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Reaction of peridotite xenoliths with host magmas as an analogue of mantle-melt interaction: microscopic characteristics

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Abstract: The mantle-melt interaction, one of the important magmatic processes in the upper mantle, may occur if a high-pressure melt comes in contact with peridotite at low pressures because the melt is undersaturated with pyroxenes, especially with orthopyroxene, and is not in equilibrium with the wall peridotite. The reactions between peridotite xenoliths and host magmas, which are usually alkaline and are strongly undersaturated with orthopyroxene at low pressures, are analogous, to some extent, to the mantle-melt interaction.

The peridotite xenoliths are sometimes disaggregated along grain boundaries inward from the contact with host magma. Morphological modification of olivine is frequently associated with the disaggregation: the peridotite olivine is sometimes partially or perfectly euhedral when in contact with host magma. The peridotite orthopyroxene is suffered from alteration through interaction with host magma, broken down into olivine ± diopsidic clinopyroxene + relatively Si-rich melt (glass). The olivine formed by the orthopyroxene breakdown is euhedral and variable in size, sometimes identical in appearance to microphenocrysts in host magma. Olivine " phenocrysts" in Mg-rich magmas, therefore, are possibly polygenetic: at least three kinds of olivines may be present, (1) disaggregated mantle olivine, sometimes modified both chemically and morphologically, (2) euhedral olivine formed by orthopyroxene breakdown, and (3) true phenocryst simply nucleated and precipitated in the magma. Some Mg-rich magmas, e.g., picritic basalts, olivine basalts, and alkali basalts, can be produced by an intense interaction between an uprising magma and mantle peridotites at lower pressures.

1. Introduction

Peridotite xenoliths frequently react with their host basalts to various extent because they have not been in equilibrium with each other under low-pressure conditions. The reaction essentially similar to this is also expected to occur between uprising magma of higher-pressure origin and peridotite wall within the upper mantle. The peridotite wall and the magma involved may exchange heat and chemical components to get equilibrium, and the process is sometimes called the mantle-melt interaction (e.g., Kelemen and

Ghiorso, 1986; Kelemen, 1990; Kelemen et al., 1990). Possible solid residua of the interaction can be frequently observed in mantle-derived peridotite massifs (e.g., Quick, 1981). The detailed process of the interaction, however, has not yet been clarified as it is difficult to find direct evidence of mantle-melt interaction in magmas on the surface (cf. Boudier, 1991).

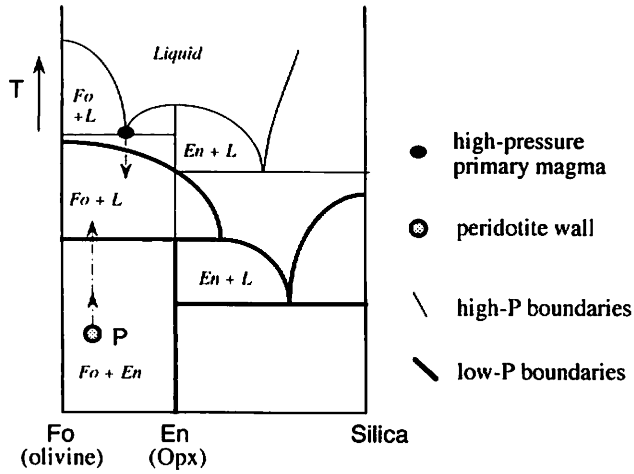

Fig. 1. Schematic phase diagram of the binary system forsterite-silica to explain the principle of mantle-melt interaction. If a high-pressure primary melt rises and comes in contact with peridotite at low-pressure conditions, they will interact with each other to have a common assemblage forsterite + melt. The wall peridotite will be heated by the melt which continues precipitating olivine during heating to release the latent heat. Phase relations are significantly simplified and modified from those of Bowen and Anderson (1914) and Chen and Presnall (1975).

The reaction (= interaction) between peridotite xenoliths and host magmas may be a good low-pressure analogue of the mantle-melt interaction. We can examine the interaction process in detail because it is frequently quenched by eruption of the magma. In this article we would like to present various microscopic features of the interaction of peridotite xenoliths with host magma to know more on the mantle-melt interaction.

2. Principles of peridotite-melt interaction

A primary melt formed by partial fusion of peridotite is not to be in equilibrium with peridotite at lower pressures because the melt may become oversaturated with olivine and undersaturated with pyroxenes with a decrease of pressure (Fig. 1). If the high-pressure melt comes in contact with low-pressure low-temperature peridotite, the melt will heat the peridotite by precipitating olivine to release the latent heat (Fig. 1). If the wall peridotite is sufficiently cool, the melt will be solidified as a mafic dike within peridotite. If the peridotite wall is sufficiently hot, the melt can interact with the peridotite (Arai, 1992). For simplicity, imagine that one grain of orthopyroxene is put into an olivine-oversaturated (orthopyroxene-undersaturated) melt (Fig. 2A). The melt may change its composition isothermally through a possible reaction, orthopyroxene + melt1 = olivine + melt2 (Fig. 2A). The melt thus can successively change the composition by precipitation of olivine combined with mixing of newly formed melt (Fig. 2B). This is a principle for the peridotite (or its orthopyroxene) -melt interaction at low pressures. If the interaction between melt and wall peridotite proceeds, dunite is formed ultimately, replacing the peridotite. The dunite is neither a simple cumulate nor a simple restite, more or less showing the structure which suggests replacement of peridotite, and is sometimes called a " discordant" or " replacive" dunite (Boudier and Nicolas, 1972; Kelemen, 1990). Chromitite (= concentration of chromian spinel) is occasionally formed with an envelope of replacive dunite (Zhou et al., 1994; Arai and Yurimoto, 1994).

Peridotite xenoliths more or less react with host magmas. Chemical modification is often remarkable for olivine, which has a high-birefringent, that is, Fe-rich, margin along the boundary with the host magma. It is apparent that orthopyroxene most prominently reacts with magmas (Fig. 3). The reaction may not be a simple congruent melting because the phenomenon is remarkable when in direct contact with the host magma as described below. Clinopyroxene often has a spongy appearance, which is due

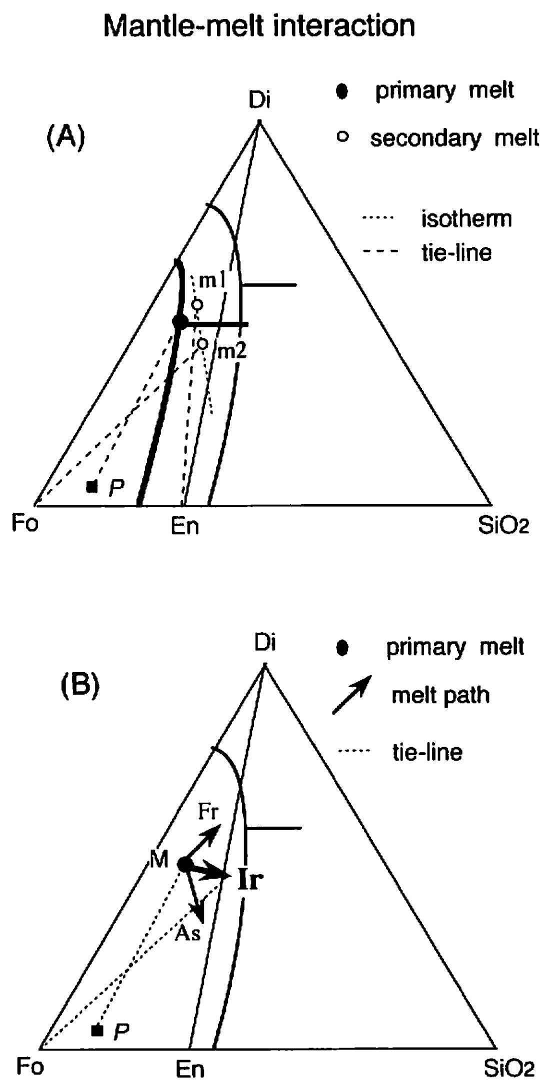

Fig. 2. Liquidus phase diagrams of the ternary system forsterite -diopside-silica to explain the mantle-melt interactions. (A) An isothermal reaction between an olivine-oversaturated melt (m1) and enstatite to produce forsterite + secondary melt (m2). (B) A possible melt path (Ir) for the mantle-melt interaction. A high-pressure melt (M) reacts with a peridotite (P) at a low pressure condition, finally producing an assemblage forsterite + secondary melt (Ir). Fr and As indicate melt paths for crystallization of olivine and assimilation of orthopyroxene, respectively. Phase relations are significantly simplified from those of Kushiro (1969, 1972)

to presence of numerous inclusions of melt ± mineral(s). This may mean a kind of incongruent melting possibly due to pressure release and/or heating. When in direct contact with the host magma, darker colored euhedral clinopyroxene is sometimes overgrown on mantle clinopyroxene. Chromian spinel is sometimes decomposed into a fine-grained dark-colored (dark brown to opaque) aggregate when in contact with the host magma. Interstitial melt is frequently observed, which is sometimes due to invasion of the host magma and sometimes due to partial melting of peridotite. It is important that the partial melt is relatively rare despite the ubiquitous presence of dissolution of individual minerals, especially orthopyroxene. This may mean a local mineral-melt reaction or a melt-assisted incongruent melting of individual minerals occurs instead of partial melting of the whole peridotite when peridotite is incorporated into magma as xenoliths and heated rapidly. The interaction between peridotite xenoliths and host magmas is, therefore, not an equilibrium process as a whole, e.g., a formation of equilibrium partial melt, but is a combination of various local reactions.

3. Five xenolith suites examined

We examined five xenolith suites, that is, peridotite xenoliths from Kawashimo and Megata, Japan, Tahiti, Okete Quarry and Todd's Quarry, New Zealand. These were selected from large amounts of mantle xenolith samples collected by the first author (S. A.) to represent various types of interactions between peridotites and host magmas.

