axial planes and fold axes plunging nearly SE, suggesting NE-SW compression. The fold axes of $F_{n+1}$ are subparallel to that of $F_n$ and $L_n$ mineral lineation. The amplitude of $F_{n+1}$ folds is up to several hundreds of meters and the wavelength is up to one kilometer, suggesting that $F_{n+1}$ folds resulted from low strain deformation.

3.2.2 Shear zone formation

The photograph and the illustration in Figs. 2B and 9 display the development of a narrow shear zone in the southern part of Forefinger Point. The shear zone postdates the $F_n$ folds. Drag pattern along the shear zone shows thrust or strike-slip sense. If it is a thrust, the northern upper mass moved several tens of meters southward.

3.2.3. Emplacement of pegmatite

Emplacement of pegmatite took place throughout Forefinger Point. The pegmatites occurs as dikes dipping 10°-20° N, and cut $F_n$ isoclinal folds, $F_{n+1}$ gentle folds and the shear

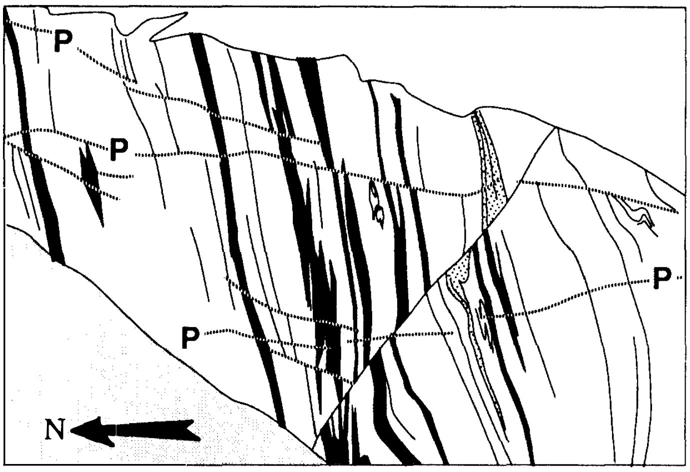

*Fig. 9. Illustration of Fig. 2B. Shear zone has disturbed foliations. Pegmatites (P) cut the shear zone.*

zone (Figs. 2B, C, 8 and 9). This shows that all deformations described above are older than the pegmatite.

## 4. Discussion

Forefinger Point metamorphic rocks experienced early intense deformation including the formation of $L_n$ mineral lineations and $F_n$ isoclinal folding. Sil and Opx commonly exhibit strong preferred orientation ($L_n$) in Opx-Sil granulites, indicating that the intense ductile deformation affected these rocks in the Opx+Sil±Qtz stability field. The *P-T* conditions for the maximum *P-T* metamorphism during intense ductile deformation are approximately up to 950°C at nearly 1.0 GPa, based on the FMAS *P-T* grid (Harley *et al*., 1990; Motoyoshi *et al*., 1994).

In contrast to the peak metamorphic assemblages, the symplectites of Opx+Crd are not deformed although the secondary Crd intergrown with Spr after Opx+Sil exhibits weak preferred orientation. These textures imply that the intense ductile deformation ceased before the following mineral reactions occurred; Opx+Sil+Qtz=Crd, Opx+Sil=Crd+Spr, Grt+Qtz=Opx+Crd (Fig. 10). The local strain of Crd may be explained by the difference of timing in mineral reactions predicted on the isothermal $P$-$\mu_{FeO}$ diagram for the FMAS *P-T* grid (Motoyoshi *et al*., 1994), in which the reactions Opx+Sil=Spr+Crd and Opx+Sil+Qtz=Crd took place earlier during decompression than the reaction Grt+Qtz=Opx+Crd. The weak and local deformation was represented by $F_{n+1}$ gentle folding, shear zone formation and emplacement of pegmatite (Fig. 11).