3.1 Xenoliths from Kawashimo, Shimane Prefecture, Southwestern Japan

Alkali basalt is exposed in a small area of Kawashimo, Masuda City, Shimane Prefecture, Southwestern Japan (Iizumi et al., 1975) . This may be a part of a small dissected monogenetic volcano of Cenozoic age in the Southwestern Japan (e.g., Takamura, 1973; Iwamori, 1991). The eruption age is 6.7 Ma (Uto et al., 1986). The alkali basalt contains up to 12 wt % of normative nepheline (Iizumi et al., 1975; Nagao and Sakaguchi, 1990). It has an intersertal texture: phenocrysts are olivine and clinopyroxene, and the groundmass is composed of clinopyroxene, olivine, titanomagnetite, plagioclase and dark interstitial glass (Nagao and Sakaguchi, 1990). Phenocrysts are characteristically small in size; olivine is nearly euhedral and is less than 1 mm across. The basalt has large amounts of ultramafic xenoliths and megacrysts (Iizumi et al., 1975; Nagao and Sakaguchi, 1990).

Xenoliths are rather small and less than 5 cm across. Nagao and Sakaguchi (1990) reported the relative abundance (volume %) of rock species in the Kawashimo xenolith suite: lherzolite 11, harzburgite 17, dunite 12, wehrlite 2.1, clinopyroxenites 21, websterite 8, and orthopyroxenite 30. Peridotites are strongly deformed and have porphyroclastic textures. Chromian spinel is rounded in shape and is rare in harzburgite. Clinopyroxene is variable in amount in peridotites, from almost nil in harzburgite to more than 20 volume

% in lherzolite (Nagao and Sakaguchi, 1990).

3.2 Xenoliths from the Fatauaa River valley, Tahiti

Xenoliths, less than 10 cm across, were collected from basanite in the Fatauaa River valley near Papeete, Tahiti: the locality is the same as that of Tracy (1980). The host basanite is porphyritic to seriate, mainly composed of olivine and titanaugite, with subordinate amounts of plagioclase, magnetite, and other trace minerals (alkali feldspar, leucite, apatite and ilmenite) (Tracy and Robinson, 1977; Tracy, 1980). The basanite is primitive, containing large amounts of magnesian olivine phenocrysts (up to Fo88.5) (Tracy, 1980).

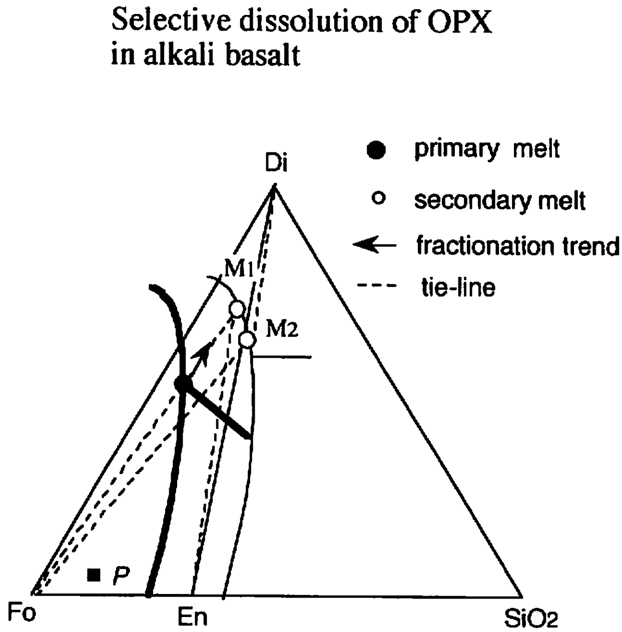

Fig. 3. Schematic phase diagram of the ternary system forsterite-diopside-silica to explain the reaction of orthopyroxene with alkali basaltic melt. An alkali basaltic melt (M1), which is undersaturated with orthopyroxene and saturated with olivine and diopside, could react with enstatite to produce forsterite + diopside + secondary melt (M2). Phase relations are significantly simplified from those by Kushiro (1969, 1972).

The peridotite suite mainly consists of dunite, lherzolite, and wehrlite (Table 1 of Tracy, 1980). The Fo content of olivine in lherzolites ranges from 87 to 90, roughly correlated with the Cr# of coexisting spinel, from 0.020 to 0.313 (Tracy, 1980). As pointed out by Tracy (1980) the marginal parts of xenoliths are considerably altered through reaction with basanite magma. Olivine, clinopyroxene, and chromian spinel in the margins are chemically modified from mantle compositions to be identical to the magmatic ones.

3.3 Xenoliths from Okete Quarry, western North Island, New Zealand

The xenoliths examined in this study were collected from the Okete Quarry, New Zealand. The basanite of the Okete Quarry, which contains abundant peridotite xenoliths (e.g., Rodgers et al., 1975), belongs to the Okete Volcanics of the Alexandra Volcanics of Plio-Pleistocene (Briggs, 1983; Briggs and Goles, 1984). The age of the Okete basanite was reported to be 1.80 or 2.69 Ma (Robertson, 1976).

The basanite from the Okete Quarry has an intersertal texture. Phenocrysts are composed of olivine, clinopyroxene, and plagioclase. The peridotite xenoliths from the Okete Quarry are very small in size, a few centimeters across, and show frequent reactions with the host magma. Clinopyroxene-poor lherzolite to clinopyroxene-bearing harzburgite, with weak porphyroclastic texture, is the main rock species. Preliminary microprobe analyses of minerals indicate that the peridotites have characteristics of primary mantle restites, plotting within the olivine-spinel mantle array (Arai, 1987, 1994a). The Fo content of olivine is around 90, and the Cr# (= Cr/(Cr + Al) atomic ratio) of chromian spinel ranges from 0.2 to 0.5.

3.4 Xenoliths from Todd's Quarry, northern North Island, New Zealand

Xenoliths were collected from the Todd's Quarry, Arapohue near Dargaville (Tokatoka area), North Island, New Zealand (Black and Brothers, 1965; Rodgers et al., 1975). They are small in size, mostly a few centimeters across, and are enclosed in a Miocene olivine nephelinite dike (Black and Brothers, 1965). The nephelinite has about 20 wt % and 7 wt % of normative nepheline and leucite, respectively (Black and Brothers, 1965). Phenocrysts are olivine and titanaugite, and the groundmass is mainly composed of titanaugite, nepheline, magnetite, and phlogopite.

According to Black and Brothers (1965) the xenolith suite mainly consists of dunites, sometimes pyroxene-bearing, harzburgite, and lherzolite. They suffer from intense alteration by reaction with host magma, especially at the marginal parts. Minerals have not yet been analyzed, but the peridotites may be similar in chemistry to those in the Okete Quarry basanite as the petrography is very similarity for the both peridotite suites.

3.5 Xenoliths from Megata volcano, the Northeast Japan arc

Megata volcano, located at the Oga Peninsula, the Northeast Japan arc, is very famous for the abundant deep-seated xenoliths (e.g., Aoki, 1987). Petrological and geochemical studies on the xenoliths have been published by many authors (e.g., Kuno, 1967; Aoki, 1971; Aoki and Prinz, 1975; Takahashi, 1980, 1986; Tanaka and Aoki, 1987). More recently Abe et al. (1992) and Abe and Arai (1993) reported detailed petrological characteristics of the Megata peridotite xenoliths. The host magma is calc-alkali andesite to dacite, ca. 10, 000 years in age (Horie, 1964), for the Ichinomegata crater, and high-alumina basalt for the Sannomegata crater (Katsui et al., 1979; Aoki and Fujimaki, 1982). Megata volcano is one of a few places on the earth where deep-seated xenoliths captured by arc magmas are available (cf. Abe and Arai, 1993).

The Megata xenolith suite is composed of peridotites, websterites, clinopyroxenites, gabbros, amphibolites, and other shallow-seated rocks (granitic rocks, metavolcanics, and sediments). The most important is that hydrous minerals (mainly pargasite) are very frequently observed in the xenoliths, especially in those from the Ichinomegata crater. The peridotite xenoliths are most frequently lherzolite and less frequently harzburgite, having chromian spinel with Cr# < 0.5 (Abe et al., 1992). The texture is protogranular to porphyroclastic. Lherzolites often have plagioclase which reacts with olivine to various extent producing a spinel-pyroxene symplectite (Takahashi, 1986). Peridotite, especially lherzolite, xenoliths from Ichinomegata crater have secondary pargasite and rarely phlogopite, of which total volume is less than 20 % (e.g., Abe and Arai, 1993).

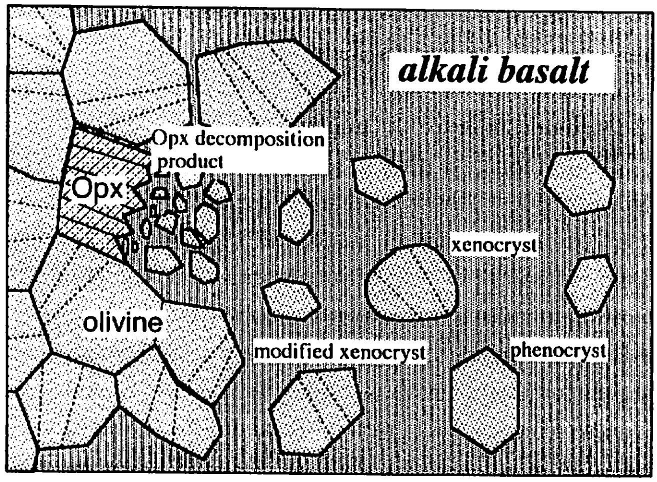

Fig. 4. An illustration of disaggregation of a peridotite xenolith due to interaction with a host alkali basalt. Note that there could be three kinds of olivine " phenocrysts" ; (1) a disaggregated mantle olivine sometimes morphologically modified to be euhedral, (2) an euhedral olivine formed by breakdown of orthopyroxene and (3) a true phenocryst precipitated from the magma.

4. Peridotite-magma interactions: microscopic observations

4.1 Morphological modification of peridotite olivine

Mantle olivine is sometimes strongly modified when in contact with the host magma (Fig. 4; Plate I). Invasion of melt into olivine, sometimes along subgrain boundaries (Boudier, 1991), and compensatory overgrowth of euhedral olivine, sometimes with minute chromian spinel inclusions, are observed along the boundary with host magma (Plate I). For example a large olivine porphyroclast in a harzburgite xenolith from Okete Quarry or Kawashimo has a zigzag boundary to host basalt (Plate I). This can be interpreted that small euhedral olivine crystals are forming by modification (dissolution coupled with crystallization) of a large strongly deformed mantle olivine. Deformation features sometimes survive the morphological modification. Overgrowth of magmatic olivine on the peridotite olivine is doubtless because small euhedral chromian spinel is sometimes enclosed only in the margin in direct contact with host magma (Plate I, fig. 3).

4.2 Disaggregation of peridotite olivine

Disaggregation of peridotite olivine proceeds by invasion of host basalt along grain boundaries (Fig. 4; Plate II; Plate X, fig. 1). The secondary melt formed by dissolution of orthopyroxene mentioned below may assist this process (Plate II, figs. 3 to 4). Anhedral and deformed olivine crystals, which are easily identified as xenocrysts, can be released into magma by this process (Plate II, fig. 4; Plate III, figs. 3 and 4; Plate X, fig. 2). Morphological modification is frequently associated with the disintegration of olivine grains, thus making discrimination of the released xenocrystal olivine with the true phenocryst olivine very difficult (Plate II, fig. 2).

4.3 Decomposition of orthopyroxene

Dissolution of orthopyroxene is most prominent (Plates II to VIII, especially Plate VIII, fig. 2). Orthopyroxene in peridotite xenoliths very frequently reacts with host magma along the contact plane. It is noteworthy that the reaction is observed not only in alkaline basalts but also in subalkaline magmas (Plate IV, figs. 3 and 4). In the Megata volcano, northeast Japan arc, peridotite xenoliths are included in high-alumina arc basalt for the Sannomegata crater (Katsui et al., 1979) and in calc-alkaline andesite to dacite for the Ichinomegata crater (Katsui et al., 1979; Aoki and Fujimaki, 1982; Aoki, 1987). Orthopyroxene in their peridotite xenoliths frequently have reaction products, which are essentially similar to those in ordinary alkaline basalts, along the boundary with host magmas (cf. Plate III, fig. 1; Plate IV, figs. 2 to 4).

Ordinary products of the interaction are olivine + clinopyroxene ± chromian spinel + melt (glass) (Fig. 3; Plates IV and V). The interaction zone is sometimes divided into two sub-zones as in the Kawashimo peridotites (Plates VI and VI; Plate VII, figs 3 and 4). Minerals are definitely finer in the inner sub-zone than in the outer sub-zone (Plate VII, fig. 4; Arai and Abe, submitted). Arai and Abe (submitted) interpreted that the inner and outer sub-zones are a reaction (or incongruent melting) zone, where orthopyroxene is decomposed into olivine + Ca-rich clinopyroxene + Si-rich melt, and a melt-mixing zone, where mixing of the Si-rich melt with more primitive host basalt occurs, respectively. In well reacted peridotites, olivine in such a zone is euhedral and is as large as a microphenocryst or phenocryst olivine in host basalt (Plate III, fig. 1; Plate VI, figs. 2 and 4). Relatively fine-grained aggregates of olivine, sometimes found in alkali basalts, may be a completely digested orthopyroxene xenocryst (Plate VII, figs 1 and 2). In the outer sub-zone of orthopyroxene-melt interaction on depleted harzburgites which have spinel with a Cr# higher than 0.4, chromian spinel is remarkably concentrated (Plate VII, figs. 3 and 4; Arai and Abe, submitted). Euhedral chromian spinel inclusion in euhedral olivine formed through interaction is sometimes inherited from chromian spinel lamellae in orthopyroxene of peridotite (Plate IV, fig. 1).

Degree of orthopyroxene-melt interaction may be partly dependent on the duration of xenolith residence in magma. For the xenoliths in scoria or pumuce, that is, in well-vesiculated magma, the interaction zone on orthopyroxene is only poorly developed, partly due to a secondary removal during an explosive eruption (Plate VIII, fig. 1). Former existence of interaction product may be suggested by the selective embayment of orthopyroxene part relative to adjacent olivine part.

4.4 Decomposition of peridotite spinel

Chromian spinel in contact with host basalt is opacitized and is usually decomposed into a fine-grained aggregate of opaque to dark-colored spinel (Plate VIII, figs. 3 and 4; Plate IX, fig. 4), which is very similar in appearance to fine spinel euhedra included in phenocryst olivine. The spinel aggregate is very similar to that associated with olivine " phenocryst" in the Oshima-Oshima picrite basalt (Plate IX) (Ninomiya and Arai, 1993).

4.5 Modifications of clinopyroxene

Mantle clinopyroxene in peridotite xenoliths, especially in small ones, is frequently decomposed into low-pressure clinopyroxene + glass, giving a spongy appearance (Plate X, figs. 1 to 3). Chemical modification along a contact with host basalt is ubiquitous: clinopyroxene has a light brown to green margin, indicating enrichment for Ti, Al, and Fe. The margin is sometimes partly euhedral in well-reacted peridotite xenoliths, indicating a morphological modification and/or overgrowth from host basalt.

5. Implications for mantle-melt interaction and origin of Mg-rich magmas: a discussion

5.1 Polygenetic nature of olivine " phenocrysts"

The interaction between peridotite xenoliths and host magmas may mimic, to some extent, the mantle-melt interaction. The most important point is for the origin of olivine " phenocrysts" in Mg-rich magmas (Fig. 4). Observations both on olivine-rich magmas and on peridotite xenoliths with significant reaction features indicate a genetical linkage between the olivine " phenocrysts" of the former and the interaction products of the latter. Ninomiya and Arai (1993) and Ninomiya (1994) successfully discriminate several types of olivine " phenocrysts" in the Oshima-Oshima picrite basalt, indicating their polygenetic nature. Accord-

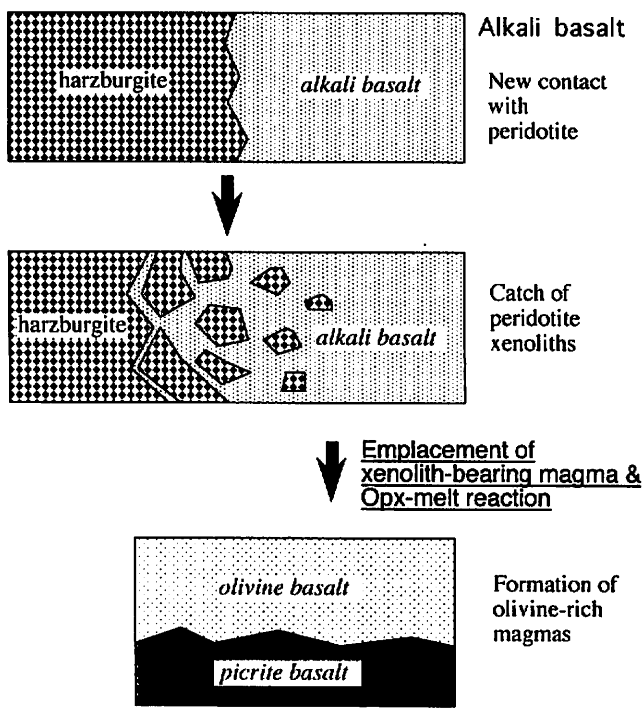

Fig. 5. An illustration of the interaction between alkali basalt and its peridotite xenoliths, which could produce olivine-rich magmas such as picrite basalt and olivine basalt. The interaction may proceed effectively if the xenolith-bearing magma is emplaced and once resides in deep parts, i.e., in the lower crust or the upper mantle.

ing to the microscopic observations mentioned above there should be at least three kinds of olivine "phenocrysts" in magmas strongly affected or formed by the mantle-melt interaction (Fig. 4). One is the true " phenocryst" which is nucleated and precipitated from the magma. The second is of xenocrystal origin, disintegrated from mantle peridotites. Anhedral and deformed olivine, which is sometimes composed of several grains, in basalt is definitely of this origin (Plate III, figs. 3 and 4; Plate X, fig. 2). Morphological modification by the magma (Plate I; Plate II, fig. 2), however, sometimes changes the anhedral mantle olivine to euhedral one, which makes discrimination from the true phenocryst difficult. The third is the relatively small and euhedral one formed by the orthopyroxene dissolution (Fig. 4; Plate III, fig. 1; Plate V, figs. 1 and 2; Plate VI).

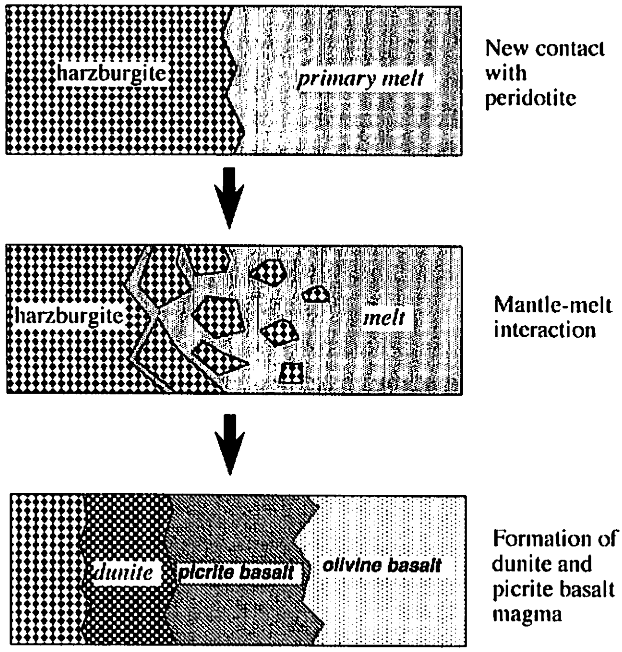

Fig. 6. An illustration of the process and result of the mantle-melt interaction. The olivine-oversaturated melt reacts with the mantle peridotite, e.g. harzburgite, to produce finally olivine + secondary melt.