Harley *et al*. (1990) speculated that the Opx+Sil assemblage and decompressional reactions are Archaean in age, and predate a phase of isobaric cooling which is commonly ascribed to rocks throughout the Napier Complex. As yet there is no geochronological evidence to confirm or deny this suggestion. We emphasize that our structural evidence

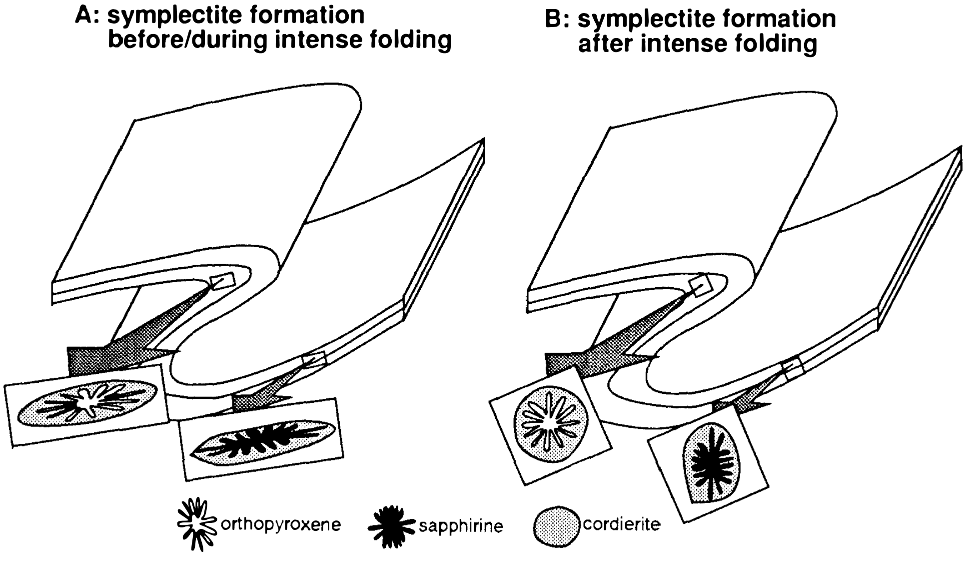

Fig. 10. Schematic illustration of symplectite formation. Strained symplectite formed before or during intense folding (A), and unstrained symplectite formed after intense folding (B).

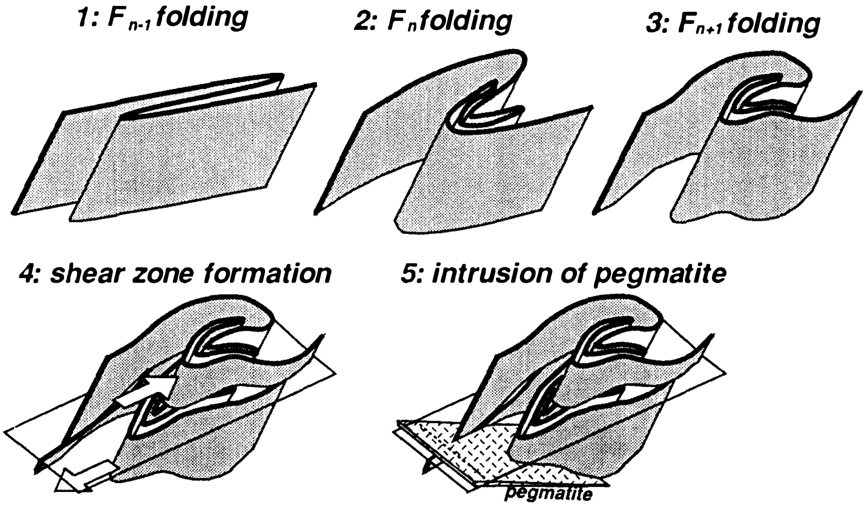

*Fig. 11. Schematic illustration of structural evolution of Forefinger Point. 1 : Development of isoclinal $F_{n-1}$ folds. 2 : Development of isoclinal $F_n$ folds during peak metamorphism. 3 : Development of $F_{n+1}$ gentle folds. 4 : Shear zone formation. 5 : Intrusion of pegmatite.*

implies that low-strain was applied during isothermal decompression, and does not constrain this decompressional phase to predate Archaean isobaric cooling. A similar structural and metamorphic history can be seen in the Lützow-Holm Complex further west (Ishikawa *et al.*, 1994), which may be Cambrian in age (Shiraishi *et al.*, 1994). The age of the textures and fabrics described here from Forefinger Point remains very uncertain.

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