5.2 Origin of olivine-rich magmas and dunites

If the mantle-melt interaction proceeds efficiently, olivine-rich crystal mush or picritic mixture may be formed in the upper mantle (Fig. 5). The peridotite wall may be partly replaced by dunite because selective dissolution of pyroxenes (Fig. 6). Nicolas and Prinzhofer (1983) interpreted that dunites in the mantle-crust transition zone of ophiolites are residual products of such an interaction. If the melt is only insufficiently removed, melt-impregnated dunites or troctolites are produced depending on the amount of interstitial melt. The troctolite and olivine gabbro drilled and recovered from Hess Deep, equatorial Pacific, may be solidified equivalent to the crystal-rich mush and the crystal-poor one, respectively (Arai and Matsukage, in press). The " wehrlite magma" of the Oman ophiolite (Benn et al., 1987) may be equivalent to the interaction-related crystal mush which was emplaced and slowly cooled in the lower crust. If the crystal much can rise to the surface and is quenched, a picritic basalt will be formed. The Miocene picrite basalts in the Circum-Izu Massif Serpentine belt, central Japan, which have up to 50 volume % of olivine crystal (Takasawa, 1976; Tazaki and Inomata, 1980; Ishida et al., 1990; Arai, 1994), may have been formed through such a process as they have various kinds of olivine " phenocrysts" (Takasawa, 1976). More generally, olivine-rich magmas, e.g., picrite basalt, olivine basalt, and alkali basalt, are possibly the mixture of the polygenetic olivine crystals and the melt which is strongly affected by mantle-melt interaction. The mantle-melt interaction may be inevitable between a magma of deeper origin and a peridotite at lower pressure conditions.

As suggested by Fisk (1986), Kelemen (1990), and Kelemen et al. (1990), the melt formed by the mantle-melt interaction is expected to become enriched with SiO_2 (Fig. 2B), that is, to trace a compositional trend similar to the calc-alkaline one, because the silica content is enhanced by selective dissolution of orthopyroxene combined with precipitation of olivine. The Mg/Fe ratio is less variable because of a kind of buffering effect of the surrounding magnesian peridotite wall. The melt which significantly reacts with mantle peridotite, especially with harzburgite, may be enriched with Cr because the involved orthopyroxene has the Cr# far higher than that in ordinary primary melt (Arai and Abe, submitted). This can lead to the formation of podiform chromitites in the upper mantle (Arai, 1992; Arai and Yurimoto, 1994).

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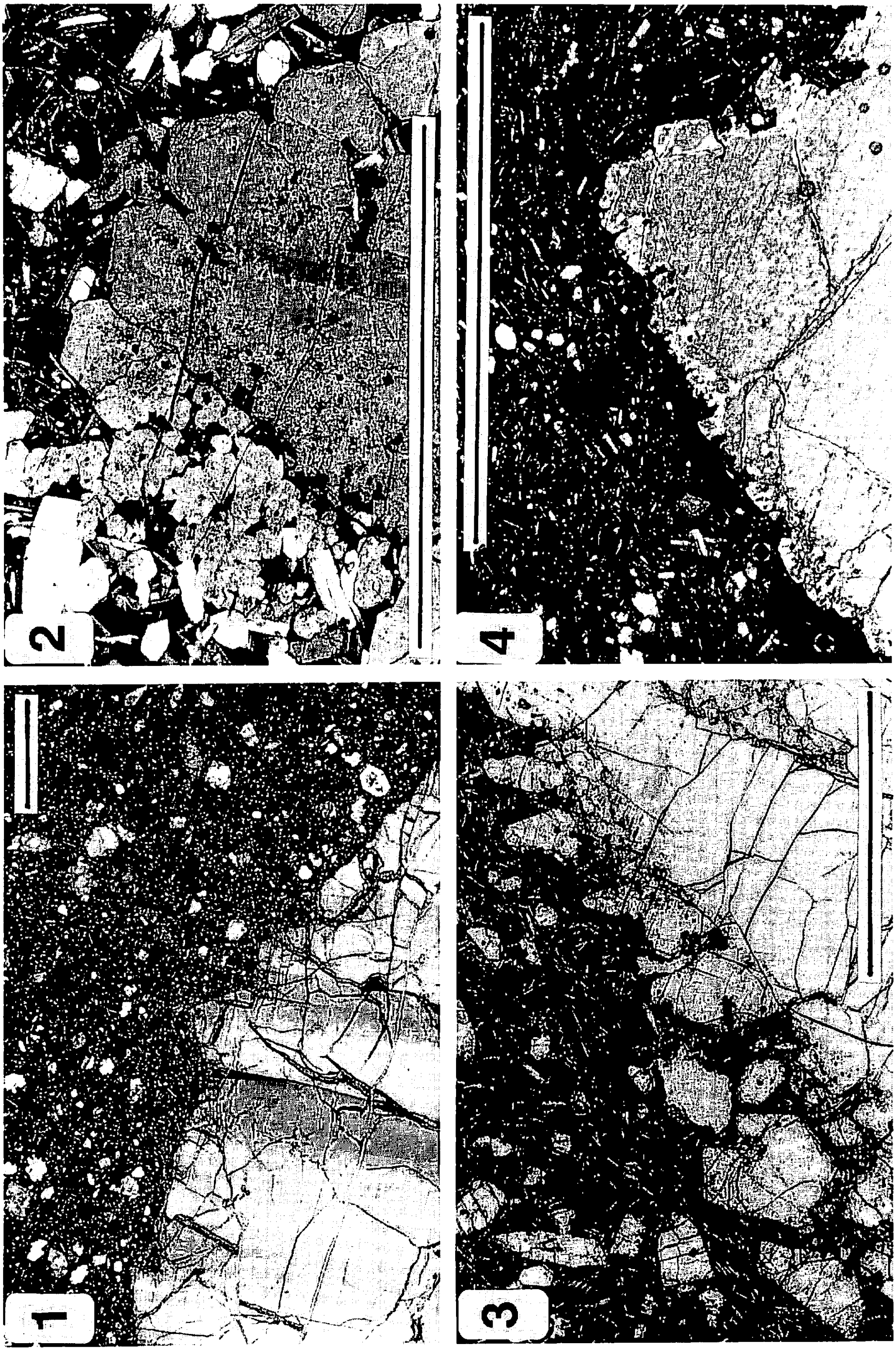
Plate

Plate I



Captions for Plates

Photomicrographs of products of the peridotite-basalt interaction and related minerals. All photographs are by transmitted light and the scale bar is 1 mm, if not otherwise mentioned.

Plate I Morphological modification (partial recrystallization) of mantle olivine along the contact with host basalt.

fig. 1 Incomplete formation of euhedral olivine crystal on a large kinked olivine porphyroclast in a harzburgite xenolith (KWS-2) from Kawashimo, southwestern Japan. Note that the size of the partly euhedral olivine is constrained by the subgrain boundary of the porphyroclast. Crossed-polarized light.

fig. 2 Formation of small euhedral olivine crystals on a large kinked olivine porphyroclast in a harzburgite xenolith (OQ-11) from Okete Quarry, New Zealand. Plane-polarized light.

fig. 3 Formation of small euhedral olivine with spinel inclusions on a large olivine porphyroclast in a harzburgite xenolith (OQ-05).

fig. 4 Formation of small euhedral crystals on a large olivine porphyroclast in a lherzolite xenolith (S-510) from the Sannomegata crater of Megata volcano. Crossed-polarized light.

Plate II

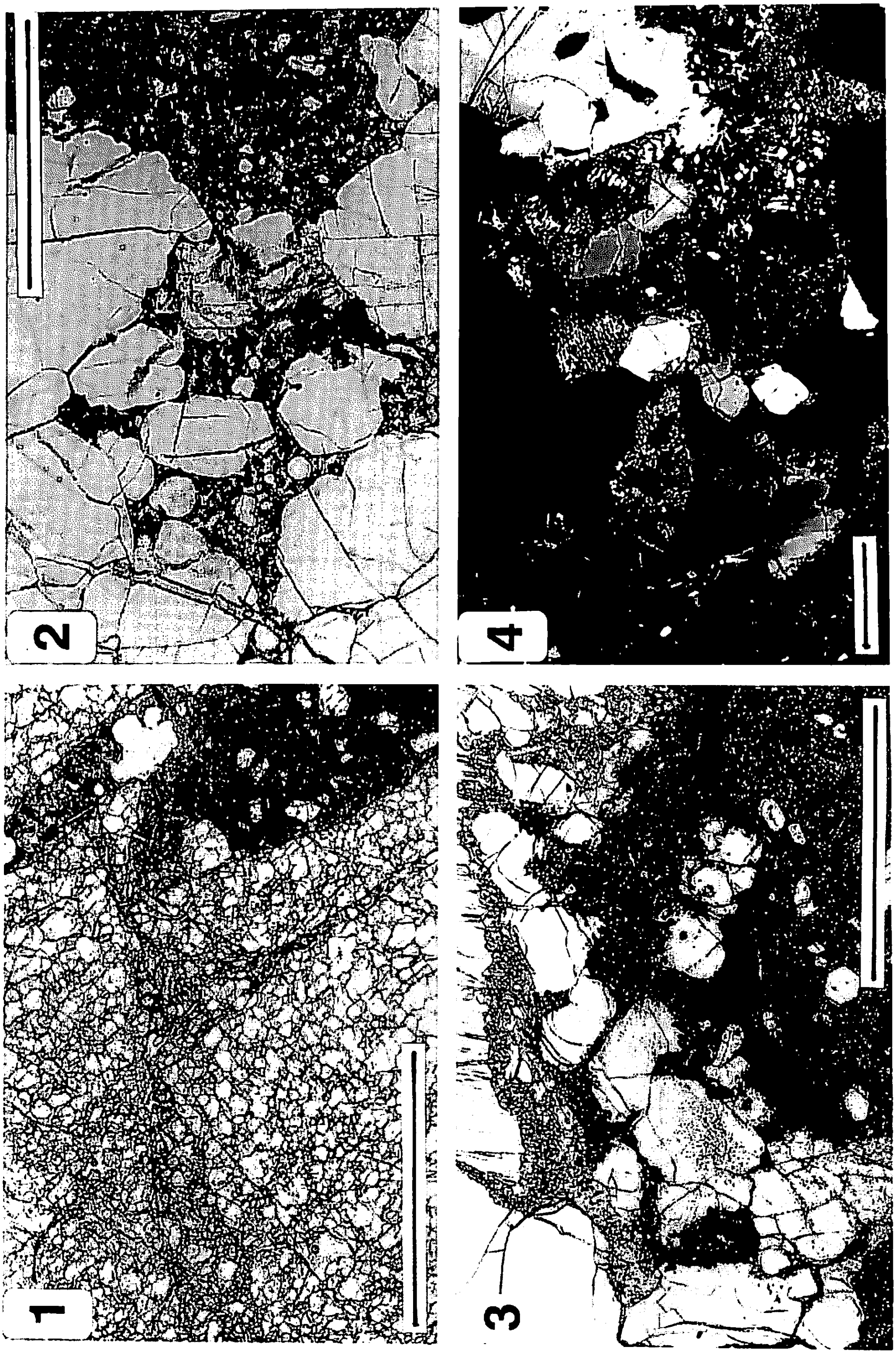


Plate II Disaggregation of olivine grains of peridotite.

fig. 1 Invasion of host alkali basaltic melt along cracks of fine-grained dunite xenolith (KWS-7) from Kawashimo. Note that the incorporation of olivine crystals into the melt. Plane-polarized light.

fig. 2 Formation of euhedral olivine phenocrysts from disintegrated mantle olivine of a harzburgite xenolith (Tahiti-2) from Tahiti.

fig. 3 Disintegration of olivine possibly assisted by the decomposition of orthopyroxene in a harzburgite xenolith (TQ-04-2) from Todd's Quarry, New Zealand. Plane-polarized light.

fig. 4 Disintegration of a harzburgite xenolith (TQ-04-1) from Todd's Quarry through the invasion of the host melt combined with the orthopyroxene decomposition. Fine-grained is the decomposition product of orthopyroxene. Crossed-polarized light.

Plate III

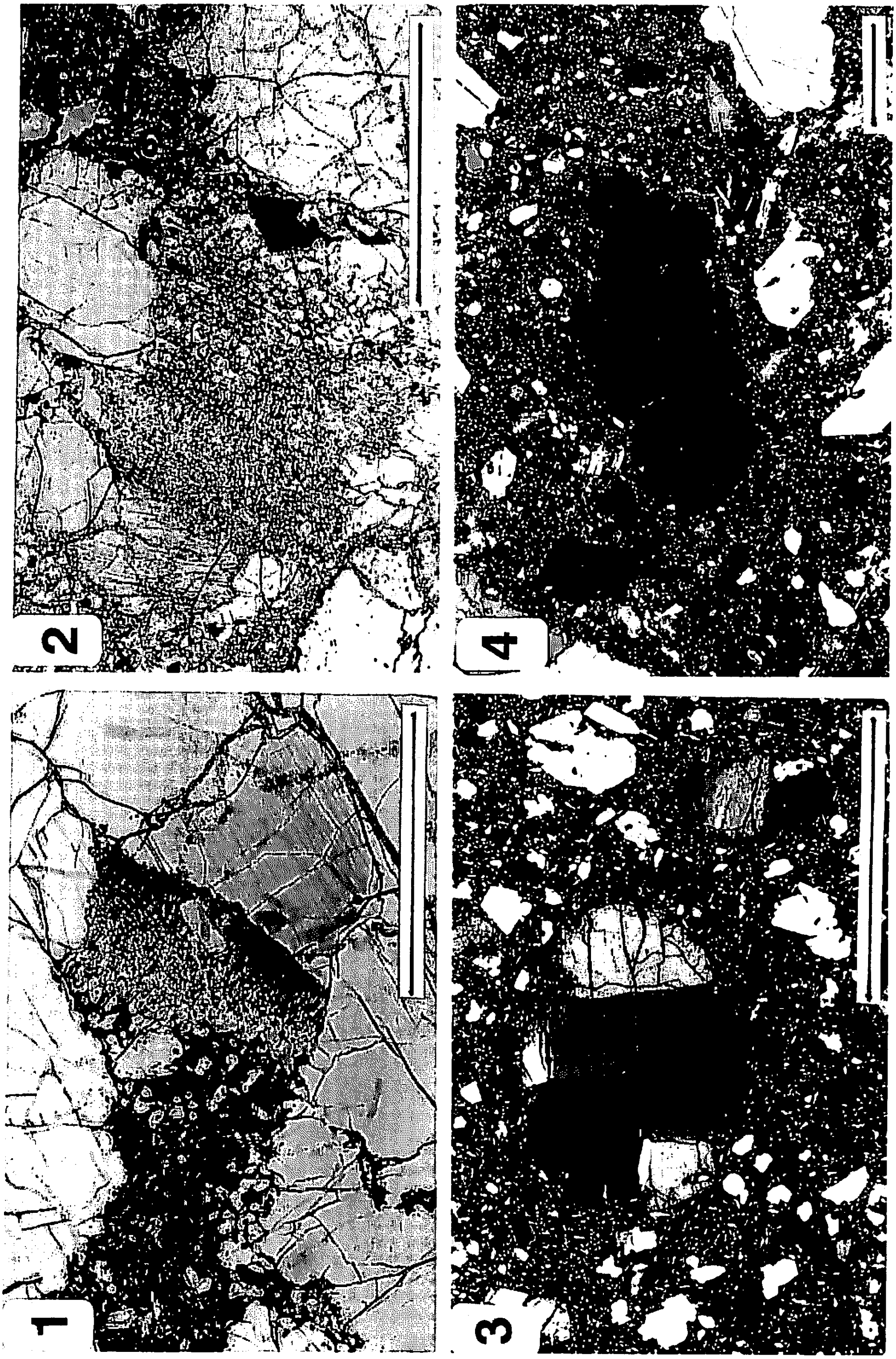


Plate III

fig. 1 Interaction between invaded melt and orthopyroxene in a harzburgite xenolith (Tahiti 1-1) from Tahiti. Note microphenocryst-size olivine formed by the interaction process. Plane-poralized light.

fig. 2 Interaction between alkali basalt melt and orthopyroxene in a harzburgite xenolith (OQ-04) from Okete Quarry. Note that the interaction product becomes coarser-grained outward. Plane-polarized light.

fig. 3 Olivine xenocryst which preserves strong deformation features in a basanite from Okete Quarry. Crossed-polarized light.

fig. 4 Anhedral olivine xenocryst which preserves a kink band in a basanite (Tahiti 3-1) from Tahiti. Crossed-polarized light.

Plate IV

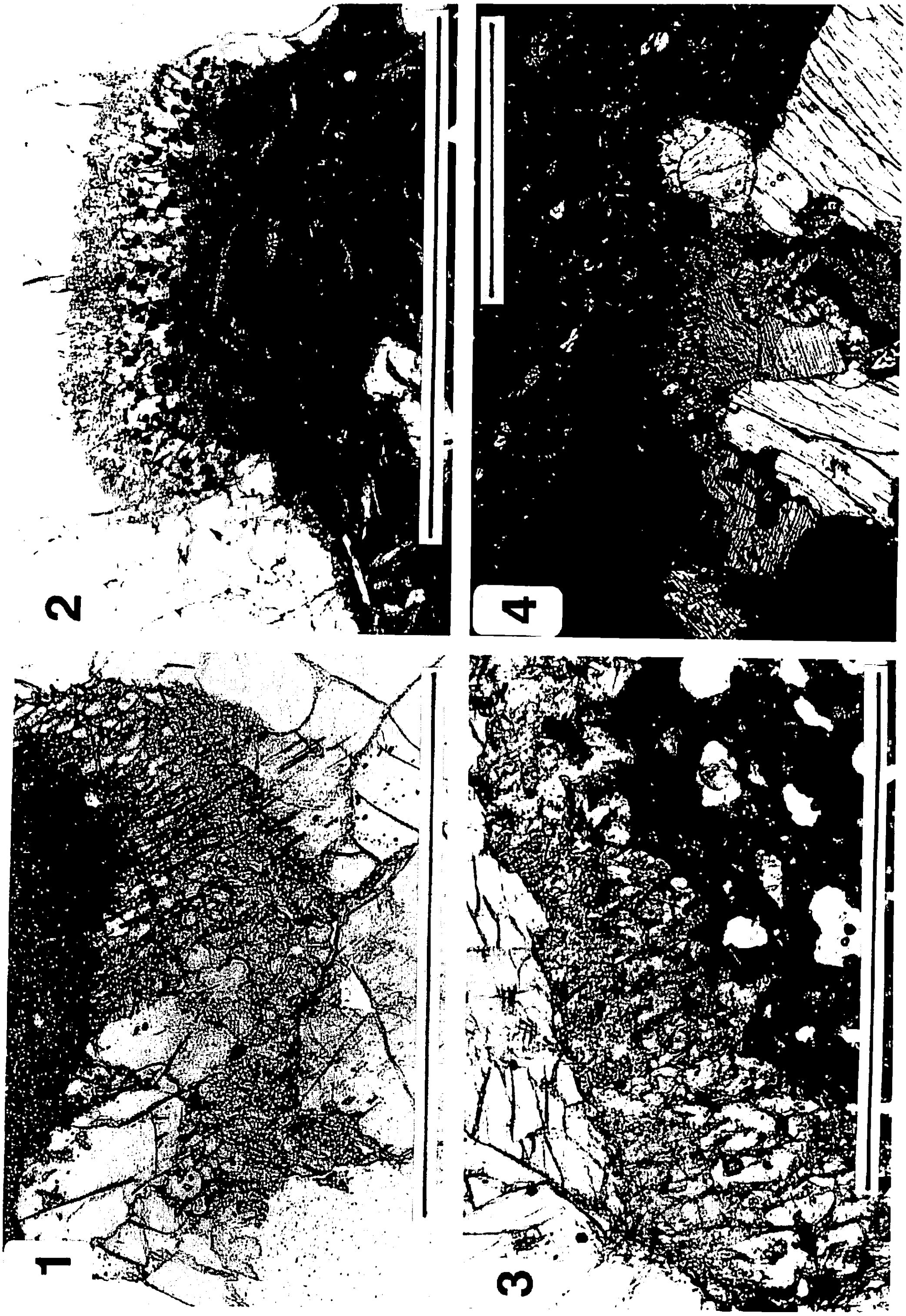


Plate IV

fig. 1 Interaction product (fine-grained aggregate) between nephelinite melt and orthopyroxene in a harzburgite xenolith (TQ-06) from Todd's Quarry. Plane-polarized light. Note the spinel lamella in orthopyroxene is converted into spinel inclusion in olivine of the interaction product.

fig. 2 Selective dissolution of orthopyroxene in a harzburgite xenolith (KWS-12) from Kawashimo. Note the embayment of orthopyroxene. Plane-polarized light.

fig. 3 Interaction product (fine-grained aggregate) between basalt (high-alumina arc basalt) and orthopyroxene of a lherzolite xenolith (S-442) from the Sannomegata crater, Megata volcano, the northeast Japan arc. Plane-polarized light.

fig. 4 Interaction product (fine-grained aggregate) on orthopyroxene of a lherzolite xenolith (I-527) enclosed by calc-alkaline andesite from the Ichinomegata crater, Megata volcano. Crossed-polarized light.

Plate V

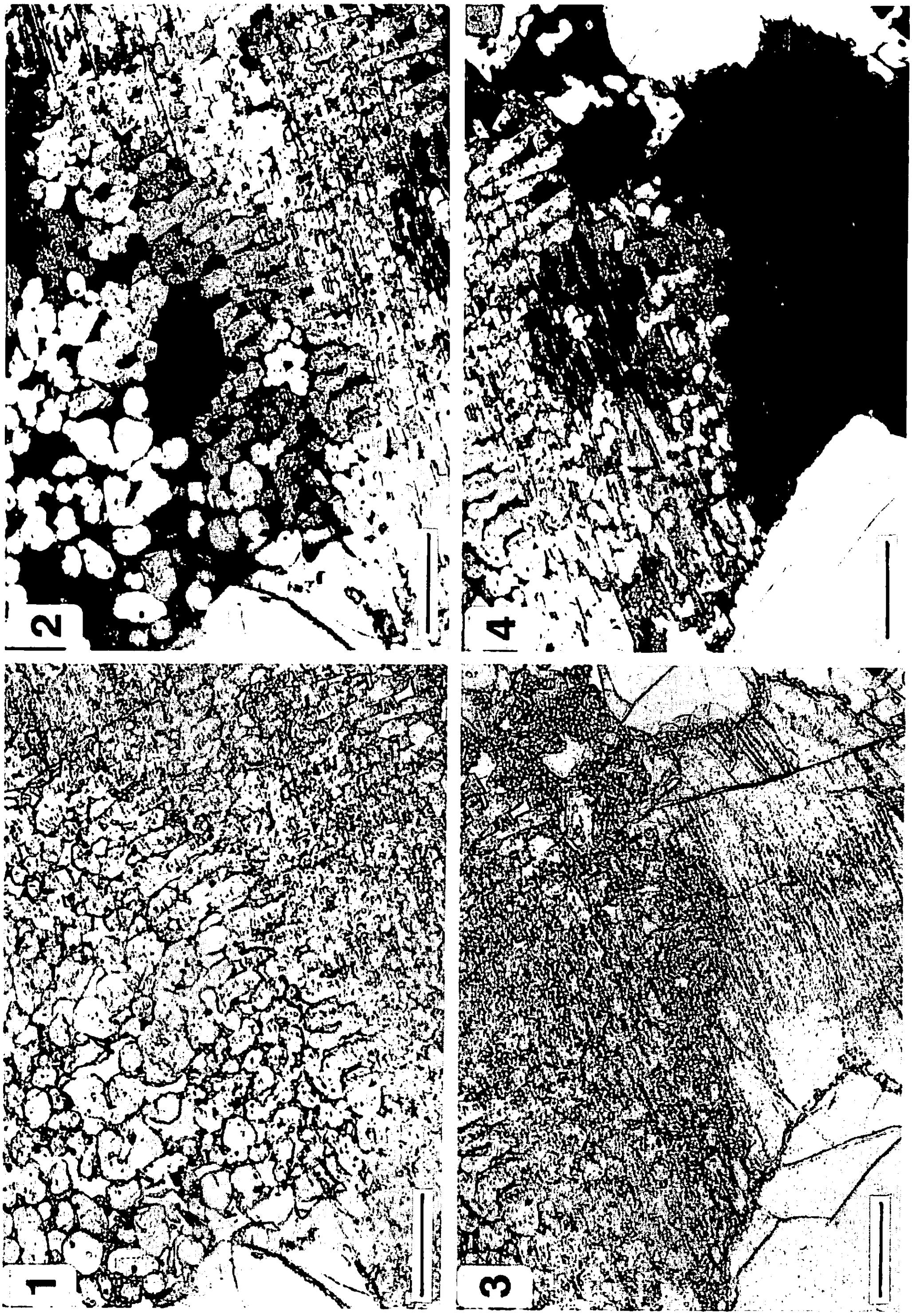


Plate V Close-up of an interaction product, a fine-grained aggregate of olivine, spinel and interstitial melt, between basanite and orthopyroxene from a harzburgite xenolith (OQ-04) from Okete Quarry. Scale bar is 0.1 mm.

fig. 1 An outer part. Note that the grain size of olivine increases outward (upward in the photo). Plane-polarized light.

fig. 2 Crossed-polarized light.

fig. 3 An inner part on orthopyroxene. Plane-polarized light.

fig. 4 Crossed-polarized light.

Plate VI

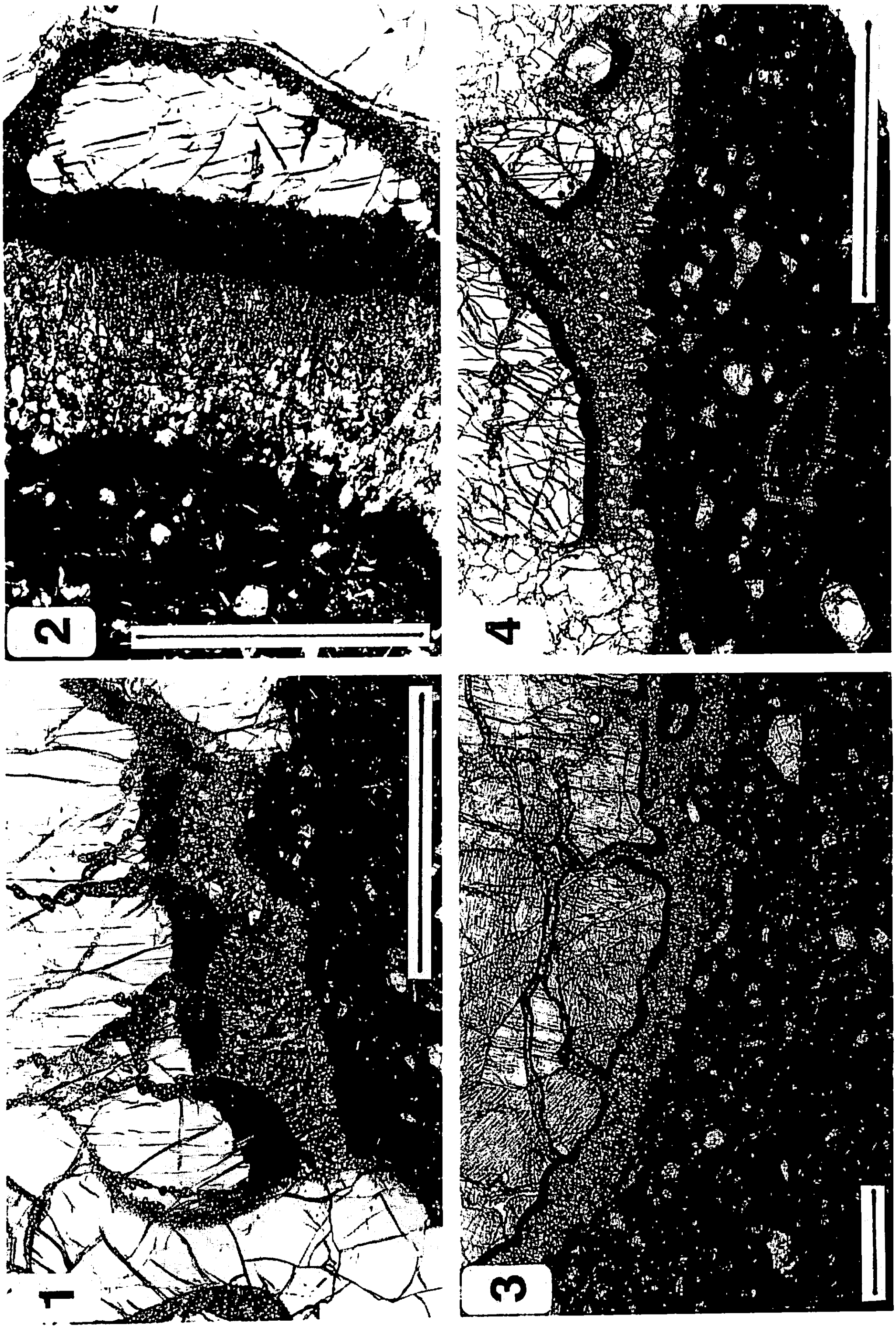


Plate VI Interaction products between basanite and orthopyroxene in ultramafic xenoliths from Kawashimo. Note the interaction zone has a dual structure: it is composed of finer-grained inner sub-zone (adjacent to orthopyroxene) and coarser-grained outer sub-zone (adjacent to melt). Plane-polarized light.

fig. 1 Lherzolite (KWS-3).

fig. 2 Lherzolite (KWS-3). Note that the decomposition of orthopyroxene occurs along the grain boundary.

fig. 3 Orthopyroxenite (KWS-33).

fig. 4 Harzburgite (KWS-5). Note the similarity of grain size of phenocryst olivine to both olivine neoblast of harzburgite and euhedral olivine of the outer sub-zone of interaction.

Plate VII

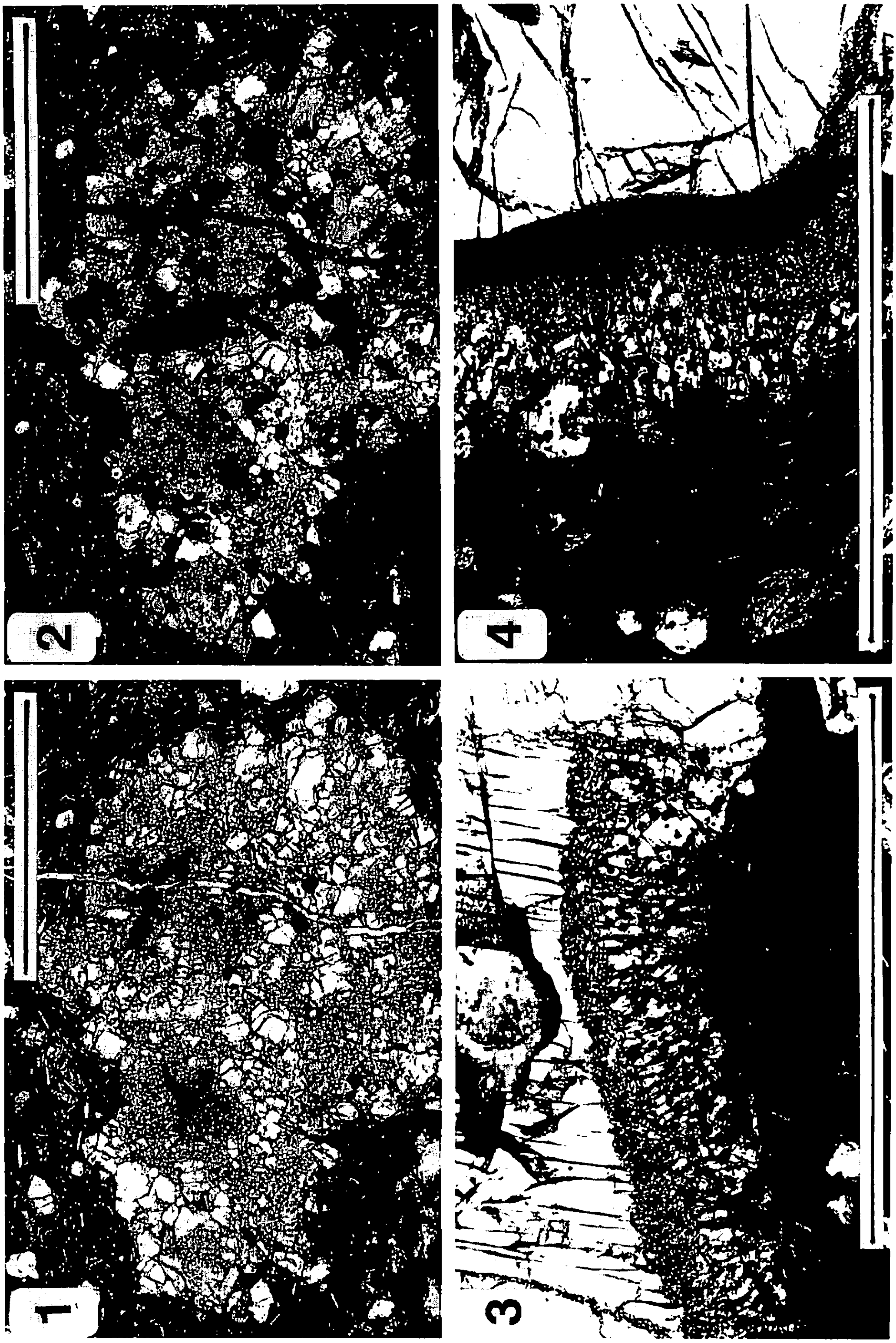


Plate VII

fig. 1 Fine-grained aggregate of olivine in alkali basalt adjacent to a websterite xenolith (KWS-15) from Kawashimo. It is derived from an orthopyroxene xenocryst. Plane-polarized light.

fig. 2 Crossed polarized light.

fig. 3 Interaction product enriched with chromian spinel (opaque dots) on orthopyroxene from a harzburgite xenolith (KWS-12) from Kawashimo. Plane-polarized light. See Arai and Abe (submitted).

fig. 4 Interaction product with spinel concentration (opaque dots) on orthopyroxene from a harzburgite xenolith (KWS-3). Plane-polarized light. See Arai and Abe (submitted).

Plate VIII

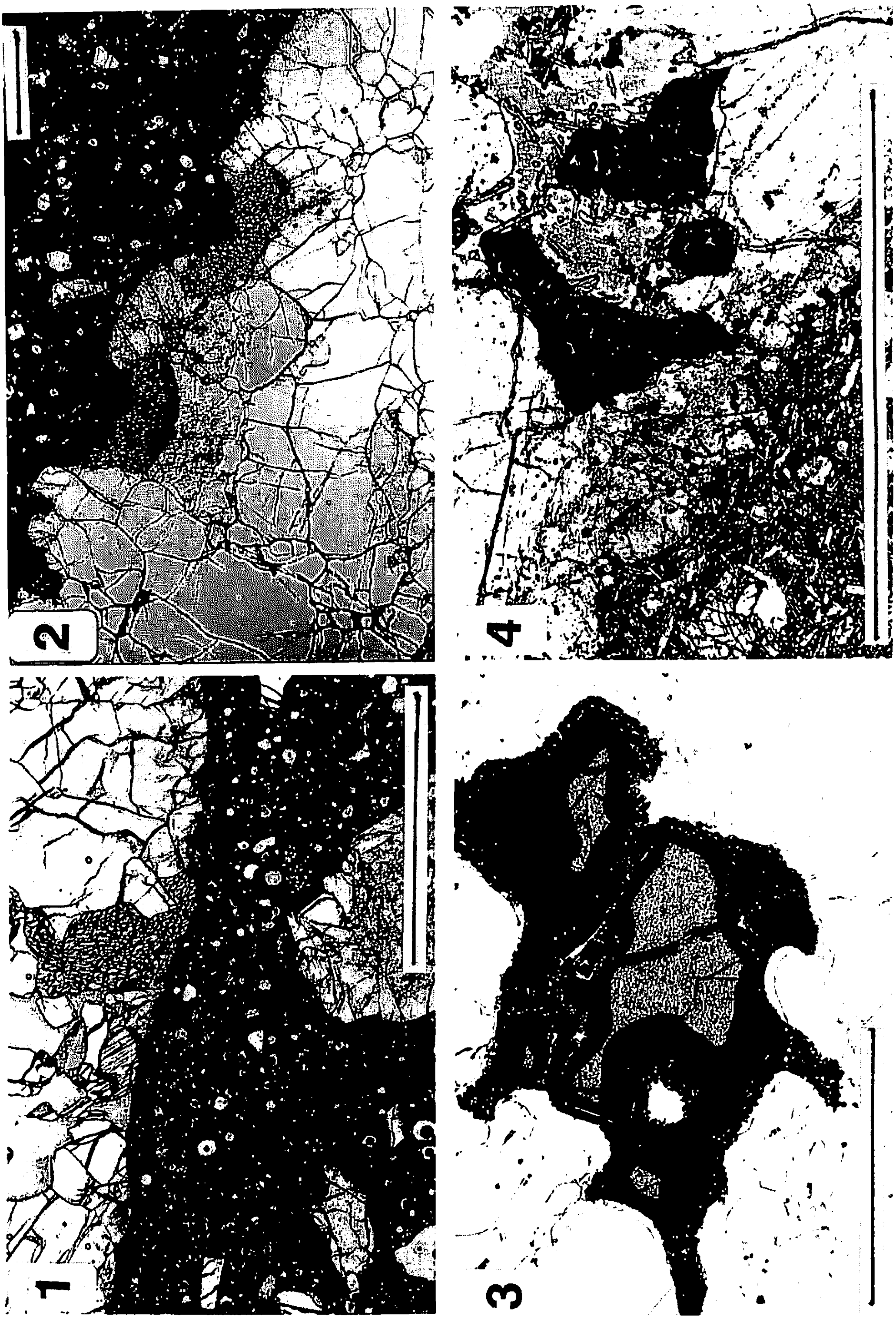


Plate VIII Plane-polarized light.

fig. 1 A lherzolite xenolith (I-643) which apparently has no sign of interaction between orthopyroxene and andesitic melt from the Ichinomegata crater, Megata volcano.

fig. 2 A harzburgite xenolith (TQ-06) which has remarkable interaction zones between orthopyroxene and basanitic melt from Todd's Quarry, New Zealand.

fig. 3 Fine-grained interaction zone around chromian spinel in a harzburgite xenolith (OQ-02) from Okete Quarry.

fig. 4 Fine-grained aggregate of opaque spinel formed by interaction between chromian spinel and basanite melt in a harzburgite xenolith (OQ-07) from Okete Quarry.

Plate IX

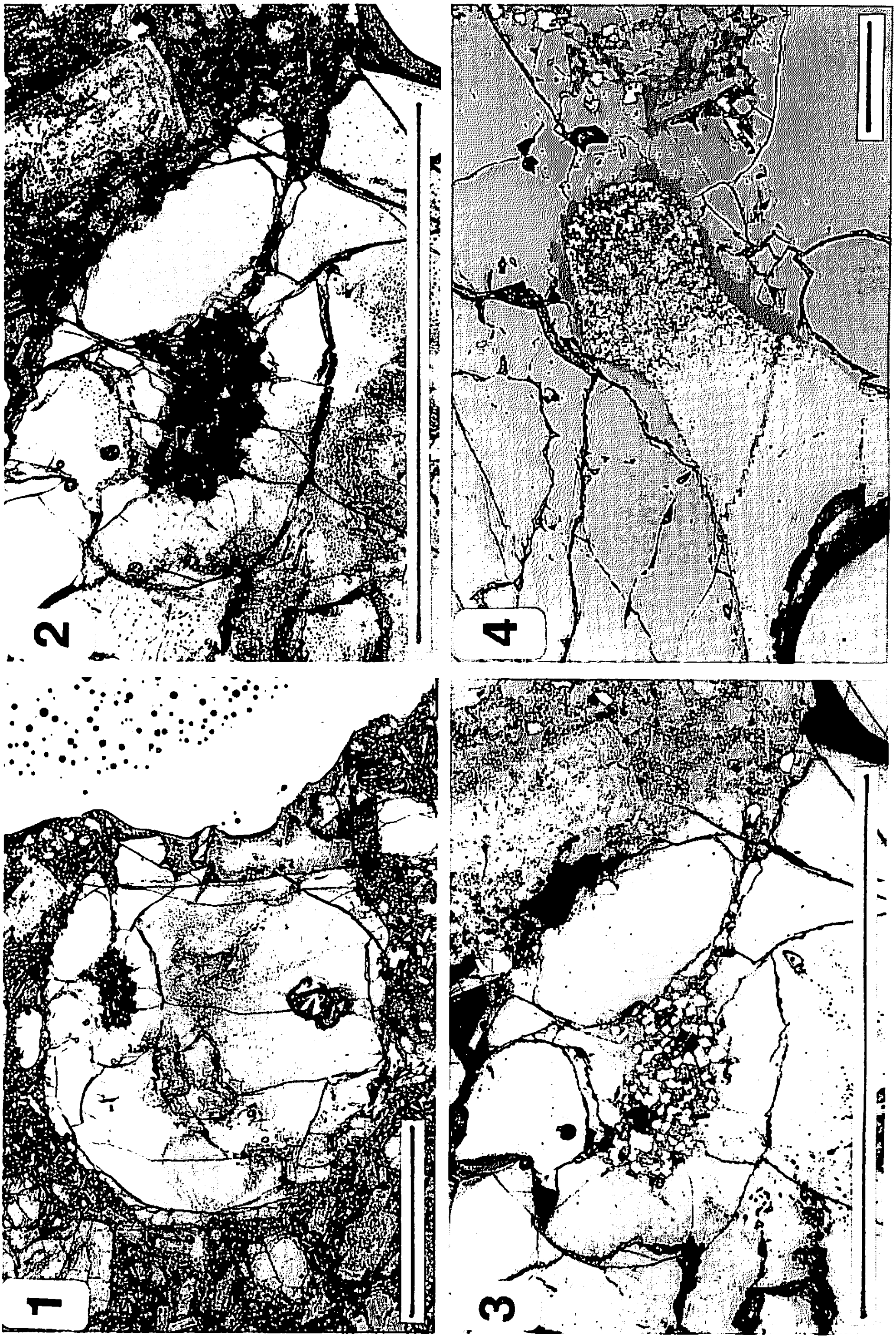


Plate IX Aggregate of opaque spinel included in olivine phenocryst of picritic basalt from Oshima-Oshima volcano, in the Sea of Japan off Hokkaido, northern Japan. Note the similarity of the decomposition product of mantle chromian spinel (figs. 3 and 4 of Plate VIII). Plane-polarized light.

fig. 1 Note the subhedral shape of olivine crystal.

fig. 2 Close-up of the opaque spinel aggregate. Note that the aggregate is open to the groundmass through a crack.

fig. 3 Reflected light.

fig. 4 Chromian spinel partly interacted with alkali basalt melt in a lherzolite xenolith (KWS-1) from Kawashimo. Reflected light. Scale bar is 0.1 mm.

Plate X

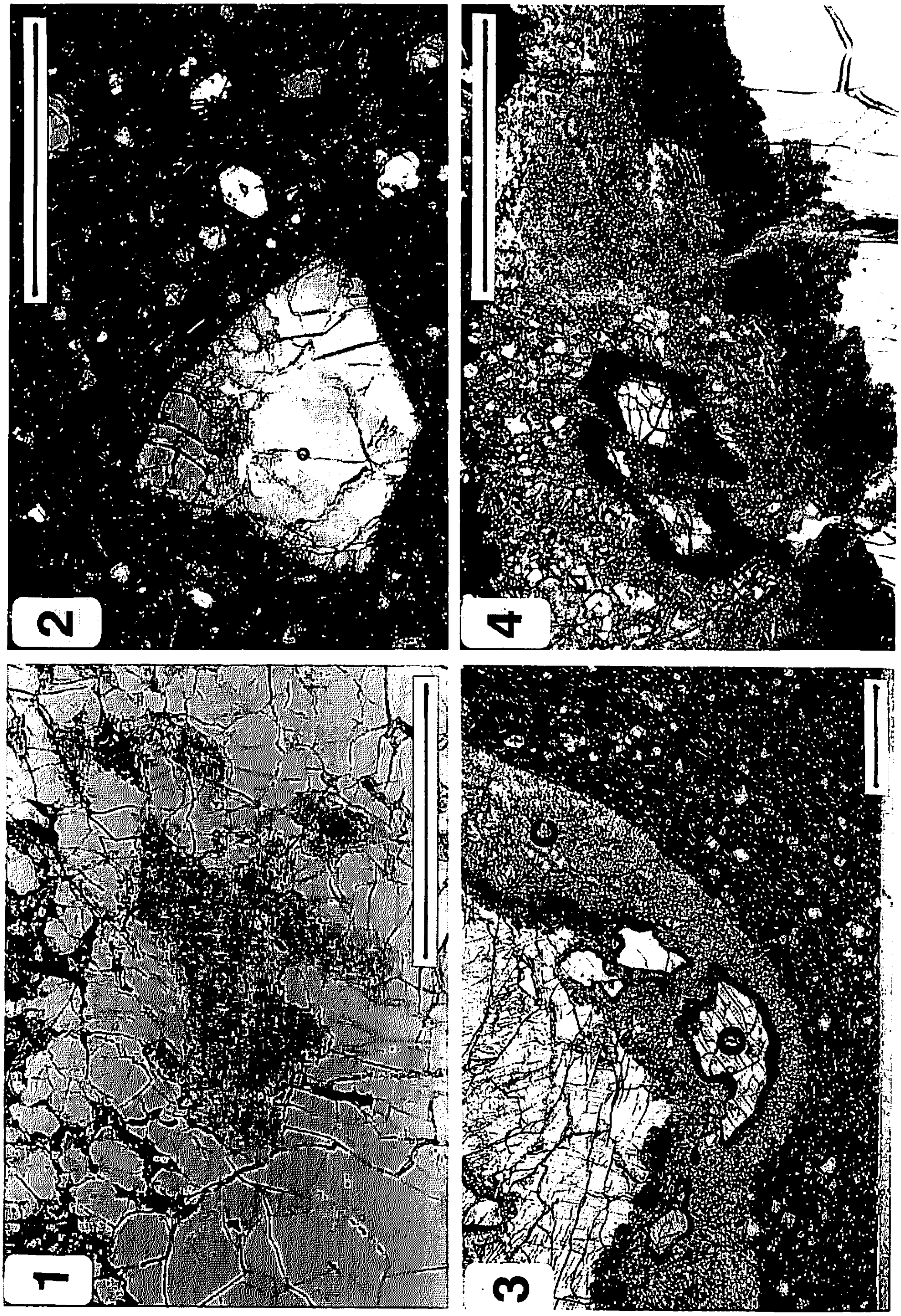


Plate X

fig. 1 Clinopyroxene with a spongy appearance in a clinopyroxene-bearing harzburgite (OQ-11) from Okete Quarry. Note also the disaggregation of olivine in the upper part. Plane-polarized light.

fig. 2 Kinked olivine xenocryst in alkali basalt adjacent to a harzburgite xenolith (KWS-2) from Kawashimo. Crossed-polarized light.

fig. 3 Thick interaction zone surrounding a websterite xenolith (KWS-15) from Kawashimo. Note the difference of the product between orthopyroxene (O) and clinopyroxene (C).
Plane-polarized light.

fig. 4 Thick spongy clinopyroxene rim in a websterite xenolith (KWS-15) from Kawashimo. Upper light part is orthopyroxene which is intensely decomposed.